Mechatronics 112 (2025) 103418

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Review

Snake robots: A state-of-the-art review on design, locomotion, control, and real-world applications☆

Syed Kumayl Raza Moosavi [a], Muhammad Hamza Zafar [a], Filippo Sanfilippo [a,b,*]

[a] Department of Engineering Sciences, University of Agder, Grimstad, 4879, Norway
[b] Department of Software Engineering, Kaunas University of Technology, 44249, Kaunas, Lithuania

ARTICLE INFO

Keywords:
Snake robots
Terrain adaptability
Locomotion strategies
Applications
Robot designs
Control

ABSTRACT

Snake robots have emerged as a transformative class of bio-inspired robotic systems, offering unparallelled adaptability in navigating complex unstructured terrains. Their limbless design, inspired by biological snakes, enables efficient movement across diverse environments, including rough terrains, confined spaces, and hazardous conditions where traditional wheeled or legged robots struggle. This review provides a comprehensive analysis of the design and development of snake robots, covering their locomotion strategies, mechanical configurations, sensor integration, control schemas, and actuation mechanisms. The review further explores the evolution of mechanical structures from rigid, soft, and hybrid designs, emphasising advancements in actuation and sensor technologies in enhancing adaptability and navigation. Applications of snake robots extend across various domains, including search and rescue (SAR), industrial inspection, and exploration of extreme environments. Despite significant progress, challenges such as optimising energy efficiency, improving environmental perception, and achieving real-time adaptability remain open research areas. This review serves as a foundational reference for researchers and engineers working towards advancing the next generation of snake robots, paving the way for their integration into real-world applications.

Contents

☆ This paper was recommended for publication by Associate Editor Oliver Sawodny.

* Correspondence to: University of Agder (UiA), Jon Lilletuns vei 9, NO-4879, Grimstad, Norway.
E-mail address: filippo.sanfilippo@uia.no (F. Sanfilippo).

https://doi.org/10.1016/j.mechatronics.2025.103418
Received 20 March 2025; Received in revised form 28 June 2025; Accepted 22 September 2025
Available online 7 October 2025

1. Introduction

In nature, not all animals have pairs of legs for locomotion. Some creatures without limbs have unique movement capabilities for forward propulsion. Surprisingly, these animals such as snakes, worms, caterpillars exhibit a wide range of locomotion morphologies adaptive to the terrain and environment they are found in. Survival pressures force animals to move from one place to another in an efficient manner. Their movements therefore require reasonable coordination of articulation, so that animals can overcome friction and gravity and push themselves forward. As a branch of animal locomotion classification, limbless locomotion exhibits its movement patterns and good performance in unique environments [1]. For example, desert snakes use sidewinding type of locomotion to avoid overheating due to extensive contact with the sand [2]. Similarly, small sized caterpillars use their posterior legs to form an anchor (Ω) type body shape for forward propulsion. Some snakes in nature mimic such caterpillars movements as well. Snakes exhibit exceptional adaptability in their locomotion, tailoring their movement patterns to suit the specific terrain and environmental challenges they encounter.

Despite having skeletons, snakes are commonly considered as expert sliders in the kingdom of soft movements. Snakes slither on flat and rocky terrains based on two principles; frictional anisotropy and dynamic weight distribution. This is done by utilising cutaneous mechanoreceptors and proprioceptors to sense pressure, surface textures, and internal body movement, allowing them to adjust contact forces and maintain efficient propulsion [3]. Snake scales provide the body low friction with the ground in the forward direction and high friction in the backwards and/or lateral direction enabling the body to move forward. Moreover, snakes have the ability to increase their speed by dynamically distributing its weight so that its concentrated on small areas of zero body curvature [4].

Inspired by the unique advantages of limbless locomotion, scientists have long been interested in designing and studying robots that can mimic these movements, adapting them to mechanical systems. Despite having decades of well developed biological and theoretical foundation of snake body movement, the development of their model is quite complex specially involving multi sensor feedback and locomotion in complex unstructured terrains.

Over the past decade, research on snake robots has progressively evolved, addressing key challenges in locomotion, maneuverability, and real-world deployment. From our research group, early contributions focused on perception-driven obstacle-aided locomotion, introducing virtual functional segmentation [5] to enhance movement efficiency and conducting comprehensive reviews on perception-driven locomotion strategies for snake robots [6,7]. Building on these foundations, SnakeSIM, a ROS-based rapid-prototyping framework, was introduced to simulate and control snake robots in complex environments [8]. Subsequent work expanded the bio-inspired steering and locomotion models, bridging the gap between biological principles and robotic implementation [9]. A major milestone was the development of Serpens, a modular snake robot, which incorporated series elastic actuators and a screw-less assembly mechanism to enhance compliance and adaptability [10,11]. This was followed by advances in perception-driven path planning, allowing snake robots to utilise environmental obstacles for improved navigation [12]. More recent efforts have focused on enhancing holonomic mobility, with the introduction of a cost-effective and compliant snake robot design [13] and the integration of grasping with locomotion [14]. The latest advancements have addressed adaptive maneuvering control under uncertain friction conditions, enabling snake robots to navigate complex terrains more effectively [15,16]. Additionally, collaborative robotics research has explored the role of snake robots in disaster response, proposing swarm-based frameworks for delivering first aid in emergency scenarios [17,18].

On that note, this review paper aims to address the following key research questions to provide a comprehensive analysis of snake robots in the literature, focusing on their locomotion capabilities, mechanical/hardware design used and applications across diverse environments.

- RQ1: How does the biology and natural locomotion of snakes inspire the design and functionality of snake robots?
- RQ2: What materials, sensors, actuators and mechanical designs are employed for snake robots?
- RQ3: What control strategies are implemented to optimise snake robot locomotion across diverse terrains?
- RQ4: What are the key applications of snake robots, and what challenges and limitation are present for terrain traversal?

This paper is organised as follows. Section 1 continues with the review procedure employed in this study and how the biological of snakes have inspired scientist and researchers to develop robots. Section 2 discusses the sensors, actuators, and materials used and the innovative mechanical designs made for different terrain locomotion applications. Section 3 discusses the control strategies implemented in literature for optimal snake robot locomotion. Section 4 documents the applications and use case scenarios in snake robot locomotion. Section 5 discusses the similarity, differences and challenges and limitations that have been identified from this review. Finally, Section 6 provides the conclusion of this study.

1.1. Systematic review procedure

This paper analyses the evolution of the academic literature on the use of snake robots in diverse terrains and applications. The paper focuses on the English-language literature on the use of robots in crisis management, because more than 90% of the indexed scientific articles globally are published in that language [19].

Electronic databases including Google Scholars, Scopus, IEEE Xplore, and Science Direct were searched for the period from 2014 to November 2024, using the specified terms combined with the Boolean operators outlined in Table 1. Additionally, relevant studies were identified by reviewing bibliographies in academic articles. The analysis of the retrieved publications followed the approach of Ivanov et al. [20] and took into account: type of publication (journal article, conference paper, chapter in a book or book), year of publication, and full bibliographic reference. The text of each publication was read. Due to the large number of publications in a single year, the studied period (from 2014 to 2024), was divided into 2-year blocks. The qualitative analysis is based on content analysis of publications by research domains. By encompassing a full decade, the review provides a balanced perspective, highlighting both the historical context and the current state-of-the-art innovations. The search and selection process for included studies is illustrated in Fig. 1. Furthermore, the titles and abstracts were screened and filtered based on the inclusion criteria, see Table 2.

Table 1
Database keyword searchers.

Google Scholars	((Snake Robots) OR (Limbless Robots) OR (Snake Locomotion) OR (Snakes)) AND ((Constrained environments) OR (Terrains) OR (Pipe Inspection) OR (Search and Rescue) OR (Applications) OR (Exploration)) AND ((Designs) OR (Materials) OR (Mechanisms) OR (Sensors) OR (Actuators) OR (Control))
Web of Science	((Snake AND Robots) OR (Limbless AND Robots) OR (Snake AND Locomotion) OR (Snakes)) AND ((Constrained AND environments) OR (Terrains) OR (Pipe AND Inspection) OR (Search and Rescue) OR (Applications) OR (Exploration)) AND ((Designs) OR (Materials) OR (Mechanisms) OR (Sensors) OR (Actuators) OR (Control))
Scopus	("Snake Robots" OR "Limbless Robots" OR "Snake Locomotion" OR "Snakes") AND ("Constrained environments" OR "Terrains" OR "Pipe Inspection" OR "Search and Rescue" OR "Applications" OR "Exploration") AND ("Designs" OR "Materials" OR "Mechanisms" OR "Sensors" OR "Actuators" OR "Control")
IEEE Xplore	("Snake Robots" OR "Limbless Robots" OR "Snake Locomotion" OR "Snakes") AND ("Constrained environments" OR "Terrains" OR "Pipe Inspection" OR "Search and Rescue" OR "Applications" OR "Exploration") AND ("Designs" OR "Materials" OR "Mechanisms" OR "Sensors" OR "Actuators" OR "Control")

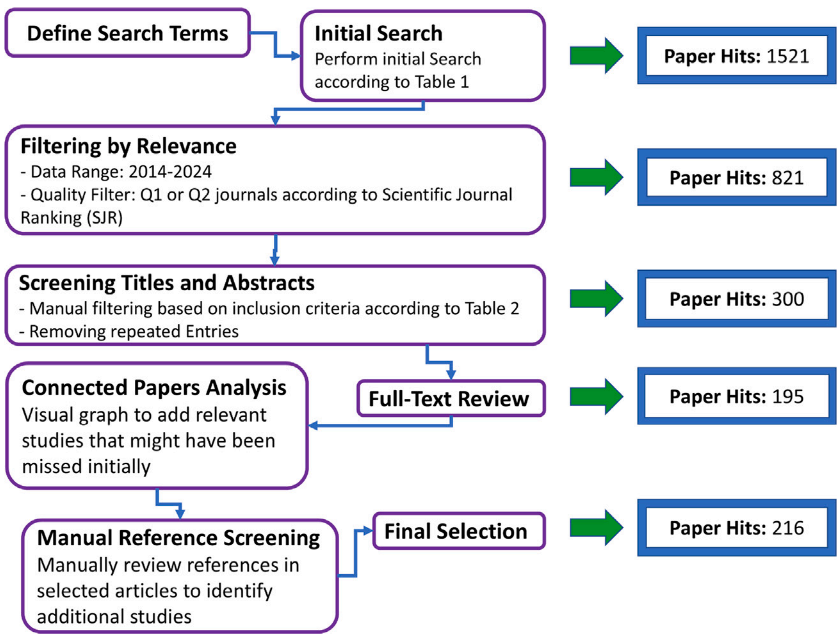

Fig. 1. Flow diagram illustrating the systematic process used to select papers, from defining search terms to final selection.

Table 2
Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
The studies focused on robots inspired by snakes.	The studies inspired by other types of limbless locomotion like caterpillars, worms.
Diverse terrain traversal applications	Terrain traversal is not the highlighted part of the study
Peer reviewed original work in a high quality journal	Published in a language other than English
Novel mechanical design of snake robots that has some level of terrain adaptability	

1.2. Snake biology to robotics

Years of research across diverse species has revealed that the global organisation of neurons responsible for locomotion is largely conserved across the skeletal structures of both vertebrates and invertebrates. As a result, animals have largely learned to solve the challenges associated with maneuvering unexpected perturbations by creating efficient and robust locomotion strategies. While the nervous system of a snake has far less neurons than of the mouse, many species in the animal kingdom principally engage motor systems by driving central pattern generators (CPG). CPG is mainly responsible for producing periodic bursts to generate a rhythmic appendage movement for forward/backward propulsion. This body movement is further calibrated by three more enhancement systems: First, the proprioceptive feedback from the body and limbs provide force adjustment to the CPG network dynamics. Second, the mechanosensory feedback from the skin provides robustness against unstructured terrains. Thirdly, the exteroception from vision, smell and hearing enable further fine tuning of navigation [21].

The biomechanics of animal structures, such as those of snakes, can now be modelled with greater realism. Advanced mathematical frameworks and control strategies that leverage degrees of freedom in interconnected structures bridge the gap between simulations and practical designs for real-world snake robots in varying scenarios and terrains. The design of snake robots can be classified into categories ranging from locomotion strategies to mechanical design components to control techniques, as shown in Fig. 2.

These advancements in modelling and design are further complemented by the integration of robust Guidance, Navigation, and Control (GNC) systems, essential for snake robots to achieve versatile and adaptive locomotion [6]. **Guidance** enables the robot to sense, map, and localise its environment using sensor feedback, providing critical data for situational awareness. **Navigation** builds on this by determining optimal paths and trajectories, often inspired by CPGs found in biological systems, to achieve efficient movement. **Control** systems then translate these trajectories into precise actuator commands, adjusting dynamically based on feedback to handle unstructured terrains

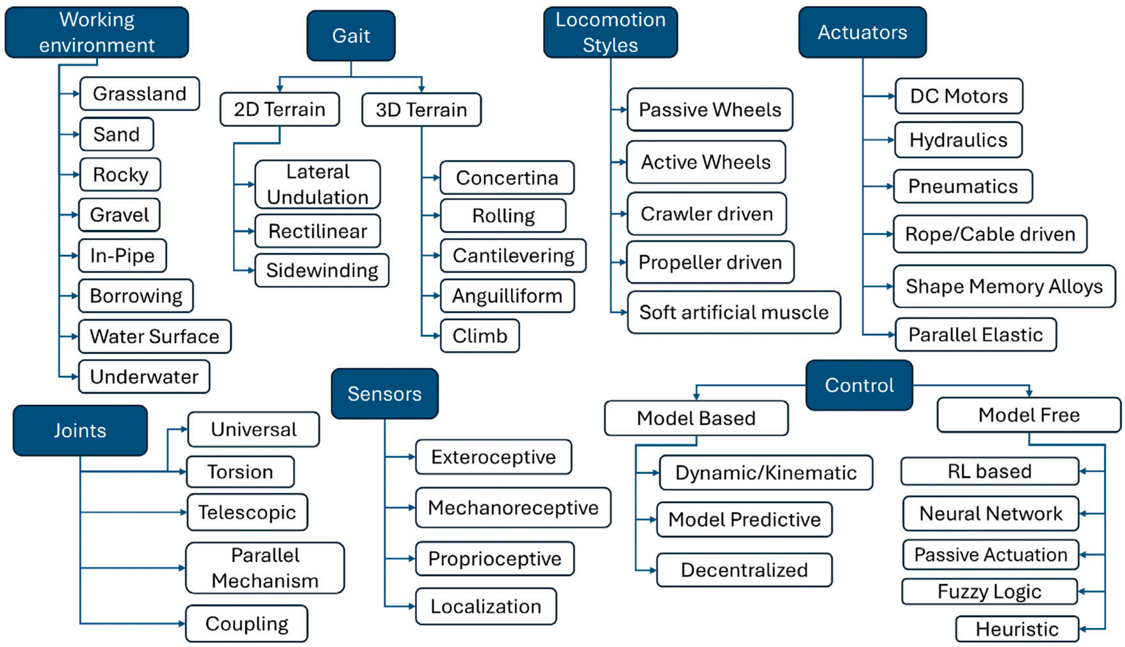

Fig. 2. Snake robot classification methods.

and environmental perturbations. Together, these systems bridge the gap between biological locomotion and engineered solutions, driving advancements in snake robotics.

1.2.1. Working environments

Snake robots are uniquely designed to operate across a wide range of environments, making them versatile tools for navigation in diverse and often challenging terrains. Inspired by the adaptability of biological snakes, these robots can potentially traverse multiple surfaces and obstacles. The working environments for snake robots can be broadly categorised into terrestrial, aquatic, and confined spaces, each presenting unique traversal challenges and opportunities.

Snake robots are particularly effective in terrestrial environments, where their design allows them to traverse various substrates. Gray et al. [22] explored the different ways snakes move on land, including serpentine, concertina, sidewinding, and rectilinear movements. Gray's research, primarily on the grass snake (Tropidonotusnatrix), demonstrated that the type of movement depends on the external forces acting on the snake's body. For example, serpentine movement is typical in most snakes, while concertina and sidewinding movements can be elicited in the grass snake under specific environmental conditions. Authors in [23], explore the use of a Driving Assistant Mechanism (DAM) for snake robots to enhance locomotion performance on grasslands, characterised by uneven and unpredictable surfaces, can interrupt locomotion and lead to instability. The DAM improves stability without requiring additional sensors or driving algorithms. Marvi et al. [24] examines how snakes excel in navigating sandy environments, using their natural ability to traverse granular media as inspiration for improving snake robot design. It highlights how snakes adapt to loose, unstable sand and granular terrain by dynamically adjusting their body mechanics. Zhu et al. [25] highlights how snakes such as the rattle snake (Crotalus cerastes) and similar organisms optimise their movement and energy efficiency by adapting their body deformation levels and wave configurations to the properties of sand as a granular medium. Using theoretical frameworks and finite element simulations, the study reveals that one-wave configurations with medium deformation are optimal for locomotion of snake robots in sand.

By leveraging lateral undulation and concertina locomotion, snakes excel in environments with scattered rocks and uneven surfaces, turning obstacles into opportunities for propulsion. The study in [26] emphasises how snake robots replicate these movements, using multiple contact points to generate forward motion even on cluttered and irregular rocky surfaces. Zhuang et al. [27] investigates the adaptability of the snake robot's modular design and telescopic movement, allowing it to overcome high-friction environments with irregular surfaces. During field tests on gravel terrains, the robot demonstrated the ability to adjust its movement by minimising frictional resistance and enhancing joint flexibility. These findings emphasise the importance of optimising material durability and motor torque for reliable snake robot operation in gravel-like environments.

Snake robots have proven to be highly effective for in-pipe inspections, addressing the challenges posed by confined and complex environments. Rashid et al. [28] provides a comprehensive review of the modelling and kinematic designs of various in-pipe robots, emphasising their adaptability to pipe geometries, including bends and irregularities. Nivethika et al. [29] discusses the development of snake robot capable of navigating industrial pipelines with servo-driven modular designs. Selvarajan et al. [30] highlights advancements in modular snake robots with degrees of freedom tailored for serpentine, inchworm, and concertina gaits, enabling efficient inspection and real-time monitoring in pipelines of varying diameters. Similarly, the authors in [31], demonstrates a machine learning-driven snake robot optimised for vertical self-burrowing in granular media. It uses sinusoidal motion and adaptive control to efficiently achieve targeted depths, showcasing its potential for tasks like soil analysis and subterranean exploration.

Snake robots exhibit significant adaptability in aquatic environments, including surface and underwater applications. For surface locomotion, the authors in [32], highlight the use of quasi-static stabilisation methods inspired by semi-aquatic snakes, enabling effective motion despite buoyant instability and external disturbances. Moving underwater, [33,34] emphasise efficient locomotion patterns, such as lateral undulation and eel-like swimming, which are optimised for speed and energy efficiency using advanced control and hydrodynamic modelling. In [35], these concepts are extended by exploring foil propulsion techniques to improve the velocity and energy efficiency of snake robots operating in subsea environments, demonstrating the advantages of integrating caudal and dorsal fin mechanisms. In [36], the focus is on the development of comprehensive hydrodynamic models and path-following control strategies, enabling snake robots to navigate complex underwater scenarios with precision and reduced energy consumption.

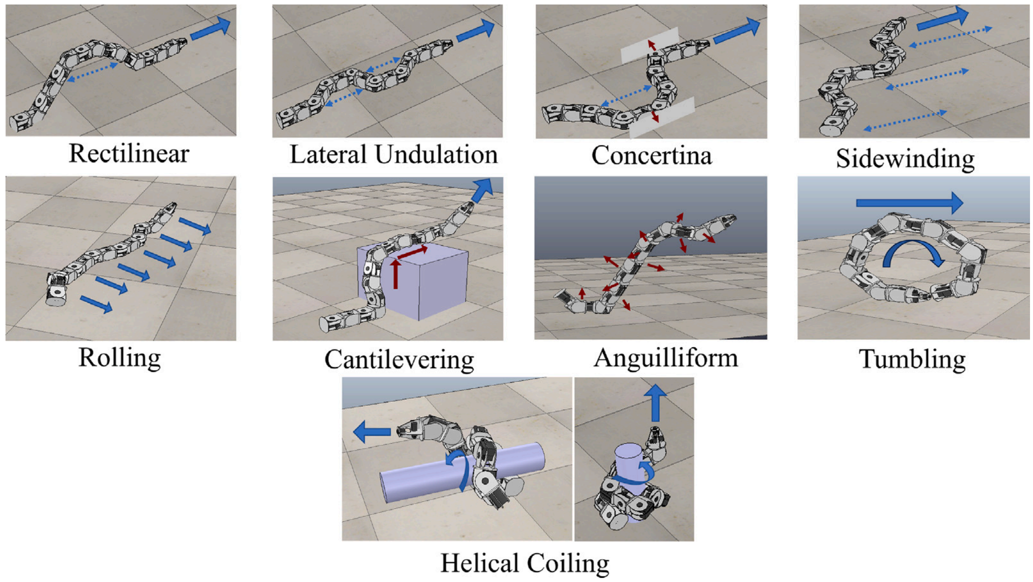

Fig. 3. Illustration of snake locomotion strategies.

Table 3
Different locomotion strategies used by snakes.

Types	Use case	Description
Lateral undulation [38]	Flat terrains	Moves by generating sinusoidal waves from head to tail, using ground roughness for propulsion, leaving a sinusoidal pattern.
Concertina [39]	Narrow passages	Forward propulsion is achieved by alternating between stretching and folding the body, making it suitable for navigating narrow pipes or passages.
Rectilinear [40]	Less friction surfaces	The motion is achieved by propagating an expansion and contraction wave through the ventral skin, anchoring the body at points of contraction for movement.
Sidewinding [41]	Sandy/granular	Movement is achieved by lifting and curving the body, leaving parallel marks on the ground, commonly used by desert snakes.
Helical coiling [42]	Cylindrical structures	The folded section of the body remains stationary, providing traction, while the extended portion stretches and pulls itself higher. This method allows them to ascend narrow vertical/horizontal spaces with control and stability.
Cantilevering [43]	Climbing steps	Involves extending a portion of the body into free space while keeping the rest anchored on a surface. This is particularly useful for traversing steps or gaps, where the anchored part provides stability while the free portion reaches upward or forward to a new step, allowing the body to pull itself up incrementally.
Anguilliform [44]	Underwater	Anguilliform locomotion involves wave-like movements along the entire body, generating thrust by undulating from head to tail. This allows for smooth, flexible movement underwater.
Rolling [45]	Slopes	The snake forms a loop with its body and rolls rapidly like a wheel, using gravity for propulsion. This unique motion is used primarily as an escape strategy on steep slopes, allowing for swift movement in desert environments.
Tumbling [46]	Flat or mildly rough	A mode of movement where the robot forms a circular loop with its body and propels itself forward through controlled rolling or flipping motions, offering enhanced speed, energy efficiency, and adaptability to flat or uneven terrains,

1.2.2. Locomotion gaits

The concept of gaits is central to understanding the locomotion strategies employed by snake robots. Gaits are the specific movement patterns or sequences used by snakes, and consequently snake robots, to propel themselves through various environments. This ability is the driving force for the development of snake robots with highly adaptive functions, and autonomous decentralised control mechanisms may be the key to understanding this movement [37]. These patterns are directly inspired by the diverse range of motions observed in biological snakes, each tailored to navigate a particular type of terrain or overcome specific challenges. The versatility of snake gaits allows them to traverse grasslands, sandy terrains, rocky surfaces, narrow passages, and even water, making them highly adaptable and efficient.

Snake gaits are broadly categorised based on the body's interaction with the environment and the underlying movement mechanics. Each gait offers distinct advantages, depending on the terrain and the task at hand. The most common gaits is Lateral Undulation, Rectilinear and Concertina. Jayne et al. [47] conducted an in-depth analysis of muscle activity in biological snakes using electromyography (EMG) and cinematography to study lateral undulating motion on land and in water, as well as concertina locomotion. Building on earlier research into the physical principles and muscle activity patterns associated with the lateral undulating gait, Moon et al. [48] investigated how muscle activity generates body curvature and facilitates propulsion in lateral undulating gait. In [49], the authors present an adaptive helical rolling motion for snake robots, enabling effective helically wrapped climbing in irregularly shaped pipes and complex surfaces.

The diverse range of gaits described in Table 3 highlights the adaptability and efficiency of snake locomotion, serving as a foundation for designing versatile and robust snake robots. Fig. 3 complements the table by visually illustrating the body mechanics and terrain interactions for each gait, providing a comprehensive understanding of their functionality and application.

2. Mechanical and hardware design

For decades, the design and advancement of snake robots have remained at the forefront of robotics research, driving innovation in both academia and industry. Researchers worldwide have explored novel methods to enhance the locomotion, adaptability, and functionality of these robots across diverse applications. The foundational work by Hirose et al. [50] in 1972 introduced a pioneering 2-metre-long snake robot with 20 single-degree-of-freedom (DOF) rotating joints, capable of forward motion on smooth surfaces. Since then, significant strides have been made in the design, actuation, sensing technologies, and control strategies of snake robots, enabling their deployment in increasingly complex environments.

This section outlines the materials and methods utilised in the design and development of snake robots, focusing on the critical components that contribute to their adaptability and performance. From modular structures to advanced actuator systems and sophisticated sensing mechanisms, each aspect is designed to replicate the unique locomotion strategies observed in biological snakes. These advancements, coupled with bio-inspired design principles, have established a robust framework for snake robots to navigate complex terrains and execute tasks in diverse environments.

2.1. Mechanical design

The mechanical design of biological snakes is a remarkable example of evolutionary adaptation. Their limbless, elongated bodies provide unparallelled flexibility and maneuverability. The snake's skin plays a vital role in its locomotion, featuring specialised scales that create anisotropic friction. The ventral scales reduce resistance during forward motion while providing traction, allowing efficient propulsion. Adaptations in scale structure vary with habitat, as seen in desert snakes with smoother scales for minimising drag on sand and arboreal snakes with keeled scales for better grip on branches. Additionally, their skin aids in waterproofing and moisture retention, crucial for aquatic species to minimise drag and maintain hydration.

Internally, the segmented vertebrae and ribs, coupled with flexible intervertebral joints, offer a blend of strength and flexibility. The highly coordinated muscular system works alongside the skeleton to enable smooth, energy-efficient motion, distributing forces evenly across the body. The linear arrangement of elongated internal organs further enhances flexibility and reduces body cavity complexity. The snake's movements are also informed by tactile sensory feedback from its skin, which helps detect surface textures and pressure, allowing real-time adjustments for optimal locomotion.

The intricate design of modular snake robots is fundamentally determined by the configuration of connections between individual links and the degrees of freedom incorporated into each joint, which collectively enhance the robot's locomotion capabilities. Compared to biological snakes, snake robots have fewer degrees of freedom per unit length. As a result, they must adjust the joint amplitudes more significantly to achieve the desired curvature profile, which complicates the efforts aimed at enhancing their locomotion performance. 1-DOF modules are the simplest configuration, with each module offering a single rotational axis. These modules are often connected with their rotational axes aligned in parallel, and passive wheels are commonly attached underneath to reduce tangential friction. This design simplifies dynamics modelling and motion control, making it well-studied and easy to implement. Although planar snake robots with 1-DOF modules can adapt to certain terrains, such as tunnels or slopes, their lack of unstructured motion limits their applicability in complex real-world environments. However, when multiple 1-DOF modules are assembled strategically, they can still achieve basic unstructured motion capabilities, albeit with limitations. Racioppo and Ben-Tzvi [51] presented cable-driven 1-DOF modular snake robot, emphasising a novel multi-radius pulley system for actuating coordinated bending across multiple joints. Shukla et al. [52] developed a 1-DOF snake robot featuring a modular rigid design with 10 universal joints. Berthet-Rayne et al. [53] introduces a novel bi-stable synchronous rolling-joint to enhance stability and force transmission.

In contrast, 2-DOF and 3-DOF modules significantly enhance the robot's ability to navigate complex terrains and perform unstructured maneuvers. 2-DOF modules are designed primarily in two configurations: stacking two rotational motors orthogonally or arranging motors in parallel with mechanisms like worm gears, angular swivel gears, or bevel gears to achieve perpendicular rotational axes. For instance, Cortez et al. [69] presented a snake robot actuated by shape memory alloy (SMA) spring-shaped actuators in an agonist–antagonist configuration, enabling motion across 2-DOF at each joint. Primerano [61] presents the design of a snake robot incorporating both translational and rotational degrees of freedom, improving its adaptability to various movement scenarios. Meanwhile, 3-DOF modules integrate three rotational axes into a compact structure, allowing for shorter robot lengths and advanced locomotion capabilities. Despite the challenges in implementing three rotational axes within a single module, these designs offer unparallelled adaptability for navigating diverse terrains. For instance, Ahmed and Billah [70] proposed a smart material-actuated, tendon-driven flexible snake robot, with three EAP tendons in each segment to achieve 3DOF motion, capable of navigating narrow and complex environments. Liu et al. [57] introduced a multi-gait snake robot for inspecting the inner walls of gas pipelines. The robot consisted of 21 rigid modules connected by orthogonal universal joints, actuated by high-torque servo motors to achieve 3-DOF motion. Pneumatic modules, which can offer 2-DOF or 3-DOF motion, provide additional benefits such as high force transmission, low cost, and linear expansion motion, but they suffer from limited control accuracy and slower propulsion speeds. To address these limitations, hybrid modules combining pneumatic joints for directional control and motors for propulsion have been developed. For instance, Wan et al. [71] presented a modular 3D-printed soft robotic snake capable of multi-modal locomotion, including lateral undulation, sidewinding, and step climbing. The evolution of these designs reflects an intricate balance between functionality, adaptability, and scalability, leading to the categorisation of snake robots into three main design paradigms [72]:

- **Rigid**: Built with solid, mechanical components, rigid robots offer robust structural integrity and precision. They are well-suited for applications that require high force or stability. However it can sometimes hinder their ability to adapt to highly irregular terrains or environments.
- **Soft**: These are constructed entirely of pliable materials, providing them with high flexibility and the ability to conform to complex shapes. This makes them particularly useful for delicate tasks such as navigating through confined spaces or working in environments where avoiding damage to surrounding structures is critical. However, the absence of rigid components can limit their force application and load-carrying capacity.
- **Soft-Rigid**: These hybrid designs combine the flexibility of soft materials with the strength of rigid components. This approach offers an optimal balance between adaptability and structural support, making soft-rigid robots the most commonly used type. Their versatility enables them to navigate complex terrains while maintaining the capacity to perform tasks that require force and stability, such as climbing, gripping, or lifting objects.

Moreover, the choice of materials is an incumbent role in the design and functionality of snake robots. The materials used must align with the robot's intended application and environment, enabling it

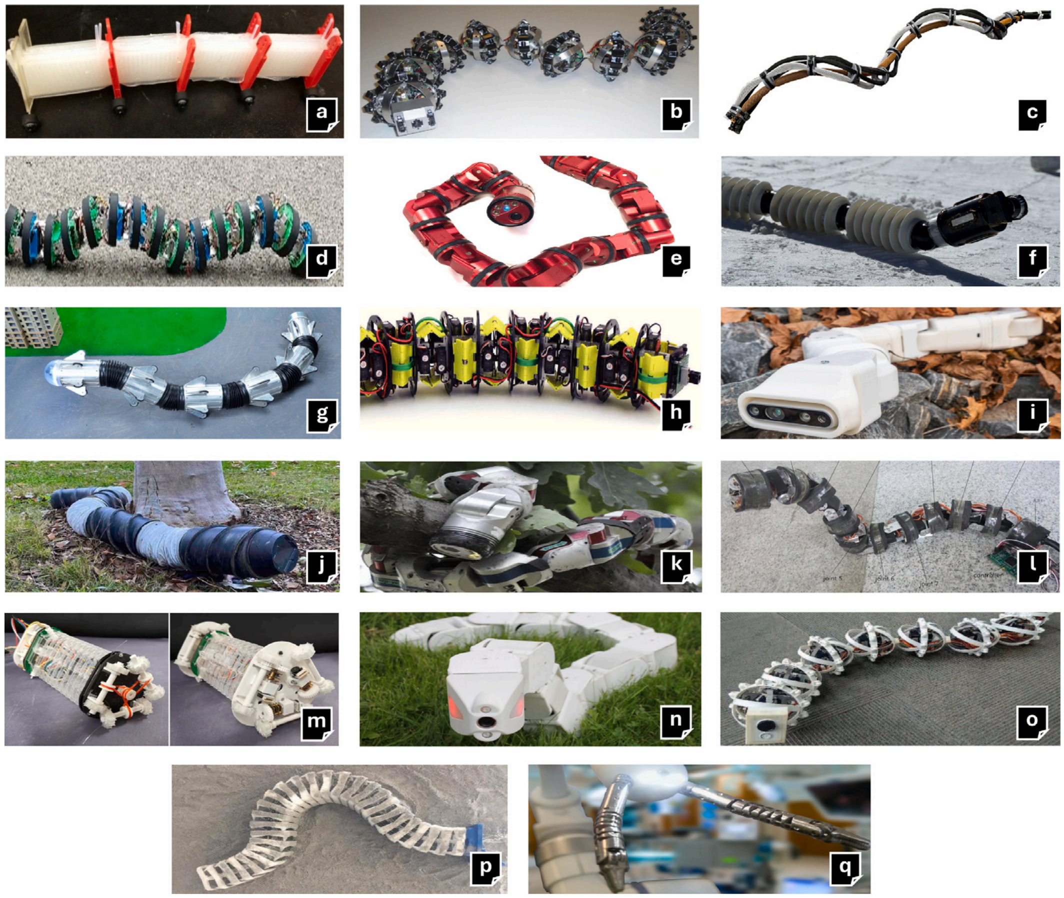

Fig. 4. Snake robots in literature navigating diverse terrains, showcasing adaptability and locomotion on uneven and challenging surfaces: (a) [54] (b) [55] (c) [56] (d) [57] (e) [58] (f) [59] (g) [60] (h) [61] (i) [10] (j) [62] (k) [63] (l) [64] (m) [65] (n) [66] (o) [67] (p) [68] (q) [53].

to navigate diverse terrains effectively. Snake robots typically use a combination of rigid, soft, or hybrid materials, each offering distinct advantages. Rigid materials, such as aluminium alloys [73,74], PLA [30], and ABS plastics [30], are widely employed for their strength and structural integrity. These materials are ideal for applications requiring precise control and high load-bearing capacity.

To balance these properties, hybrid designs integrating both rigid and soft materials have become increasingly popular. These designs utilise rigid components for structural support while incorporating soft materials to enhance flexibility and adaptability. Ahmed and Billah [70], for instance, employed EAPs in a soft-rigid snake robot, achieving unstructured motion while maintaining structural stability. Similarly, kirigami skins and braided meshes are incorporated into hybrid designs to improve traction and adaptability on challenging terrains, such as granular media or foam surfaces [75].

In addition, the mechanical design of joints defines the range of motion and adaptability of snake robots. Universal joints, constructed from materials like aluminium or other lightweight metals, provide two-axis rotation and are commonly used in rigid modular robots. Torsional joints, often made from elastic materials such as polyurethane, allow for twisting motions, making them suitable for navigating confined spaces. Telescopic joints, utilising materials like spring steel, enable linear extension and retraction, which is advantageous in tubular environments. Additionally, parallel mechanism joints, incorporating a mix of silicone and PLA, support multi-DOF motion, as seen in soft artificial muscle-driven robots [71].

The locomotion style of snake robots further highlights the interplay between material choice and mechanical design. Passive wheels, commonly used in rigid designs, utilise materials like aluminium or ABS to reduce friction and simplify motion on flat surfaces [74]. Active wheels, constructed with durable materials such as rubber or reinforced polymers, provide propulsion for uneven terrains. Crawler-driven locomotion, leveraging soft-rigid materials such as silicone or TPU, ensures stability on surfaces with variable friction. Propeller-driven mechanisms, typically used in underwater robots, utilise lightweight materials like acrylic to reduce drag. Finally, soft artificial muscles, made from materials such as pneumatic actuators or electroactive polymers, mimic the wave-like motion of biological snakes [76]. Table 7, provided in the Appendix section, summarises various snake robot designs over the last decade, detailing their joint types, locomotion styles, materials used, link configurations, control schemas, and terrain adaptability, highlighting diverse mechanical implementations. Fig. 4 shows designs found in literature over the last decade that have been developed for diverse terrain adaptability.

2.2. Actuators

Actuators play a pivotal role in the design and functionality of snake robots, as they are responsible for generating the motions and forces required for locomotion and manipulation. These components act as the “muscles” of the robot, converting various forms of energy into mechanical motion. The effectiveness of a snake robot’s design is heavily reliant on the type, configuration, and integration of its actuators. As snake robots are increasingly deployed in complex and unstructured environments, the choice of actuators becomes a critical design consideration, evaluated based on the following criteria: torque capacity, joint bending range, controllability, and module dimensions. Additionally, snake robots, designed as a serial chain of actuators, offer a high degree of versatility in navigating complex environments, such as pipes and tree branches. The individual control of each actuator

Table 4
Comparison of actuator types for snake robots.

Actuator type	Advantages	Disadvantages
Electric motors	High precision and controllability Widely available and cost-effective. Compact servos with integrated gears and encoders simplify design.	Limited torque and force output. Bulky modules when designed for 2-DOF or 3-DOF. Higher power consumption.
Pneumatic/Hydraulic	High force transmission and flexibility. Simple design for linear deformation. Capable of smooth and compliant motion.	Requires pumps and air supply, increasing system complexity. Limited control accuracy and slower response time. Bulky and less portable.
SEA/PEA	High compliance and energy efficiency. Shock absorption and precise force control (SEA). Energy storage and reduced actuator fatigue (PEA).	Increased mechanical complexity. Limited force and torque capacity compared to direct actuation. Complex design and control algorithms required.
SMA	High power-to-weight ratio. Compact design with biomimetic motion. Simple mechanical structures for actuation.	Slow response time due to heating/cooling cycles. Limited durability under repeated loading. Hysteresis and nonlinear dynamics complicate control.

enables precise movement, facilitating the robot's ability to maneuver in unstructured spaces. Ryo Ariizumi et al. [77] focus on the trajectory tracking control of snake robots, emphasising the role of actuators in maintaining the robot's head trajectory.

Moreover, the environment in which the robot operates often dictates the actuator's required properties, such as force output, precision, energy efficiency, and durability. Over the years, a wide variety of actuator technologies have been explored and implemented in snake robots, each offering distinct advantages and trade-offs. Following is a brief description of each type of actuator mechanism used in literature over the last decade (see Table 4).

- **Electric Motors**: Electric motors, particularly direct current (DC) motors, have long been a dominant choice for actuating snake robots due to their reliability, versatility, and ease of control. In the simplest implementations, DC motors are placed directly on the robot to control the movement of joints. For instance, Bianchi [78] used a DC motor actuation mechanism using waterproof servomotors enabling precise and efficient aquatic locomotion. A cost effective 10 link snake robot design was manufactured in [52] using MG996R servo motors. Similarly, an advanced actuation mechanism employing DYNAMIXEL XH540-V270-R servomotors [79] were integrated into 28 pitch–yaw rotational joints, enabling precise adaptation to complex environments. While this approach allows for straightforward integration and precise control, it introduces challenges related to the size and weight of the motors, posing limitations for miniaturisation and the robot's ability to navigate narrow or constrained spaces.
  To address these limitations, an alternative class of DC motor-based designs uses offboard motors, where the generated forces are transmitted to the joints through bands and pulleys. For instance, a cable-driven snake robot [80] utilising Maxon EC-MAX30 motors for actuation was developed.
- **Pneumatic/Hydraulic**: Soft, pliable material-based snake designs offer high flexibility and the ability to conform to intricate and irregular shapes. These designs often employ pneumatic and hydraulic actuators, which enable nonrigid movements and provide significant capacity for object manipulation. While these actuators excel in delivering smooth, compliant motion and high force output, they require pumps and additional infrastructure, which can increase the overall cost and complexity of the robot, as well as pose challenges for portability and deployment.
  For instance, Qi et al. [81] present a pneumatic soft snake robot designed using modular pneumatic bending actuators with four air chambers per module, enabling serpentine motion with precise deformation and adaptability. Similarly, a 3D-printed soft robotic snake was presented in [71] actuated by modular pneumatic silicone rubber chambers with embedded air control systems. The authors in [82] presented a fibre-reinforced pneumatic actuated snake robot. Building on the advantages of pneumatic actuators, Pneumatic Artificial Muscles (PAMs) mimic the natural contraction and extension of biological muscles, providing smooth, compliant, and high-force motion with lightweight and compact designs. For instance, the authors in [83] describe a PAM-based snake robot that utilises braided pneumatic actuators to achieve biomimetic movements. Similarly, HISSbot [56] is a soft snake robot actuated using McKibben PAMs arranged in a helical configuration.
- **Series/Parallel Elastic Actuator (SEA/PEA)**: are advanced actuation mechanisms designed to improve force modulation, energy efficiency, and compliance in robotic systems. SEAs incorporate an elastic element, such as a spring, in series with the actuator and the load, enabling precise force control and shock absorption while reducing wear on the actuator. The authors in [10,58,76] demonstrate the effectiveness of SEAs in allowing the robot to store and release energy while mitigating excessive impact forces. PEAs, on the other hand, place the elastic element parallel to the actuator, allowing the spring to share the load. This configuration is particularly effective for storing and releasing elastic energy in cyclic tasks. The authors [84] propose a novel approach by integrating PEAs into an N-link planar snake robot. The actuators use tension springs connected in parallel with the motor, allowing the robot to synchronise actuator output with the natural resonance frequency of the springs.
- **Shape memory alloys (SMAs)** [69]: are a transformative actuation technology for snake robots, offering high power-to-weight ratios and unique shape transformation properties through thermally induced phase changes. These alloys transition between martensite and austenite phases when heated, enabling significant deformation and recovery capabilities. Wright et al. [63] present a Unified Modular Snake Robot, a highly redundant serial-linkage robotic system designed for navigating complex environments. However, their deployment is not without challenges, including slower response times due to heating and cooling cycles, limited durability under repeated loading, and the need for advanced control strategies to address hysteresis and nonlinear dynamics.

2.3. Sensors

To achieve high locomotion adaptability to varying environments, snake robots require an advanced perception system combined with efficient mechanical exploitation of their surroundings. This includes a high degree of environmental awareness through precise sensing capabilities and the ability to interact dynamically with obstacles. These robots rely on tactile responses from their skin and coordinated joint forces to navigate and adapt to complex terrains. By leveraging mechanoreceptive sensors and carefully tuned actuation mechanisms, snake robots can exploit environmental features, such as obstacles or surface textures, as propulsion aids rather than barriers. This synergy between perception and mechanical design forms the foundation for

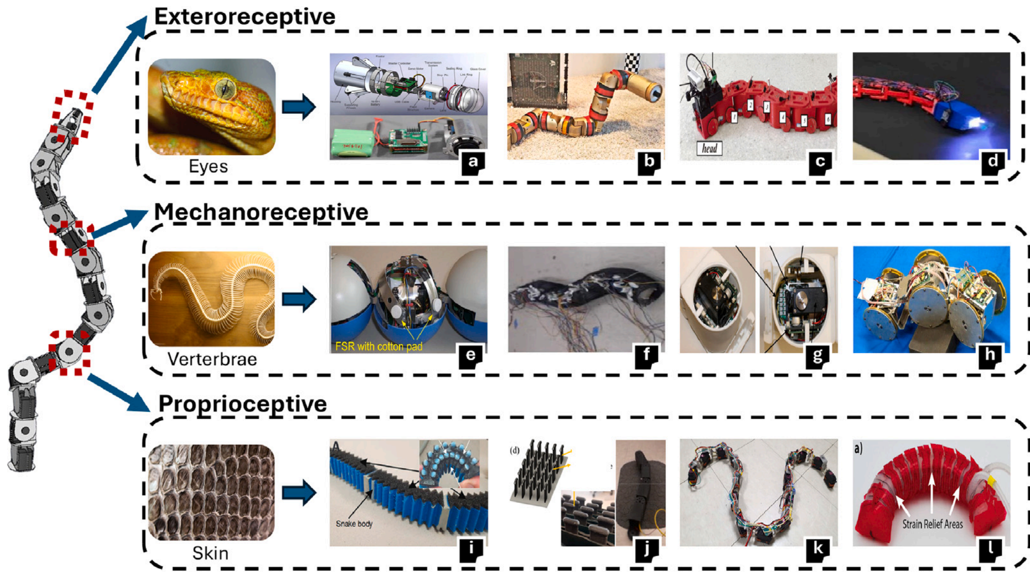

Fig. 5. State of the art sensors designed on snake robot in literature — exteroceptive: (a) [85] (b) [86] (c) [87] (d) [30] Proprioceptive: (e) [88] (f) [89] (g) [90] (h) [91] Mechanoreceptive: (i) [92] (j) [16] (k) [93] (l) [94].

their exceptional adaptability and efficiency in diverse operational terrains [6]. This section, provides a descriptive analysis of the use of different types of sensors that have been used by researchers to solve varying terrain specific locomotion problems. Sensor technology, essential for snake robot locomotion, can be broadly categorised into four distinct categories: exteroceptive, mechanoreceptive, proprioceptive, and localisation. Together, these systems provide snake robots with the ability to seamlessly adapt to diverse and unpredictable terrains, ensuring efficient and robust locomotion. Fig. 5 shows the different types of state of the art sensors employed in literature to imitate snake locomotion.

2.3.1. Exteroceptive

For robots to operate autonomously and effectively interact with their environment, they must acquire and process information about their surroundings to plan and execute actions accordingly. Exteroceptive sensors, particularly vision systems, are critical in enabling robots to perceive and navigate their environment, in various application scenarios, such as search-and-rescue operations, industrial inspections, and exploration tasks, allowing these robots to adapt their motion and behaviour dynamically. Research on biological snakes [95] highlights the importance of vision as a primary sensory channel for navigation, even in low-light conditions, while other sensory modalities like infrared (IR) sensing play a supplementary role [85].

Zhao et al. [85] proposed a 3D visual sensing technique for snake robots based on light field imaging from focal stack data, enabling high-precision depth maps and 3D point clouds for navigation. Ponte et al. [96] developed a structured light sensor tailored to the stringent size and power constraints of snake robots, enabling the generation of dense 3D point clouds for autonomous behaviours. Jiang et al. [97] introduced a neuromorphic vision sensor (NVS) combined with a spiking neural network (SNN) for snake robots, achieving robust pipe-like object tracking [98]. Li et al. [99] developed a vision-based exploration system for snake-like robots, combining a head-mounted camera for target detection and an overhead camera for localisation, enabling efficient path planning and navigation in structured environments. Chang et al. [100] presented a monocular vision-based navigation framework for snake-like robots, enabling autonomous traversal of cluttered environments. In [101], two cameras with a top-down view of the operating area are used to detect the obstacles and calculate the snake robot's pose. In [102], a similar setup uses a stereovision system to measure the head's position of the robot and target coordinates.

One significant challenge in utilising exteroceptive sensors for snake robots is ensuring head stabilisation to achieve accurate sensor data. Snake robots often rely on a head-mounted camera for environmental perception, but the constant motion of the robot's body, especially during undulatory or rectilinear locomotion, introduces considerable instability. This motion leads to problems such as motion blur, inconsistent image capture, and difficulty maintaining focus on specific features in the environment. Bao et al. [103] proposed a control strategy using an inertial sensor to stabilise the head during planar motion. Similarly, Li et al. [104] developed a head stabiliser for serpentine locomotion by leveraging the parametric equations of the Serpenoid curve to calculate inflection points. These solutions can add complexity, weight, and energy consumption, which are already constrained in the compact design of snake robots.

2.3.2. Mechanoreceptive

Mechanoreceptive sensors, often referred to as artificial skins, are pivotal in enhancing the adaptability and environmental interaction of snake robots, drawing inspiration from the role of scales in biological snakes. These sensors enable advanced tactile perception by mimicking the frictional anisotropy of snake scales—a phenomenon characterised by directional friction that arises from micro-scale surface structures and scale orientation. In biological snakes, this anisotropy, allows for varying coefficients of friction depending on movement direction. For instance, the static coefficient of friction (μ) is lowest when sliding forward ($\mu_f = 0.11 \pm 0.011$), intermediate towards the tail ($\mu_b = 0.14 \pm 0.015$), and highest moving flank-wise ($\mu_t = 0.20 \pm 0.015$). This behaviour stems from the interaction of overlapping scales with surface asperities, enabling efficient locomotion across diverse terrains [115].

For instance, Chitikena et al. [16] introduced an anisotropic friction skin that utilised both interlocking and molecular interaction-based designs to achieve directional friction control, significantly improving propulsion capabilities. Similarly, Qi et al. [92] and Branyan et al. [94] focused on bio-inspired artificial skins, where Qi et al. employed a 3D-printed snakeskin design providing orthotropic frictional properties for better adaptability, and Branyan et al. used a kirigami-inspired skin to create dynamic frictional anisotropy that facilitates efficient lateral undulation.

Lamping et al. [107] developed a modular and flexible artificial skin that offered friction anisotropy by embedding scales into a stretchable base, enhancing mobility on smooth surfaces. A soft crawling robot,

Table 5
Summary of mechanoreceptive sensor technology in snake robots.

Ref	Year	Artificial skin design	Application
[46]	2024	Whole-body tactile sensors	Navigation in complex terrains, caves
[105]	2024	Soft artificial skin inspired by snake scales	Navigation across smooth and rough terrains
[106]	2024	Anisotropic friction model for screw–ice interaction	Surface and subsurface mobility in extreme terrains
[93]	2023	Body compliance-based mechanoreception with uniform body tension	Improved locomotion efficiency and stability in undulatory and sidewinding gaits
[16]	2023	Anisotropic friction skin (interlocking, molecular)	Search and rescue operations
[92]	2023	Bio-inspired 3D-printed snakeskin	Improved friction control for better adaptability
[107]	2022	Anisotropic friction modelling in simulator	Space exploration on icy worlds
[108]	2021	Alterable angle scales with autonomous vibrating valve	Forward and backward crawling, enhanced stability on uneven surfaces
[94]	2020	3-D origami continuum modules	Lateral undulation, sidewinding
[109]	2018	Scale-like structures with varied geometry	Improved crawling rate
[110]	2018	OriSnake, 3-D origami continuum modules	Lateral undulation, sidewinding with tactile feedback
[111]	2017	Biomimetic temperature-sensing layer using pectin films	Temperature-sensitive artificial skin for enhanced robot–environment interaction
[112]	2016	Resistive force measurement with snake scale interaction model	Enhanced understanding of frictional anisotropy for improved robotic design
[113]	2015	Rigid scales integrated into the chassis to confer anisotropic friction	Improved displacement for inchworm and lateral undulation gaits
[54,114]	2014	Fluidic elastomer actuators integrated with anisotropic friction skin	Soft, serpentine locomotion with enhanced frictional control

developed by Mei et al. [116], was inspired by the movement of snake scales and utilised friction anisotropy to adapt effectively across smooth and rough terrains. Luo et al. [110] introduced OriSnake, a lightweight 3-D origami snake robot with continuum modules, utilising tactile feedback to achieve effective lateral undulation and sidewinding. Hasseler et al. [106] included an anisotropic friction model for screw–ice interaction, helping validate the robot's capabilities for surface and subsurface mobility in extreme terrains. Table 5 shows different designs utilised in literature over the years that have helped in snake robot locomotion.

2.3.3. Proprioceptive

The simplest way for a snake robot to perceive its surrounding environment is through proprioception—leveraging its internal states, such as joint angles or motor currents, to deduce environmental properties. In contrast, the skeleton of a biological snake, the vertebrae, can rotate approximately 10 to 20 degrees in the axis through contraction and relaxation of muscles. Among the sensing methods commonly used for environmental perception in snake robots, force or contact sensors stand out. Force sensors are also widely used to help the robot adapt its body to uneven terrains [117,118]. For instance, research in [119] demonstrated that a snake robot could estimate the tilt angle of a slope using only its internal state, derived from joint angles. Liljebäck et al. [88] developed a snake robot with a contact force measurement system, specifically designed to enhance obstacle-aided locomotion. Liljebäck et al. [90] also introduced a modular and waterproof joint mechanism, integrating a custom-designed force/torque sensor based on strain gauges. Taal et al. [91] introduced a 3-axial force sensor designed for semi-autonomous snake robots equipped with active wheels, enabling adaptive motion and obstacle avoidance.

Robots that base their environment perception in contact based sensors exclusively allow for limited motion planning. The snake robot described in [120] was specifically designed to support obstacle-aided locomotion. In a subsequent study [66], the same research group implemented strain gauges in the joint actuators of a waterproof snake robot to measure contact forces by detecting deformations in the actuators. Takanashi et al. [121] conducted an in-depth analysis of reaction forces during obstacle-aided locomotion in snake robots using piecewise helix structures. SenSnake [89], a snake robot equipped with piezo-resistive contact force sensors distributed along its body for studying locomotion in complex unstructured terrains was developed.

2.3.4. Localisation

The ability to determine the precise position and orientation is essential for maintaining control, avoiding obstacles, and executing planned trajectories. By integrating localisation technologies with environmental sensing, snake robots can achieve robust navigation even in environments with limited GPS availability, such as underground tunnels, collapsed structures, or densely packed industrial sites. Body-derived sensors provide immediate feedback necessary for maintaining stability, detecting obstacles, and adjusting locomotion strategies, while localisation ensures the robot remains aware of its position within a broader operational space.

For instance, Syed Izzat Ullah et al. [122] proposed an autonomous navigation and mapping framework for snake robots in urban search-and-rescue (USAR) scenarios. The system utilises GPS and inertial navigation systems (INS) for localisation, combined with a stereo camera for mapping and obstacle avoidance. Shahid et al. [123] proposed a localisation framework for snake robots using a sensor fusion approach that combines odometry with one or two inertial measurement units (IMUs). Zhao et al. [60] proposed an autonomous navigation method for snake robots using a MEMS IMU without relying on external localisation aids.

3. Control

The control of snake robots represents one of the most challenging aspects of their design and implementation, requiring sophisticated algorithms to coordinate the motion of multiple interconnected segments while adapting to diverse terrain conditions [72]. The control challenge is fundamentally rooted in the snake robot's unique characteristics: their high degree of redundancy, underactuated nature, and the complex nonlinear dynamics arising from contact forces with the environment. Biological snakes achieve remarkable locomotion through sophisticated neural control mechanisms, including CPGs that produce rhythmic muscle contractions, proprioceptive feedback systems that monitor body configuration, and adaptive responses to environmental perturbations.

The wide range of techniques for control of snake robots can be broadly classified into two primary categories: model-based and model-free approaches [124]. Model-based control strategies rely on precise mathematical models that represent the robot's dynamics and its interaction with the environment. These models allow for the prediction of the system's behaviour, enabling the use of optimisation techniques to derive control actions that can achieve the desired outcomes. On the other hand, model-free control approaches do not require an explicit model of the system's dynamics. Instead, they rely on learning algorithms, heuristic methods, or trial-and-error techniques to determine the best control actions. These approaches are particularly useful in environments where an accurate model is difficult to obtain, or when the robot must adapt rapidly to unforeseen changes in its environment.

3.1. Model-based

Model-based control strategies for snake robots rely on mathematically formulated representations of the robot's kinematics and dynamics to generate precise, constraint-aware motion. These methods allow for the direct incorporation of physical limitations such as joint ranges and actuation bounds into the control framework [125,126]. Kinematic and dynamic models serve as the foundation for many classical control approaches. For example, Nakajima et al. [127] developed a kinematic control strategy tailored for traversing multiple inclined planes by modulating the relative wheel-plane contact to prevent slippage. Takagi et al. [128] enhanced kinematic controllability through a dual-structure snake robot with omnidirectional wheels, allowing better alignment between system inputs and motion constraints. Koopaee et al. [129,130] introduced adaptive stiffness control using SEAs to dynamically adjust joint compliance in response to external forces, enabling robust pedal wave locomotion over uneven terrain. Racioppo et al. [51] complemented kinematic control with a dynamic feedback linearisation approach, improving performance in the presence of environmental disturbances. Similarly, Mukherjee et al. [131] proposed a sliding mode controller (SMC) integrated with Virtual Holonomic Constraints (VHCs), offering robustness against frictional uncertainties while ensuring reliable velocity and head-angle tracking.

To further address the challenge of constrained optimisation in real-time, Model Predictive Control (MPC) has emerged as a powerful solution. MPC predicts future robot states over a finite horizon and optimises control inputs accordingly, ensuring smooth and adaptive behaviour while respecting physical constraints [125]. Marafioti et al. [132] demonstrated the benefits of Nonlinear MPC (NMPC) for path-following tasks, significantly outperforming traditional PID-based strategies in both stability and accuracy. Building on this, Nonhoff et al. [133] introduced an Economic MPC framework that prioritises energy-efficient locomotion by minimising power consumption while maintaining desired motion patterns. Fukushima et al. [125] further contributed to MPC-based control by decoupling path-following from gait generation, allowing for more flexible and responsive trajectory execution using an averaged kinematic model.

Recent innovations have explored hybrid control schemes by combining biologically inspired rhythms with predictive optimisation. Orucevic et al. [134] integrated CPGs with MPC, allowing real-time adjustment of gait parameters to support obstacle avoidance and trajectory adaptation. Hannigan et al. [135] extended this by formulating gait generation itself as an optimisation problem, enabling adaptive, task-specific movement strategies without relying on pre-defined locomotion patterns. Wang et al. [136] further refined this approach by proposing a real-time MPC framework for whole-body path following and collision avoidance, effectively balancing smooth locomotion and safe navigation in cluttered spaces.

In addition, decentralised control has also gained traction for its scalability and robustness. These approaches eliminate the reliance on a central controller by enabling each robot module to operate autonomously using local sensing and decision-making. Jia et al. [137] proposed a decentralised Bayesian control scheme where each module updates its motion plan based on probabilistic inference from local observations, enhancing resilience in uncertain or partially observable environments. Similarly, Sartoretti et al. [138] presented a shape-based navigation framework in which individual segments independently adjust their actions using local feedback, allowing the robot to navigate densely cluttered environments without explicit central coordination. Together, these model-based control strategies provide a comprehensive toolbox for enabling robust, efficient, and adaptable snake robot locomotion, effectively addressing the nonlinearities, constraints, and unpredictability of real-world environments.

3.2. Model free

Model-free control approaches for snake robots have gained significant attention due to their adaptability in complex and dynamic environments, where precise system models may be unavailable or too difficult to develop. These methods do not rely on explicit system dynamics but instead use learning algorithms, heuristic methods, or trial-and-error techniques to optimise control strategies [139,140].

Reinforcement Learning (RL) has proven to be an effective model-free control strategy for snake robots, allowing them to learn optimal control policies through interaction with the environment. RL-based controllers improve over time by receiving feedback in the form of rewards or penalties, enabling the robot to adapt its behaviour in response to environmental changes. For instance, Wang et al. [140] introduced Path Integral RL to follow paths efficiently without needing a model of the robot's dynamics. Liu et al. [141] demonstrated a path following RL using a Transferable Constrained-Residual Gait Generator, which allows efficient policy learning without explicit robot dynamics. Similarly, Qi et al. [142] introduced Back-Stepping Experience Replay, which improves sample efficiency and learning stability in complex environments. Jia et al. [143] developed a Coach-Based Bayesian RL, which combines expert guidance with Bayesian updates to accelerate learning. Additionally, Bing et al. [144] proposed an RL framework for controlling a snake robot with a CPG-based policy representation. Their approach enables the robot to learn and modulate CPG parameters directly for efficient locomotion. Bing et al. [145] also used Proximal Policy Optimisation to learn efficient locomotion strategies across varied terrains.

Neural Network (NN)-based controllers are another prominent model-free technique for snake robot control. Kim and Suh [146] used a backpropagation neural network (BPNN) to map desired trajectories to joint control commands, enabling smooth and adaptive locomotion. Liu et al. [147] proposed a hybrid control strategy combining ANN with CPG, allowing the robot to generate adaptive locomotion patterns. Woodford et al. [148] used genetic algorithms to evolve NN controllers for snake robots, demonstrating the power of data-driven methods to generate effective locomotion strategies through trial and error. Woodford et al. [149] also presented a NN-based controller that learns biologically inspired gaits, enabling the robot to adapt its movement behaviour across a range of environmental conditions.

Fuzzy logic-based approaches have been used to address uncertainties and improve adaptability in snake robot locomotion. Xue et al. [150] integrated a fuzzy PID control strategy for deep-water snake robots, reducing tracking errors and improving stability. Wu et al. [151] introduced a fuzzy Extended State Observer-based joint angle control strategy, which compensates for system uncertainties and external disturbances, enabling smooth and adaptive locomotion in real time. Zeng and Yuan [152] presented a fuzzy adaptive PID control scheme for snake arm robots, improving motor response and stability.

Heuristic methods, such as optimisation algorithms, also contribute to model-free control strategies. Souad et al. [153] explored the Manta Ray Foraging Optimisation (MRFO) algorithm for optimising gait control in bioinspired underwater snake robots. This approach maximises forward velocity and minimising power consumption, by adapting to the dynamic hydrodynamic environment. Gao et al. [154] used a hybrid Rain Forest Algorithm and Particle Swarm Optimisation to optimise the gait parameters of snake robots for efficient serpentine locomotion.

Passive actuation is another effective model-free approach that relies on the natural contraction and expansion of joints to generate movement. Dear et al. [155] introduced a passive actuation system for a multi-link snake robot, where only one or two joints are actuated while the remaining joints remain passive. This approach leverages dynamic interactions among the joints to drive the robot's motion, improving flexibility and energy efficiency. Lopez et al. [156] explored the use of PAMs to enable rotational movement at joints, mimicking lateral undulation patterns. Parvaresh et al. [75] presented a bioinspired soft snake robot for rectilinear locomotion, using tendon-driven actuation to simulate muscle-like contractions and move smoothly through confined spaces. Together, these model-free control strategies offer significant advantages, enabling snake robots to operate effectively in dynamic, unstructured environments without the need for precise mathematical models.

3.3. Other control methods

Snake robots are designed to navigate large-scale terrains with complex geometries, and they can move from one position to another by applying adaptive motion behaviour, which allows them to adjust to changing conditions as they progress [157]. In addition to locomotion control, snake robots require specialised control strategies for various tasks. These methods, while not directly related to movement, are critical for enabling the robot to interact effectively with its environment in applications such as search and rescue, object manipulation, and maintaining stability during operation. These control strategies expand the robot's functionality, enhancing its versatility in dynamic and complex environments.

- **Head Stabilisation**: is essential for reliable exteroceptive sensing in snake robots, as the oscillations from their travelling wave-based locomotion can disrupt visual feedback, affecting perception and navigation. To address this, various control strategies have been developed in literature to minimise the effect of these oscillations and ensure stable sensing, thereby improving the robot's ability to navigate in dynamic environments. Mukherjee et al. [158] proposed an adaptive sliding mode controller that ensures robust head-angle and velocity tracking using virtual holonomic constraints, achieving finite-time convergence without requiring prior knowledge of disturbance bounds. To address nonlinear disturbances and sensor noise during motion, Kim et al. [159] introduced a back-stepping control strategy combined with RBF neural networks and an adaptive robust term to stabilise a 2-DOF snake head, enhancing visual steadiness. Building on this, Kim and Suh [146] developed a nonsingular terminal sliding mode control scheme integrated with RBF-NNs and an adaptive robust term, which accelerates convergence while reducing chattering. In contrast to controller-based approaches, Li et al. [104] proposed a geometric stabiliser that derives head orientation from the Serpenoid body curve using inflection point analysis, effectively reducing oscillation through trajectory geometry alone. Ariizumi et al. [77] tackled head trajectory tracking under actuator failure conditions by leveraging observer-based estimation and viscous friction modelling to ensure robustness in unstructured environments. For non-wheeled snake robots executing inchworm gaits, Bao et al. [103] implemented a real-time stabilisation strategy based on inertial sensors that feeds back direction data to compensate head swing, validated through simulations and physical experiments. Together, these diverse methodologies address the complex challenge of maintaining head stability in dynamically moving snake robots across various environments.
- **Grasping**: control methods play a crucial role in the design and functionality of snake robots, enabling them to interact with objects or terrain for efficient locomotion. These robots utilise various grasping mechanisms, each tailored to specific tasks. One approach involves a grasping arm located at the head of the robot, allowing it to manipulate objects. For instance, Han et al. [160] presented a compact three-finger gripper module for snake robots, designed for search and rescue tasks in confined environments, with a camera-equipped fingertip for effective object handling and exploration. Ji et al. [74] introduced a snake robot with an integrated gripper and vision system for performing inspection and grasping tasks in tight spaces, using a three-stage grasping strategy and CPG-based locomotion control. Liu et al. [161] presented a flexible robotic manipulator inspired by snake motions, utilising SMA actuators for object grasping with high dexterity in confined environments, controlled by visual perception and deformation planning. Xue et al. [162] proposed a snake-like robot equipped with a gripper, allowing it to perform object grasping and manipulation through a combination of snake-like gaits and precise gripper control for enhanced task execution in complex environments. Another method focuses on grasping pipes, where the robot can anchor itself to navigate or traverse challenging environments. For example, Konishi et al. [163] introduces a novel approach for snake robot motion on pipes, where the robot uses partial grasping rather than wrapping its body around the pipe, enabling it to move along or around the pipe axis. Reyes et al. [164] explores the conditions under which a snake robot can achieve form-closure using three contact points to grasp circular objects, introducing a grasp condition and two workspaces to determine if an object is graspable and within reach. Mendoza et al. [165] provide a geometric framework to analyse planar grasping by snake robots, defining the minimum requirements for form-closure and introducing contact and grasp workspaces to evaluate object graspability based on the robot's link configuration. Additionally, snake robots can leverage their body shape for dynamic grasping during locomotion, using the flexibility of their bodies to interact with and secure objects or surfaces as they move. Sanfillipo [14] presented a control framework that integrated grasping and adaptive locomotion, enabling snake robots to perform complex tasks in unstructured environments through tactile and visual perception. The authors in [17,18], proposed framework that combined grasping with adaptive locomotion in snake robots, enabling them to grasp and transport emergency items during disaster relief operations, integrating collaborative human–robot control and path planning for effective rescue efforts. These diverse grasping techniques enhance the robot's versatility and performance across a range of applications.
- **Climbing**: When a snake robot encounters vertical obstacles or confined spaces, or obstacles it cannot go around, it employs a climbing control mechanism. Climbing approaches are classified into two broad categories [166]; free climbing, where robots raise modules vertically using only their joints without external support; and aided climbing, where front modules lean against obstacles for assistance. Fu et al. [43] illustrated that snakes use lateral oscillation combined with cantilevering for stable obstacle traversal, and that adding body compliance improved the snake robot climbing performance. Kon et al. [167] developed a mixed integer programming method for semi-autonomous snake robot step climbing with online trajectory generation and sensing strategy optimisation. For aided climbing, to climb up a cylinder, snake robots have to coil on the cylinder tightly to gain enough friction force and apply lateral rolling gait to climb up [168]. Wang et al. [169] presented a snake robot design using universal joints for enhanced 3D dexterity and adopted inchworm locomotion along isometric spiral curves for climbing. Koike et al. [170] presented a visual-aided obstacle climbing system for modular snake robots that uses computer vision to identify step parameters and implements two climbing algorithms (pitch–pitch and pitch–yaw) to autonomously navigate prismatic obstacles.
- **Obstacle Aided**: Snake robots exploit environmental obstacles to enhance locomotion efficiency by bracing against rocks, vegetation, or debris to generate reaction forces for propulsion,

mimicking biological snakes that use stationary objects to increase friction and forward thrust. This obstacle-aided locomotion requires sophisticated perception and control systems to identify and utilise environmental features as locomotion aids rather than barriers [6]. Building upon the foundational work of Hirose et al. [50] for utilising reaction forces from obstacles in wheeled snake robots, obstacle-aided locomotion has evolved through sophisticated theoretical and practical frameworks. Kamegawa et al. [171] developed extended asymmetric control methods for obstacle exploitation, while Løwer et al. [172] introduced form closure theory to define regions where environmental constraints render snake robots fully actuated, enabling predictable locomotion through lateral undulation. Advanced control strategies have emerged including Yoshida et al.'s [173] connecting parts approach for traversing between different planes, Qiu et al.'s [174] combination of Monte Carlo Model Predictive Control with Curvature Derivative Control for underwater environments, and Takanashi et al.'s [175] piecewise helix method for three-dimensional obstacle utilisation. Recent breakthrough approaches include the obstacle triplet model [8] requiring three simultaneous contact points for locomotion, economic MPC frameworks [176] that integrate gait pattern creation while maximising forward velocity through compliant obstacle-snake contact models, and obstacle disturbance selection frameworks [155] that treat environments as disturbance force fields with robot legs acting as selective force generators, revealing how different gaits create stable equilibrium orientations through spatial period matching between gait patterns and environmental structure. These approaches collectively enable snake robots to adaptively use environmental features for enhanced mobility in cluttered and uncertain environments.

- **Obstacle Avoidance**: In cluttered environments, snake robots must navigate around obstacles rather than climbing over them, requiring sophisticated obstacle avoidance algorithms that treat obstacles as passive objects while the robot adapts its body shape to prevent contact. Given the unique morphological and locomotion characteristics of snake robots effective obstacle avoidance necessitates a combination of robust motion planning, environment perception, and real-time control. To address these challenges, Kelasidi et al. [177] and Kohl et al. [178] introduce set-based and COLREGs-inspired switching strategies for underwater snake robots, enabling smooth transitions between straight path following and circular obstacle avoidance. Complementing this, Li et al. [179] and Itani et al. [180] adopt physics-informed and optimisation-based methods, using immersed boundary modelling and constrained trajectory shaping to maintain safe distances while ensuring locomotion efficiency. Meanwhile, Hsu et al. [181] enhances traditional sampling-based planning through a gravity-biased Bi-RRT algorithm that improves both success rate and path smoothness. In confined or highly structured spaces, Gu et al. [182] leverages piecewise Bézier curves and adaptive control to achieve sub-centimetre tracking accuracy in serpentine manipulators. On the sensory side, Qi et al. [183] integrates deep learning with binocular vision and fuzzy logic to improve real-time decision-making under uncertain conditions. Haghshenas et al. [184] further demonstrate the use of probabilistic threat exposure maps and expert rule-based navigation for generating safe waypoint trajectories. Additionally, Krishna et al. [185] blends artificial potential field methods with PID-based head tracking for reactive navigation in cluttered scenes, while Xiu et al. [186] proposes a comprehensive guidance-control architecture incorporating sliding mode control and virtual reference models to ensure COLREGs-compliant behaviour. Together, these contributions reflect a rich diversity of approaches for enabling snake robots to navigate safely and efficiently through obstacle-laden environments.

4. Applications

The slender design and versatile locomotion of snake robots have revolutionised mobile robotics, enabling navigation through unstructured and confined environments that were previously inaccessible. Traditionally, both snake robots and mobile robots were limited to structured settings due to technological constraints. However, advancements in sensing and control techniques over the past decade have significantly enhanced their adaptability and versatility. While snake robots have applications ranging from surgical procedures to industrial inspections, this section focuses on their terrain adaptability and traversal capabilities, highlighting their ability to maneuver complex landscapes with ease.

Many studies on snake robots showcase promising applications, yet their practical impact remains limited due to a narrow focus on specific aspects of terrain adaptability. Research in this field often concentrates on isolated challenges, such as climbing steps, navigating slopes, or underwater locomotion, rather than developing comprehensive solutions for real-world deployment. While significant advancements have been made in control and sensing techniques, these innovations are rarely tested beyond simulation or controlled lab environments. Table 6 provides a detailed analysis of existing research on snake robot applications, categorising them based on whether they were evaluated in simulations, experimental testbeds, real-world environments, or a combination of these methods. This table summarises research trends over the past decade, highlighting the extent to which different applications have been validated in real-world conditions. Taking into account the contributions done in the field, two potential key applications can be derived for terrain adaptable snake robotics: (a) search and rescue; (b) exploration. While surgical robotics presents a valuable application for snake robot designs, such as the I2Snake [187] designed for minimally invasive endoscopic surgery, it falls outside the scope of this study, which focuses on terrain adaptability. Therefore, we have opted to exclude this application.

4.1. Search and rescue

Search and rescue (SAR) operations present complex challenges due to the unpredictable nature of disaster-stricken environments, which often involve confined spaces, unstable terrains, and hazardous conditions that impede human and conventional robotic interventions. As depicted in Fig. 6, the potential applications of snake robots in search and rescue encompass a variety of scenarios, including collapsed building surveys, firefighting operations, nuclear disaster reconnaissance, underwater wreckage inspection, mine collapses, and avalanche rescue missions. However, these applications, while theoretically promising, remain largely idealised due to the gap between advancements in research and real-world implementation.

One of the most critical applications of snake robots in SAR is their deployment in urban search and rescue (USAR) missions following structural collapses. For instance Whitman et al. [218], demonstrated the feasibility of snake robots in post-disaster environments, such as the 2017 Mexico City earthquake to assess the structural integrity of debris. Firefighting scenarios represent another critical domain where snake robots can significantly enhance rescue capabilities. In environments with extreme heat, dense smoke, and toxic gases, traditional robotic systems often fail due to thermal limitations and restricted mobility. These robots can traverse ventilation systems and tight corridors, reaching victims who might otherwise remain undetected by conventional search methods.

Another significant use case involves reconnaissance missions in hazardous environments, particularly in nuclear disaster sites and chemically contaminated zones. Nuclear hotspots, such as those encountered in the Fukushima Daiichi disaster, pose extreme risks to human responders due to radiation exposure. Research conducted by Kamegawa et al. [219] introduced a separable search-and-rescue robot

Table 6
Application comparison of simulation, experimental and real-world contributions in snake robot research.

Ref.	Year	Simulation	Lab testbed	Real World Testing	Application
[188]	2024	✓	X	X	Large scale terrain traversal
[79]	2023	X	✓	✓	Pipe climbing
[92]	2023	✓	✓	✓	Traversal on concrete, grass, Inpipe
[71]	2023	X	✓	X	Step climbing
[189]	2023	✓	✓	X	Helical pipe wrapping
[106]	2023	X	✓	✓	Icy surface for slope, trench, flat and Mars sand
[190]	2022	✓	✓	X	Underwater
[191]	2022	X	✓	✓	Multi-terrain traversal
[192]	2022	✓	X	X	VR based inpipe
[193]	2021	✓	✓	X	Inpipe inspection
[179]	2021	X	✓	X	Water surface
[23]	2020	X	✓	✓	Rough terrain traversal
[194]	2020	✓	✓	X	In pipe inspection
[68]	2020	X	✓	X	Probing lunar crater walls
[43]	2020	X	✓	X	Large scale step climbing
[195]	2020	✓	✓	X	Different incline slope
[196]	2020	X	✓	X	Steps climb
[197]	2020	✓	✓	✓	Plant inspection
[30]	2019	X	✓	X	Indoor inspection
[130]	2019	X	✓	X	Obstacle climbing
[198]	2019	X	✓	X	Obstacle avoidance using SLAM
[199]	2019	X	✓	X	Underwater
[200]	2019	X	✓	X	Agricultural irrigation
[86]	2019	✓	X	X	Brain inspired locomotion
[201]	2019	✓	X	X	Horizontal/Vertical pipe wrap
[202]	2018	X	✓	X	Pipe climbing, debris traversal, steps climb
[203]	2018	✓	✓	X	Water surface
[60]	2018	X	X	✓	Rough cement terrain
[204]	2018	X	✓	X	Ladder climbing
[205]	2018	✓	X	X	POAL
[206]	2018	✓	X	X	Helical coiling
[207]	2018	X	✓	X	Inpipe for nuclear plants
[208]	2018	X	✓	X	Obstacle avoidance
[82]	2017	X	✓	X	Gait testing
[209]	2017	✓	✓	X	Water surface
[210]	2017	X	✓	X	Slope
[211]	2017	X	✓	X	Coal mine rescue
[212]	2017	✓	✓	X	Object tracking using DVS camera
[213]	2017	X	✓	X	Steps climbing, Obstacles, Narrow spaces
[214]	2016	X	✓	✓	In pipe inspection
[34]	2016	✓	X	X	Underwater
[215]	2016	✓	✓	X	Infrared sensor-based obstacle avoidance
[64]	2016	✓	✓	X	Traversal on flat, sand, gravel, rocky, grass, tall grass
[216]	2015	✓	✓	X	Steps climbing
[101]	2015	X	✓	X	Gait testing
[217]	2015	X	✓	X	Obstacle avoidance
[24]	2014	X	✓	✓	Traversal on sand
[55]	2014	✓	✓	X	Line following on flat

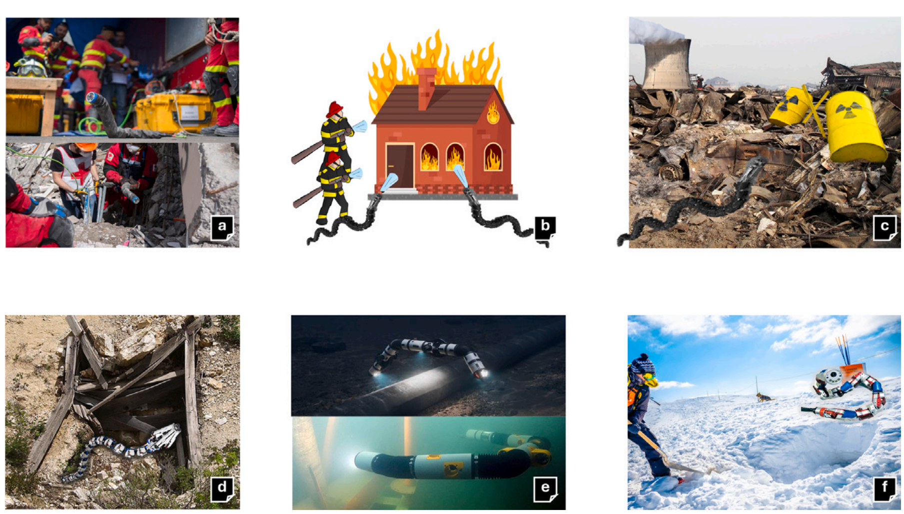

Fig. 6. Applications for Search and Rescue (a) Collapsed building survey, (b) Firefighting, (c) Nuclear hotspot recon, (d) Collapsed mine investigation, (e) Underwater wreckage, (f) Avalanche rescue.

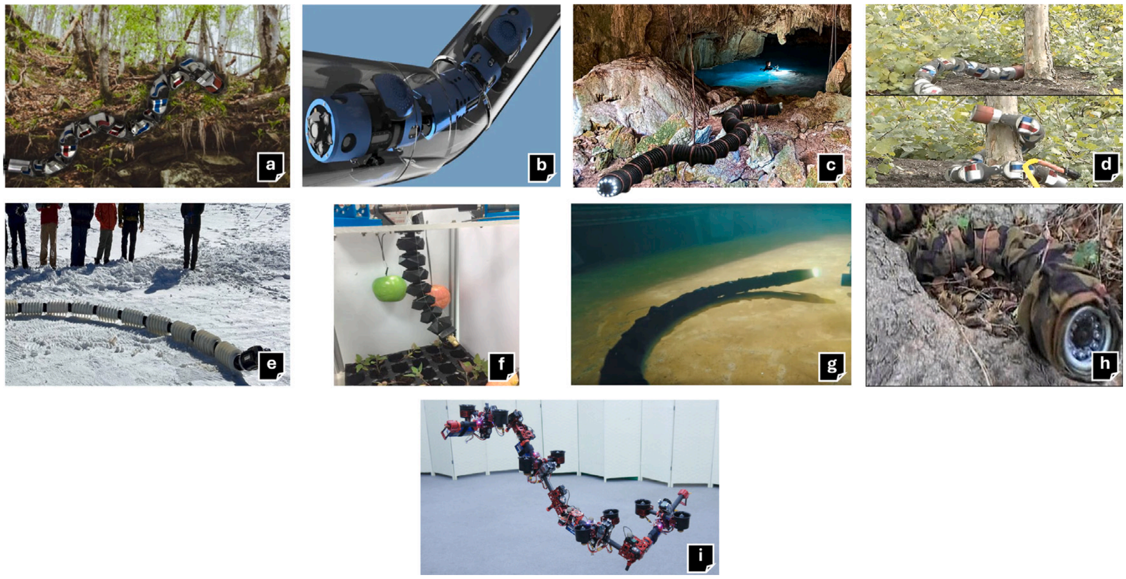

Fig. 7. Applications for exploration (a) Dense forest, (b) Inpipe, (c) cave/underground, (d) Tree climb for eco system, (e) Icy areas, (f) Agricultural irrigation, (g) Underwater, (h) Stealth reconnaissance (i) Aerial reconnaissance.

system that integrates a mobile platform with a detachable snake robot, allowing for adaptive mission strategies where the mobile base provides power and processing while the snake robot navigates hazardous terrain autonomously.

Advances in soft robotics have further enabled the development of waterproof, amphibious snake robots capable of transitioning between land and water, enhancing their applicability for flood rescue missions and deep-sea recovery operations. Experimental studies have demonstrated the ability of snake robots to inspect underwater wreckage, search for survivors in submerged vehicles, and assist divers in confined underwater environments. Jiang et al. [188] proposed a hierarchical reinforcement learning (HRL) framework that enables snake robots to adapt to diverse terrain conditions by incorporating tactile feedback into their control loop.

4.2. Exploration

Robots have revolutionised exploration by enabling humans to investigate environments that are otherwise inaccessible. Snake robots present an untapped potential for exploration due to their uniquely flexible and adaptable design. For example Ji et al. [74] introduced a snake robot equipped with a gripper, camera, and laser distance sensor for inspection and maintenance tasks in narrow spaces. Wang et al. [67] presents a snake robot designed for planetary surface exploration with a lightweight design for efficient movement across obstacles.

The applications illustrated in Fig. 7 demonstrate the extensive potential of snake robots in exploration. One of the most compelling areas of deployment is planetary exploration, where snake robots could traverse the uneven surfaces of celestial bodies. Unlike traditional rovers that may become immobilised in loose sand or struggle with steep inclines, snake robots can coil, slither, or even climb over obstacles, providing greater mobility in challenging extraterrestrial terrains. Furthermore, equipped with advanced sensors and imaging technologies, these robots could assist in geological surveys, agricultural irrigation, analysing soil composition, detecting subsurface water sources, and gathering crucial data for future human missions. For instance, Huang and Chang [200] developed a bio-inspired snake bone-armed robot for agricultural irrigation and pesticide spraying. They could, furthermore, be deployed to investigate the uncharted depths of the ocean, caves, lava tubes, and dense forests, where extreme pressure and limited visibility pose significant barriers to conventional robotic systems.

These robots have demonstrated significant potential for cave exploration, as evidenced by the adaptation of sidewinding locomotion to navigate unstable sandy slopes, enabling improved maneuverability in confined and hazardous environments [24]. Zhao et al. [220] presented a novel aerial snake-like robot with multilinked transformation capabilities. This robot can modify its configuration in-flight, enhancing its maneuverability in confined or dynamic environments. Eisaman et al. [221] presented the EELS, a snake-like robot designed by NASA's Jet Propulsion Laboratory to explore icy worlds like Enceladus, where subsurface oceans may harbour signs of life. In [222], the authors introduce a butterfly spiral propulsion gait that enhances snake robot maneuverability in confined spaces like caves and pipelines by counteracting lateral torque forces.

5. Discussion

This comprehensive review reveals both convergent trends and significant divergences in snake robot research over the past decade, highlighting the field's maturation while exposing persistent challenges that limit real-world deployment. The field has converged towards soft-rigid hybrid designs as the dominant paradigm, with over 60% of reviewed systems adopting this approach. This convergence reflects a collective understanding that pure rigid systems lack adaptability while pure soft systems sacrifice structural integrity and control precision. Universal joints have emerged as the preferred articulation mechanism, appearing in approximately 45% of designs, due to their balance of complexity and functionality. Despite the diversity of available gaits, lateral undulation remains the most extensively studied and implemented locomotion strategy, with concertina and rectilinear gaits serving as secondary options for specific environments. This similarity across research groups suggests that these fundamental biological patterns provide the most practical foundation for robotic implementation. However, significant divergences persist in actuation and control strategies. Electric motor-based systems dominate for precision applications, while pneumatic and soft artificial muscle approaches are preferred for compliant interaction tasks, reflecting differing priorities between precision and adaptability. A notable divide exists between model-based control approaches that favour mathematical rigour and predictability, and model-free approaches that emphasise adaptability and learning. As observed in Table 7, most practical designs employ dynamic control for locomotion, while model-free approaches like reinforcement learning are primarily confined to simulation studies with limited real-world validation.

Perhaps the most significant limitation identified is the gap between biological and robotic adaptation capabilities. While biological snakes seamlessly adjust their locomotion strategies when transitioning between surfaces, robotic implementations typically optimise for single terrain types, representing a fundamental constraint in current approaches [16,222,223]. Although gait transition has been addressed in literature [224–226], practical terrain adaptability for seamless gait transitions remains largely unexplored. Most research pursues specialised solutions for particular environments rather than addressing the greater challenge of smooth transitions between diverse terrains. Table 6 reveals a stark disparity between theoretical advancement and practical validation, with over 70% of reviewed studies remaining confined to simulation or controlled laboratory environments with minimal real-world testing. This gap indicates significant immaturity in translating research advances to practical deployment. Furthermore, research efforts remain largely siloed, with advances in sensing, control, and mechanical design proceeding independently. The lack of integrated system-level approaches contrasts sharply with the holistic nature of biological snake locomotion, suggesting that future breakthroughs may require more interdisciplinary integration towards developing universal snake designs capable of handling diverse locomotion scenarios.

6. Conclusion and future work

Snake robots represent a transformative advancement in bio-inspired robotics, offering exceptional mobility and adaptability for navigating complex unstructured terrains where conventional robotic systems struggle. Their unique limbless design, inspired by biological snakes, allows them to traverse confined spaces, uneven terrains, and hazardous environments, making them valuable for applications in search and rescue, and exploration. This review has provided a comprehensive analysis of snake robot designs, locomotion strategies, control schemas and applications, shedding light on both their capabilities and the challenges that still hinder their real-world implementation. Despite significant progress, many locomotion algorithms remain highly specialised for specific terrains and ideal conditions, lacking the ability to dynamically adjust to changing terrains. The transition between different terrains, as well as navigation in dynamic environments with moving obstacles, remains an unsolved challenge.

Future research must prioritise adaptive locomotion strategies and unified control frameworks that can handle multi-terrain scenarios. The integration of advanced machine learning approaches, particularly reinforcement learning, shows promise for bridging the terrain adaptability gap between biological and robotic systems. Additionally, addressing the substantial gap between simulation studies and real-world deployment—with over 70% of current research remaining in controlled laboratory environments—is critical for practical implementation. These advancements will pave the way for the next generation of snake robots, making them more reliable, efficient, and capable of performing complex tasks in unstructured and challenging environments.

CRediT authorship contribution statement

Syed Kumayl Raza Moosavi: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Muhammad Hamza Zafar:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation. **Filippo Sanfilippo:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is supported by the Artificial Intelligence, Biomechatronics, and Collaborative Robotics research group at the Top Research Center Mechatronics (TRCM), University of Agder (UiA), Norway.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.mechatronics.2025.103418.

Data availability

No data was used for the research described in the article.

References

[1] Li G, Zhang H, Zhang J. Bio-inspired locomotion control of limbless robots. Springer; 2023.
[2] Astley HC, Mendelson III JR, Dai J, Gong C, Chong B, Rieser JM, Schiebel PE, Sharpe SS, Hatton RL, Choset H, et al. Surprising simplicities and syntheses in limbless self-propulsion in sand. J Exp Biol 2020;223(5):jeb103564.
[3] Schiebel PE, Hubbard AM, Goldman DI. Comparative study of snake lateral undulation kinematics in model heterogeneous terrain. Integr Comp Biol 2023;63(1):198–208.
[4] Zhu L, Yang P, Li F, Wang K, Shui L, Chen X. On the snake-like lateral undulatory locomotion in terrestrial, aquatic and sand environments. J Mech Phys Solids 2021;157:104629.
[5] Sanfilippo F, Stavdahl O, Marafioti G, Transeth AA, Liljeback P. Virtual functional segmentation of snake robots for perception-driven obstacle-aided locomotion? In: 2016 IEEE international conference on robotics and biomimetics. ROBIO, 2016, p. 1845–51.
[6] Sanfilippo F, Azpiazu J, Marafioti G, Transeth AA, Stavdahl Ø, Liljebäck P. Perception-driven obstacle-aided locomotion for snake robots: The state of the art, challenges and possibilities †. Appl Sci 2017;7(4).
[7] Sanfilippo F, Azpiazu J, Marafioti G, Transeth AA, Stavdahl Ø, Liljebäck P. A review on perception-driven obstacle-aided locomotion for snake robots. In: 2016 14th international conference on control, automation, robotics and vision. ICARCV, 2016, p. 1–7.
[8] Sanfilippo F, Stavdahl Ø, Liljebäck P. SnakeSIM: A ROS-based rapid-prototyping framework for perception-driven obstacle-aided locomotion of snake robots. In: 2017 IEEE international conference on robotics and biomimetics. ROBIO, 2017, p. 1226–31.
[9] Rañó I, Eguíluz AG, Sanfilippo F. Bridging the gap between bio-inspired steering and locomotion: A braitenberg 3a snake robot. In: 2018 15th international conference on control, automation, robotics and vision. ICARCV, 2018, p. 1394–9.
[10] Sanfilippo F, Helgerud E, Stadheim PA, Aronsen SL. Serpens: A highly compliant low-cost ROS-based snake robot with series elastic actuators, stereoscopic vision and a screw-less assembly mechanism. Appl Sci 2019;9(3).
[11] Sanfilippo F, Helgerud E, Stadheim PA, Aronsen SL. Serpens, a low-cost snake robot with series elastic torque-controlled actuators and a screw-less assembly mechanism. In: 2019 5th international conference on control, automation and robotics. ICCAR, 2019, p. 133–9.
[12] Hanssen KG, Transeth AA, Sanfilippo F, Liljebäck P, Stavdahl Ø. Path planning for perception-driven obstacle-aided snake robot locomotion. In: 2020 IEEE 16th international workshop on advanced motion control. AMC, 2020, p. 98–104.
[13] Duivon A, Kirsch P, Mauboussin B, Mougard G, Woszczyk J, Sanfilippo F. The redesigned serpens, a low-cost, highly compliant snake robot. Robotics 2022;11(2).
[14] Sanfilippo F. Combining grasping with adaptive path following and locomotion for modular snake robots. Int J Mech Eng Robotics Res 2022;11(2):59–65.
[15] Chitikena H, Gravdahl I, Pettersen KY, Mohammadi A, Sanfilippo F, Stavdahl Ø, Ma S. Adaptive manoeuvring control for planar snake robots in uncertain friction environments. In: 2024 American control conference. ACC, 2024, p. 2844–50.
[16] Chitikena H, Mohammadi A, Sanfilippo F, Poursina M. Anisotropic friction skin for holonomic snake robot mobility*. In: 2024 IEEE international conference on advanced robotics and its social impacts. ARSO, 2024, p. 222–7.
[17] Moosavi SKR, Zafar MH, Sanfilippo F. Collaborative robots (cobots) for disaster risk resilience: a framework for swarm of snake robots in delivering first aid in emergency situations. Front Robot AI 2024;11.
[18] Moosavi SKR, Zafar MH, Sanfilippo F. Collaborative robots (cobots) for emergency situations: a snake robot as a team member for delivering first aid in emergency situations. In: Hawaii international conference on system sciences 2024. HICSS-57, 2024, 2.

[19] Di Bitetti MS, Ferreras JA. Publish (in english) or perish: The effect on citation rate of using languages other than english in scientific publications. Ambio 2017;46:121–7.
[20] Ivanov S, Gretzel U, Berezina K, Sigala M, Webster C. Progress on robotics in hospitality and tourism: a review of the literature. J Hosp Tour Technol 2019;10(4):489–521.
[21] Ramdya P, Ijspeert AJ. The neuromechanics of animal locomotion: From biology to robotics and back. Sci Robot 2023;8(78):eadg0279.
[22] Gray J. The mechanism of locomotion in snakes. J Exp Biol 1946;23(2):101–20.
[23] Bae J, Kim M, Song B, Jin M, Yun D. Snake robot with driving assistant mechanism. Appl Sci 2020;10(21).
[24] Marvi H, Gong C, Gravish N, Astley H, Travers M, Hatton RL, Mendelson JR, Choset H, Hu DL, Goldman DI. Sidewinding with minimal slip: Snake and robot ascent of sandy slopes. Science 2014;346(6206):224–9.
[25] Zhu L, Yang P, Li F, Wang K, Shui L, Chen X. On the snake-like lateral undulatory locomotion in terrestrial, aquatic and sand environments. J Mech Phys Solids 2021;157:104629.
[26] Astley HC. Chapter ten - slithering across worlds—snake-inspired robots for extraterrestrial exploration. In: Shyam V, Eggermont M, Hepp AF, editors. Biomimicry for aerospace. Elsevier; 2022, p. 261–89.
[27] Zhuang Z, Guan Y, Zhang Z, Wei W, Tang Z, Dai J. SLPM based snake-like robot. In: 2022 IEEE international conference on artificial intelligence and computer applications. ICAICA, 2022, p. 37–41.
[28] Ab Rashid MZ, Mohd Yakub MF, Zaki bin Shaikh Salim SA, Mamat N, Syed Mohd Putra SM, Roslan SA. Modeling of the in-pipe inspection robot: A comprehensive review. Ocean Eng 2020;203:107206.
[29] Nivethika SD, Nivethetha T, Priyadharshini P, Nithyasri VT, SenthilPandian M, Sivaprasad R. Design and development of pipe inspection snake locomotion robot. In: 2022 international conference on power, energy, control and transmission systems. ICPECTS, 2022, p. 1–5.
[30] Selvarajan A, Kumar A, Sethu D, bin Ramlan MA. Design and development of a snake-robot for pipeline inspection. In: 2019 IEEE student conference on research and development. sCOReD, 2019, p. 237–42.
[31] Even S, Gordon H, Yang H, Ozkan-Aydin Y. Machine learning-driven burrowing with a snake-like robot. In: 2024 IEEE international conference on robotics and automation. ICRA, IEEE; 2024, p. 1477–83.
[32] Xie X, Herault J, Clement É, Lebastard V, Boyer F. Quasi-static motion of a new serial snake-like robot on a water surface: a geometrical approach. In: 2021 IEEE/RSJ international conference on intelligent robots and systems. IROS, IEEE; 2021, p. 7372–7.
[33] Kelasidi E, Liljeback P, Pettersen KY, Gravdahl JT. Innovation in underwater robots: Biologically inspired swimming snake robots. IEEE Robot Autom Mag 2016;23(1):44–62.
[34] Kelasidi E, Jesmani M, Pettersen KY, Gravdahl JT. Multi-objective optimization for efficient motion of underwater snake robots. Artif Life Robot 2016;21:411–22.
[35] Strømsøyen S. Propulsion methods for under water snake robots-Investigation and simulation using foil for propulsion of a snake robot Master's thesis, NTNU; 2015.
[36] Wang J-L, Song J-L, Liu A-R, Liang J-Q, Zhou F-B, Liang J-J, Fu J-Y, Chen B-C. Design and architecture of a slender and flexible underwater robot. Intell Serv Robot 2024;1–20.
[37] Kano T, Yoshizawa R, Ishiguro A. Tegotae-based decentralised control scheme for autonomous gait transition of snake-like robots. Bioinspiration Biomim 2017;12(4):046009.
[38] Liljebäck P, Pettersen KY, Stavdahl Ø, Gravdahl JT. Lateral undulation of snake robots: a simplified model and fundamental properties. Robotica 2014;31(7):1005–36.
[39] Virgala I, Kelemen M, Božek P, Bobovskỳ Z, Hagara M, Prada E, Oš ̌ cádal P, Varga M. Investigation of snake robot locomotion possibilities in a pipe. Symmetry 2020;12(6):939.
[40] Gmiterko A, Kelemen M, Virgala I, Surovec R, Vacková M. Modeling of a snake-like robot rectilinear motion and requirements for its actuators. In: 2011 15th IEEE international conference on intelligent engineering systems. 2011, p. 91–4.
[41] Ariizumi R, Matsuno F. Dynamical analysis of sidewinding locomotion by a snake-like robot. In: 2013 IEEE international conference on robotics and automation. IEEE; 2013, p. 5149–54.
[42] Liao B, Zang H, Chen M, Wang Y, Lang X, Zhu N, Yang Z, Yi Y. Soft rod-climbing robot inspired by winding locomotion of snake. Soft Robot 2020;7(4):500–11.
[43] Fu Q, Gart SW, Mitchel TW, Kim JS, Chirikjian GS, Li C. Lateral oscillation and body compliance help snakes and snake robots stably traverse large, smooth obstacles. Integr Comp Biol 2020;60(1):171–9.
[44] Bianchi G, Lanzetti L, Mariana D, Cinquemani S. Bioinspired design and experimental validation of an aquatic snake robot. Biomimetics 2024;9(2):87.
[45] Zhen W, Gong C, Choset H. Modeling rolling gaits of a snake robot. In: 2015 IEEE international conference on robotics and automation. ICRA, IEEE; 2015, p. 3741–6.
[46] Jiang S, Salagame A, Ramezani A, Wong LL. Snake robot with tactile perception navigates on large-scale challenging terrain. In: 2024 IEEE international conference on robotics and automation. ICRA, IEEE; 2024, p. 5090–6.
[47] Jayne BC. Muscular mechanisms of snake locomotion: an electromyographic study of the sidewinding and concertina modes of crotalus cerastes, nerodia fasciata and elaphe obsoleta. J Exp Biol 1988;140(1):1–33.
[48] Moon BR, Gans C. Kinematics, muscular activity and propulsion in gopher snakes. J Exp Biol 1998;201(19):2669–84.
[49] Takemori T, Tanaka M, Matsuno F. Adaptive helical rolling of a snake robot to a straight pipe with irregular cross-sectional shape. IEEE Trans Robot 2022;39(1):437–51.
[50] Morishima A, Hirose S. Impedance control of articulated body mobile robot'' Koryu''. In: Proceedings of 1993 IEEE/RSJ international conference on intelligent robots and systems. IROS'93, Vol. 3, IEEE; 1993, p. 1786–90.
[51] Racioppo P, Ben-Tzvi P. Design and control of a cable-driven articulated modular snake robot. IEEE/ASME Trans Mechatronics 2019;24(3):893–901.
[52] Shukla V, Singh B, Patil S. The development of bio-inspired snake robot. In: 2023 IEEE engineering informatics. 2023, p. 1–7.
[53] Berthet-Rayne P, Leibrandt K, Kim K, Seneci CA, Shang J, Yang G-Z. Rolling-joint design optimization for tendon driven snake-like surgical robots. In: 2018 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2018, p. 4964–71.
[54] Luo M, Agheli M, Onal CD. Theoretical modeling and experimental analysis of a pressure-operated soft robotic snake. Soft Robot 2014;1(2):136–46.
[55] Rezapour E, Pettersen K, Liljebäck P, et al. Path following control of planar snake robots using virtual holonomic constraints: theory and experiments. Robot Biomim 2014;1(1):3.
[56] Rozaidi F, Waters E, Dawes O, Yang J, Davidson JR, Hatton RL. HISSbot: Sidewinding with a soft snake robot. In: 2023 IEEE international conference on soft robotics. roboSoft, 2023, p. 1–7.
[57] Liu J, Li M, Wang Y, Zhao D, Deng R. Multi-gait snake robot for inspecting inner wall of a pipeline. Biomim Intell Robot 2024;4(2):100156.
[58] Rollinson D, Bilgen Y, Brown B, Enner F, Ford S, Layton C, Rembisz J, Schwerin M, Willig A, Velagapudi P, Choset H. Design and architecture of a series elastic snake robot. In: 2014 IEEE/RSJ international conference on intelligent robots and systems. 2014, p. 4630–6.
[59] Thakker R, Paton M, Strub MP, Swan M, Daddi G, Royce R, Tosi P, Gildner M, Vaquero T, et al. EELS: Towards autonomous mobility in extreme terrain with a versatile snake robot with resilience to exteroception failures. In: 2023 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2023, p. 9886–93.
[60] Zhao X, Dou L, Su Z, Liu N. Study of the navigation method for a snake robot based on the kinematics model with MEMS IMU. Sensors 2018;18(3).
[61] Primerano R, Pietrocola A, Janko M. A snake-like robot incorporating translational and rotation degrees of freedom. In: 2013 IEEE/RSJ international conference on intelligent robots and systems. 2013, p. 3279–84.
[62] Richter F, Gavrilov PV, Lam HM, Degani A, Yip MC. ARCSnake: Reconfigurable snakelike robot with archimedean screw propulsion for multidomain mobility. IEEE Trans Robot 2022;38(2):797–809.
[63] Wright C, Buchan A, Brown B, Geist J, Schwerin M, Rollinson D, Tesch M, Choset H. Design and architecture of the unified modular snake robot. In: 2012 IEEE international conference on robotics and automation. 2012, p. 4347–54.
[64] Wang H, Wang H, Xu W, Mu Z. Development and experiment of a snake-like robot composed of modularized isomorphic joints. In: 2016 IEEE international conference on systems, man, and cybernetics. SMC, 2016, p. 003160–5.
[65] Sun Y, Jiang Y, Yang H, Walter L-C, Santoso J, Skorina EH, Onal C. Salamanderbot: A soft-rigid composite continuum mobile robot to traverse complex environments. In: 2020 IEEE international conference on robotics and automation. ICRA, 2020, p. 2953–9.
[66] Liljebäck P, Stavdahl Ø, Pettersen KY, Gravdahl JT. Mamba-A waterproof snake robot with tactile sensing. In: 2014 IEEE/RSJ international conference on intelligent robots and systems. IEEE; 2014, p. 294–301.
[67] Wang H, Liu T, Xu W, Shenzhen HW. A snake-like robot composed of 2-DOFs modularized spherical-shape joints for space application. In: 2016 14th international conference on control, automation, robotics and vision. ICARCV, 2016, p. 1–6.
[68] Hou X, Shi Y, Li L, Tian Y, Su Y, Ding T, Deng Z. Revealing the mechanical characteristics via kinematic wave model for snake-like robot executing exploration of lunar craters. IEEE Access 2020;8:38368–79.
[69] Cortez R, Sandoval-Chileño MA, Lozada-Castillo N, Luviano-Juárez A. Snake robot with motion based on shape memory alloy spring-shaped actuators. Biomimetics 2024;9(3).
[70] Ahmed M, Billah MM. Smart material-actuated flexible tendon-based snake robot. Int J Adv Robot Syst 2016;13(3):89.
[71] Wan Z, Sun Y, Qin Y, Skorina EH, Gasoto R, Luo M, Fu J, Onal CD. Design, analysis, and real-time simulation of a 3D soft robotic snake. Soft Robot 2023;10(2):258–68, PMID: 35976088.
[72] Liu J, Tong Y, Liu J. Review of snake robots in constrained environments. Robot Auton Syst 2021;141:103785.

[73] Inazawa M, Takemori T, Tanaka M, Matsuno F. Unified approach to the motion design for a snake robot negotiating complicated pipe structures. Front Robot AI 2021;8.
[74] Ji Z, Song G, Wang F, Li Y, Song A. Design and control of a snake robot with a gripper for inspection and maintenance in narrow spaces. IEEE Robot Autom Lett 2023;8(5):3086–93.
[75] Parvaresh A, Seyidoğlu B, Rafsanjani A. Metamaterial soft snake robot for rectilinear locomotion. In: 2024 IEEE 7th international conference on soft robotics. roboSoft, 2024, p. 519–24.
[76] Koopaee MJ, Bal S, Pretty C, et al. Design and development of a wheel-less snake robot with active stiffness control for adaptive pedal wave locomotion. J Bionic Eng 2019;16:593–607.
[77] Ariizumi R, Takahashi R, Tanaka M, Asai T. Head-trajectory-tracking control of a snake robot and its robustness under actuator failure. IEEE Trans Control Syst Technol 2019;27(6):2589–97.
[78] Bianchi G, Lanzetti L, Mariana D, Cinquemani S. Bioinspired design and experimental validation of an aquatic snake robot. Biomimetics 2024;9(2).
[79] Takemori T, Tanaka M, Matsuno F. Adaptive helical rolling of a snake robot to a straight pipe with irregular cross-sectional shape. IEEE Trans Robot 2023;39(1):437–51.
[80] Tang L, Huang J, Zhu L-M, Zhu X, Gu G. Path tracking of a cable-driven snake robot with a two-level motion planning method. IEEE/ASME Trans Mechatronics 2019;24(3):935–46.
[81] Qi X, Shi H, Pinto T, Tan X. A novel pneumatic soft snake robot using traveling-wave locomotion in constrained environments. IEEE Robot Autom Lett 2020;5(2):1610–7.
[82] Branyan C, Fleming C, Remaley J, Kothari A, Tumer K, Hatton RL, Mengüç Y. Soft snake robots: Mechanical design and geometric gait implementation. In: 2017 IEEE international conference on robotics and biomimetics. ROBIO, 2017, p. 282–9.
[83] Lopez M, Haghshenas-Jaryani M. A study of energy-efficient and optimal locomotion in a pneumatic artificial muscle-driven snake robot. Robotics 2023;12(3).
[84] Kakogawa A, Jeon S, Ma S. Stiffness design of a resonance-based planar snake robot with parallel elastic actuators. IEEE Robot Autom Lett 2018;3(2):1284–91.
[85] Zhao X, Liu C, Dou L, Qiu J, Su Z. 3D visual sensing technique based on focal stack for snake robotic applications. Results Phys 2019;12:1520–8.
[86] Chen G, Bing Z, Röhrbein F, Conradt J, Huang K, Cheng L, Jiang Z, Knoll A. Toward brain-inspired learning with the neuromorphic snake-like robot and the neurorobotic platform. IEEE Trans Cogn Dev Syst 2019;11(1):1–12.
[87] Liu L, Xi W, Guo X, Fang Y. Vision-based path following of snake-like robots. In: 2021 IEEE international conference on robotics and automation. ICRA, 2021, p. 3084–90.
[88] Liljeback P, Pettersen KY, Stavdahl Ø. A snake robot with a contact force measurement system for obstacle-aided locomotion. In: 2010 IEEE international conference on robotics and automation. 2010, p. 683–90.
[89] Ramesh D, Fu Q, Li C. SenSnake: A snake robot with contact force sensing for studying locomotion in complex 3-D terrain. In: 2022 international conference on robotics and automation. ICRA, 2022, p. 2068–75.
[90] Liljeback P, Stavdahl Ø, Pettersen KY, Gravdahl JT. A modular and waterproof snake robot joint mechanism with a novel force/torque sensor. In: 2012 IEEE/RSJ international conference on intelligent robots and systems. 2012, p. 4898–905.
[91] Taal SR, Yamada H, Hirose S. 3 axial force sensor for a semi-autonomous snake robot. In: 2009 IEEE international conference on robotics and automation. 2009, p. 4057–62.
[92] Qi X, Gao T, Tan X. Bioinspired 3D-printed snakeskins enable effective serpentine locomotion of a soft robotic snake. Soft Robot 2023;10(3):568–79, PMID: 36454198.
[93] Ha J. Robotic snake locomotion exploiting body compliance and uniform body tensions. IEEE Trans Robot 2023;39(5):3875–87.
[94] Branyan C, Hatton RL, Mengüç Y. Snake-inspired kirigami skin for lateral undulation of a soft snake robot. IEEE Robot Autom Lett 2020;5(2):1728–33.
[95] Schraft HA, Clark RW. Sensory basis of navigation in snakes: the relative importance of eyes and pit organs. Anim Behav 2019;147:77–82.
[96] Ponte H, Queenan M, Gong C, Mertz C, Travers M, Enner F, Hebert M, Choset H. Visual sensing for developing autonomous behavior in snake robots. In: 2014 IEEE international conference on robotics and automation. ICRA, 2014, p. 2779–84.
[97] Jiang Z, Bing Z, Huang K, Knoll A. Retina-based pipe-like object tracking implemented through spiking neural network on a snake robot. Front Neurorobotics 2019;13.
[98] Jiang Z, Bing Z, Huang K, Chen G, Cheng L, Knoll A. Event-based target tracking control for a snake robot using a dynamic vision sensor. In: Liu D, Xie S, Li Y, Zhao D, El-Alfy E-SM, editors. Neural information processing. Cham: Springer International Publishing; 2017, p. 111–21.
[99] Li G, Waldum HB, Grindvik MO, Jørundl RS, Zhang H. Development of a vision-based target exploration system for snake-like robots in structured environments. Int J Adv Robot Syst 2020;17(4):1729881420936141.
[100] Chang AH, Feng S, Zhao Y, Smith JS, Vela PA. Autonomous, monocular, vision-based snake robot navigation and traversal of cluttered environments using rectilinear gait motion. 2019, arXiv preprint arXiv:1908.07101.
[101] Xiao X, Cappo E, Zhen W, Dai J, Sun K, Gong C, Travers MJ, Choset H. Locomotive reduction for snake robots. In: 2015 IEEE international conference on robotics and automation. ICRA, 2015, p. 3735–40.
[102] Yamakita M, Hashimoto M, Yamada T. Control of locomotion and head configuration of 3D snake robot (SMA). In: 2003 IEEE international conference on robotics and automation (cat. no.03CH37422). Vol. 2, 2003, p. 2055–60 vol.2.
[103] Bao L, Sun Y, Wang Q, Xie Z. Study on head stabilization control strategy of non-wheeled snake robot based on inertial sensor. Appl Sci 2023;13(7).
[104] Li Z, Hu J, Ren Q. A head stabilizer of a snake robot crawling in serpentine locomotion. In: 2022 IEEE 17th conference on industrial electronics and applications. ICIEA, 2022, p. 1086–91.
[105] Mei D, Yu X, Tang G, Kong W, Zhao X, Zhao C, Li B, Wang Y. A soft crawling robot with multi-modal locomotion inspired by the movement mechanism of snake scales. IEEE Robot Autom Lett 2024.
[106] Hasseler TD, Leake C, Gaut A, Elmquist A, Swan RM, Royce R, Jones B, Hockman B, Paton M, Daddi G, Ono M, Thakker R, Jain A. EELS-DARTS: A planetary snake robot simulator for closed-loop autonomy development. Aerospace 2024;11(10).
[107] Lamping F, Gorb SN, de Payrebrune KM. Frictional properties of a novel artificial snakeskin for soft robotics. Biotribology 2022;30:100210.
[108] Shen D, Zhang Q, Wang C, Wang X, Tian M. Design and analysis of a snake-inspired crawling robot driven by alterable angle scales. IEEE Robot Autom Lett 2021;6(2):3744–51.
[109] ZHU N, ZANG H, LIAO B, LIU D, TUO J, ZHOU T, WANG Q. The effect of different scales on the crawling rate of bionic snake robot. In: 2018 WRC symposium on advanced robotics and automation. WRC SARA, 2018, p. 22–7.
[110] Luo M, Yan R, Wan Z, Qin Y, Santoso J, Skorina EH, Onal CD. OriSnake: Design, fabrication, and experimental analysis of a 3-D origami snake robot. IEEE Robot Autom Lett 2018;3(3):1993–9.
[111] Di Giacomo R, Bonanomi L, Costanza V, Maresca B, Daraio C. Biomimetic temperature-sensing layer for artificial skins. Sci Robot 2017;2(3):eaai9251.
[112] Marvi H, Cook JP, Streator JL, Hu DL. Snakes move their scales to increase friction. Biotribology 2016;5:52–60.
[113] Serrano MM, Chang AH, Zhang G, Vela PA. Incorporating frictional anisotropy in the design of a robotic snake through the exploitation of scales. In: 2015 IEEE international conference on robotics and automation. ICRA, 2015, p. 3729–34.
[114] Luo M, Tao W, Chen F, Khuu TK, Ozel S, Onal CD. Design improvements and dynamic characterization on fluidic elastomer actuators for a soft robotic snake. In: 2014 IEEE international conference on technologies for practical robot applications. tePRA, 2014, p. 1–6.
[115] Lee M. Snake skin: Small scales with a large scale impact. In: Remarkable natural material surfaces and their engineering potential. Springer; 2014, p. 103–14.
[116] Mei D, Yu X, Tang G, Kong W, Zhao X, Zhao C, Li B, Wang Y. A soft crawling robot with multi-modal locomotion inspired by the movement mechanism of snake scales. IEEE Robot Autom Lett 2024;9(9):7589–96.
[117] Gonzalez-Gomez J, Gonzalez-Quijano J, Zhang H, Abderrahim M. Toward the sense of touch in snake modular robots for search and rescue operations. In: Proc. ICRA 2010 workshop "modular robots: state of the art. 2010, p. 63–8.
[118] Wu X, Ma S. Development of a sensor-driven snake-like robot SR-i. In: 2011 IEEE international conference on information and automation. IEEE; 2011, p. 157–62.
[119] Gong C, Tesch M, Rollinson D, Choset H. Snakes on an inclined plane: Learning an adaptive sidewinding motion for changing slopes. In: 2014 IEEE/RSJ international conference on intelligent robots and systems. 2014, p. 1114–9.
[120] Liljebäck P, Pettersen KY, Stavdahl Ø. A snake robot with a contact force measurement system for obstacle-aided locomotion. In: 2010 IEEE international conference on robotics and automation. IEEE; 2010, p. 683–90.
[121] Takanashi T, Nakajima M, Takemori T, Tanaka M. Reaction force analysis for obstacle-aided locomotion of snake robot using piecewise helixes. IEEE Access 2023;11:44150–66.
[122] Ullah SI, Mahmood T, Anayatullah. Autonomous navigation and mapping of snake robot for urban search and rescue. In: 2023 international conference on robotics and automation in industry. ICRAI, 2023, p. 1–8.
[123] Shahid R, Baloch A, Tahir H, Ullah A. Odometry and inertial sensor-based localization of a snake robot. In: 2023 international conference on robotics and automation in industry. ICRAI, 2023, p. 1–6.
[124] Zhang B, Liu P. Model-based and model-free robot control: A review. In: Chew E, P. P. Abdul Majeed A, Liu P, Platts J, Myung H, Kim J, Kim J-H, editors. RiTA 2020. Singapore: Springer Singapore; 2021, p. 45–55.

[125] Fukushima H, Yanagiya T, Ota Y, Katsumoto M, Matsuno F. Model predictive path-following control of snake robots using an averaged model. IEEE Trans Control Syst Technol 2021;29(6):2444–56.
[126] Li N, Wang F, Ren S, Cheng X, Wang G, Li P. A review on the recent development of planar snake robot control and guidance. Mathematics 2025;13(2).
[127] Nakajima M, and MT. Motion control of a snake robot on multiple inclined planes. Adv Robot 2024;38(11):784–800.
[128] Takagi Y, Ishikawa M, Osuka K. A kinematic-dual snake robot: Undulatory mobile robot driven by controllable side-thrust links. Mechatronics 2023;90:102944.
[129] Koopaee MJ, Pretty C, Classens K, Chen X. Dynamical modeling and control of modular snake robots with series elastic actuators for pedal wave locomotion on uneven terrain. J Mech Des 2019;142(3):031120.
[130] Koopaee MJ, Bal S, Pretty C, Chen X. Design and development of a wheel-less snake robot with active stiffness control for adaptive pedal wave locomotion. J Bionic Eng 2019;16:593–607.
[131] Mukherjee J, Mukherjee S, Kar IN. Sliding mode control of planar snake robot with uncertainty using virtual holonomic constraints. IEEE Robot Autom Lett 2017;2(2):1077–84.
[132] Marafioti G, Liljebäck P, Transeth AA. A study of nonlinear model predictive control (NMPC) for snake robot path following. In: 2014 IEEE international conference on robotics and biomimetics. ROBIO 2014, 2014, p. 568–73.
[133] Nonhoff M, Köhler PN, Kohl AM, Pettersen KY, Allgöwer F. Economic model predictive control for snake robot locomotion. In: 2019 IEEE 58th conference on decision and control. CDC, 2019, p. 8329–34.
[134] Orucevic A, Foseid EL, Lysø MEB, Pettersen KY, Gravdahl JT. Nonlinear model predictive control for sinusoidal gait tracking for an underwater snake robot. IFAC-PapersOnLine 2024;58(20):253–8, 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles CAMS 2024.
[135] Hannigan E, Song B, Khandate G, Haas-Heger M, Yin J, Ciocarlie M. Automatic snake gait generation using model predictive control. In: 2020 IEEE international conference on robotics and automation. ICRA, 2020, p. 5101–7.
[136] Wang L, Wang G, Li Y, Li P, Ji Y, Wang C, Shen Y. Real-time whole-body collision avoidance and path following of a snake robot through MPC-based optimization strategies. In: 2023 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2023, p. 2362–7.
[137] Jia Y, Ma S. A decentralized Bayesian approach for snake robot control. IEEE Robot Autom Lett 2021;6(4):6955–60.
[138] Sartoretti G, Wang T, Chuang G, Li Q, Choset H. Autonomous decentralized shape-based navigation for snake robots in dense environments. In: 2021 IEEE international conference on robotics and automation. ICRA, 2021, p. 9276–82.
[139] Kiumarsi B, Vamvoudakis KG, Modares H, Lewis FL. Optimal and autonomous control using reinforcement learning: A survey. IEEE Trans Neural Netw Learn Syst 2018;29(6):2042–62.
[140] Wang R, Xi W, Guo X, Fang Y. Path following for snake robot using crawler gait based on path integral reinforcement learning. In: 2021 6th IEEE international conference on advanced robotics and mechatronics. ICARM, 2021, p. 192–8.
[141] Liu L, Guo X, Xi W, Huang W, Fang Y. A reinforcement learning path following strategy for snake robots based on transferable constrained-residual gait generator. IEEE Trans Ind Electron 2024;71(12):16013–25.
[142] Qi X, Chen D, Li Z, Tan X. Back-stepping experience replay with application to model-free reinforcement learning for a soft snake robot. IEEE Robot Autom Lett 2024;9(9):7517–24.
[143] Jia Y, Ma S. A coach-based Bayesian reinforcement learning method for snake robot control. IEEE Robot Autom Lett 2021;6(2):2319–26.
[144] Bing Z, Lemke C, Cheng L, Huang K, Knoll A. Energy-efficient and damage-recovery slithering gait design for a snake-like robot based on reinforcement learning and inverse reinforcement learning. Neural Netw 2020;129:323–33.
[145] Bing Z, Lemke C, Morin FO, Jiang Z, Cheng L, Huang K, Knoll A. Perception-action coupling target tracking control for a snake robot via reinforcement learning. Front Neurorobotics 2020;Volume 14 - 2020.
[146] Kim S-J, Suh J-H. Adaptive robust RBF-NN nonsingular terminal sliding mode control scheme for application to snake robot's head for image stabilization. Appl Sci 2023;13(8).
[147] Liu X, Gasoto R, Jiang Z, Onal C, Fu J. Learning to locomote with artificial neural-network and CPG-based control in a soft snake robot. In: 2020 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2020, p. 7758–65.
[148] Woodford GW, Plessis MCD, Pretorius CJ. Evolving snake robot controllers using artificial neural networks as an alternative to a physics-based simulator. In: 2015 IEEE symposium series on computational intelligence. 2015, p. 267–74.
[149] Woodford GW, du Plessis MC. Robotic snake simulation using ensembles of artificial neural networks in evolutionary robotics. In: Proceedings of the genetic and evolutionary computation conference. GECCO '18, New York, NY, USA: Association for Computing Machinery; 2018, p. 173–80.
[150] Xue F, Fan Z. Kinematic control of a cable-driven snake-like manipulator for deep-water based on fuzzy PID controller. Proc Inst Mech Eng I: J Syst Control Eng 2022;236(5):989–98.
[151] Wu L, Liu Y, Zhou J, Wang Z, Wang Y, Tang Y. A fuzzy ESO-based joint angle control design of snake robots. In: 2021 IEEE international conference on robotics and biomimetics. ROBIO, 2021, p. 956–61.
[152] Zeng HT, Yuan J. A fuzzy adaptive PID system of DC brush motor for snake arm robot. In: 2022 2nd international conference on electrical engineering and control science. IC2ECS, 2022, p. 1012–7.
[153] Larabi-Marie-Sainte S, Eisa TAE, Al-Wesabi FN, Albraikan AA, Hamza MA, Motwakel A, Yaseen I, Duhayyim MA. Locomotion of bioinspired underwater snake robots using metaheuristic algorithm. Comput Mater Contin 2022;72(1):1293–308.
[154] Gao Q, Wang Z, Li H. An optimization algorithm with novel RFA-PSO cooperative evolution: Applications to parameter decision of a snake robot. Math Probl Eng 2015;2015(1):316826.
[155] Qian F, Koditschek DE. An obstacle disturbance selection framework: emergent robot steady states under repeated collisions. Int J Robot Res 2020;39(13):1549–66.
[156] Lopez M, Haghshenas-Jaryani M. A muscle-driven mechanism for locomotion of snake-robots. Automation 2022;3(1):1–26.
[157] Wang G, Yang W, Shen Y, Shao H, Wang C. Adaptive path following of underactuated snake robot on unknown and varied frictions ground: Theory and validations. IEEE Robot Autom Lett 2018;3(4):4273–80.
[158] Mukherjee J, Kar IN, Mukherjee S. Adaptive sliding mode control for head-angle and velocity tracking of planar snake robot. In: 2017 11th Asian control conference. ASCC, 2017, p. 537–42.
[159] Kim S-J, Jin M, Suh J-H. A study on the design of error-based adaptive robust RBF neural network back-stepping controller for 2-DOF snake robot's head. IEEE Access 2023;11:23146–56.
[160] Han S, Chon S, Kim J, Seo J, Shin DG, Park S, Kim JT, Kim J, Jin M, Cho J. Snake robot gripper module for search and rescue in narrow spaces. IEEE Robot Autom Lett 2022;7(2):1667–73.
[161] Liu W, Jing Z, Huang J, Dun X, Qiao L, Leung H, Chen W. An inchworm-snake inspired flexible robotic manipulator with multisection SMA actuators for object grasping. IEEE Trans Ind Electron 2023;70(12):12616–25.
[162] Xue Y, Zhang Y, Zheng W, Jiang C, Xiao X. Design, control and experiment of a snake-like robot with gripper. In: 2020 17th international conference on ubiquitous robots. UR, 2020, p. 50–5.
[163] Konishi R, Nakajima M, Tanaka K, Matsuno F, Tanaka M. Design for snake robot motion via partial grasping on pipes. Adv Robot 2023;37(4):227–40.
[164] Reyes F, Ma S. On planar grasping with snake robots: Form-closure with enveloping grasps. In: 2014 IEEE international conference on robotics and biomimetics. ROBIO 2014, 2014, p. 556–61.
[165] Mendoza N, Haghshenas-Jaryani M. Combined soft grasping and crawling locomotor robot for exterior navigation of tubular structures. Machines 2024;12(3).
[166] Nilsson M. Snake robot-free climbing. IEEE Control Syst Mag 1998;18(1):21–6.
[167] Kon K, Tanaka M, Tanaka K. Mixed integer programming-based semiautonomous step climbing of a snake robot considering sensing strategy. IEEE Trans Control Syst Technol 2016;24(1):252–64.
[168] Liao B, Zang H, Chen M, Wang Y, Lang X, Zhu N, Yang Z, Yi Y. Soft rod-climbing robot inspired by winding locomotion of snake. Soft Robot 2020;7(4):500–11, PMID: 31986109.
[169] Wang C, Deng H-b, Xia F, Li Y. Study on climbing locomotion mechanism of snake robot with universal unit. In: 2016 8th international conference on modelling, identification and control. ICMIC, 2016, p. 460–5.
[170] Koike CC, Viana DM, Yudi J, Batista FA, Costa A, Carvalho V, Rocha T. Visual-aided obstacle climbing by modular snake robot. Sensors 2024;24(13).
[171] Kamegawa T, Kuroki R, Gofuku A. Evaluation of snake robot's behavior using randomized EARLI in crowded obstacles. In: 2014 IEEE international symposium on safety, security, and rescue robotics (2014). 2014, p. 1–6.
[172] Løwer J, Gravdahl I, Varagnolo D, Stavdahl Ø. Form closure for fully actuated and robust obstacle-aided locomotion in snake robots. IEEE Robot Autom Lett 2023;8(11):7360–7.
[173] Yoshida Y, Chin CW, Tanaka M. Traversing between two planes using obstacle-aided locomotion of a snake robot. IEEE Robot Autom Lett 2024;9(11):10288–94.
[174] Qiu Y, Date H. Obstacle-aided locomotion for underwater snake robot using Monte Carlo model predictive control and curvature derivative control. In: 2023 62nd annual conference of the society of instrument and control engineers. SICE, 2023, p. 690–5.
[175] Takanashi T, Nakajima M, Takemori T, Tanaka M. Obstacle-aided locomotion of a snake robot using piecewise helixes. IEEE Robot Autom Lett 2022;7(4):10542–9.
[176] Müller E, Köhler PN, Pettersen KY, Allgöwer F. Economic model predictive control for obstacle-aided snake robot locomotion. IFAC-PapersOnLine 2020;53(2):9702–8, 21st IFAC World Congress.
[177] Kelasidi E, Moe S, Pettersen KY, Kohl AM, Liljebäck P, Gravdahl JT. Path following, obstacle detection and obstacle avoidance for thrusted underwater snake robots. Front Robot AI 2019;Volume 6 - 2019.

[178] Kohl AM, Moe S, Kelasidi E, Pettersen KY, Gravdahl JT. Set-based path following and obstacle avoidance for underwater snake robots. In: 2017 IEEE international conference on robotics and biomimetics. ROBIO, 2017, p. 1206–13.

[179] Li D, Deng H, Pan Z, Xiu Y. Collaborative obstacle avoidance algorithm of multiple bionic snake robots in fluid based on IB-LBM. ISA Trans 2022;122:271–80.

[180] Itani O, Shammas E, Abou Jaoude D. Optimal reorientation of planar floating snake robots with collision avoidance. Robot Auton Syst 2024;178:104711.

[181] Hsu K. Obstacle avoidance path scheme of snake robot based on bidirectional fast expanding random tree algorithm. J King Saud Univ - Sci 2022;34(4):101975.

[182] Gu H, Gao H, Zhao Y, Ma X, Wei C. Dexterous obstacle-avoidance motion control of rope driven snake manipulator based on the bionic path following. Mech Mach Theory 2023;189:105406.

[183] Qi W, Chun Y, Sheng Y, Zhao G, Wang L. Stability analysis of obstacle avoidance ability and environment adaptation modeling of snake robot based on deep learning and binocular vision. In: 2022 3rd international conference on smart electronics and communication. ICOSEC, 2022, p. 299–302.

[184] Haghshenas-Jaryani M, Sevil HE. Autonomous navigation and obstacle avoidance of a snake robot with combined velocity-heading control. In: 2020 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2020, p. 7507–12.

[185] Krishna G, S LPP, R HK. Obstacle avoidance in snake robot navigation using artificial potential field. In: 2024 international conference on e-mobility, power control and smart systems. ICEMPS, 2024, p. 1–6.

[186] Xiu Y, Deng H, Li D, Law R, Wu EQ, Zhu L. Collision avoidance regulation-compliant orientation guidance and maneuvering control approach for snake robots. IEEE Trans Ind Electron 2024;71(9):10955–65.

[187] Berthet-Rayne P, Gras G, Leibrandt K, et al. The i2Snake robotic platform for endoscopic surgery. Ann Biomed Eng 2018;46(10):1663–75.

[188] Jiang S, Salagame A, Ramezani A, Wong LLS. Snake robot with tactile perception navigates on large-scale challenging terrain. In: 2024 IEEE international conference on robotics and automation. ICRA, 2024, p. 5090–6.

[189] Elsayed BA, Takemori T, Tanaka M, Matsuno F. Mobile manipulation using a snake robot in a helical gait. IEEE/ASME Trans Mechatronics 2022;27(5):2600–11.

[190] Zhang J, Chen Y, Liu Y, Gong Y. Dynamic modeling of underwater snake robot by hybrid rigid-soft actuation. J Mar Sci Eng 2022;10(12).

[191] Zhao W, Wang J, Fei Y. A multigait continuous flexible snake robot for locomotion in complex terrain. IEEE/ASME Trans Mechatronics 2022;27(5):3751–61.

[192] Zhu Q, Zhou T, Du J. Upper-body haptic system for snake robot teleoperation in pipelines. Adv Eng Inform 2022;51:101532.

[193] Virgala I, Kelemen M, Prada E, Sukop M, Kot T, Bobovský Z, Varga M, Ferenčík P. A snake robot for locomotion in a pipe using trapezium-like travelling wave. Mech Mach Theory 2021;158:104221.

[194] Virgala I, Kelemen M, Božek P, Bobovský Z, Hagara M, Prada E, Ošˇ cádal P, Varga M. Investigation of snake robot locomotion possibilities in a pipe. Symmetry 2020;12(6).

[195] Lim J, Yang W, Shen Y, Yi J. Analysis and validation of serpentine locomotion dynamics of a wheeled snake robot moving on varied sloped environments. In: 2020 IEEE/aSME international conference on advanced intelligent mechatronics. AIM, 2020, p. 1069–74.

[196] Fu Q, Li C. Robotic modelling of snake traversing large, smooth obstacles reveals stability benefits of body compliance. R Soc Open Sci 2020;7(2):191192.

[197] Tanaka M, Kon K, Nakajima M, Matsumoto N, Fukumura S, Fukui K, Sawabe H, Fujita M, Tadakuma K. Development and field test of the articulated mobile robot T2 Snake-4 for plant disaster prevention. Adv Robot 2020;34(2):70–88.

[198] Chang AH, Feng S, Zhao Y, Smith JS, Vela PA. Autonomous, monocular, vision-based snake robot navigation and traversal of cluttered environments using rectilinear gait motion. 2019, CoRR arXiv:1908.07101. arXiv:1908.07101.

[199] Kelasidi E, Moe S, Pettersen KY, Kohl AM, Liljebäck P, Gravdahl JT. Path following, obstacle detection and obstacle avoidance for thrusted underwater snake robots. Front Robot AI 2019;6:57.

[200] Huang CC, Chang CL. Design and implementation of bio-inspired snake bone-armed robot for agricultural irrigation application. IFAC-PapersOnLine 2019;52(30):98–101, 6th IFAC Conference on Sensing, Control and Automation Technologies for Agriculture AGRICONTROL 2019.

[201] Yaqub S, Ali A, Usman M, Zuhaib KM, Khan AM, An B, Moon H, Lee J-Y, Han C. A spiral curve gait design for a modular snake robot moving on a pipe. Int J Control Autom Syst 2019;17(10):2565–73.

[202] Takemori T, Tanaka M, Matsuno F. Gait design for a snake robot by connecting curve segments and experimental demonstration. IEEE Trans Robot 2018;34(5):1384–91.

[203] Kelasidi E, Kohl A, Pettersen K, Hoffmann B, Gravdahl J. Experimental investigation of locomotion efficiency and path-following for underwater snake robots with and without a caudal fin. Annu Rev Control 2018;46:281–94.

[204] Takemori T, Tanaka M, Matsuno F. Ladder climbing with a snake robot. In: 2018 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2018, p. 1–9.

[205] Sanfilippo F, Stavdahl Ø, Liljebäck P. SnakeSIM: A ROS-based control and simulation framework for perception-driven obstacle-aided locomotion of snake robots. Artif Life Robot 2018;23:449–58.

[206] Qi W, Kamegawa T, Gofuku A. Helical wave propagation motion for a snake robot on a vertical pipe containing a branch. Artif Life Robot 2018;23:515–22.

[207] Huang C-W, Huang C-H, Hung Y-H, Chang C-Y. Sensing pipes of a nuclear power mechanism using low-cost snake robot. Adv Mech Eng 2018;10(6):1687814018781286.

[208] Singh A, Anshul, Gong C, Choset H. Modelling and path planning of snake robot in cluttered environment. In: 2018 international conference on reconfigurable mechanisms and robots. reMAR, 2018, p. 1–6.

[209] Kelasidi E, Liljebäck P, Pettersen KY, Gravdahl JT. Integral line-of-sight guidance for path following control of underwater snake robots: Theory and experiments. IEEE Trans Robot 2017;33(3):610–28.

[210] Nakajima M, Tanaka M, Tanaka K, Matsuno F. Motion control of a snake robot moving between two non-parallel planes. Adv Robot 2018;32(10):559–73.

[211] Bai Y, Hou YB. Research of environmental modeling method of coal mine rescue snake robot based on information fusion. In: 2017 20th international conference on information fusion (fusion). 2017, p. 1–8.

[212] Bing Z, Cheng L, Huang K, Jiang Z, Chen G, Röhrbein F, Knoll A. Towards autonomous locomotion: Slithering gait design of a snake-like robot for target observation and tracking. In: 2017 IEEE/RSJ international conference on intelligent robots and systems. IROS, 2017, p. 2698–703.

[213] Pfotzer L, Klemm S, Roennau A, Zöllner J, Dillmann R. Autonomous navigation for reconfigurable snake-like robots in challenging, unknown environments. Robot Auton Syst 2017;89:123–35.

[214] Rollinson D, Choset H. Pipe network locomotion with a snake robot. J Field Robot 2016;33(3):322–36.

[215] Lu Z, Feng D, Xie Y, Xu H, Mao L, Shan C, Li B, Bilik P, Zidek J, Martinek R, Rykala Z. Study on the motion control of snake-like robots on land and in water. Perspect Sci 2016;7:101–8, 1st Czech-China Scientific Conference 2015.

[216] Tanaka M, Tanaka K. Control of a snake robot for ascending and descending steps. IEEE Trans Robot 2015;31(2):511–20.

[217] Tanaka M, Kon K, Tanaka K. Range-sensor-based semiautonomous whole-body collision avoidance of a snake robot. IEEE Trans Control Syst Technol 2015;23(5):1927–34.

[218] Whitman J, Zevallos N, Travers M, Choset H. Snake robot urban search after the 2017 Mexico city earthquake. In: 2018 IEEE international symposium on safety, security, and rescue robotics. SSRR, 2018, p. 1–6.

[219] Kamegawa T, Akiyama T, Sakai S, Fujii K, Une K, Wang Y, Matsumura Y, Kishutani T, Nose E, Yoshizaki Y, et al. Development of a separable search-and-rescue robot composed of a mobile robot and a snake robot. Adv Robot 2020;34(2):132–9.

[220] Zhao M, Anzai T, Shi F, Chen X, Okada K, Inaba M. Design, modeling, and control of an aerial robot DRAGON: A dual-rotor-embedded multilink robot with the ability of multi-degree-of-freedom aerial transformation. IEEE Robot Autom Lett 2018;3(2):1176–83.

[221] Vaquero TS, Daddi G, Thakker R, Paton M, Jasour A, Strub MP, Swan RM, et al. EELS: Autonomous snake-like robot with task and motion planning capabilities for ice world exploration. Sci Robot 2024;9(88):eadh8332.

[222] Li D, Zhang B, Wu C, Xu Y, Huang J, Wu EQ, Zhu L. Tracking control of snake robots with butterfly spiral propulsion for multiscenario applications. IEEE Trans Ind Inform 2024;20(12):13526–36.

[223] Hopkins JK, Gupta SK. Design and modeling of a new drive system and exaggerated rectilinear-gait for a snake-inspired robot. J Mech Robot 2014;6(2):021001.

[224] Liu X, Lin G, Wei W. Adaptive transition gait planning of snake robot based on polynomial interpolation method. Actuators 2022;11(8).

[225] Shu X, Tang C, Zhou G, Zhou P, Sun L, Yan X. Extension and experimental demonstration of gait transition network for a snake robot. IEEE Robot Autom Lett 2022;8(1):352–9.

[226] Droge G, Egerstedt M. Optimal decentralized gait transitions for snake robots. In: 2012 IEEE international conference on robotics and automation. 2012, p. 317–22.

Syed Kumayl Raza Moosavi received his bachelors degree in Mechatronics engineering in 2016 and his masters degree in Artificial Intelligence in 2023 from the National University of Sciences and Technology (NUST), Islamabad, Pakistan. He is pursuing a PhD degree in the field of Robotics and AI from the Department of Engineering Sciences, University of Agder, Grimstaad, Norway. His research interests include Robotics, Artificial Intelligence and Disaster Management. He is also reviewer of several International Conferences and Journals.

Muhammad Hamza Zafar received his bachelor's degree in Electronics engineering in 2015 and his master's degree in electrical engineering in 2022 from the Capital University of Science and Technology, Islamabad, Pakistan. He is pursuing a PhD degree in the field of Robotics and AI from the Department of Engineering Sciences, University of Agder, Grimstad, Norway. His research interests include Robotics, Machine Vision, Human-Robot Teaming and Swarm Optimisation. He is currently an IEEE Student Section Representative of the Norway Section. He is also reviewer of several International Conferences and Journals.

Filippo Sanfilippo holds a PhD in Engineering Cybernetics from the Norwegian University of Science and Technology (NTNU), Norway His research interests include robotics, wearables, human–robot collaboration, collaborative robotics, artificial intelligence and control theory. He is currently appointed as a Professor at the Faculty of Engineering and Science, University of Agder (UiA), Grimstad, Norway. He is also an adjunct Professor at the Faculty of Informatics, Kaunas University of Technology, Kaunas, Lithuania. He has authored and co-authored several technical papers in various journals and conferences. He is a reviewer for several international conferences and journals.