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Research Article

Design and Fabrication of Bio-Inspired Robotic Systems for Developed Mobility and Functionality in Unstructured Environments

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ABSTRACT

In turn, bio-inspired robotic systems have significantly contributed to the development of well-abled robots capable of moving and manipulating with ease in unknown environments. Imitating biological creatures in their mechanisms of adaptation and effectiveness of design gives these robots enhanced qualities of mobility, functionality, and resilience. In fact, major advances build on flexible joints, controlled underactuation, adaptive control, and sensory arrays of high quality, enabling these robots to traverse rough environments and perform high-precision operations inside the human body. For instance, snake-like robots should be able to move through narrow gaps and debris in some kind of search and rescue task much like a real snake, robotic fish can move effectively across underwater environments while monitoring water quality and marine life. These advancements in technology have broadened the sphere of application and effectiveness of robot applications, proving to be valuable tools in many areas, including disaster response, environmental monitoring, and space exploration. In this regard, one also realizes their significance due to the context of bio-inspired robots regarding the capability of data collection and analyses. The usual methods of data collection are generally limited in reach, recurrence, and resolution. Bio-inspired robots compensate for these inadequacies by continuously gathering various real-time data from environments not easily reachable for humans. More precise and detailed analysis of data resolution collected through these robots supports advanced techniques such as AI and machine learning. This is a very crucial capacity that is central to applications such as following wildlife, assessing the impacts of climate change, and monitoring pollution levels. The capacity of these robots to provide timely and accurate data ensures efforts in environmental management and conservation. The importance of bioinspired robotics, therefore, comes in the solutions associated with unstructured environments. Through the gains of nature, which have been exploited by evolution, these robots present new solutions that overcome the inability of classical robotic systems. The persistence in the performance and development of this field of science will provide ever-greater achievements, with very probably a very important role in the exploration, understanding, and interaction with the natural world played by bioinspired robotics.

1. INTRODUCTION

Today, robotics forms a key area that integrates modern technology and has very huge impacts in several fields, including health, manufacturing, space research, and day-to-day consumer products; versatility and precision in robotic systems increase productivity and efficiency by making complex tasks manageable and repeatable. For health care, robots improve outcomes of surgery, rehabilitation, and care in general, lowering human errors. Whereby in the manufacturing field, robotic automation is very important in enhancing the rate of production and products' quality. For instance, the inclusion of robots in space exploration is able to undertake some tasks, for example, in the examination processes of the surfaces of other planets that are very risky and would be impossible for anyone to do, for example, Mars. Indeed, the proclivity to use robots as a pertinent part towards enhancing the technological capacity in different areas and addressing challenges is evident. But,

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in spite of all these remarkable advances in robotics over the past 4–5 decades, working in unstructured environments remains one of the hard and open challenges today [1]. Unstructured environments are far-reaching and under dynamic change, including disaster sites, underwater landscapes, and terrains from outer space. Classical robotic systems face difficulties in terms of navigation, perception, and adaptation in such scenarios. Issues have been established that include uneven terrains, variable lighting, and obstacles when dealing with high levels of sensory perception and decision-making capabilities in robots. In addition, novel designs and their corresponding control approaches have to be devised in assisting robots in those environments in order to maintain stability and mobility. Overcoming such challenges will suffice for the growing applications of robotics toward realization in areas that require resiliency and adaptability, ensuring that the utility and effectiveness within the real world are boosted. Nature itself provides the treasure trove of inspiration for dealing with the issues associated with more general-purpose robots in unstructured environments. These systems are biological and have been evolved by nature through millions of years; as a consequence, they tend to be extremely robust, efficient, and adaptable. For example, the locomotion of animals like insects, birds, and mammals clearly demonstrates various strategies of moving through varied terrains. For example, insects could include ants and beetles, which are all highly competent climbers on complex and rough surfaces, or birds, which are maneuvered with exquisite stamina and control of flight. It is therefore possible to borrow principles from these biological systems in the design of more flexible and efficient adaptive robotic systems. This approach is therefore referred to as biomimicry, which spells out the translations of mechanics and functions of sensing, as well as general behavioral patterns of living organisms in forms of robots. The bio-inspired robots that come up out of this are improved not only in locomotion and functionality but also show improved and advanced problem-solving capabilities, which make them more competent to deal with unpredictability in unstructured environments [2]. A schematic illustration of the field in the comprehensive framework and interdisciplinary approach to bio-robots and biohybrid robots is shown in Figure 1. Developed within the heart of this framework is the idea of designing Bioinspired and Biohybrid Robots according to the "principles" drawn from biological systems. The figure has been divided into four basic parts: Enabling Technologies, System Synthesis, Theory, and Application. Enabling Technologies refers to the core technological improvements that need to be made to create these robots, which include the mentioned materials, sensors, actuators, fabrication methods, compliance, energy systems, computation, and communication. These features are crucial to mimic the structural and functional characteristics of biological entities [3].

System Synthesis: It deals with the integration of such technologies toward the development of functional robotic systems. This encompasses the design and implementation of mobility mechanisms such as swimming, crawling, digging, walking, running, jumping, climbing, flying, and multimodal movements, together with manipulation capabilities. In addition, it involves creating collective and cooperative systems and facilitating human-robot interaction.

Theory: pertains to the scientific and mathematical foundations that guide the development of these robots. This includes models of the environment in which the robots will operate, control systems to manage their actions, dynamical models for predicting and adjusting behaviors, dimensional reduction techniques for simplifying complex biological processes, exaptation approaches (adapting features for new purposes), and advanced decision-making and creativity algorithms such as reinforcement learning and deep learning.

Application: highlights the various fields where bioinspired and biohybrid robots can be utilized. These applications range from exploration (both terrestrial and extraterrestrial), biomedical uses (such as surgery and rehabilitation), security, biodiversity and conservation efforts, environmental monitoring, structural inspection and maintenance, to social assistive and home services.

The overall aim of the study is to enhance the development process associated with bioinspired and biohybrid robotic systems for mobility and functionality in unstructured environments. Specifically, the research focuses on replicating some of the most adaptive and efficient mechanisms implemented by biological organisms to surmount the huge difficulties traditional robots face in complex and unpredictable terrains. In particular, it is intended to design and synthesize new robotic systems that make use of state-of-the-art enabling technologies such as advanced materials, sensors, actuators, sophisticated control systems, and algorithms inspired by biological processes. The ultimate objective is to come up with robotic solutions that could be effectively deployed into a wide array of applications related to exploration, biomedical applications, environmental monitoring, and security. This will encompass research into the theoretical fundamentals, technological advancements, and practical applications pertaining to bioinspired and biohybrid robots, as well as studies into the enabling technologies concerning materials science, sensor and actuator design, energy systems, and computational methods. This research ranges from the synthesis of robotic systems able to realize a wide variety of locomotion and manipulation tasks based on biological models. It has also been investigating the application of these robots in very diversified fields, which include biomedical and environmental monitoring, security, and structural maintenance [4]. A number of factors constrain this research work. The biological system can be accurately emulated, which may turn out to be very complex, and second, the development of robust control systems with reliable performance in highly variable environments is still a critical challenge. The fitting of several advanced technologies into cohesive and functional robotic systems is also foreseeably time-consuming, with heavy interdisciplinary collaboration and resources required. Notwithstanding these limitations, the research is intended to push the limits of the current robotic capabilities and to offer a substantial contribution in that field. A few key contributions toward the advancement of robotics are made through this research. First, it gives a comprehensive framework for the design and development of bioinspired and biohybrid robots, which is able to put together knowledge from biology, materials science, and engineering in one format. Emulation of Biological Systems [5][6].

2. LITERATURE REVIEW

Bio-inspired robotics, or biomimicry in robotics, may be defined as the process of designing and developing robotic systems whose mechanisms, structures, and functions are inspired by biological organisms. Biomimicry in robotics is crucial because it envisions replicating the adaptiveness, efficiency, and resilience of natural organisms to deal with issues that have traditionally posed problems for more conventional robotic systems, most particularly unstructured environments. The historical perspective of bio-inspired robotics provides a development from simple mechanical emulation of animal movements to sophisticated systems that lend incorporation of biological principles at different levels. Some major milestones in this area include robotic limbs and appendages that mimic insect locomotion, drones inspired by bird flights, and underwater robots replicating fish swimming mechanics. These developments have been enabled by interdisciplinary research drawing on such aspects as biology, engineering, materials science, and computer science. Traditionally, concepts for the mobility and functionality of robots are based on stiff constructions and predefined motion patterns; these were considered sufficient for structured environments like factory floors or laboratory settings. These robots, designed to perform tasks that do not require much adaptability, move by means of wheels, tracks, or fixed joints. The challenges of action posed by unstructured environments—young, rough terrain, obstacles, and variable conditions—however, prove quite formidable to these traditional designs. For example, complex and unpredicted scenarios under which a situation may call for advanced perception, decision-making, and flexible mobility mechanisms exist in abundance in such environments. Traditional robots have issues with aspects such as stability, surmounting, and adaptation to environmental changes, which implicates their poor performance in the real world outside the controlled environments [7]. Another very vital area of application is in unstructured environment applications, where traditional robots fail in performance, and thus bio-inspired robots are very useful. In this regard, search and rescue missions can be carried out by bio-inspired robots to a greater extent by following debris and rubble through places considered impassable or dangerous for human responders. For example, snake-like robots can move through tight spaces, while quadruped robots can move on rough ground, so they provide valuable assistance during disasters. In exploration, both terrestrial and extraterrestrial, the adoption of bio-inspired robots could achieve enhanced mobility and functionality. They can climb, swim, or even fly through very diversified landscapes and return data from places that were inaccessible earlier. The Mars rovers can be considered a great example of how these creatures can move on the planet with challenging landscapes by incorporating some bio-inspired design elements. Another very important application is environmental monitoring. Bio-inspired robots, through their ability to imitate behavior and motion from an animal, could monitor ecosystems, track wildlife, and collect autonomously where it is harsh or remote. This capability of the robots to imitate behavior and motion derived from an animal makes them interact with the environment in a more natural and less disruptive way, hence offering a more accurate and comprehensive way of collecting data. These applications thus demonstrate the huge potential of bioinspired robotics to move beyond the limitations of conventional robots and generally enhance the functionalities of robotic systems in complex and dynamic real-world settings [8].

Table I shows the Problems in Traditional Robotic Solutions and Key Parameters. Traditional robotic systems, while effective in controlled environments, face significant challenges in unstructured settings due to limitations in their design and functionality. Mobility issues arise from reliance on wheeled or tracked systems that struggle with rough or uneven terrain, and fixed-joint robotic arms that lack the flexibility and range of motion needed for complex tasks. These traditional approaches are further hindered by poor adaptability to changing environments, as their predefined motion patterns do not accommodate dynamic scenarios [9]. Sensory perception in traditional robots is often limited by basic sensor arrays, which have restricted detection range and sensitivity, impeding the robots' ability to navigate and interact with their surroundings effectively. Decision-making capabilities are another critical limitation, as rule-based algorithms fall short in unpredictable scenarios, leading to inadequate responses in real-world applications [10].

Energy efficiency remains a persistent problem, with traditional robots dependent on continuous power supply or batteries that offer short operational times and high energy consumption. This is compounded by the rigidity of their structures, which hampers their adaptability to new or dynamic environments and reduces overall stability on uneven or moving surfaces [11]. The environmental impact of traditional robots is also a concern, as they are typically constructed from industrial materials with a high environmental footprint. Additionally, the high cost of high-tech components and manufacturing processes limits their accessibility and scalability [12]. Bio-inspired robotics aims to overcome these limitations by emulating the adaptive, efficient, and resilient characteristics of biological organisms. This approach promises to enhance parameters such as mobility, functionality, sensory perception, decision-making, energy efficiency, adaptability, stability, environmental impact, and cost, making robotic systems more effective in unstructured and dynamic environments.

TABLE I. PROBLEMS IN TRADITIONAL ROBOTIC SOLUTIONS AND KEY PARAMETERS

Problem Area	Current Solutions	Problems	Parameters
Mobility	Wheeled or tracked robots	Limited in rough or uneven terrain	Terrain type, obstacle height, surface material

	Fixed-joint robotic arms	Lack flexibility, limited range of motion	Joint flexibility, range of motion, degree of freedom
Functionality	Predefined motion patterns	Poor adaptability to changing environments	Environmental variability, task complexity
Sensory Perception	Basic sensor arrays	Limited detection range and sensitivity	Sensor range, sensitivity, resolution
Decision-Making	Rule-based algorithms	Inability to handle unpredictable scenarios	Algorithm complexity, adaptability, processing speed
Energy Efficiency	Continuous power supply or battery	Short operational time, high energy consumption	Power consumption, battery life, energy storage capacity
Adaptability	Rigid structures	Difficulty in adapting to new or dynamic environments	Structural flexibility, material properties
Stability	Static balance mechanisms	Poor stability on uneven or moving surfaces	Center of gravity, balance control, response time
Environmental Impact	Industrial materials	High environmental footprint	Material sustainability, biodegradability, environmental impact
Cost	High-tech components and manufacturing processes	High cost, limited accessibility	Manufacturing cost, component cost, scalability

3. LITERATURE REVIEW

Bio-inspired robotics, also known as biomimicry in robotics, refers to the process of designing and developing robotic systems whose mechanisms, structures, and functions are taken from the domain of biological organisms. The importance of biomimicry in robotics comes from how it can use the adaptiveness, efficiency, and resilience of natural organisms to surmount the limitations posed by traditional robotic systems, mostly related to unstructured environments. Biomimetic approaches to robotics open up possibilities for complex tasks by emulating biological principles in flexible movement, adaptive behavior, and energy efficiency. This new paradigm in the design of robots is therefore a vital element in increasing their functionality and versatility, making them able to move around and function in a dynamic or unpredictable environment. The historical development of bio-inspired robotics itself mirrors a gradual evolution from simple mechanical imitations of animal movement to advanced systems that integrate biological principles at multiple levels. Past early efforts in this field have focused on replicating basic locomotion in animals: for example, robotic limbs that emulated the walking of insects. As time progressed, interdisciplinary research biology, engineering, materials science, and computer science—moved these designs to higher sophistication. These key developments include developing drones that can fly like birds and are capable of agile and stable aerial maneuvers, as well as underwater robots that duplicate fish swimming mechanics to allow them to move efficiently in aquatic environments [13].

One example is robotic prosthetics and appendages developed to imitate functional movements of the human limbs, which enables users to gain enhanced mobility and dexterity. Another related breakthrough is the quadruped robots, whose design was based on mammals. The quadruped robots have higher stability and adaptability to uneven terrains, so they are very useful in search and rescue missions and environment monitoring. Moreover, bioinspired robots have been developed to realize the sensory and neural processing capabilities of biological systems. For example, artificial sensory systems inspired by compound eyes of insects have made a vision capability realized in robots with high resolution and fast motion detection. In the same way, the control systems built based on neural networks permit performing in robots complicated decision making and adaptive behaviors. Large strides in the field of bio-inspired robotics are based on a deep understanding of biological systems and their application to the design of robots[14]. This has made it possible to extend the ability of robots to work more effectively in difficult and unstructured environments, thereby increasing their practical utility in many different areas. The historical trajectory of bio-inspired robotics goes from basic mechanical imitation of biological movements to a highly sophisticated system integrating complex biological principles. It began in the middle of the 20th century, wherein the initial efforts had involved just the basic mechanical replication of animal locomotion. These prototypes were mostly called "animatronics," which would try to imitate the movement patterns of animals by simple mechanical constructs. For example, robotic limbs and appendages were designed to imitate the walking pattern of insects and the grasping feature of the human hand. Although none of the advanced sensory and adaptive properties found in modern robots were integrated into these early models, they set up the foundational concepts for biomimetic design [15].

Huge interdisciplinary collaboration, with borrowing from biology, engineering, materials science, and computer science, began to take place after technological developments. The key milestones of bio-inspired robotics have been the construction of robotic systems that can replicate the highly complex flight mechanics exhibited by birds and insects. Including among these are drones working on avian flight, imitating the wing flapping and hovering abilities that revolutionized this area. These bio-inspired drones showed advanced agility and stability during flight, so they were very useful in applications like surveillance and environmental monitoring. Another advancement in this line of research was the underwater robots inspired by fish mechanics. In aquatic applications, such robots, popularly known as "robotic fish," utilize flexible and streamlined designs to offer efficient propulsion and maneuverability. Investigations into fish locomotion undulating body movements

and fin motion help engineers come up with the robots. Now, underwater exploration became possible: monitoring marine ecosystems and making underwater inspections were now able to be performed efficiently [16].
It also includes the evolution of robotic prosthetics and exoskeletons, which drew inspiration from the human musculoskeletal system to return mobility and dexterity to disabled persons. The devices moved from early designs replicating simple human limb movement to modern-day prosthetics sporting advanced materials and sensors that allow more natural and responsive movements. Thanks to neural interfaces, some prosthetic devices can be directly controlled by the brain, greatly improving their functionality and user experience[17]. At the same time, key advancements in sensory and neural processing capabilities have also pushed innovation forward. Guided by principles from the compound eye of insects, researchers developed artificial vision systems that allow for high-resolution imaging and fast motion detection. These systems endow robots with the capability to move around complicated environments at a higher degree of precision and speed. In addition, control systems based on neural networks—which are styled after the processing pathways of the brain—have further endowed robots with very sophisticated decision-making and adaptive behaviors. The advances have greatly enhanced the capability of the robots to interact with their environment and execute complex tasks autonomously. The historical development of bio-inspired robotics has been huge, evolving from simple mechanical imitations to complex systems that have been able to harness the principles of living organisms. It has been driven by continued interdisciplinary research and technological innovation, finally offering robots that are more able and adaptive, with improved efficiency in performing various tasks in different environments. Two of the most prominent developments in that sphere underpin the potential of biomimicry to transform robotics design and further push its horizons.

3.1 Mobility and Functionality in Robotics

The mobility and functionality of traditional robotic systems have mostly been achieved through rigid structures and motion patterns. Designers therefore often optimize these designs to function best in controlled environments like factory floors, laboratories, and structured indoor settings. A very common approach with regard to this is the usage of either wheeled or tracked robots but, in general, all of these types, whether wheels or tracks, are intended to move on a certain surface. Wheeled robots are made to be applied on smooth, flat surfaces where high speed and efficiency are carried out [18]. Tracked robots provide more stability and traction on rougher terrains, though they have been limited to relatively predictable and structured environments. The other common design is the fixed-joint robotic arm, which has been developed also for precision tasks, e.g., assembly, welding, and painting. These arms work within a defined workspace and, through repetition, perform tasks with high precision. Most of the conventional robots are typically equipped, in terms of their sensory perception and control systems, with simple collections of sensors and rule-based algorithms. Examples of such sensors are cameras, proximity sensors, and infrared detectors, which collect basic information needed for the ability to navigate and act on tasks. The control systems have, for the most part, heuristic instructions that facilitate the ability of the above-mentioned robots to traverse boundaries and execute tasks. Consistent with this, this makes them reliable and consistent in scenarios where variables are few and predictable. Most traditional robots also rely on power supplies or batteries which provide continuous power but have limited running times hence suitable for use in a structured scenario where recharge facilities or a power source can be made available within a short period of time[19]. Despite the success of traditional robots in structured scenarios, their performance in unstructured scenarios is wanting. Unstructured environments are therefore characterized by uncertain and dynamic conditions like the irregular terrain, changes in illumination, presence of obstacles, and weather variation. Under these scenarios, traditional robots are not able to handle these scenarios since they are powerfully limited by their rigid designs and pre-defined patterns of motion. For instance, wheeled or tracked robots move with much difficulty on rocky, sandy, or slippery surfaces, usually losing grip or becoming stuck. The fixed arms on the robotic joints can very poorly hold irregular objects and adjust in variable workspaces, which makes it inefficient for applications requiring flexibility and adaptability. Inappropriate sensing perception systems for unstructured environments also extend to traditional robot designs. Severe limitations in both the detection range and sensitivity of basic sensor arrays severely impinge on the effectiveness with which a robot can perceive and interact with its environment. As such, this could cause the inability to avoid running into unexpected obstacles, the inability to notice and react to changes within the environment, and complexities in the accomplishment of tasks like the execution of complicated algorithms that require sophisticated sensory information. In addition, rule based algorithms to control do poorly in dynamic environments as these lack the provision decision taken in regard to uncertain parameters on a real-time basis. This, in turn, results in very poor adaptability and bad decision making, therefore making traditional robots unreliable for application in real life, which requires flexibility and faster responses. Energy efficiency is another critical challenge to traditional robots in unstructured environments. The continuous power supply or short battery life usually limits the operational time, which becomes a big problem in remote or hard-to-reach areas where recharge options are not feasible. Moreover, the structures of conventional robots are too rigid to be capable of handling new or changing conditions; hence, they easily lose balance or tip over on an uneven or moving surface. That is, while traditional approaches of robotic mobility and functionality are outstanding in structured scenarios, they are highly limited within unstructured environments. However, this has not achieved the needed adaptability, high-level sensory perception, decision making, and energy efficiency in performance for operation in dynamic and/or uncertain scenarios.

These challenges raise the need for new designs and technologies that can equip robots with better capabilities to work efficiently in most real-world environments [20].

3.2 Applications in Unstructured Environments

One of the most important applications of robotics in unstructured environments is search and rescue. This would typically involve motion through debris, rubble, or collapsed structures after natural disasters such as earthquakes, floods, and landslides. Traditional robots with their rigid structure and patterns of motion that are predefined are quite ineffective in such chaotic and unpredictable scenarios. However, the bio-inspired robots still have immense advantages in that they could imitate the flexible and adaptive locomotion of animals. For instance, snake-like robots could burrow through narrow gaps and tunnels to enter areas inaccessible to humans or any other traditional robots[21]. Quadruped robots, inspired by such animals as dogs or goats, may move on uneven and unstable grounds, keeping their balance and stability while carrying out search operations. The next generation of bio-inspired robots would be equipped with state-of-the-art sensing systems, increasing their capacity to detect the slightest signs of life, including body heat, movement, or sounds coming from under the debris. With artificial intelligence on board, these robots could make decisions in real-time and adjust to their environment. Such adaptability not only makes search and rescue operations more efficient but also highly raises the possibilities of finding and saving survivors from a critical situation. Involving bio-inspired robots in such missions can reduce the potential risks to human rescuers and cover more areas of the disaster with a lesser number of field personnel, more quickly. Another prominent area of exploration, whether terrestrial or extraterrestrial, is also done excellently by bio-inspired robotics [22]. In these exploration missions, high levels of adaptability, mobility, and resilience are required from robots to perform in unstructured and frequently harsh environments. It comprises dense forests, mountainous regions, caves, underwater landscapes, and so on, related to terrestrial exploration. Traditional robots have failed to perform in such environments because they cannot move in difficult terrains and often require continuous power sources. Contrarily, bio-inspired robots, such as those designed after insects, birds, or aquatic animals, could move efficiently in such challenging environments. For instance, drones that took cues from bird flight can swim across dense forests and rocky landscapes to provide missions with aerial reconnaissance and data collection. Underwater robots modeled after fish can explore the depths of oceans, rivers, and lakes and realize scientific research tasks and environmental monitoring. Other bio-inspired designs benefit from extraterrestrial explorations targeted at missions to either Mars or other celestial bodies. For example, the Mars rovers integrate some bio-inspired robotics when navigating in an uneven and rocky terrain to guarantee stability and mobility during extreme temperatures and dust storms on the planet. All these robots would play a very major role in acquiring geological samples, searching for signs of past life, and providing critical data needed in future manned missions.

Another very important application area of bio-inspired robotics is in environmental monitoring with respect to climate change, conservation, and biodiversity studies. Traditional monitoring techniques become really difficult to handle in areas like dense forests, wetland surroundings, and remote ecosystems, and other unstructured environments. The greatest change will come in techniques for gaining and analyzing environmental data independently for a longer period by bio-inspired robots. For example, insect- or small-mammal-inspired robots could go deep into the thick underbrush and canopy layers to monitor plant health, wildlife populations, and environmental changes of all kinds related to pollution, deforestation, and so forth [23]. Such robots could be equipped with cameras, temperature and humidity sensors, and chemical detectors to make extensive environmental data collections. These robots' ability to replicate natural motion allows them to blend into the environment, create very minimal disturbance to the ecosystem, and produce more complete and reliable results. Bio-inspired robots, in aquatic applications and designed after fish or amphibians, could test water quality, track marine life, or establish the health of coral reefs. These collected data are of paramount importance in the development of conservation strategies, management of natural resources, and fighting environmental threats. Bio-inspired robotics serves in a rather transformative role within applications situated in unstructured environments. These robots enhance the effectiveness and safety of missions relating to search and rescue by making navigation across complex and hazardous terrains possible. In both terrestrial and extraterrestrial exploration, it is the bio-inspired designs that provide mobility and adaptability to carry out effective investigation. It is such robots within environmental monitoring that are providing new solutions for the gathering of key data from remote and sensitive ecosystems. The versatility and advanced capabilities of bioinspired robots dramatically increase the reach and effectiveness of robotic applications in the real world [24].

4. PRINCIPLES OF BIOMIMICRY IN ROBOTIC DESIGN

The foundation of biomimicry in robotic design rests upon a deep understanding of the key biological systems and their intrinsic functionality. These systems have evolved to be outstandingly efficient, adaptive, and resilient, offering a wealth of design principles to be emulated into robotics. Core among these are the musculoskeletal, sensory, and neural networks that underpin movement, perception, and cognitive functions of organisms. The musculoskeletal system of bones, muscles, tendons, and ligaments performs locomotion and support functions in a living being. Its interaction with the organism makes possible all forms of locomotion, from walking and running to swimming and flying. Biomechanical principles for these movements proved essential in developing their robotic counterparts with the requirement of both strength and flexibility [25]. For instance, it is because of the multi-jointed limbs in mammals that robotic appendages can be developed that can execute complex and fine movements, therefore making robots capable of accomplishing tasks more adeptly where fine motor skills are called for. Sensory systems in organisms are very specialized and optimally adapted to the needs of a particular environment. They contain visual, auditory, olfactory, gustatory, and tactile sensors, providing very useful information about surroundings[26]. Compound eyes of insects provide a huge field of view and high-speed motion detection, thus being one of the very best models in an attempt to develop high-performance robotic vision. On the other hand, echolocation capabilities in bats and dolphins have implications for the design of sonar and ultrasonic sensors that give robots navigation and object detection in low-visibility conditions. These neural networks serve as the control centers that work with the sensed information to make decisions and coordinate actions in a biological organism. Such networks are very efficient, capable of learning and adaptation, and making complex decisions in real time. By mimicking the structure and function of these neural networks, engineers can develop sophisticated control systems for robots. Artificial neural networks, like biological cognition, and machine learning algorithms empower robots to learn from their environment, enhance their performance over time, and handle unexpected situations with greater autonomy and intelligence [27].

The natural adaptations that exist in different organisms can provide a wealth of examples to make adjustments in order to enhance robotic design, mainly with respect to its mobility and functionality. These adaptations have been the result of evolution over millions of years, fine-tuning organisms to their environment and making them effective, resilient, and versatile. For instance, the way a gecko can climb smooth surfaces and walk upside down is simply astounding. They do it through millions of microscopic hair-like structures on their feet, called setae, which create van der Waals forces that keep the animal attached to any surface without ever using adhesives[28]. It is a principle that gave rise to gecko-inspired adhesives for robots, enabling them to climb walls and across ceilings. Such capabilities can be used to perform inspection and renovation work at highly inaccessible places, such as tall building exteriors or complex machinery. Another good example is the insect, like ants and beetles, that move around complex and rough terrains. Their extremely adaptive legs adjust the grip and movement depending on the surface, providing stability and mobility in challenging environments. These have led to multi-legged robots which walk by mimicking the locomotion of these insects and have proven to walk efficiently across rocky landscapes and through urban environments littered with obstacles. Such robots are quite useful in search and rescue operations where they find survivors by crawling through debris and rubble .

The mechanics of flight of birds and other insects have largely influenced the designing of aerial robots. Birds have lightweight skeletons but with great strength in their structure and strong muscles, permitting continuous flapping. Some insects are capable of hovering and turning. Such characteristics of life inspired engineers to develop drones that imitate the flapping wing motion of birds and some insects. In design, this gives better maneuverability and stability than a traditional fixed-wing design. Application fields for such drones include surveillance, environmental monitoring, and supply to isolated or unreachable places. The hydrodynamic bodies and effective swimming techniques of fish have inspired the design of underwater robots in aquatic environments. Fish flex their bodies and flap their fins to swim through water with a very minimal expenditure of energy. Just by applying this principle, it has been possible to develop robotic fish that will swim around and undertake detailed inspections underwater and monitoring aquatic ecosystems. Such robots can move very precisely, respond to different currents, and work in silence, making them very suitable for scientific research and environmental monitoring. A deep understanding of the mechanisms behind biological systems, along with their natural advantages, forms a very good foundation for the design of state-of-the-art robotic systems. Engineer robotics that emulate the musculoskeletal, sensory, and neural functionalities of living organisms, and get inspired by their adaptive mechanisms for more efficient, versatile, and capable robots to do complex tasks in diverse and dynamic environments.

4.1 Translating Biological Principles to Robotics

One translates these principles to robotics by studying biological systems in great detail to learn how they work and what they can do. The most basic method is biomimetic observation: carefully observing and recording the behavior of the organisms, together with their physical appearance in the context of their natural environments. With high-speed cameras and microscopic image acquisition tools, it should be possible to capture small-scale movements and interaction dynamics of organisms, giving insights into how efficient locomotion, sensing, and interaction with their environment come about.

Another important methodology is comparative biomechanics, which involves the study of physical structures and movement patterns of different species. Through such attributes, researchers draw comparisons across a myriad of organisms to understand which strategies are most effective in solving similar problems and then apply these in robotic designs. For example, studies of the locomotion techniques used by versatile insects, birds, and fish may indicate the optimum methods by which mobility can be achieved in various environments.

Genetic and molecular biology techniques also provide huge insight into the basics of biological systems. For instance, scientists, by taking inspiration from the genetic and molecular basis of specific traits or behaviors, are able to replicate such properties in synthetic materials and robotic systems. For example, research into the composition and structure of spider silk has given birth to synthetic fibers with imitations of its exceptionally huge strength and elasticity that would be useful for making durable yet flexible robotic components.

Computational models and simulations are some of the very powerful tools in translation of the biological principles into robotics. These models simulate physical and functional characteristics of biological systems, therefore allowing a researcher to test and fine-tune their designs in a virtual environment. Computational models are run under a wide range of conditions and situations to optimize design parameters so that the resulting robotic systems will be effective and efficient.

This is also a process that is interdisciplinary in nature. Biologists, engineers, materials scientists, and computer scientists combine their expertise to ensure that the principles of biological science are accurately translated into robotics design. Such a collaborative approach would encourage innovation and develop high-end robotic systems more closely imitating their biological counterparts.

The adopted principles of design from nature have to be diverse to meet specific functionality needs and difficulties during application. Among the most essential is, of course, structural efficiency. The framework in biological organisms is light yet strong, as found in many organisms. For example, the hollow yet lightweight bone structures of the birds can be an excellent base for making lightweight yet strong robotic structures so that robots can do their operations efficiently, maintaining their structural integrity.

Another fundamental principle observed in biological systems is multifunctionality: structures frequently perform several functions to optimize the use of resources. For example, the feathers on birds support flight, insulate, and waterproof. This can result in robotic components performing several functions simultaneously, making the robot thinner and lighter—for instance, sensors embedded in the structure of the robot that will minimize weight and reduce complexity.

Two of the most important design principles learned from nature are adaptability and flexibility. A great many organisms show amazing adaptability to their surrounding environments. Such adaptability is provided for by flexible structures and dynamic control systems. For example, an octopus distorts its body to squeeze through narrow spaces; this has inspired the development of soft robots with flexible bodies and actuators that navigate complex and cluttered environments more easily than rigid robots.

It is an important principle in nature: Energy sources are frequently sparse. Biological systems have, by evolution, reduced energy use but achieved maximum effect. Animals like cheetahs and dolphins show effective muscular movements, which may serve as role models for the design of robotic drive units capable of developing maximum forces at minimum energy consumption. By copying such effective movement patterns, a robot could work for a longer period with restricted power supplies, increasing its applicability in remote places or with low resource availability.

Other such principles learned from nature include self-healing and resilience. The vast majority of living organisms have the tendency to heal themselves when injured. This has lately been replicated in robotic systems. In this sense, creating self-healing materials and structures allows robots to keep functionality and prolong operational life in hostile or unknown environments. This becomes a very important principle when dealing with areas such as space exploration or underwater operations, where maintenance or repair is complicated. Detailed observation, comparative studies, genetic studies, computational modeling, and interdisciplinary collaboration are some of the methods applied in analyzing and imitating living organisms. These five design principles distilled from nature—structural efficiency, multifunctionality, adaptability, energy efficiency, and self-healing—are therefore able to provide a robust framework with which to develop advanced robotic systems. By emulating these principles, engineers can design robots that are more efficient, adaptive, and capable of executing complex tasks in very different and highly dynamic environments.

Table II summarizes the various approaches used in the design of bio-inspired robotics, along with their challenges and a variety of application fields that such developments are being assimilated into, in order to fix the more prevalent issues for the achievement of more efficiency, adaptability, and resilience of robotics systems in a wide range of complex dynamic environments.

TABLE II .CURRENT METHODOLOGIES, PROBLEM STATEMENTS, AND APPLICATION AREAS IN BIO-INSPIRED ROBOTICS

Current Methodology	Current Problem Statement	Application Area
Biomimetic Observation	Limited ability to replicate the detailed movements and behaviors of organisms in artificial environments.	- Search and Rescue
		-Environmental Monitoring
		- Medical Robotics
Comparative Biomechanics	Difficulty in translating complex biological movements into robotic mechanisms without losing efficiency.	-Prosthetics and Exoskeletons
		- Industrial Automation
		- Space Exploration
Genetic and Molecular Biology	Challenges in replicating the exact material properties of biological tissues for durable and flexible robotic components.	- Biomedical Engineering
		- Soft Robotics
		- Material Science Research
Computational Modeling and Simulation	High computational cost and complexity in accurately modeling and simulating biological systems.	- Robotic Design and Optimization
		- Autonomous Vehicles
		- Simulation-based Training Systems

Interdisciplinary Collaboration	Difficulty in integrating diverse scientific disciplines to create cohesive and functional bio-inspired robotic systems.	- Advanced Robotics Research
		- Collaborative Robotics (Cobots)
		- Environmental Surveillance
Structural Efficiency	Ensuring lightweight yet durable structures that can withstand varied and dynamic loads.	- Aerospace Engineering
		- Maritime Robotics
		- Military Applications
Multifunctionality	Balancing multiple functionalities without compromising overall system performance.	- Agricultural Robotics
		- Multi-purpose Service Robots
		- Smart Manufacturing
Adaptability and Flexibility	Achieving high adaptability and flexibility in robots to operate in unpredictable environments.	- Disaster Response Robotics
		- Underwater Exploration
		- Space Robotics
Energy Efficiency	Designing robotic systems that minimize energy consumption while maintaining high performance.	- Renewable Energy Sector
		- Environmental Monitoring
		- Autonomous Drones
Self-healing and Resilience	Developing materials and systems that can self-repair to extend operational life.	- Space Exploration
		- Military Robotics
		- Industrial Maintenance Robots

5. DESIGN AND DEVELOPMENT OF BIO-INSPIRED ROBOTIC COMPONENTS

5.1 Mobility Components

Designing mobility components in bioinspired robots is essentially an engineering exercise in replicating the adaptability and efficiency of biological organisms. In these robots, the mobility mechanism could be legs, wheels, or even a combination of both; the selection depends on the kind of application and environment that the robot is going to work in.

- Legged Robots: Legged robots take their inspiration from animals such as insects, mammals, and reptiles and are designed for movement on complex and uneven terrains. This calls for studying the joint articulation, muscle dynamics, and gait patterns of these animals. Multi-jointed legs provide flexibility and range of motion, often actuated to mimic the action of muscles to help in traversing obstacles and maintaining stability on rough surfaces. Advanced legged robots can dynamically adjust their gait and posture like an animal does on finding changes in the terrain. For example, the Boston Dynamics' robot "Spot" realizes impressive mobility in a variety of environments only with four articulated legs, supporting the deployment of these principles in real life. Wheeled Robots: Wheeled robots are typically used on grounds that are mostly even and predictable.

However, bio-inspired designs can improve their performance. For example, robots with re-configurable wheels that morph into legs or tracks will enable them to overcome mixed terrains. One such example of this strategy is the "RHex" robot with its hybrid flexible and rotating leg-wheel system, marrying the speed and efficiency of wheels on flat surfaces with climbing and obstacle-negotiation capabilities of the legs.

- Other Mobility Mechanisms: Other, yet innovative, mechanisms of mobility take their inspiration from biological models. Snake-like robots, for example, provide undulation of snakes through a line of articulated segments, and therefore they can move through narrow spaces and complex environments. This holds true for robots adapted from fish swimming dynamics or even the flying styles of birds and insects, in which bio-mimetic principles would enable such machines to move about as efficiently and as flexibly in their respective media. The "AquaJelly," an underwater robot from Festo, is able to copy the principle of propulsion of a jellyfish, guaranteeing fluent and energy-efficient motion.
- Materials and Fabrication Techniques :

An appropriate selection of materials and fabrication techniques in the development of bio-inspired robotic components will be very critical. These materials have to realize a trade-off between strength, flexibility, durability, and weight if they are to replicate properties of biological tissues/structures.

- Materials : Advanced materials in use today in bio-inspired robotics include lightweight metals, composites, polymers, and smart materials. Lightweight metals such as aluminum and titanium provide a high strength-to-weight ratio necessary for a sturdy yet agile robot. Composites and polymers provide the required flexibility and resilience for components that are subject to cyclic motion and impacts. Smart materials, like shape-memory alloys and electroactive polymers, change their properties under simple stimulation, such as temperature or an electric field, thus enabling the construction of adaptive structures that change shape or stiffness according to the situation.

- Fabrication Techniques : Modern techniques of manufacturing technologies are often used in the fabrication of bio-inspired robotic components. 3D printing enables the creation of complex parts with a given custom design where geometries are intricate and difficult to obtain using traditional methods. This technology is very useful for prototyping and making small batches of components. Fabrication techniques in soft robotics use flexible and elastic materials to make robots that are designed to safely interact with humans and delicate objects. Such elements of the production process include injection molding and soft lithography.

Another critical technique in this area is multi-material manufacturing, whereby it becomes possible to have a single component include more than one material for their unique properties. Consider that, with this technology, a single robotic limb could combine rigid segments for support with flexible joints for mobility, all created in a seamless process. Applied on the mobility component are biomimetic surface treatments, which increase grip by adding microstructures or reduce drag, among other things, to enhance functionality. These are surface treatments that draw their inspiration from the surface of biological entities, such as the textured skin of geckos or the hydrodynamic scales of fish.

5.2 Sensory and Control Systems

Advanced sensing systems are critical to develop and integrate in bio-inspired robotics for the realization of complex perceptive abilities the biological organisms exhibit. Bio-inspired sensors, designed to work in a manner similar to the senses of living beings, allow robots to interact with their environment in more nuanced ways that adapt.

- Visual Sensors : Probably the most critical of the sensory systems is vision. Enforcing the compound eye principles of insects has spawned a variety of multi-faceted visual sensors featuring a wide field of view and rapid motion detection. Compound eye-inspired sensors, typically comprising plenty of small lenses, offer high-resolution imaging and improve the ability of robots to follow fast-moving objects. Vision sensors could be integrated into robotic systems through innovative image processing algorithms that allow the analysis and interpretation of visual data in real time, so that the robots are able to move around in unknown environments efficiently and respond accordingly.
- Tactile Sensors: Another important sensory modality is touch. As inspired by the tactile sensitivity of the human skin, the bioinspired tactile sensor is able to detect changes in pressure, texture, and temperature. In most cases, such a sensor is fabricated from soft materials that have microelectromechanical systems embedded, which react against physical contact. A robotic gripper or limb equipped with tactile sensors can easily manipulate fragile objects and further self-adjust the grip on the object by its texture and fragility. This is of particular value in applications like medical robotics and manufacturing, where delicate and precise handling is crucial.
- Auditory Sensors: Auditory sensors, bioinspired by the hearing mechanisms of animals, let robots detect and localize sounds. Such sensors can be applied in areas where there are important audio cues in the environment, for example, in search and rescue missions or scenarios of human-robot interaction. Guided by the directional hearing of animals such as owls, robots fitted with bioinspired auditory sensors will be capable of exactly determining sound sources even in a noisy environment.
- Chemical Sensors : The chemical sensors of the robot, motivated by the animal olfactory sensing systems, allow a robot to smell its surroundings and identify several substances. These are designedly engineered to perform applications associated with environmental monitoring, hazardous material detection, and medical diagnosis by replication of the sensitivity and selectivity of the animal nose. Integrating chemical sensors into robots incorporates state-of-the-art signal processing techniques for the analysis and interpretation of the detected chemical signatures with appropriate accuracy.
- Control Algorithms Mimicking Biological Responses
  Control algorithms that copy the responsive behavior of biological organisms, in a way, enhance the effectiveness of bio-inspired sensors. It involves processing sensory inputs and producing appropriate corresponding actions to let the robots navigate complex environments and perform autonomous achievement of tasks.
- Neural Network-Based Control Systems : Artificial neural networks, inspired by neural networks in biological brains, process sensory information and provide decisions. ANNs could learn from experience, and hence, once trained over time, they exhibit improved performance. This would enable a robot to adapt to new and changing environments. For example, in a dynamic environment where obstacles and conditions keep changing, ANNs let the robot learn optimal navigation paths for avoiding collisions effectively.
- Reinforcement Learning : The RL algorithms borrow elements from how animals learn through trial and error. In RL, robots will learn to do something for which rewards or penalties are given, based on the outcome of their actions. In the process, robots can create ways through which they can achieve a set goal effectively. For instance, a robot equipped with RL algorithms could learn how to optimize its energy use while performing a series of tasks in the same way an animal would conserve its energy while foraging or hunting.
- Bio-Inspired Reflexive Responses : This embedding of reflexive responses into the control systems of robots is quite similar to what happens in animals: very fast, automatic responses to address immediate, unanticipated problems. For example, were a robot to bump into some unexpected obstacle, a reflexive control algorithm might fire an evasive maneuver just in time to avoid collision—not too different from when a human instinctively recoils from a hot surface.

- Central Pattern Generators (CPGs): CPGs are neural circuits found in animals that are able to generate rhythmic outputs of behaviors like walking and swimming without the need for sensory feedback. In light of this example of the operation of CPGs, robotic control systems can generate stable and adaptive patterns of locomotion. It will aid in the balance of legged robots on any kind of terrain and adjustment of pace according to different paths, exactly like living beings do. The embedding of the CPG into the robot guarantees a continuous and fluid locomotion in complex and changing environments.

5.3 Energy Efficiency and Autonomy

One of the most appealing features of biological systems is their great energy efficiency. Having undergone millions of years of evolution, organisms have optimized movements to achieve minimum energy spending—a very important principle that will aid in the development of bio-inspired robots. Grasping and applying these biological insights into energy-efficient movement fundamentally enhances performance and prolongs operational life of robotic systems.

- Gait Optimization: Many animals can realize very energy-efficient gaits. For instance, the walking and running patterns of quadrupeds and bipeds are in a way that reduces the fatigue of muscles and maximizes the conservation of momentum. Such natural gaits, engineers can study and design robots that imitate these efficient movement patterns. Algorithms can make machine-like, energy-efficient walking and running gaits similar to human movement, as seen in robots like the bipedal "Atlas" from Boston Dynamics, which enables them to cover varied terrains using very minimal energy.
- Aerodynamics and Hydrodynamics : Birds and fish are classic examples of organisms evading drag in air and water. The smoothly curved shape of fish reduces drag, thereby allowing them to swim with great efficiency, while birds evolve wing shapes and flapping patterns that maximize lift while minimizing the energy expended in flight. These principles are applied in aerial and underwater robots. Drones that mimic the flapping of birds and underwater robots that imitate the motion of fish exploit aerodynamic and hydrodynamic efficiencies to offer equivalent range while consuming less power.
- Elastic Energy Storage: Many animals store elastic energy to be able to move efficiently. Consider kangaroos, for example, or some insects: Such animals store energy in their tendons and exoskeletons, which again is released to help jump or run. This principle can be implemented in robotics using compliant materials and spring-loaded mechanisms. It means that robots including elastic energy storage can move dynamically jump and run with far less energy; this would be helpful in tasks relevant to rapid and powerful movements.
- Metabolic Cost Reduction : Animals have also evolved mechanisms to reduce metabolic costs associated with movement. Techniques, such as passive dynamics—using the intrinsic dynamics of the body to aid in movement—can be applied in robotic design. Passive dynamic walkers are robots, for example, that can walk using minimum energy input through gravity and inertia, hence duplicating the efficiency of natural locomotion.
- Autonomous Behaviors Based on Natural Systems
  In this way, directly from the self-sufficient behaviors witnessed in natural organisms, the autonomy of robotic systems advances a great deal. Thus, such autonomous behaviors offer the potential to make robots able to operate independently, make real-time decisions, and adapt to changing environments without human intervention.
- Swarm Intelligence: Swarm intelligence is a paradigm which gets its inspiration from the very collective behaviour of social insects like ants and bees, where simple robotic units work together in realizing complex tasks. Every robot in a swarm acts in respect to local information and by using simple rules, but collective behavior gives rise to sophisticated capabilities of solving problems. Applications include environmental monitoring, search and rescue, and agricultural tasks, where the power of having several robots by virtue of their large area efficiency gets to be replicated, mimicking decentralized decision-making processes from nature.
- Adaptive Learning: Many animals learn in an adaptive way, changing behavior according to past experiences and environmental feedback. Machine learning algorithms embedded within a robot implement common machine learning in the way the machines learn from interaction and improve performance over time. For example, reinforcement learning may enable robots to acquire optimal strategies concerning navigation, manipulation, and avoidance in a good number of tasks. These robots could learn how to react to novel, unforeseen events in ways similar to how animals might adapt to new features of the environment through their continuous updating of their knowledge base.
- Autonomous Navigation: The way migratory animals, such as birds or sea turtles, can navigate by themselves will teach us a lot about autonomous navigation. These are animals that can combine several environmental cues, from magnetic fields and stars to landmarks, to get their way across distances. Advanced sensors and navigation algorithms enable robots to imitate such natural ways of navigation so that they can self-navigate, explore, and map large areas. This is useful in, say, planetary exploration, underwater mapping, and autonomous vehicle operation.
- Energy Foraging: Some animals, such as bees and squirrels, display energy foraging behavior by searching for energy resources to supply their activities. The same view can be applied to robots for self-configuringly finding and harvesting energy from the environment. For instance, solar-powered robots adjust their relative positions to optimize the sunlight in order to guarantee a power supply. Besides, along with the energy-scavenging technologies, it is possible to use

complementary energy sources from the ambient environment for example, vibrations or thermal gradients to balance out the supply of energy in such robots.

6. FABRICATION TECHNIQUES

6.1 Materials and Manufacturing Processes

Materials selection plays a most important role in determining the durability and flexibility of bioinspired robotic systems. They should be able to survive heterogeneity in environmental conditions and mechanical stress without losing their functional integrity. For example, elastomers and flexible polymers are often selected since one can bend, stretch, or twist around without breaking, thus emulating the soft tissues of biological organisms. Patterning these materials makes the robot move in complex and unstructured environments because of adaptive and resilient motions. Besides, other commonly utilized metals include titanium and aluminum alloys for their high strength-to-weight ratio; in other words, these metals keep the robot light while maintaining enough strength to hold the structure. Advanced composite materials combine the properties of various substances to substantially improve the functioning of robotic systems. These types of composites could provide a reasonable compromise of flexibility, durability, and strength and are largely suitable for applications that demand robust and flexible robotic solutions. Much of the fabrication of bio-inspired robotic systems relies on advanced manufacturing techniques, where attributes are specified in precise and complex forms that conventional methods cannot achieve. Some of the other techniques include 3D printing to implement very high customization of very complex structures. This allows the manufacture of complex lightweight and strong geometry parts, thereby allowing the realization of robots for tasks in hard environments. Another approach would be rapid prototyping of research designs to test and quickly iterate. Another innovative approach to be highlighted is soft robotics: the use of flexible materials and considerations in actuators to create robots that are able to adapt their shape and movement. In turn, soft robotics is fully dependent on recently developed sophisticated fabrication techniques such as molding, casting, laser cuttings, and even micromachining. These will enable good fabrication of the soft components that can deform and recover the shape with the greatest adaptability and function. In relation to this use, hybrid manufacturing processes have come up with combined approaches. The methods merge the benefits taken from different fabrication methods in the creation of robotic systems with more sophistication and ability. For example, the integration of 3D printing with traditional machining would enhance component accuracy and structural integrity. The utilization of advanced sensors and actuators, developed through microfabrication techniques, further elevates the performance levels of these robots through high sensing and responsiveness. Such integration of advanced manufacturing techniques becomes of importance for developing effective bio-inspired robotic systems for operation in an unstructured environment. This will enable development of robots that have durability and versatile functionality with the desired complex and adaptiveness in their behavior by integrating strong points concerning material and fabrication method. These advances will be critical in opening up the applications of bio-inspired robots in the areas of exploration, environmental monitoring, and medical assistance.

6.2 Prototyping and Testing

All the steps in prototyping bio-inspired robotic systems are important in transforming a simple concept into an operative prototype. First of all, ideation and conceptual design are necessary for defining the main purpose, functions, and features of a robot. At this stage, preliminary sketches and CAD models of a future robot's structure and mechanisms are elaborated by a designer or engineer. This phase is critical in understanding and working out problems that a design may have and can be changed before its actual fabrication. Conceptual design is followed by material selection and procurement. Materials to be used have to meet up with the requirement of durability, flexibility, and functionality. After the materials are selected, fabrication of individual components is commenced. Advanced techniques of manufacturing, such as 3D printing, laser cutting, and micromachining, are used to make parts that are at the same time both precise and intricate. Methods such as these enable engineers to fabricate components that replicate structural and functional characteristics from biological organisms. The second aspect is assembly, which occurs subsequent to the fabrication of individual parts. During assembly, engineers bring together the different parts and fit them to work accordingly. This phase mainly comprises the use of specialized tools and techniques so that it provides precision and reliability. Electrical and control systems are also integrated in this phase, which makes the robot able to work for the intended purpose. The last step in prototyping process is initial testing and debugging. It involves testing of the assembled prototype for any issues or improvement areas. Testing is a series of tests by engineers to make sure all the components blend together harmoniously, and the Robot is able to perform its basic functions. Issues identified are addressed through iterative adjustments and refinement to have the prototype meet the desired specification and performance criteria.

Testing of bio-inspired robotic systems in unstructured environments is a critical phase of assessing their performances under real-world conditions. It goes through a number of rigorous testing protocols that evaluate varied performance metrics concerning durability, adaptability, and functionality. The laboratory tests are the first stage of trials whereby the robot is exposed to simulated conditions replicating the unstructured environments expected to be encountered by the said robot. The tests check whether the mechanical and electrical systems can stand up against the stresses and strains of real-world operations. For instance, obstacle negotiation, adaptation to changes of the terrain, stability, and balance maintenance with different loads can be tested on robots. Laboratory tests are followed by field tests in real environments without structuredness. These are very important tests, providing information about the performance of the robot working in the presence of natural obstacles, changing weather conditions, and other unpredictable challenges. Field tests check the robot's mobility, accuracy in sensing, and general operational efficiency. Closely connected to the performance of the robot, engineers look for data gathering on adaptability to new and changing conditions, maintenance of functionality, and execution of tasks efficiently. Specific protocols are followed to ensure comprehensive evaluation during such tests. These would involve pre-designed test cases to simulate the type of applications the robot is meant for, whether search and rescue, environmental monitoring, or medical aid. All performance metrics, such as speed, agility, power consumption, task completion rates, are meticulously recorded and analyzed. Any failures or malfunctioning are documented, and data is used to derive inferences on improvement. The other important element in the testing protocols is the post-test analysis. Engineers then analyze this data to assess the strengths and weaknesses of the robot. In this way, one could find out the design flaws, performance bottlenecks, and areas that need enhancement. The insights learned from testing are used in refining the design of the robot and functionality, which leads to iterations of the prototype. Rigorous prototyping and testing processes will ensure that any bio-inspired robotic systems work perfectly in performance within unstructured environments. This will involve well-defined processes and protocols that will enable engineers to come up with robots that not only will be innovative but also reliable and effective when deployed in real applications.

7. APPLICATIONS AND CASE STUDIES

7.1 Search and Rescue Operations

Bio-inspired robots have huge potential in applications like search and rescue, particularly in scenarios where traditional techniques of search and rescue are considered impractical or dangerous. Several case studies have been conducted demonstrating the effectiveness of these robots in disaster response efforts. One such example includes using snake-like robots in disaster situations like earthquakes, right after the event, inspired by the flexibility and maneuverability of a real snake. Therefore, such robots can penetrate through small loopholes in the debris to areas inaccessible to human rescue personnel and machinery. Snake robots have been utilized to scour for survivors from rubble immediately after the 2011 earthquake and tsunami disaster in Tohoku, Japan. As these robots can move through tight spaces, rescue workers can easily identify survivors buried under the rubble and even communicate with them, which increases their chances of being rescued. Another case example is the deployment of swarms of drones in scenarios of wildfires. Taking a cue from coordination behavior in insects, these drones are deployed to map large areas, identify hotspots, and send real-time information back to firefighters. During the Australian 2019-2020 bushfire season, drone swarms were adopted for surveying the spread of fires and monitoring evacuation routes. Critical information provided by the drones coordinated firefighting efforts and protected the safety of first responders and civilians. In addition, bio-inspired robots based on dogs and rodents have been applied in urban search and rescue missions. These robots are equipped with sensors and cameras that render them quite suitable for negotiating complex and dangerous scenes, such as collapsed buildings. For instance, after the Mexico City earthquake in 2017, a robotic dog was sent to probe unstable structures in search of survivors and to transmit video in real time to the rescue teams. Its design, like that of the dog in terms of flexibility and resilience, helped the robot to move on uneven ground and climb over various obstacles. This greatly helped in locating trapped people. Mobility and functioning are, therefore, very critical considerations in making the bio-inspired robots effective for search and rescue operations in times of disaster. Mobility refers to the ability of the robot to move through various terrains and environments, while functionality refers to the range of tasks that the robot is able to perform, such as sensing, mapping, and communication. The bio-inspired robots are built mainly to provide mobility, which is accomplished by mimicking strategies for locomotion seen in animals. In contrast, snake-like robots could move through rubble and debris by a combination of lateral undulation, concertina, and sidewinding motions. This versatility can conform to a variety of surfaces and obstacles, keeping the robot stable and progressive in very difficult conditions. Testing of these robots is often related to the ability of the robot to move through cramped spaces, climb over obstacles, and maintain balance on uneven ground. Results from such tests are critical for fine-tuning in design and making necessary improvements toward the performance of the robot in real life.

Performance is assessed based on the ability of the robot to do some of the missions foreseen in search and rescue. It comprises advanced sensors and cameras that establish a map of the environment to detect victims. Robots installed with thermal cameras can detect survivors through thick smoke or debris by their heat signature. Other sensors, including gas detectors, may be useful in detecting hazardous substances in the surrounding, which will also ensure rescue team safety. Field tests and simulations in a near real-life disaster scenario are conducted to test the effectiveness of these functionalities. Another critical aspect of functionality is communication capability. The bioinspired robots should be able to transfer real-time information to the rescue teams for coordination and decision-making purposes. This quite often makes use of wireless communication systems and advanced data processing algorithms. Testing measures the metrics for reliability and speed of data transmission to ensure that robots are able to provide timely and accurate information during rescue operations. Case studies have demonstrated several applications of bio-inspired robots in search and rescue operations that might be useful for disaster response efforts. Their mobility and functionality should therefore be tested to establish whether these robots can move around such environments and perform their operations. With continuous design and capability enhancements, the prospective significance of bio-inspired robots to search and rescue missions in improving the efficiency and safety of disaster response efforts remains very high.

7.2 Exploration Missions

Bio-inspired robots mirroring the locomotion and sensing mechanisms of biological organisms have vastly increased the capability of exploration missions in space and underwater. These robots are, in fact, designed to work in hostile and otherwise inaccessible environments, exploiting principles analogous to those of adaptiveness and efficiency in natural systems. Bio-inspiration is playing a leading role in the design of robotic systems to be used in the harsh, unpredictable terrain of Martian and lunar exploratory missions. A case in point is the design of Mars' Curiosity and Perseverance for NASA, which is more biologically inspired. These rovers articulate legs that mimic insects and articulated wheels that act like the legs of mammals. The suspension systems, through an adaptation, allow such musculature in these rovers to be preserved, and then provide it the ability of maintaining the musculature in animals and providing stability over rough grounds and other obstacles, thereby providing improved operational terrains and data capture capabilities. Similarly, bioinspired designs applied to drones go much further—in modeling bird flight mechanics so that drones can explore caves and cliffs on Mars that are not accessible to ground-based rovers. Underwater exploration is likewise largely benefiting from bio-inspired robotics. The engineered robots to imitate fish and other sea creatures can move through water very efficiently and dexterously. For example, fish-like robots developed at MIT can swim underwater thanks to flexible fins and a streamlined body to apply all possible maneuvers with the least energy expended. All these undertakings are necessary to support the long endurance missions that robotic fish can perform for marine biology research, underwater archaeology, and environmental monitoring. Bio-inspired robots in the water can also accommodate different types of fluctuating currents of water and pressure levels, hence perfect for deep-sea exploration where the ordinary submersibles would not possibly operate. The application of biologically inspired robots in exploration poses some challenges and considerable successes. The paramount challenge is the high complexity in correctly imitating the biologically based system's intricate mechanisms. In doing so, it puts high demands on both material and fabrication technologies of the robots in question; therefore, it can be technically difficult and very costly to be performed in a lab. Assuring reliability and robustness of robotic systems, emulating bioinspired robots in harsh conditions of outer space or high pressure in demanding marine environments, makes the task an arduous one. Remarkably, however, success in the exploration missions of bio-inspired robots remains unabated. "Deploying rovers like Curiosity and now Perseverance into space is just one of many groundbreaking discoveries about the Martian surface, geology, and potential signs of life or at least, signs of past life. That's an inspiration to make very good robotic systems that can go to these very difficult terrains and make very good science experiments. The same parallels can be drawn with underwater exploration, which uses the same bio-inspired robotic technique in the hope of gaining similar kinds of breakthroughs.". For instance, robotic fish developed at MIT have shed significant light into marine ecosystems and underwater habitats. The robots could venture into areas that were too risky or hard to reach for human divers, providing real-time, continuous, and detailed monitoring of the environment. This is of prime importance in studying the impacts of climate change on marine life and ecosystems and contributes to more informed conservation effort. The use of advanced robotics integrated with bio-inspired design principles has therefore found new frontiers of exploration. Although some challenges still exist, the continuous improvement and development of such technologies give the promise of further success in understanding and exploring both terrestrial and extraterrestrial environments. Table 3 shows some shortcomings of conventional robotic solutions in relation to various design and functional issues and therefore emphasizes the need for new approaches, such as bio-inspired robotics. Researchers and engineers, by understanding these challenges and the corresponding parameters, can also address the shortcomings and enhance their capabilities for future robotic systems.

TABLE III. CHALLENGES AND PARAMETERS IN TRADITIONAL ROBOTIC SOLUTIONS

Problem Area	Current Solutions	Problems	Parameters	Values
Mobility	Wheeled or tracked robots	Limited in rough or uneven terrain	Terrain type	Rocky, sandy
			Obstacle height	10-50 cm
			Surface material	Mud, gravel
	Fixed-joint robotic arms	Lack flexibility, limited range of motion	Joint flexibility	0-90 degrees
			Range of motion	0-100 cm
			Degree of freedom	3-6 joints
Functionality	Predefined motion patterns	Poor adaptability to changing environments	Environmental variability	Temperature range -20°C to 40°C
			Task complexity	Object manipulation, navigation
Sensory Perception	Basic sensor arrays	Limited detection range and sensitivity	Sensor range	0-5 meters
			Sensitivity	50-80%
			Resolution	320x240 pixels

Decision-Making	Rule-based algorithms	Inability to handle unpredictable scenarios	Algorithm complexity	50-200 rules
			Adaptability	Response time: 100-500 milliseconds
			Processing speed	1000-5000 operations per second
Energy Efficiency	Continuous power supply or battery	Short operational time, high energy consumption	Power consumption	50-200 watts
			Battery life	2-6 hours
			Energy storage capacity	2000-10000 mAh
Adaptability	Rigid structures	Difficulty in adapting to new or dynamic environments	Structural flexibility	Bend radius: 10-50 cm
			Material properties	Young's modulus: 70-200 GPa
Stability	Static balance mechanisms	Poor stability on uneven or moving surfaces	Center of gravity	20-50 cm
			Balance control response time	50-200 milliseconds
Environmental Impact	Industrial materials	High environmental footprint	Material sustainability	10-50% recycled content
			Biodegradability	10-50 years
			Environmental impact	CO2 emissions: 100-500 kg
Cost	High-tech components and manufacturing processes	High cost, limited accessibility	Manufacturing cost	10,000-50,000 USD
			Component cost	100-5000 USD
			Scalability	100-1000 units per month

7.3 Environmental Monitoring

More and more frequently, bio-inspired robots are put into action for ecological and environmental monitoring, thus opening new solutions to challenges that traditional methods of observation pose. Such development makes them capable of moving in complex and, at the same time, hardly accessible environments in the same way that living organisms do. It makes them very helpful during ecosystem monitoring, tracking wildlife, and setting variations in the environment. This could involve both insect- and small mammal-inspired robots for work on land, such as in dense forests, wetlands, and other hard landscapes. These robots could thus potentially move through undergrowth and canopy layers, logging information on plant health, plant species, and their diversity, soil composition, and animal populations. For instance, small, agile robots equipped with cameras, sensors, and other above-system abilities can penetrate deep into the forests to monitor biodiversity, early signs of disease in plants, and animal movement. This is especially significant because the researchers can gather a broad range of information without necessarily disturbing the environment, hence, accurate and repeatable ecological research. Moreover, the bio-inspired robots have significant benefits in underwater. For example, the narrow robots, which are built like fish and other sea creatures, are fast. These make a brilliant use to navigate through the water sources in an attempt to monitor the sea environment. Robots can be able to monitor the water quality, tracking marine life as well as conducting a reef health study. For instance, robotic fish collecting water samples and detecting the differences in the chemical composition of the water are used to monitor the effects of this pollution on aquatic life. They are able to monitor the effects of climate change on coral reefs by taking detailed images and data on reef health. The ability to operate in harsh and remote underwater environments enables constant and long-term data collection, which is necessary for the understanding and mitigation of the impacts of environmental changes on marine ecosystems. Aerial robots, inspired both by birds and insects, have been sent into the sky to survey huge and remote stretches of land. These drones can cover large landscapes while capturing high-resolution images and videos that turn out to be very useful data in showing land use, vegetation cover, and wildlife habitats. For example, drones fitted with multispectral cameras are able to assess crop and forest health through analyzing the reflected light from the vegetation. Such information helps in detecting early signs of stress or disease, allowing for timely intervention and management. In addition, drones can also monitor the effects of deforestation, land degradation, and habitat fragmentation. This will provide effective data for purposes of conserving them on time. Environmental monitoring via bio-inspired robots has taken a different turn in relation to how some data are collected and analyzed, thereby revolutionizing the way scientists are able to study and manage ecosystems. One major advantage of such robots is their ability to collect data from environments people cannot reach or where danger is involved. Traditional data collection methods, such as manual surveys and satellite imaging, generally have restrictions in reach, frequency, and resolution. Therefore, bioinspired robots aid in overcoming these drawbacks by providing continuous real-time data from diverse and challenging terrains. These robots provide high-resolution data to be collected and enable, therefore, more precise and detailed analysis. For instance, the sensors of modern robots are created to measure the temperature, humidity, chemical composition, light intensity, and other parameters in the environment. This data could be used in order to create detailed maps and models of an ecosystem and bring out information about its structure, functioning, and health. The possibility of monitoring changes made over time will also offer scientists trend and pattern detection capability, which is important for understanding the impacts of environmental changes in the short and long runs, including human-induced disturbances. Furthermore, algorithms in artificial intelligence and machine learning technologies have been incorporated for data analysis in bio-inspired robotic systems. The algorithms in these systems quickly and efficiently churn out large datasets to point out anomalies, correlations, or emerging trends that standard methods of analysis could overlook. As an example, data collected by drones has nowadays been analyzed using artificial intelligence to identify areas losing forest cover, tracking wildlife movements, or early indicators of environmental degradation in South Sudan. The process is automated and, therefore, fast, hence increasing response with less use of resources, and it helps scientists invest their time in detailed analyses for future reference and management. Real-time data that bio-inspired robots provide goes a long way in supporting rapid response and intervention in environment management, such as when a robotic fish can be sent to measure how far an oil spill has gone and monitor cleanliness measures. Similarly, drones can be used to monitor forest fires in real time for information about the spreading of the fire, allowing for the coordination of firefighting efforts. Such timely data is rather helpful and up for utilization to alleviate the effect of disasters on the environment.

8. CONCLUSION

It is in this line that bio-inspired robotics studies have also been instrumental in the field of robotics, leading up to a view of impressive developments and contributions as far as the theme of locomotion and performance of tasks in unstructured environments is concerned. Having borrowed from the mechanisms of adaptation and efficient designs of biological organisms, such robots have set up Camps of advanced mobility, functionality, and resilience. The potential robots could overcome very challenging terrains, adapt to dynamic conditions, and handle complex tasks earlier inaccessible to traditional robotic systems by equipping them with flexible joints, adaptive control systems, and state-of-the-art sensory arrays. The key findings point out the remarkable effectiveness of the role of bio-inspired designs in very important applications: search and rescue operations, environmental monitoring, and space and underwater exploration. These robots have already been able to access inaccessible places, gather sophisticated data about the environment, make precise interventions, and thus broaden the scope of applicability and the effectiveness of robotic applications to a number of domains. These results imply tremendous implications for the future design of robotic systems and their applications. The success of the bioinspired robots operating in unstructured environments can be an indication of a change of paradigm in the design principles of robots from stiff, predefined motion patterns to systems that are much more flexible, adaptive, and resilient. This is going to influence the next generation of robots working autonomously in very varied scenarios, ranging from disaster response to environmental conservation, industrial automation, and health. Inbuilt bio-inspired principles in the design of robots could further enhance their energy efficiency, durability, and functionality, thus being versatile and able to operate in real-world scenarios. Furthermore, fusions of state-of-the-art AI and machine learning algorithms with bio-inspired robotics could raise smarter, more independent systems that would learn from their surroundings to perform tasks better over time. The importance of bioinspired robotics in the solution of issues related to unstructured environments cannot be overstated. Taking a cue from nature's evolution, such robots avail solutions to some of the major challenges that traditional robot systems have been facing. Their capability to support complex terrains and adapt to unpredictable circumstances, while executing a range of tasks with high-precision and efficiency, has made them extremely important tools in many applications. Much research and development is in the pipeline, and this makes the future still more promising with further possible advancements that again may strengthen capabilities and impacts of bio-inspired robots. With technology getting more real by the day, the contribution of bio-inspired robotics to enhancing our capability for exploration, understanding, and interaction with the natural world will be huge. This will entail great service to technological progress and the betterment of society.

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References

[1] S. E. Nodehi, L. Bruzzone, and P. Fanghella, "SnakeTrack, a bio-inspired, single track mobile robot with compliant vertebral column for surveillance and inspection," *Mech. Mach. Sci.*, vol. 120, pp. 513–520, 2022.

[2] L. Bruzzone and G. Quaglia, "Locomotion systems for ground mobile robots in unstructured environments: A review," *Mech. Sci.*, vol. 3, pp. 49–62, 2012.

[3] J. Stückler, M. Schwarz, M. Schadler, A. Topalidou-Kyniazopoulou, and S. Behnke, "NimbRo Explorer: Semiautonomous exploration and mobile manipulation in rough terrain," *J. Field Robot.*, vol. 33, pp. 411–430, 2016.

[4] R. E. Arvidson et al., "Mars Science Laboratory Curiosity Rover megaripple crossings up to Sol 710 in Gale Crater," *J. Field Robot.*, vol. 34, pp. 495–518, 2017.
[5] M. Dayarathna, Y. Wen, and R. Fan, "Data center energy consumption modeling: A survey," IEEE Communications Surveys & Tutorials, vol. 18, no. 1, pp. 732–794, 2016. https://doi.org/10.1109/COMST.2015.2481183.
[6] M. Saleem, G. Di Caro, and M. Farooq, "Swarm intelligence-based routing protocol for wireless sensor networks: Survey and future directions," *Information Sciences*, vol. 181, no. 20, pp. 4597–4624, 2011.
[7] C. E. Perkins, E. M. Belding-Royer, and S. Das, "Ad hoc on-demand distance vector (AODV) routing," IETF RFC 3561, Experimental, July 2003. https://doi.org/10.17487/RFC3561.
[8] A. B. Alnajjar et al., "Wireless sensor network optimization using genetic algorithm," *J. Robot. Control*, vol. 3, no. 6, 2022, doi: 10.18196/jrc.v3i6.16526.
[9] F. L. Benmansour and N. Labraoui, "A Comprehensive Review on Swarm Intelligence-Based Routing Protocols in Wireless Multimedia Sensor Networks," International Journal of Wireless Information Networks, vol. 28, pp. 175–198, 2021. https://doi.org/10.1007/s10776-021-00508-9.
[10] K. Christidis and M. Devetsikiotis, "Blockchains and smart contracts for the Internet of Things," IEEE Access, vol. 4, pp. 2292–2303, 2016. https://doi.org/10.1109/ACCESS.2016.2566339.
[11] M. Dayarathna, Y. Wen, and R. Fan, "Data center energy consumption modeling: A survey," IEEE Communications Surveys & Tutorials, vol. 18, no. 1, pp. 732–794, 2016. https://doi.org/10.1109/COMST.2015.2481183.
[12] F. Zhang, Y. Li, and J. Wang, "Energy-efficient data center design and architecture: A review," *IEEE Trans. Cloud Comput.*, vol. 9, no. 2, pp. 241–255, 2021.
[13] S. Rodinò et al., "Design, simulation, and preliminary validation of a four-legged robot," *Machines*, vol. 8, no. 82, 2020.
[14] A. Mahapatra, S. S. Roy, and D. K. Pratihar, "Multi-legged robots: A review," in *Multi-body Dynamic Modeling of Multi-legged Robots. Cognitive Intelligence and Robotics*, Singapore: Springer, 2020, pp. 11–32.
[15] W. Tao, Y. Ou, and H. Feng, "Research on dynamics and stability in the stairs-climbing of a tracked mobile robot," *Int. J. Adv. Robot. Syst.*, vol. 9, pp. 1–9, 2012.
[16] D. Karaboga and B. Basturk, "A powerful and efficient algorithm for numerical function optimization: Artificial bee colony (ABC) algorithm," Journal of Global Optimization, vol. 39, no. 3, pp. 459–471, 2007. https://doi.org/10.1007/s10898-007-9149-x.
[17] G. Quaglia et al., "UGV epi.q-Mod. Mechanism and machine science," in *Proc. 20th CISM-IFToMM Symp. Theory and Practice of Robots and Manipulators, ROMANSY 2014*, Udine, Italy, 2022, vol. 22, pp. 331–339.
[18] M. Arsenault et al., "Multi-modal locomotion robotic platform using leg-track-wheel articulations," *Auton. Robot.*, vol. 18, pp. 137–156, 2005.
[19] Z. Luo, J. Shang, G. Wei, and L. Ren, "A reconfigurable hybrid wheel-track mobile robot based on Watt II six-bar linkage," *Mech. Mach. Theory*, vol. 128, pp. 16–32, 2018.
[20] L. Bruzzone et al., "Functional design of a hybrid leg-wheel-track ground mobile robot," *Machines*, vol. 9, no. 10, 2021.
[21] M. Schaffner, J. A. Faber, L. Pianegonda, P. A. Rühs, F. Coulter, and A. R. Studart, "3D printing of robotic soft actuators with programmable bioinspired architectures," Nature Communications, vol. 9, p. 878, Feb. 2018. https://doi.org/10.1038/s41467-018-03216-w.
[22] N. Shahrubudin, T. C. Lee, and R. Ramlan, "An overview on 3D printing technology: Technological, materials, and applications," Procedia Manufacturing, vol. 35, pp. 1286–1296, 2019. https://doi.org/10.1016/j.promfg.2019.06.089.
[23] Y. K. Salih et al., "A proactive fuzzy-guided link labeling algorithm based on MIH framework in heterogeneous wireless networks," *Wirel. Pers. Commun.*, vol. 75, no. 4, pp. 2495–2511, 2014, doi: 10.1007/s11277-013-1479-z.
[24] S. Q. Salih and A. R. A. Alsewari, "A new algorithm for normal and large-scale optimization problems: Nomadic People Optimizer," *Neural Comput. Appl.*, vol. 32, no. 14, pp. 10359–10386, 2020, doi: 10.1007/s00521-019-04575-1.
[25] A. M. Kadim et al., "K-means clustering of optimized wireless network sensor using genetic algorithm," *Period. Eng. Nat. Sci.*, vol. 10, no. 3, p. 276, Jun. 2022, doi: 10.21533/pen.v10i3.3059.
[26] H. Tao et al., "A newly developed integrative bio-inspired artificial intelligence model for wind speed prediction," *IEEE Access*, vol. 8, pp. 83347–83358, 2020, doi: 10.1109/ACCESS.2020.2990439.
[27] S. Q. Salih et al., "Integrative stochastic model standardization with genetic algorithm for rainfall pattern forecasting in tropical and semi-arid environments," *Hydrol. Sci. J.*, vol. 65, no. 7, pp. 1145–1157, May 2020, doi: 10.1080/02626667.2020.1734813.
[28] T. Hai et al., "DependData: Data collection dependability through three-layer decision-making in BSNs for healthcare monitoring," *Inf. Fusion*, vol. 62, pp. 32–46, Oct. 2020, doi: 10.1016/j.inffus.2020.03.004.