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Evaluate the extent to which movement inspired by biological organisms enhances overall robotic development in unstructured environments

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Abstract:

This article evaluates the extent to which movement inspired by biological organisms enhances robotic development in unstructured environments. It examines how biological principles influence robotic mobility, stability, sensing, energy use, and practical adaptability across mountainous terrain, underwater environments, disaster response, and industrial contexts. Drawing on secondary research, the discussion compares bio-inspired systems, including ALPINE, underwater soft robots, BigDog, SoFi, and HIT_Spibot, with traditional wheeled, legged, and industrial robots. The analysis suggests that bio-inspired movement can improve robotic performance where conventional designs struggle with irregular surfaces, aquatic disturbance, and unpredictable hazards. However, the article also identifies limitations, including technical complexity, energy requirements, material constraints, and the difficulty of translating biological movement directly into engineered systems. It concludes that bio-inspired movement is a significant but not complete route for improving robotic development in unstructured environments.

Keywords: bio-inspired robotics; biomimetic movement; unstructured environments; soft robots; quadruped robots; terrain adaptability

1. Introduction

In the past few years, technology has been rapidly developing and leading robotics standing at the forefront. According to data, marketing of industrial robots has increased by 11% annually (Müller, 2025). This reflects that people are starting to rely on technology more and it impacts our daily life. The field of robots undergo a complex network of engineering and observance in nature and linking to real world circumstances. The invention of robotics has brought up several applications in many domains, such as deep sea or daily basis. These different domains are categorized as unstructured environments, which are spaces not pre-defined and lack the consistency of smoothness. Thus, these terrains further present many challenges that people are forced to alter the system within traditional robots, often prioritizing precision over resilience.

Scientists have observed biological organisms forging in dynamic environment for survival. It fosters ideal sources of inspiration for tackling the adaptability of robots in unstructured environment. Engineers study the "design of amphibious robots that can navigate both land and water environments" (Zhong, 2025). Bio-inspired robots perfectly define these principles and delve into mechanical systems, mobility and energy efficiency levels. Moreover, the robots have derived to different types for them to suit in this condition and match with the corresponding environment. Furthermore, evaluating the diverse unstructured environment clarifies how morphological strategies shape differences in robotic construction.

Consequently, to analyse the performance of bio inspired robots operating in unstructured environment, such as rugged terrain, disaster zones, dense forests, or aquatic settings, this study will systematically examine how principles derived from biological organisms. For instance, how they move and the locomotion in mammals.

The methodology will involve the collection of both qualitative and quantitative data from research. It will focus on the performance of stability, speed and a cost in terms of robot marketing, etc. By analyzing and contrasting data, the study aims to establish several comparisons between the robot models. Hence, to identify the most common bio-inspired principle that drives the development and advantages. Connecting the gap between biological and engineering principles will enhance adaptability in robot control systems and helps the society to develop more rapidly.

2. Literature review

2.1 Impact of Unstructured Environments on Robotic Design

The shift of the setting to unstructured environment has largely impacted the robotic design and altered the philosophy of robotics in the society. It has reshaped the integration of human gait sensors to the robots, hence to replace the two-legged robots which become outmoded. "Mountains slopes are perfect examples of harsh environments in which humans are required to perform difficult and dangerous operations" (Focchi, 2025). Focchi posits that mountain harsh environment represents unstructured and challenging terrains, combining difficult technical issues with complexity. Mountainous terrain is one the example where implying human characteristics will be difficult to discover. This further suggests it is necessary to alter operations based on the unpredictable conditions that robots are placed in for work. This paradigm clearly underlines the inescapable nature of prioritizing adaptability, robustness, and sensory intelligence.

In structured environments, it doesn't require complex sensors but rather placing a fixed camera on the robot would help sufficiently to function correctly. Conversely, in unstructured environment, robots are more demanding and difficult to control. Hence, it will require more operations and multi-modal sensing which suits particularly for unstructured domains. Taking Alpine robots as an example, it uses two independently controlled ropes anchored at the top for stability, heavy payload capacity, and energy-free stationary positioning (Focchi, 2025). This sensory data elucidates the progress human is making and further leading to an advanced AI and machine learning for real-time processing. Consequently, robotic systems will rely on logic controllers to insert robotic coding for decision-making, in order to process data more fluently under uncertain circumstances.

To meet the demands, Alpine robot adapts in unstructured environment, its core philosophy is not legged mobility but anchored stability and controlled. Alpine "hangs on ropes, and uses a retractable leg to jump away from the mountain walls." (Prete, 2025). People adjust rope-based system fulfills the critical needs for safety and energy efficiency to allow robots to navigate across highly irregular surfaces for longer of time without running out of battery. Thus, implementing this specific rope-based system to control the robots' mobility and highly reduces the fails and high energy cost.

In addition, it necessitates a parallel lining of artificial intelligence and sensing mobility. The report written by Prete (2025) stresses on the adaptation and transformation of climbing robots, coincidentally, heightening the level of autonomy of mountainous robot for exploring unknown terrains in society. Operating in an unpredictable, and three-dimensional space requires real-time processing of multi-modal sensor data to localize the robot, meanwhile temporarily make adjustments to surface irregularities and wind conditions. Therefore, the unstructured environment forces a revolution from two legged to four-legged, prioritizing integration of rough surfaces with mobility. This will effectively shape a reliable operation where traditional robots will be replaced due to their unitability and weak strain capability.

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2.2 Influence of Bionic Concepts on Robotic Design

The pursuit to robot mobility has rapidly drove the realization of nature biological inspiration, by bringing in bionic concepts under unpredictable conditions. The influenced robotic models not only are demonstrated by smooth robotics underwater but rather fine legged robots, such as those epitomized by the Boston Dynamics' BigDog project (Raibert 2024). By further observing the animal kingdom, people has successfully observed key improvements and gathered inspirations from biological organisms. “BigDog has about 50 sensors. Inertial sensors measure the attitude and acceleration of the body, while joint sensors measure motion and force of the actuators working at the joints. ” (Raibert, 2024). It eliminated the potential rise of limitations such as traditional wheeled and tracked vehicles, transcending to an unprecedented format of agility and ability to perform skills. This argues that this specific robotic innovation, such as legged robot, did not merely improve transportation systems but also suggests that the underlying principles are obsolete, shifting the development of bionic concepts on robots from evolution to revolution.

At its core, bionic design in robotics seeks to emulate the principles of animal locomotion but not having the same appearance. The BigDog model stemming from Raibert's Leg Laboratory clearly breaks legged motion into three parts “supporting the body with a vertical bouncing motion, controlling the attitude of the body... and by placing the feet in key locations.” (Raibert, 2024). This mirrors many coordination that are found in animals, separates complex problem of running into manageable and controllable tasks. The philosophy of "self-contained quadruped robot that uses many of the ideas and concepts of the Leg Laboratory robots.” (Blankespoor, 2024). This evaluates the influence of bionic concepts, for example, four legs, a torso, and an articulated spine, these represents the evolution of homo sapiens and simulates the development of robots. It shaped robotic development by transitioning from functional designs to inspired structures that enhances adaptability and mobility.

The influence of these concepts extends deeply into BigDog's control systems, conveying the stability of an animal and applications onto rough terrain. The robot does not execute gait sensors but constantly react to “reflex responses to external disturbances” (Raibert, 2024). This is achieved through the integration of sensor and reaction, hence, creating a closed-loop system of combining engineering knowledge with biological systems. The control system allows the BigDog to constantly adapt to terrain changes through terrain sensing and posture control. This active system directly correlates to bionic principle, where it allows to adapt to unstructured environment to maximise its benefits and effectiveness.

Furthermore, in underwater robotics, the aquatic environment presents a far more profound impact on biomimetic robotic design. Hasib (2025) asserts soft robots mimic biological resilience, enabling diverse functions in dynamic, unpredictable underwater settings. The streamlined shaped as showed in Figure 1, shows a fundamental engineering principle driven by usefulness and efficiency. The inherent flexibility and high degree of freedom of soft robots' mimics how biological systems interact with principles. It can navigate underwater terrains without damaging marine ecosystems. The morphology is dictated by robots modeled after jellyfish and starfish. Hence, this review highlights the importance of soft-body shape on effective movement and navigation. Park (2024) embedded SMA wires in silicone to create a soft eel robot with silent, pollution-free propulsion replicating aquatic locomotion. This suggests that SMAs shape muscles that enable the soft robotics to manoeuvre underwater, also further specifies that the absence of pollution and reduction of aquatic disturbance. SMAs are wires that act as tendons in robotic grippers, when activated, they close fingers around irregularly shaped objects smoothly to be precisely controlled prevent damage to fragile specimens. Pelrine (2020) states DEAs deform under high voltage, creating motion in soft biomimetic robotics. This electrostatic force compresses thickness and expand significantly in area and removes the voltage to get back to its original shape. Therefore, both mechanics are examples of how people uses biological principles to integrate with robotic mobility.

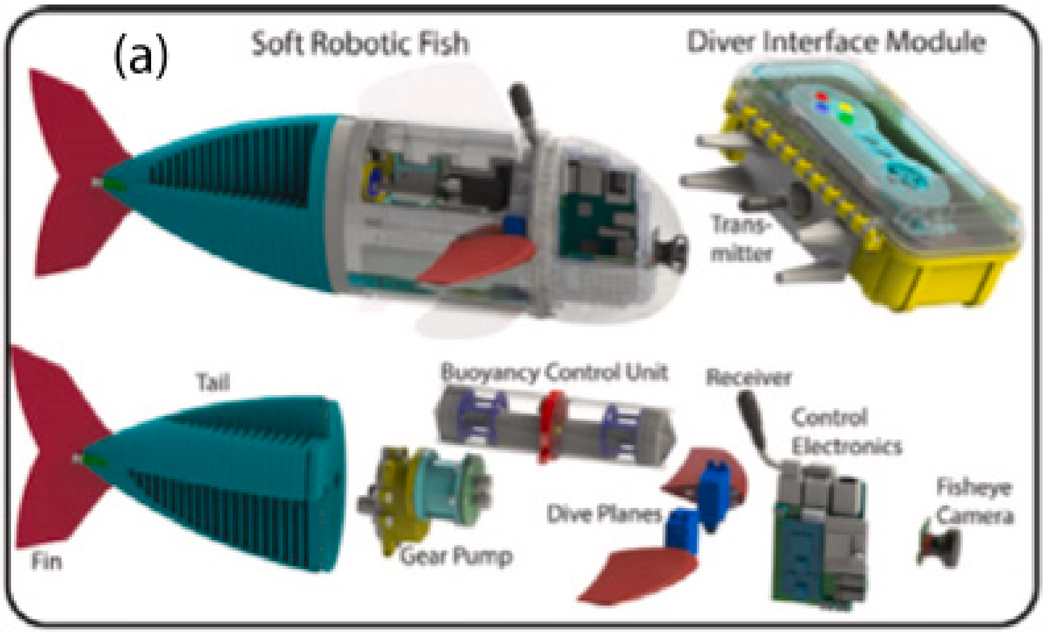

Figure 1 Model of underwater robot (Hasib, 2025)

In conclusion, this deep bionic integration introduces unique challenges that pushes robotic design into materials science and control theory. The future of the field lies in embracing biological principles in morphology and also material capabilities. The materials determine how well bionic concepts are used and influence development of robots.

2.3 Advantages and Development Progress of Bionic Robots

Building on bionic concepts and impacts in specific domains like legged and aquatic robots, the industrial and commercial aspects convey how these robotic principles have been shaping growth of technology. The global robotics market, as detailed in the World Robotics (2025) report is experiencing a fundamental shift towards traditional two legged or robots that are used in daily basis dominates the market in sectors like automotive and electronics. One of the advantages for traditional robots is that they are "low-cost" to attract new customer segments that have just started or not yet used robots. These are also directly linking with bionic principles; which are simpler, more adaptable, and often softer robotic systems inspired by biological mechanisms are easier to handle and teach. The work by Müller (2025) states that the wide range of engineering capabilities in vision or process design, often prevent the adoption of robots." Additionally, through this piece of evidence, it shows that traditional robots are belonged to bionic robots but just by reducing its flexibility and ability to adapt to certain complex environments.

The development progress of bionic robots is also reflected through industrial output and strategies priorities. The staggering growth of the operational stock in Asia, particularly in China which holds "43% of global robotic stock" (Lyoner, 2025). This stack of numbers not only shows the huge number of robots but also shows the benefits that robots have brought to our human life. The share of domestically produced robots will continue to increase in China due to the rapid accumulation of technologies. This growth is potentially tailoring bionic concepts as mentioned in Topic 2.2 and local manufacturing demands. Lyoner (2025) notes China's 128,899 robot installations in 2024 demonstrate robotics' overwhelming industrial advantages. Engineers shifting the focus of developing only tangible and traditional robots to a varied range of specified bionic robots, perfectly progressed in tandem with market demands.

The core advantages of bionic robots are soon becoming their primary attraction commercially and solving strenuous industrial challenges. Firstly, their inherent adaptability and safe interaction directly address the issue of "tight labour markets hampering production" (Frego, 2024). This suggests that robots can share responsibility and relieve human working stress when dealing with harsh difficulties and mechanics or a vast amount of calculations. Robots can work safely with human supervising and expanding the range of automatable tasks. Secondly, their potential for energy efficiency and resilience aligns with their conditions they are placed in. Bionic locomotion and actuation, such as the fluid movements of a robotic

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fish often aim for greater energy than traditional systems which is a crucial factor for sustainable operations. For instance, underwater relies on energy efficiency due to its endurance or mountainous robots require more batteries for energy loss in walking on rough surfaces.

Lastly, bionic designs enable them to operate in unstructured environments, from deep-sea exploration to disaster response, it covers beyond marketing and daily use but to solve earth problems. The article by Peer (2025) mentions that "government programs should focus on supporting this type of robotics infrastructure", this reveals the demand for robots to develop and unlock broader economic benefits. The word "government" indicates that robotic systems and engineering has greatly impacted the marketing. People will focus more on the system rather on the function in the future, where nations compete for the physicality and supply chain of bionic robots.

Looking ahead, the projection of bionic robots will be shaped by the intersection of market forces and human reliance. The World Robotics Report stated that "by 2028, global installations of robots will surpass 700,000 units." this indicates a growing paradigm in Asian but still challenges remain in Europe. The war between Russian and Ukraine expands, causes energy crisis that affect bionic robots. "Dielectric elastomers require high-voltage amplifiers; SMA actuators require Joule heating" (Peer, 2025). This elucidates that bionic robots require electricity to function correctly, hence energy vulnerability is driving manufacturing investment away from Europe. The future progress hinges on overcoming material and controlling challenges, developing "novel materials that seamlessly combine stiff and soft parts" (Peer, 2025). Self-healing methods enable robots to operate autonomously without battery replacement. Their development progress will be measured in their growing trend and how robots are bringing biological principles with industrial methods.

3. Methodology

This study conducts a mixed-methods comparative analysis of secondary data to evaluate three distinct robotic patterns as will discussed below, mountainous robots, soft robots and traditional industrialized robots that are used in daily life (wheeled or legged). This report's objective is to assess how each three different categories have combined with unstructured environment and indeed, economic marketing strategies. A secondary data methodology was selected because technologies have developed under investigation. The research amongst three domains are given with high-quality, peer-reviewed validation studies. Simultaneously, this study will also evaluate institutional reports from the International Federation of Robotics and World Industry. Both sources are selected because they provide peer validated reports and data results on global robotics trends and industry standards. Lastly, it will include technical reports that have statistics about the finalized model and compare with the original model, such as size, weight, and length. This comparison is essential because it quantifies performance improvements through data analysis and finalization. All information is supported by a vast number of citations to primary research articles, allowing for verification.

To ensure this report mitigates source bias, every document was evaluated using CRAAP test. Currency showed from recent robotic advancement like SMA cycling and DEA miniaturisation have rapidly evolved since 2024. Relevance requires sources to address marketing strategies and how each type of robot react with unstructured environment. Each report has at least 4 authors, which indicates the heavily weighed peer review status to strengthen authority. Authority is shown by triangulating sources, for example it will confirm SMA cycle life underwater potential to reveal bionic concepts. Purpose was scrutinised to highlight any bias and documents should be linked to future robotic development, rather than just focusing on its function and technical objectives.

Data will be separated in three sections, which are terrain adaptability, functioning (such as energy efficiency or mobility), and marketing. First, this study will focus on how mountainous robots are assessed against traditional robots under steep slopes. Contemporaneously, underwater soft robots (SMA and DEA systems) will be compared against traditional robots, to mirror some potential ecological balance risks and inspiration of engineering principles. At last, there will be a comparison between bionic robots (overall performance of robots suggested from before and traditional robots. All three comparison further builds a clearer format of general robotic development and their future trend. This framework ensures that research findings are critically verifiable and trustworthy, allows the construction of conclusions about relative strengths and limitations of each robotic patterns across unstructured environments.

4. Analysis and Discussion

4.1 Brief Introduction

By analysing the three comparisons, it assesses to which degree bio inspired movement promotes the robotic development technologically. The three comparisons involve mountainous climbing robots (ALPINE), soft underwater robots, and traditional industrial robots. It will be assessed through terrain adaptability, functional performance, and market positioning.

4.2 Terrain adaptability: Bio Inspired robot against traditional robots

4.2.1 Mountainous robots versus traditional robots on unstructured environments

The data comparison between Alpine and traditional robot has a huge gap, it reveals how steepness in unstructured environment has greatly impacted the robotic designs. In Focchi's (2025) report, it stated, "We set friction coefficient at 0.8, distance of anchor at 5m, the relative landing wheeling distance is 0.8m and the wall clearance is 0.4m." The friction coefficient represents the assumed friction in between the road and the contacted surface on the robot. However, it only sheds light on the impact of soft materials, hence, as shown in Figure 2, the coefficient has drastically dropped to 0.4, suggests why Alpine base will shrink immediately shown in the blue area. The lack of frictional force will pull the robot back to function correctly. While the jumping mechanism enhances stability by allowing the robot to clear obstacle, but it cannot maintain momentum in icey surfaces, hence the lack of surface contact makes it slightly uncontrollable compared to the sliding mechanism.

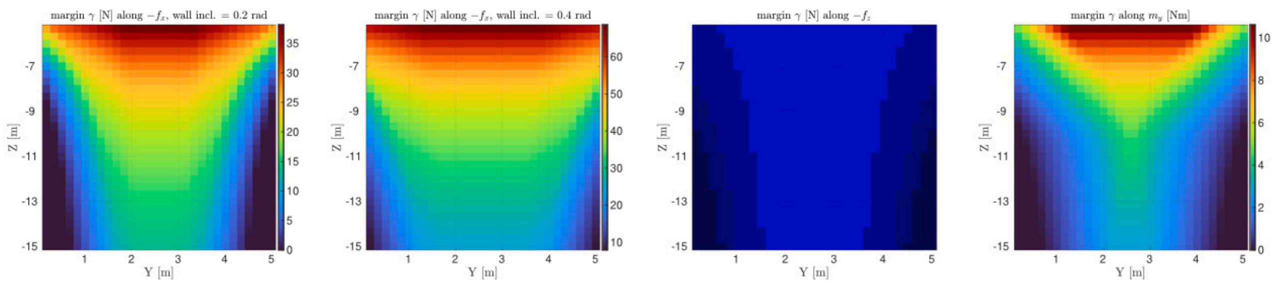

Figure 2 Heat maps (Focchi, 2025)

Additionally, the anchor distance defines the original range of movement of the robot, "5m" suggests that the reachable area is approximately 25 square metres. It reflects that on rougher surfaces it will perform better due to a stronger base grip. Unlike the traditional robot, "the continuous movement maximises working efficiency but has a huge power consumption" (Nelson, 2024). Linking to Figure 3, the illustration of BigDog model, it clearly shows a continuous integrated system with 4 legs and each having a force sensore to keep moving forward and supporting locomotion. Furthermore, Nelson (2024) describes a tightly coupled power train with engine, pump, computer, and actuators operating continuously during movement. This statement lifts the limitation of traditional industrialized robots, because it consumes extravagant power of "2kW". Objectively, BigDog's 10 km consumes 28 kWh, which is enough to light up an average UK house for 9 days. The extreme usage of power leads to a higher energy cost. The high energy cost of BigDog significantly limits its range of movement and are expensive to pay. This makes it unsuitable for long duration jobs. By contrast, Alpine carries no continuous-power components comparable to BigDog's engine pump system, but instead using the rope system. Focchi (2025) describes that this system can "remain stationary with minimal energy consumption using brakes." By implementing a triangular motion range, it moves by jumping rather than gait cycles which relies on power output more. This elucidates Alpine's triangular motion has considerably increased stability and maintained energy efficiency. Unlike BigDog's continuous gait cycles that uses energy when its stationary, the jumping system enhances stability while maintaining energy.

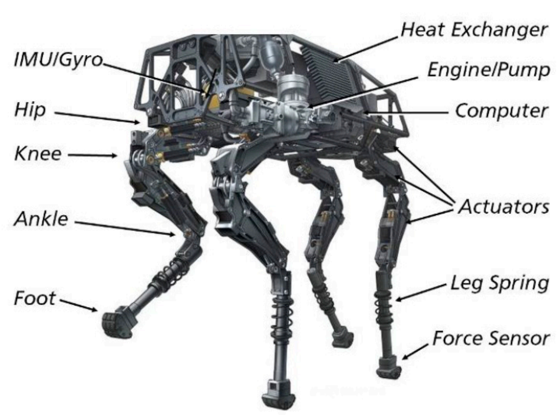

Figure 3 Illustration of BigDog model (Nelson, 2024)

Frego (2025) found feasibility margins increased from 30 N on 0.2 rad to 70 N on 0.4 rad inclines when centrally positioned. This underlines that steeper walls increase normal forces at the landing wheels through gravity components, further enhances the force capacity that Alpine can hold. This robot shows an opposite effect where it can stabilise more under steeper mountains, heightening a larger safety margin for terrain discovery studies. On a steeper slope (0.4 rad), the robot's weight vector changes. Gravity at that point pulls the robot more, but the articulated limbs

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redirect gravitational force and causes the landing wheels at the bottom to press onto the mountains harder.

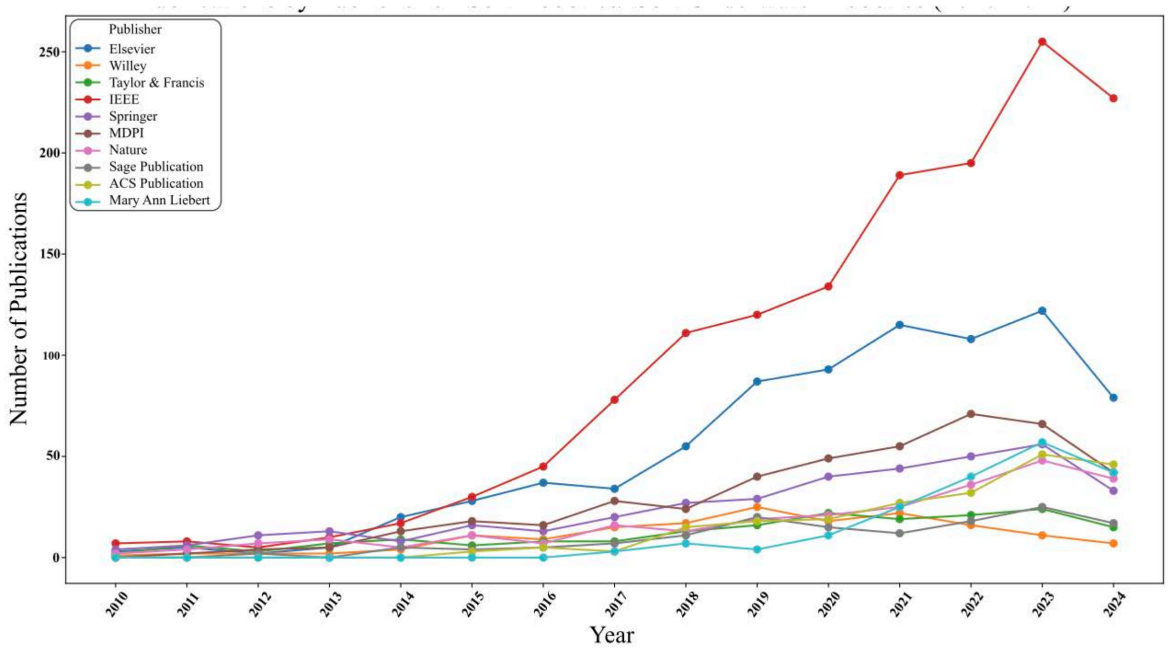
On the other side, traditional robots experience a reduced traction force at steeper slopes. According to the formula N=mgcos(theta), it creates an inversely proportional relationship, as steepness increases, the performance of the corresponding robot decreases. BigDog's documented performance on 35-degree (0.61 rad) slopes with loose scree surfaces establishes the foundation of legged robot. "The front wheels began to lose contact at 0.61 rad." (Blankespoor, 2024). Although the robot has successfully reached an angle of 0.61 rad by using crawl gait sensor but still failed. Despite the strong traction force that mountainous robots have and the success at discovery, but BigDog's "109 kg mass and 154 kg" (Waltham, 2024) demonstrated payload capacity whereas Alpine is only 5-15kg. This indicates that traditional legged systems maintain advantages for heavy-load applications despite terrain limitations.

This demonstrates the evaluation between Alpine and BigDog as an example of traditional industrial robots. It reveals that bio inspired systems are mostly useful in extreme conditions and energy efficiency, where traditional systems prioritise payload capacity and continuous power supply across extended regions.

4.2.2 Soft robots versus traditional quadruped robots

Soft robots are robots that used in smooth environment but still remain unpredictable due to extreme environments. It is categorised into underwater systems. This section focuses on comparing soft robotics against traditional quadruped robots (HIT_Spitbot) and evaluate the extend how bio inspired sensors enhances robotic development in unstructured environments.

Soft robots represent a fundamentally different approach to navigate unstructured environments. Hasib (2025) defines soft robots as elastic systems enabling fluid mobility, safe interactions, and rapid environmental adaptability. This effectively maximises material to their functional advantages, creating a clear chain of what robot can do and how they can perform.



Graph 1 Production trends and analysis for soft robotics and underwater soft robotics from 2010 to 2024. (Zhang et al. 2024)

Graph 1 shows an increasing trend in production of soft robots which reflects underwater robots are suited for underwater environments due to their inherent compliance and flexibility. This links to the mechanism behind underwater soft robots, as clarified in section 2, DEAs and SMAs builds a stronger system for overall robotic development. DEA mimics muscle speed and efficiency, like the snakes, they contract their muscles for movement underwater. Skeletal muscles achieve power contraction by using electrochemical signals to trigger responses and activate muscle tissues. When high voltage is applied across, the electrostatic pressure squeezes the soft materials in the robot and expand rapidly in area. Hence, this will convert electrical energy to mechanism work. With the help of SMA, when there are huge number of forces contracted, it is able to stabilise it and apply fluid actuators into robot's structure. Organisms like worms and octopus arms lack a rigid skeleton, but the fluid actuators highly emulate the fluid filled cavity that they surround around muscles (hydrostatic skeleton). The contraction of muscles adds pressure against the fluid and causes the structure to elongate. With all of these new elements applied to underwater soft robots in 2023, they can maintain posture for navigation with minimal energy input by simply just closing the valve to trap the fluid around the muscle for bending. The valve will help underwater soft robots to maintain a bent posture and conserves energy, offering low need of energy in long duration of mission. This conservation of energy is also crucial, because at marine places, disturbance and maintenance are key factors. Unlike HIT_Spibot, which requires constant power to maintain stability.

Table 1 Underwater soft robotic systems and characteristics with actuation principle and movement. (Hasib, 2025)

Table 2 (*continued*).

Robot type	Actuation/Materials type	Inspirations	Compliance	Movement type	Characteristics	Year	Ref.
Octopus	Printed molds, pour silica gel	Octopus's tentacle	Moderate	Bipedal walking	This biped walking robot, modeled after an octopus, is constructed from two trained soft arms.	2022	[109]
Hydraulic soft robotic arm	Soft elastomer and single-chamber actuation	Arm	Advance	Manipulator	The robot model takes into account the nonlinear viscoelasticity of soft materials.	2022	[110]
Octopus	Soft silicon material	Glowing sucker octopus	Avance	Grasping objects	A moving turtle, irregular objects, scattered things, flat objects, and objects outside of its grabbing range can all be held by the soft gripper.	2022	[111]
Fish	Undulating hydraulic silicone elastomer tail	Soft robotic fish (SoFi)	Advance	Swimming and Turning motions	For pitch control and diving, SoFi has two symmetric control surfaces.	2022	[112]
Soft robotic fish	Antagonistic fast-PneuNet actuators	Fish	Advance	Swimming	Hyperelastic eutectic gallium–indium (eGaIn) embedded in silicone channels for strain sensing	2021	[113]
Jelly-Z	Twisted and coiled polymer (TCP)	Jellyfish	Advance	Swimming	Particle image velocimetry (PIV) experiments and simplified Fluid–structure modeling were used to examine the wake structure from the robot's bell margin.	2023	[114]
Eel-like robot	Fluid Electrode DEA (FEDEA)	Leptocephalus (Eel Larva)	Advance	BCF undulation	Simplifying the implementation of soft, actuated submersible devices	2018	[63]
Octopus arm	Motor-driven cables actuation	Octopus	Advance	Movement through crawling	Robot arm can grasp objects and move in a pushing-based manner.	2011	[25]
RoboScallop	Fluidic Elastomer Actuators (FEAs)	Scallop	Moderate	Jet propulsion	Pulsating thrust is produced via a single-DoF, reciprocating crank mechanism housed inside the robot's shell enclosure.	2019	[115]
Octobot	Chemical reaction based Fluidic Elastomer Actuators (FEAs)	Octopus	Advance	Swimming	Molding and soft lithography are used to create the robot's body and microfluidic logic.	2016	[75]
Starfish-like soft robot	Shape memory alloy	Starfish	Advance	Movement through crawling	Two types of soft rays were created and then their deformation was examined, and the SMA actuators were modeled.	2014	[116]
Jellyfish-inspired soft robot	Dielectric elastomer actuators (DEA)	Jellyfish	Advance	Movement through propulsion	A waterproof untethered power source was created to power the robot independently in order to facilitate untethered propulsion.	2019	[66]

Table 1 clearly shows bio inspiration movement is crucial for functioning in underwater, as each part of the mechanism represents a specific biological movement, such as an octopus's bipedal walking or a jellyfish's jet propulsion. DEA is designed to solve challenges of unstructured aquatic environments. By emulating parts of biological organisms into engineering, the field has moved beyond ROVs to create robots with enhanced capabilities like fluid mobility. Specifically focusing on SoFi robot, it explores marine areas that is 3D and imitates fish motion, with the help of fluid actuator, it controls buoyancy units for adjusting battery in deeper ocean. Tuhin (2023) states buoyancy reveals fluid dynamics insights that shape underwater robotic development.

Contrastingly, HIT_Spibot as an example of traditional quadrupod robot is characterised by precise movements. “The robot's foot workspace forms a truncated ring from intersecting circles.” (Xu, 2024). This allows for precise control with theoretically 100% efficiency, whereas SoFi operates in fluid space and must deform its shape, this will eventually add cost onto it. For navigating unstructured environments, HIT_Spibot uses a hierarchical motion planning system that combines orientation and gait sensors together to provide pathways. However, this will lead

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to operational speed cost increase and some malfunctions to occur.

Figure 4 shows 4 leg modules, 4 toe modules and 1 tool module. Xu et al (2025) describes this as a central hub connecting all components, this houses the primary system and provides the structural balance and calculations. It depicts the forces map on each module, clearly labelling how each module balances out the force to maintain stability. 2 rotating joints on leg module, provide "2R-type serial mechanism" kinematics (Xu, 2025). The joints enable rotation within "[-π, π]" ranges, providing precise angular control.

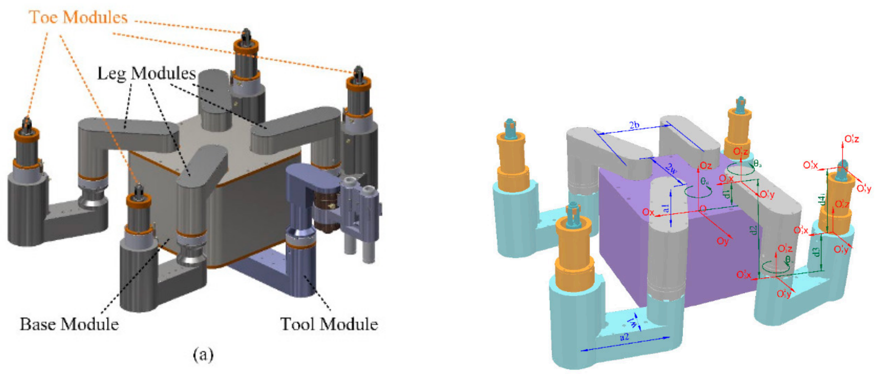

Figure 4 HIT_Spibot models (Kuan, 2025)

$$\begin{cases} r_i = r_B + \sqrt{b^2 + w^2}\cos(\alpha_i + \theta_{1i}) + a_1\cos(\alpha_i + \theta_{1i} + \theta_{2i}) \\ \qquad + a_2\cos(\alpha_i + \theta_{1i} + \theta_{2i} + \theta_{3i}) \\ c_i = c_B + \sqrt{b^2 + w^2}\sin(\alpha_i + \theta_{1i}) + a_1\sin(\alpha_i + \theta_{1i} + \theta_{2i}) \\ \qquad + a_2\sin(\alpha_i + \theta_{1i} + \theta_{2i} + \theta_{3i}) \end{cases}$$

Figure 5 Robot foot positions calculation formula (Xu, 2025)

By implementing the formula as shown in Figure 5 above, the position of every component can be precisely calculated using forward and inverse kinematics. Hence, knowing the forward and inverse kinematics, the computer can directly observe the current angles of all joints (theta values) and track down current robot configuration for simulation. SoFi uses bio inspiration with DEAs and fluidic actuators to achieve mobility and energy efficiency, which are essential for maintaining ecological balance and avoid disturbance during marine observation. HIT_Spibot selectively uses toe and leg modules for stability that outweighs precise movement and stability over material selection and ecological protection. The extent of bio-inspired enhancement depends on the interplay of function and application, where traditional robots may harm aquatic environment, on the other side, SoFi enables capabilities by developing new technologies. Both demonstrate bio-inspiration enhances robotic development, but by different mechanisms and leading to a different extend. SoFi is best suited for observing marine life where it obtains high energy efficiency. Despite HIT_Spibot is better suited for rugged underwater tasks requiring high stability because of having 4 stable leg modules, where structural support outweighs ecological concerns.

4.2.3 Overall bionic robots versus traditional legged robots and future directions

The bionic robots combines both underwater and mountainous robots and traditional industrial robots reveal a distinct comparison in multiple metrics as shown in Table 2. Alpine achieves a 0.8 payload-to-weight ratio, carrying 4kg on a 5kg vehicle, and lifts up to a ratio of 2.6. This statistic is large, hence, this exceptional data shows the advantage of the new rope support system brought up in 2024. It transfers weight directly into anchors rather than also requiring activation by compressing gravity. The perfect application of engineering principles mirrors biological systems where skeletal systems transform into rope smooth systems, allowing their muscles to use everytime.

Table 2 Comparative performance metrics: Bionic Versus Traditional Robots (Focchi et al. 2025)

Metric	ALPINE (Mountain)	Soft Underwater	BigDog (Traditional Legged)	Industrial Robot Arm
Terrain accessibility	Vertical slopes (0-0.4 rad overhang)	Complex 3D aquatic structures	35° slopes, loose scree	Level factory floor
Speed	1.52 m/s (navigation)	0.03-0.20 m/s (swimming)	3.1 m/s (bounding)	2-10 m/s (end effector)
Payload/weight ratio	0.8-2.6 (5 kg robot, 4-13 kg payload)	0.1-0.5 (estimated)	1.4 (109 kg robot, 154 kg payload)	0.1-0.3 typical
Energy consumption (navigation)	0.03 kJ/kg	0.1-1.0 kJ/kg (estimated)	257 Wh/kg (92.5 kJ/kg)	0.5-5 kJ/kg (duty cycle)
Stationary energy	0 kJ (brakes engaged)	0 kJ (passive buoyancy)	~2 kW idle (engine running)	0.1-1 kW (standby)
Environmental impact	Minimal (point contacts)	Low (compliant materials)	Moderate (ground	Confined to facility
Control complexity	High (hybrid dynamics)	Very high (infinite DOF)	High (dynamic balance)	Moderate (kinematic
Technology readiness	Research prototype	Laboratory stage	Field prototype	Mature commercial

Energy consumption is also an essential concept to cover in robotic systems, it values and shapes future terrain studies. ALPINE's 0.03 kJ/kg for navigation (Focchi et al. 2025) compared to BigDogs' 92.5 kJ/kg (Boston Dynamics, 2025). This comparison further explains 3000J advantage in saving energy by having a lighter weight and a rope system. Looking at soft underwater robots, they consume low energy (0.1-1kJ) compared to traditional industrial robots. This extends mission duration, where they are capable of being used longer and observe places deeper. Hasib et al. (2025) noted, the goal of long-duration robots that do not disturb marine life for biological interaction. Hence, low energy consumption allows for smaller batteries to work and without human need to recharge. Another advantage is that underwater robot often requires high energy consumption but it generates huge noise that disturbs marine life, SoFi's soft actuation and low energy, robotic development is rapid and at the same time, does not startle marine life and maintains natural balance.

It reveals that bio-inspired movement enhances robotic development not just merely technological advance but through constant trial and correcting errors. Each biological principles: Alpine's rope support system, soft robot's material selection (DEA and SMAs), BigDog and HIT_ Spibot quadruple dynamic balance, all addresses different complicate challenges.

In future, when these technologies bind into together, it leads to a formation of control architecture that integrates bio inspired principles with engineering methods. When the controlled system fits with reflex coordination, this larger achitecture then will have a low energy efficiency but greater disturbance. Splitting the system into three sections, the first section has passive mechanical systems that include bio inspired techniques, the second section forms coordination with sensor and computer calculations (video analysis) for better observation, and lastly the plan through maintenance of natural ecosystems. Material science advances identified by Hasib et al. (2025) point toward convergence between soft and rigid materials. For example, SMA from soft robots could improve thermal cycling and stability in fluctuating weather, elongates the thermal duration during repeated electric motors tasks. Simultaneously, the integration of rigid components, for example combination toe modules and gait sensors from traditional quadrupod robot. This also balances flexibility and transit between soft and hard conditions, allowing them to work in a wider range and provide more structural help. By allowing robots to transit in between soft and hard states, they can now adapt their structural support in wider range of unstructured environments. In conclusion, the operational envelope of robots will expand in unstructured environments beyond their capabilities.

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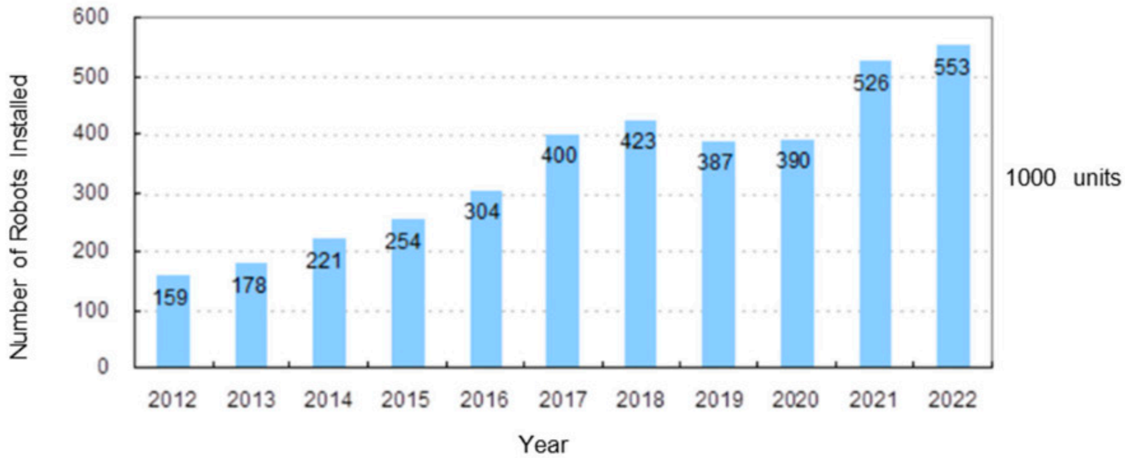
4.3 Overall marketing performances



Graph 2 Annual installations of industrial robots from 2012 to 2022 (Hashimoto, 2024)

The global robotic market is dependent on technological advancements in the society. Before 2021, the market has been fluctuating as shown in Graph 2. Indeed, the market has also been dominated by traditional industrial robots. But turning to 2025, more and more bionic robots has appeared to the market and eventually overtook the market. Hence, more industries relying on new technology, demanding in unstructured environments. Chen (2025) notes exoskeleton robots now reach 2599¥ for rescue and deep-sea use, rising from 299¥ in 2015 due to low market exposure.

The underwater robotics is predicted to expand from 3% to 12% through 2035, due to more studies exploring sea mining interests and climate research in deep regions. In this type of unstructured terrain, "ALPINE's zero-energy stationary capability enables 30-minute hammering tests without power consumption," (Focchi 2025). On the other hand, traditional industrial robots lack energy efficiency and more power input. Hence, bionic robots can work for long duration monitoring work.

Secondly, natural disasters will cause dangerous environments which will create harsh conditions for human to explore. "Global warming caused by anthropogenic climate change has increased 20% annual to 35%" (Ann 2025). This piece of information indicates more possibilities of having earthquakes and collapsed structures. The global search and rescue robotics market is expected to reach USD 8.5 billion by 2028, due to their capability of mimicking snake, insect, or quadruped locomotion which increases mobility in these unstable surfaces. They will be able to adapt quickly to disaster environments without mapping in the computer.

Lastly, high risk industrial work includes inventing nuclear facilities or removing chemical plants that remained hazardous to human body. Traditional wheeled robots struggle with uneven surfaces, whereas bio inspired climbing and crawling sensors help them to connect bridges or store materials without disrupting the workers. "The industrial inspection robotics market is projected to grow at 10.2% CAGR through 2030" (World's Robotic, 2025). This shows the adaptation of bionic robots in the market specified for complex, unstructured inspection tasks.

The bionic robot market demonstrates a gradual growth when traditional industrial robot has dropped. Hence, it positions deep-sea exploration, extreme rescue, and high-risk work as primary

factors why bio inspired robotic technology has rapidly developed.

5. Conclusion

Bio-inspired movement enhances robotic development to a substantial degree. It enables many operations that are inaccessible by using traditional old robots that are legged and wheeled. This enhancement is demonstrated through a vast number of improvements as shown clearly from the 3 comparisons between Alpine, SoFi and quadruple robots such as HIT_Spibot and BigDog. Energy savings and reduction of power consumption expand the robotic design space with adaptive control. Thus, it creates a fulfilled system that is capable of multitasking and a variety of operations over unstructured environments.

However, the research area of robotic development also reflects some limitations. A primary issue is that the difficulty of discovering the complexity of biological sytems and applying them into machineries. While robots like SoFi or BigDog applies gross motor functions, it is still harsh to combine sensory information into their activities. Ma (2025) mentioned that "there has been a gap between what people think to make and the actual product", it means that bio-inspired movement often falls on adaptability observed in nature when actually experiencing in unpredictable unstructured environments. Furthermore, the mechanical and control systems required to mimic biological movement based on their environment. These systems require expensive material cost and failure, leading to anxiety. This trade off may negate the benefits that the bio inspiration system brought to the society. Finally, current robotic research paradigm only focuses on one single biological system, for instance the DEA or SMA or crawling motors. This overlooks the power of nature and the actual metabolism in biological organisms. Until the invention of integration of different robots, it will remain challenging to achieve a substantial improvement in robotics, overlooking at material improvement rather than a development.

To advance bio inspired robots, future research should prioritize the combination of different biological systems rather than keeping only one single system. Developing hybrid control architectures would connect the gap between reality and ideas, further delving into the complexity of nature and improving robots' ability to adapt in harsh conditions. Additionally, investing in sustainable and cost-effective in simple materials would decrease the cost and reduce the barrier in between companies manufacturing robots. Ultimately, fostering collaboration between engineers and biologists will be essential to discuss potentiality of bio-inspired movement in unstructured environments.

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