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CRITICAL REVIEW

Underwater Snake-Like Robots: A Review on Design, Actuation, and Modelling Methods

Ardit Poka[1,2,3] · Daniele Ludovico[1] · Federico Manara[1,2,4] · Lorenzo De Mari Casareto Dal Verme[1] · Carlo Canali[1,4] · Giovanni Berselli[1,2] · Darwin G. Caldwell[1] · Jovana Jovanova[3]

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Abstract
In recent years, significant advancements have been made in robotics, especially with the introduction of continuum and hyper-redundant robots. These robots can be highly flexible and manoeuvrable, which makes them suitable for intricate underwater maintenance, exploration, and inspection tasks. Inspired by the motions of aquatic life, underwater snake-like robots offer a good way to accomplish subsea maintenance, exploration, and inspection activities. While many studies have been conducted on hyper-redundant, snake-like robotic arms for maintenance and inspection in land-based applications, not as much about robotics intended for marine or underwater applications has been studied. This review critically examines recent advancements in the design, actuation, and modelling of these robotic systems, categorising them into two primary families: untethered mobile robots and tethered robotic manipulators. Key insights include the identification of strengths and limitations associated with various designs and actuation strategies, such as the high manoeuvrability but limited speed of bioinspired swimming robots compared to thruster-driven designs, and the complexity versus precision trade-offs inherent in tendon-driven manipulator arms. Furthermore, the modelling techniques employed across categories are systematically analysed, as well as challenges such as the modelling of fluid–structure interactions and the need for improved real-time models for compliant and soft robots.

Keywords Literature review · Robotics · Underwater · Snake-like · Hyper-redundant

1 Introduction

Conventional underwater robotic systems, like autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), have been indispensable in performing subsea maintenance, repair, and inspection (INS) operations [1, 2]. Robots operating in tight or complex underwater spaces must be able to combine flexibility, manoeuvrability, and efficient movement due to the unique constraints given by underwater conditions. However, these technologies often

✉ Ardit Poka
ardit.poka@iit.it

Daniele Ludovico
daniele.ludovico@iit.it

Federico Manara
federico.manara@iit.it

Lorenzo De Mari Casareto Dal Verme
lorenzo.demaricasareto@iit.it

Carlo Canali
carlo.canali@iit.it

Giovanni Berselli
giovanni.berselli@unige.it

Darwin G. Caldwell
darwin.caldwell@iit.it

Jovana Jovanova
j.jovanova@tudelft.nl

1 Advanced Robotics (ADVR), Italian Institute of Technology, Genova, Italy

2 Department of Mechanical, Energy, Management and Transportation Engineering (DIME), University of Genova, Genova, Italy

3 Department of Marine and Transport Technology (M&TT), Delft University of Technology, Delft, Netherlands

4 RAISE Ecosystem, Genova 16126, Italy

lack the adaptability and accuracy required to work well in confined spaces, including those between closely spaced undersea pipelines or inside shipwrecks [3]. Researchers are increasingly using bioinspired designs, especially those based on the fluid, undulating movement of marine animals, to overcome these constraints [4]. Among these, underwater snake-like robots represent an interesting research field. Robots that resemble underwater snakes are designed to emulate the agility of natural creatures like sea snakes and eels, which are well-suited to manoeuvring in constricted, unpredictable environments [5]. Because of their adaptability and their long, thin, manoeuvrable structures, snake-like robots may perform tasks like inspection and maintenance in offshore energy installations, as well as access locations that are hard for traditional ROVs or AUVs to reach, such as the inside of intricate underwater structures, which would be difficult for typical systems. These robots frequently rely on hyper-redundant designs, which allow precise movement and typically carry a larger weight, and continuum structures, which allow compliant, smooth movements [6–8]. Numerous actuation techniques are possible with these designs, including fluidic actuation (FA), bioinspired undulatory motion, propelled systems, and tendon-driven manipulators [9]. Given their versatility, snake-like robots can function in a range of underwater situations from shallow waters to deep-sea settings. As these robots evolve, their applications expand from industrial tasks, including pipeline inspection and repair, exploration, or environmental monitoring (EM) [10, 11]. Actuation of snake-like robots often takes inspiration from natural phenomena, including the undulating motion of eels, which has been demonstrated to be an efficient and effective means of producing propulsion in water [12]. In addition, using sophisticated materials like polymers and lightweight composites can optimise the design of these robots to minimise drag and improve robustness. With the help of actuation strategies that draw inspiration from marine life, robots can adjust to changing environmental factors like water currents without the assistance of intricate feedback control systems [13, 14]. The layout of these robots often includes segmented structures, considering modular flexibility. Each segment may be actuated independently, presenting a high manoeuvrability and allowing the robot to carry out sensitive tasks, which include grasping or manipulating objects in underwater environments.

This systematic literature review is focused on the modelling, design, and actuation of underwater snake-like robots. Furthermore, the structural and mechanical advances that allow these robots to function in underwater settings are highlighted. This survey also analyses the inclusion of flexible actuation systems into these bio-inspired structures. This review, unlike prior surveys, focuses on the critical examination of design principles, actuation mechanisms, and modelling approaches of underwater snake-like robots. With a detailed categorisation, it provides a clearer understanding of the current state of the art and identifies future research opportunities across these domains. While control is a fundamental challenge in the development of continuum and hyper-redundant robots, the scope of this review is to allow a more in-depth technical analysis of these foundational elements, which often form the basis upon which advanced control strategies are developed. This paper intends to highlight the potential of underwater snake-arm robots in various subsea applications, including energy, marine research, and underwater inspection, by incorporating lessons from recent advancements in bioinspired robotics.

This work is organised as follows: Section 2 presents the research process of the survey and categorisation. Sections 3 and 3.1 examine the various types of robotic systems, namely untethered and tethered underwater robots, respectively, which examine the design concepts that follow the materials, structural arrangements, and mechanical advancements that give these robots great levels of manoeuvrability and adaptability. In Section 3.1.1, the modelling strategies that allow these robots to replicate the undulating motion of marine life and the manoeuvrability of robotic arms while preserving structural integrity are examined. Section 3.1.2 presents the discussion of the results of this survey. Lastly, Section 3.2 draws the conclusions.

2 Research methodology and categorisation

The research process for this systematic literature review is based on the Scopus database, as it provides comprehensive coverage of documents and sources while supporting various search operators, allowing for a thorough, precise, and reproducible systematic literature review, as evidenced by the studies of Delgado et al. [15], Giustini et al. [16], Singh et al. [17], Mart´ın-Mart´ın et al. [18]. The intention was to find documents that include robots classified as snake-like, eel-like, or more generally as continuum robots for underwater or marine environments. The research was performed by looking for terms within the documents' titles, abstracts, and keywords, using the following string as a search query: TITLE-ABS-KEY(snake* OR eel* OR hyper-redundant OR continuum*) PRE/3 (robot* OR manipulator*) AND ("underwater" OR "subsea" OR "marine" OR "ocean" OR "aquatic" OR "undersea" OR "submerged" OR "subaqueous") AND ("design*" OR "mechanical design*" OR "actuation*" OR "actuator*" OR "kinematic*" OR "dynamic*" OR "material*"OR "modelling" OR "structure*"). The main discriminating criterion is that the analysed works should present a description and/or analysis of the mechanism, actuation or modelling method, which is the primary focus of this work. No discrimination was made on the number of citations or the publication year, although very few documents were found before 2015. Only manuscripts written in English were considered. The Scopus search, last updated on May 2025, returned 202 papers. Among them, 91 documents were excluded since their focus is not on snake-like manipulators or similar underwater robots. Subsequently, other documents studying control and gait generation in the serpentine movement of snake-like mobile robots were excluded, resulting in 47 remaining documents. The survey was then enriched by a backwards and forward snowballing on the 47 papers resulting from Scopus, generating another 15 documents. The final number of relevant documents analysed is 62.

In this survey, two families of underwater robots have been identified: tethered and untethered underwater robots. Untethered mobile robots can navigate without being fixed to a platform, making them capable of moving like eels. On the contrary, tethered robots rely on a fixed platform and can not navigate without an external thrusted base, acting as robotic arms. Within these two families, the robots have been divided into categories. In the family of untethered robots, two categories of different types of robots have been identified: thrusted robots (TR) and swimming robots (SR). Within these categories, a further classification into sub-categories was made based on fundamental characteristics of the actuation system. Regarding TRs, two sub-categories were identified: thrusted robots with rigid joints (TRRJ), thrusted robots with soft joints (TRSJ). Regarding SRs, four sub-categories were identified: swimming robots with rigid joints (SRRJ), swimming robots with compliant joints (SRCJ), swimming robots with soft joints (SRSJ), and a sub-category including a few other particular types of swimming robots. Likewise, three categories have been identified within the tethered robots family: compliant robotic arms (CRA), rigid-joint robotic arms (RJRA), and soft robotic arms (SRA). This classification was based on the design, actuation, and motion transmission strategies, which also dictate the modelling strategies of the robots. For this reason, this classification identifies the fundamental differences in design, actuation, and modelling techniques in different snake-like underwater robots. Figure 1 shows the percentages of documents found in each category of both robot families.

This field of robotics is relatively new and began to be explored in the 1990's, as demonstrated by the survey results and shown in Fig. 2. It is also shown that before the year 2015, research in this field remained quite stagnant, then a significant rise in research papers began from 2021.

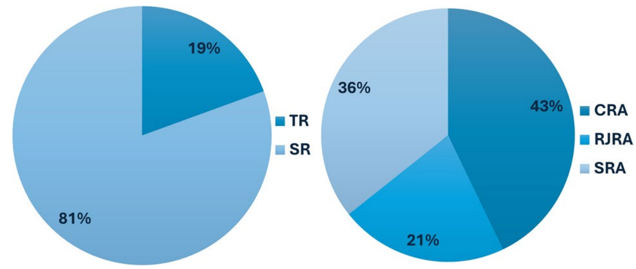

Fig. 1 Percentages of works found on underwater robot designs for each category. Left: untethered robots. Right: tethered robots

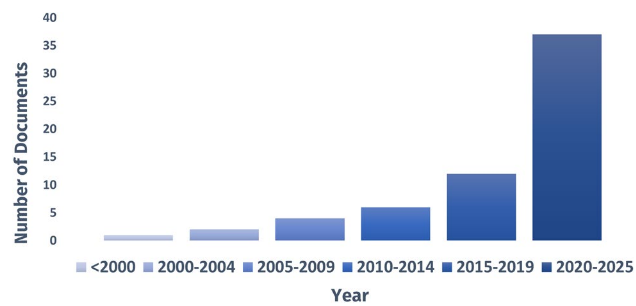

Fig. 2 Number of yearly documents on snake-like underwater robots

3 Untethered underwater robots

Inspired by snakes and eels, underwater snake-like robots are designed for complex aquatic environments where flexibility and adaptability are necessary. The design and actuation of these robots are important in their ability to execute tasks such as INS, maintenance, and EM. In the next section, the designs of snake-like underwater robots are categorised based on differences in design strategy and actuation method. These include thrusted robots and swimming robots. Figure 3 shows the conceptual schematic designs for each category of untethered underwater robots, and Table 1 provides a summary of the design and actuation features of each category belonging to the untethered robot family.

3.1 Thrusted robots

This category includes underwater robots that are propelled by thrusters distributed along the robot structure, while the joints are actuated by different types of actuation methods, hence, the following sub-categories. This category includes two sub-categories: TRRJs and TRSJs.

3.1.1 Thrusted robots with rigid joints

TRRJs employ rigid rotational joints combined with thrusters to propel and move the robotic system.

One of the first thrusted snake-like underwater robots is the Eelume, presented by Liljeback et al. [19], which is a modular, flexible underwater robot designed for INS, maintenance, and repair tasks in subsea environments. It has an articulated structure composed of joint modules with two

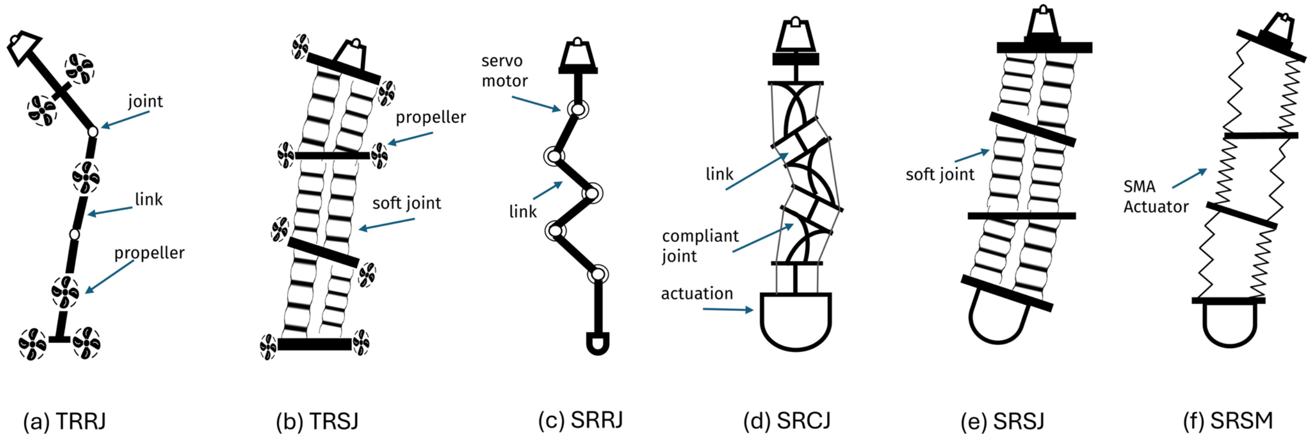

Fig. 3 Schematic representations of the six categories of untethered underwater robots: (a) Thrusted Robots with Rigid Joints, (b) Thrusted Robots with Soft Joints, (c) Swimming Robots with Rigid Joints, (d) Swimming Robots with Compliant Joints, (e) Swimming Robots with Soft Joints, and (f) Swimming Robots with Smart Materials

Table 1 Summary of untethered snake-like underwater robots

Category	Design features	Applications	Actuation	Benefits	Limitations	Ex
TRRJ	Rigid links and joints	Offshore INS	Thrusters	Propulsion efficiencyand stability	Flexibility	[19]
TRSJ	Soft joints	Delicate INS	FA	Adaptability	Maintenance and control	[20]
SRRJ	Rigid joints	EM	Servomotors	Modularity andprecision	Adaptability	[21]
SRCJ	Flexible joints	EM	Tendons	Flexible and adaptive	Actuation complexity	[22]
SRSJ	Fluid-actuated joints	Delicate EM	FA	Adaptability and safety	Accuracy	[23]
SRSM	Soft, adaptable designs	Small-scaleEM	SM (hydrogels)	Lightweight	Low actuation force	[24]
Hybrid	Rigid-flexible modules	Robust INS	Thrusters andservomotors	Speed and adaptability	Mechanical complexity	[25]

Ex = example reference

degrees of freedom (DOF), thruster modules for movement in various directions, and camera modules for inspection. The robot's flexibility allows it to change shape and act as a robotic arm, enabling it to access tight spaces that traditional remotely operated vehicles (ROVs) cannot. Ma et al. [26] proposed a similar swimming robot with rolling joints and rotary thrusters. A dynamic model is used to optimise energy consumption through SQP-based thrust allocation. Another similar design was proposed by Sverdrup et al. [5], a snake-like multi-joint robot designed for subsea inspection and light intervention tasks. The robot consists of serially connected rigid links with actuated joints and distributed thrusters for propulsion. Each joint has one DOF, and the thrusters allow precise control of the robot's position and orientation.

Lyu et al. [27] designed a robot to perform INS and intervention tasks on complex undersea infrastructures like pipelines and subsea production systems. The robot uses propellers to move forward, and its modular architecture makes it adaptable and scalable depending on the task requirements. The basic framework consists of a control module, a function module, a battery, and two joints. Each joint was equipped with two orthogonally mounted actuating gears, allowing the robot to have two DOFs at every joint. Zhu et al. [28] propose an eel-like robot consisting of two power modules, three load compartments, and four active steering joints. The power modules are equipped with multiple thrusters, while the active joints allow multi-directional bending and undulatory motion, providing the flexibility necessary for navigating complex underwater environments. The robot has four propellers: two tangential thrusters mounted on either side of the body and two normal thrusters installed inside the body. This actuation system, combining propeller-based thrust with active joint movements, enhances the robot's manoeuvrability, allowing it to adapt to diverse underwater environments.

3.1.2 Thrusted robots with soft joints

Thrusted robots with soft joints (TRSJs) use soft, fluid-driven joints and thrusters to move and propel the robot. The robot designed by Zhang et al. [20, 29] features a modular design with rigid propulsion modules and soft joint modules connected in series. The rigid modules contain propellers, while the soft joints allow multi-directional bending, enhancing flexibility and reducing collision risks. The soft joints are composed of three hydraulic soft actuators evenly distributed around the joint, allowing the robot to bend in all directions. The rigid modules are 3D-printed and equipped with external and internal propellers.

3.2 Swimming robots

This category includes underwater robots that are propelled by the undulatory motion of the robot body, similar to that of eels, while the joints are actuated by different types of actuation methods, hence the following sub-categories. This category is further divided into sub-categories: SRRJs, SRCJs, SRSJs, and a category that includes swimming robots actuated by smart materials (SRSM) and a hybrid solution.

3.2.1 Swimming robots with rigid joints

SRRJs employ rigid joints and motors in each joint to move the robot's body and propel it through an undulatory swimming motion.

One of the earliest robots developed in this category is the one proposed by McIsaac et al. [30], which is an eel-like underwater robot with five rigid segments connected by watertight servomotors. Each segment is an elliptical cylinder with modular links, ensuring robustness and modularity. The servomotors used provide high torque, allowing the joints to perform undulatory motion. The robot is designed for forward and backwards swimming using travelling wave gaits. Crespi et al. [21] developed a modular underwater robot, with single DOF segments, aligned to allow lateral undulatory locomotion, mimicking the movement of snakes and eels in both water and on land, making it amphibious. The body of each segment is made of polyurethane, ensuring the robot is waterproof. The system is designed to be slightly buoyant, aiding in swimming efficiency. Gallot et al. [31] designed a robot with multi-directional joints composed of 12 identical parallel modules connected in series, resulting in a 3D eel-like design. Each module is based on a spherical joint structure with a base, three legs, and a platform, providing multi-directional bending capabilities. Each module is equivalent to a three-DOF spherical joint, allowing a wide range of motion. Mintchev et al. [32] presented the ANGELS robot, a reconfigurable modular platform composed of nine independent modules that can connect to form a long, eel-like structure. It has a neutrally buoyant design and can operate up to a depth of 3 m. When connected in series, the modules can perform snake-like undulatory swimming. Each module has a rotational joint driven by a brushless motor and lever mechanism, enabling the system to bend and swim with eel-like undulations. Each module has three propellers: two axial propellers for forward/backwards and pitch control and one lateral propeller for yaw control. A compact buoyancy system in each module adjusts navigation depth via a cam-driven mechanism, altering the robot's volume and weight variation.

Tang et al. [33] presented a robot combining two telescopic joints at the front and rear sections and five pitch-yaw joints in the middle snake-like part. The telescopic joints control buoyancy and change the robot's position by shifting the centre of gravity (CG) relative to the centre of buoyancy (CB), enabling the gliding gait. With the pitch-yaw joints, the robot is able to move laterally and vertically like a snake. The telescopic joints can extend or contract through a guide screw mechanism powered by actuators that provide a buoyancy change to ascend or descend in order to vary the relative CG position from CB as a glider. An anguilliform swimming robot is presented by Struebig et al. [34], which is propelled in an effective and eco-friendly way using a travelling wave created by the bio-inspired helical structure. The design has 15 passive elements and is driven by a single brushless DC motor, which generates a smooth travelling wave along the body for propulsion. It is a flexible tail that gives most of the thrust, while pectoral fins allow steering and diving.

Gorma et al. [35] developed a multi-element RoboFish comprising 3D-printed segments connected by magnetic coupling joints, with a flexible eel-like structure. Every segment is made of acrylonitrile styrene acrylate. The tail has a caudal fin mounted on an actuated joint that helps during propulsion and manoeuvrability. It uses rotary actuators in each joint, driven by brushless DC motors. These actuators transmit torque via the magnetic coupling joints, enabling the robot to generate eel-like undulatory movements. The robot has units of adjustable buoyancy in each segment for achieving pitch control or adjustment of the vertical position. Similarly, Huang et al. [36] focuses on optimising the caudal fin for propulsion efficiency. The robot consists of six active segments, connected in series with one rigid caudal fin mounted on the last segment. Every segment consists of a waterproof shell, a servo motor, one rotary joint, and one microcontroller and therefore offers one DOF per segment. The robot is 3D printed, and each shell is made up of three parts and bolted together using O-ring sealing to ensure its waterproof nature. The caudal fin's geometry is systematically varied by changing the leading and trailing edge angles.

A similar design, with a larger head module which contains additional components for navigation and sensing, resulting in a bulkier head compared to the rest of the body, is presented by Bianchi et al. [37]. The robot consists of eight identical rigid modules and a larger head module, providing a total of eight DOF. Each module is connected through rotational joints, allowing the robot to reproduce undulatory movements. The robot is designed to float with half of its body submerged, thanks to a welded polyethylene cylinder that ensures waterproofing. The robot presented by Rajendrakumar et al. [38] consists of four joints and five links, and the head and tail components are 3D printed in ABS, while the links are made of aluminium alloy, providing strength and corrosion resistance. The design includes a caudal fin at the tail to improve swimming efficiency. The electronics are protected by a waterproof box sealed with silicone rings. However, the actuators are designed to function directly in water without additional waterproofing. The robot can perform serpentine and eel-like motions by varying joint angles, achieving undulatory swimming similar to biological snakes. Another robot driven by waterproof servomotors for undulatory motion was developed by Wright et al. [39]. The robot has a modular design and a streamlined body to minimise drag, and each of its modules is connected through magnetic couplings. It makes assembly and disassembly easy, letting the robot change its length and configuration depending on the task. Each module consists of a 3D-printed frame with joints covered with silicone for better flexibility and waterproofing.

The robot presented by Bianchi et al. [40] uses servomotors for undulatory motion. It consists of eight identical modules connected by rotational joints, and a head module, making it able to reproduce the anguilliform swimming gait. The modules are fabricated by 3D printing from ABS, thus being lightweight with a strong structure, and waterproof without any kind of external cover, allowing them to be in direct contact with water and reducing the hydrodynamic drag produced.

3.2.2 Swimming robots with compliant joints

Swimming robots with compliant joints (SRCJs) comprise compliant joints and motors in each joint to move and propel the robot using an undulatory swimming motion. By closely replicating natural snake movements, these robots exhibit smoother, more lifelike swimming by employing continuum and compliant structures.

The robot presented by Gautreau et al. [22] is designed to replicate the undulatory movements of eels. It features a flexible body of compliant joints based on anatomical studies of various snake species, incorporating realistic variations in flexibility along the length of the body. The robot's skeleton consists of 45 compliant joints connected in series. It was manufactured using Nylon (PA12), allowing for a monolithic structure that is both flexible and robust. Although the prototype was not fitted with active motors, it was designed to be actuated using a tendon-driven mechanism. The steel cables are routed through the holes in each vertebra, pulled by servomotors to generate the undulatory motion. The same authors presented a more advanced tendon-driven snake robot design [41]. It is a hybrid tendon-driven robot combining rigid and flexible modules for better fluidity and more realistic motion. It also aims to mimic snake movement, but this design involves using servomotors and actuators distributed along the robot's body to control bending and motion, representing a more developed and autonomous prototype than the one discussed before. Another tendon-driven robot is introduced by Hall et al. [42], which consists of three identical flexible modules made from 3D-printed thermoplastic polyurethane (TPU), creating a compliant, soft body capable of anguilliform swimming. Each module is designed with oval wave springs, providing lateral flexibility and structural integrity, allowing for realistic, smooth, eel-like undulatory movements. This design resembles the multi-module structure seen in previous designs but is fabricated as a continuous, soft unit.

Wang et al. [43] designed a robot able to operate in challenging underwater environments, where it can perform tasks like inspection and monitoring of subsea structures. The design of the robot is inspired by snakes' natural musculoskeletal system and locomotion mode. It has a modular configuration comprising a head module, a tail module, a number of cavity modules, rotating head modules, flexible joint modules, and omnidirectional thruster modules. It contains a flexible joint upon which the two endplates were fixed by springs of variable stiffness. The spring stiffness gradient helps maintain the robot's structural integrity and ensures smoother joint deformations.

3.2.3 Swimming robots with soft joints

Swimming robots with soft-joints (SRSJs) use soft fluid-actuated joints to move and propel the robot in an undulatory swimming motion. Soft robotics also offers a promising approach for creating compliant, flexible robots that can adapt to their environments. This class of robots typically employs soft actuators that mimic the movements of soft-bodied marine organisms, enabling tasks like delicate object manipulation.

Kamamichi et al. [44] introduced a snake-like swimming robot that uses ionic polymer-metal composite (IPMC) actuators to achieve undulatory motion. The design consists of three soft links connected by IPMC films, which bend when low-voltage electric inputs are applied. The body is made of styrene foam, and the segments are linked by flexible IPMC joints, providing smooth and biomimetic movement in water. Since the actuation is performed entirely by IPMC, it does not require waterproofing. Feng et al. [45] presented a robot designed with four fibre-reinforced, bidirectional bending fluidic elastomer (FE) actuators that allow for flexible undulatory anguilliform movement. Each actuator comprises two semicircular chambers made of silicone rubber, reinforced with fibre windings, and an inextensible layer in between, enabling bidirectional bending. The FE actuators are hydraulically actuated and assembled in a serial configuration with tube connections through chambers, ensuring consistent bending stiffness and maintaining a slender body profile resembling the elongated shape of eels.

The robot designed by Chen et al. [23] features a soft-bodied robotic eel composed of fluidic soft actuators. The body of the robot is made up of three actuating segments, each of which can bend bidirectionally through the two fluidic chambers. Symmetrical distribution of the chambers means smooth and continuous undulation. Pneumatic power drives the robot through a series of fluid pipes connected to the actuators. The structures of the actuator have a hollow core inside for fluid to pass through and a pair of fibre-reinforced outside walls that prevent or reduce radial expansion when pressurised to enhance the swimming performance of the robot.

Trinh et al. [46, 47] designed an eel-inspired robot with of three soft segments, each formed using a pair of soft actuators connected by a flexible backbone. The robot is actuated using compressed air pumped into the soft actuators' hollow chambers. It is possible to generate undulation movements that propel the robot by controlling the pneumatic pressure. Cervera et al. [48] designed an underwater soft robot inspired by anguilliform swimming. It comprises a rigid head containing electronics, three bidirectional fluidic elastomer actuator modules, and a soft tail. Each module contains fluidic elastomer actuators (FEAs) designed with an elliptical cross-section for hydrodynamic efficiency. Rigid couplings connect these actuators and feature two pneumatic network (PneuNets) actuators separated by a flexible constraint layer, enabling bidirectional bending similar to real eel movements. The robot utilises hydraulic pumps to move water between chambers in the bidirectional FEAs, generating bending motions. This method allows precise control over bending angles and enables efficient anguilliform swimming.

3.2.4 Other swimming robots

A more particular type of swimming robots are the SRSMs. These materials, often sensitive to external stimuli such as light or heat, enable soft and adaptable movements, allowing more precise navigation and manipulation in delicate operations. Wang et al. [24] presented a robot driven by smart materials (SM). The robot is designed with a soft, monolayer structure that mimics the body of a snake, using hydrogel combined with carbon nanotubes. This structure allows the robot to achieve reversible deformations in response to light, which are converted into heat, causing the hydrogel to shrink on the illuminated side, mimicking natural snake-like movements. These biomimetic movements improve the robots' manoeuvrability, making them effective in environmental monitoring or underwater exploration applications. Building on this direction, Parra Rubio et al. [49] introduced a large-scale underwater robot composed of modular, morphing lattice units that allow complex shape deformation through pressure-driven actuation. Similar to other SRSM systems, their design emphasises high compliance and adaptability but focuses on scalability and distributed control, showing potential for long-range, untethered operations in remote aquatic environments. Ming et al. [50] developed a sea snake-inspired robot actuated by piezoelectric fibre composites. The design exploits third-mode oscillation to mimic natural swimming, demonstrating the potential of smart materials for biomimetic aquatic locomotion.

Smart materials can convert external stimuli (such as light or electricity) into mechanical movements with relatively low energy consumption. However, smart materials often produce less force compared to traditional motors or hydraulic actuators, which can limit the robot's speed, payload, and overall propulsion power.

Another unique underwater robot is the Mamba robot, presented by Kelasidi et al. [25], a hybrid between a swimming robot and a thrusted robot, designed with a series of connected, watertight modules, including 18 joint modules and a tail thruster module. Each module is connected using rotational joints actuated by servomotors. A key feature of this design is integrating a thruster module at the tail end. These thrusters enable the Mamba to overcome water resistance and move fast, relying solely on body undulation. The outer surface of the robot is covered with a watertight skin to reduce drag, making it more efficient for underwater movement. Another hybrid swimming robot was introduced by Jia et al. [51], a modular swarm robot that allows flexible deployment through electromagnetic coupling, with nine detachable snake-inspired units capable of hybrid locomotion, combining undulatory movement and propeller-driven thrust.

3.3 Untethered robots final remarks

Untethered underwater robots offer a wide range of structural and actuation strategies, each with trade-offs between manoeuvrability, thrusting efficiency, and adaptability. This classification highlights how design choices impact performance in underwater navigation, from high-speed thrust-driven systems to soft-actuated robots for delicate environments. While thruster-driven robots have clear advantages in speed and can navigate larger areas more quickly due to the thrust generated by propellers, undulatory robots excel in manoeuvrability but are generally slower, which can be a disadvantage in tasks requiring rapid deployment or covering long distances. Undulatory swimming robots tend to be more energy-efficient during slow or medium-speed locomotion because they emulate the natural energy-saving movements of biological snakes. However, propulsion-driven robots may become more efficient at higher speeds or when moving against currents, where the added power of thrusters is beneficial.

4 Tethered underwater robots

This category includes underwater manipulators, robotic arms that are fixed to a platform. This category includes CRAs, RJRAs, and SRAs. Designed for tasks that require dexterity and precision, such manipulators are often driven by tendons, allowing continuous bending and a high degree of control in constrained underwater spaces while offering high payloads. Figure 4 shows the conceptual schematic designs for each category of tethered underwater robots and Table 2 summarises the design and actuation features of each category belonging to the tethered robot family.

4.1 Compliant robotic arms

CRAs are continuum-structure snake-like robots with compliant joints usually actuated by tendons. Xue et al. [52] presented an underwater snake arm robot composed of ten modular segments, each with a cross-axis universal flexure joint that allows for two rotational DOF per segment. Each segment is connected via a series of tendons running through 40 holes on the joint discs. The robot employs a driving motor-synchronous belt-cable system located at the base to actuate the tendons. This system allows a single motor to control two tendons simultaneously, providing precise movement. Similarly, Sitler et al. [55] introduced a modular, tendon-driven continuum manipulator for underwater ROV operations, designed to be open-source and reconfigurable, aiming to lower development challenges while maintaining precise manoeuvrability through tension-controlled tendons. Janabi-Sharifi et al. [56] and Jia et al. [57] presented hydraulically actuated continuum arms for subsea inspection, offering a fluidic alternative to tendon-driven systems, with a focus on compliant motion, onboard water-powered actuation, and pressure-force analysis to enhance bending flexibility and output efficiency. Another tendon-driven manipulator with compliant joints is proposed by Xue et al. [58]. Although this work focuses more on kinematic analysis and control, it is interesting to analyse the proposed manipulator. It consists of seven sections with 14 DOF. It uses a rack and pinion structure to control two tendons per joint, significantly reducing the number of motors needed for actuation. The manipulator presented by Li et al. [59] is also a tendon-driven manipulator with compliant joints designed to house an optical fibre probe for near-infrared underwater spectral detection. The robot arm is designed using a combination of stainless-steel springs, aluminium alloy discs, and titanium alloy traction wires, ensuring durability and flexibility. The manipulator incorporates a compressed air system that blows water away from the probe's detection path, allowing for accurate infrared spectral analysis by minimising water interference.

The manipulator is driven by eight steering engines that control the winding pulleys, altering the lengths of the traction lines. Ma et al. [60] proposed a tendon-driven dual-arm continuum robot with six DOF per arm. Inside

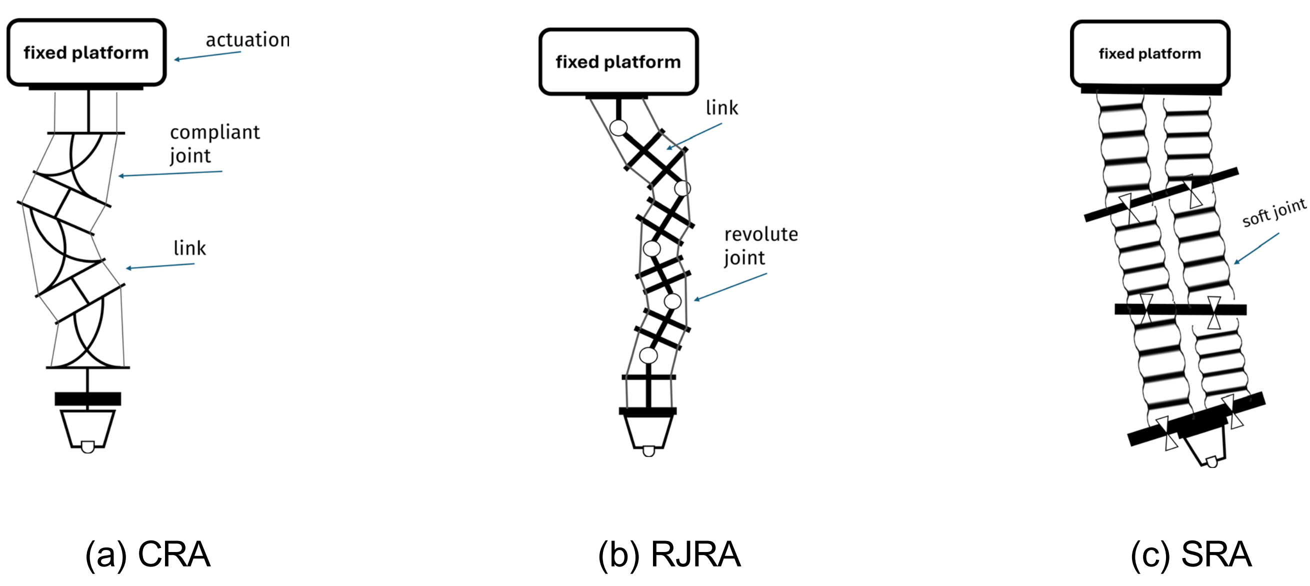

Fig. 4 Schematic representations of the three categories of tethered underwater robots

Table 2 Summary of tethered snake-like underwater robots

Category	Design	Applications	Actuation	Benefits	Limitation	Ex
CRA	Flexible joints	Constrained spaces; INS of subsea pipelines	Tendons	High adaptability and lightweight	Tendon friction and routing complexity	[52]
RJRA	Rigid segments	Robust INS, repair, and precise operations	Tendons or servomotors	Structural robustness and strong actuation	Flexibility and volume	[53]
SRA	Soft structure	Delicate INS and EM	FA or tendons	Safe interaction and lightweight	Force output and control	[54]

Ex. example reference

each section are flexure hinges in a diamond shape, flexible leaf spring-like elements distributed evenly around a central ball joint. This way, stiffness in the manipulator is achieved, and hence, kinematic accuracy is improved. The hinges allow the robot to achieve orthogonal rotational motion and maintain precision during operation. The cables are actuated by motors housed in an actuation box located under the ROV, ensuring the robot's centre of mass remains stable (Fig. 4).

4.2 Rigid joint robotic arms

RJRAs are manipulators comprised of rigid joints usually actuated by tendons. Barbieri et al. [61] designed an underwater robotic arm with a modular design with links, modules, and bridges. It is driven by servomotors, and the arm uses a worm gear mechanism to avoid retrograde motion, providing precise control and reduced component complexity.

Another tendon-driven hyper-redundant manipulator is proposed by Tang et al. [53], consisting of multiple cylindrical joint modules, each connected by a universal joint, allowing the manipulator to bend, rotate, and extend. The manipulator's length and the number of joints can be customised based on the specific underwater tasks. The manipulator features a hollow, tubular structure made from aluminium alloy, which ensures a lightweight and pressure-resistant design, making it suitable for underwater applications. The tubular structure also provides passageways for the tendons driven by motors at the manipulator's base. Sourkounis et al. [62] introduced a similar, rigid-link tendon-driven manipulator for deep-sea sediment sampling. It consists of stacked, bevelled cylindrical links connected by swivel joints, forming a flexible and adaptable structure capable of bending continuously along its length. The hollow centre contains the sampling tube, allowing for a compact design. All parts are made from corrosion-resistant plastic, and the design eliminates air pockets to withstand high underwater pressure.

4.3 Soft robotic arms

SRAs are manipulators which employ soft, fluid-actuated joints. Kang et al. [54] presented a design to replicate the octopus arm's anatomy, featuring a hyper-redundant structure with multiple segments capable of elongating, contracting, and bending at any point along its length. Each segment of the manipulator is constructed as a parallel mechanism, comprising a fixed base, a moving platform, four actuated "limbs," and a central strut. The limbs function like linear hydraulic actuators, providing the manipulator two DOF and one translational DOF. This mechanism precisely controls bending and elongation movements along the manipulator's length. The robot comprises 20 serially connected segments, allowing for extensive reach and adaptability, much like a real octopus arm. Gong et al. [63] proposed a soft robotic arm composed of two segments, each made of modular soft chambers that allow for 3D bending. These chambers are actuated pneumatically, creating fluidic channels to control bending motions. The design includes corrugated textures along the arm's surface to reduce unwanted radial expansion (ballooning) of the chambers. This corrugated structure also incorporates embedded rubber tendons to further control and limit radial expansion while allowing smooth bending. The entire soft robotic arm is enclosed in a cylindrical shape to streamline its movement in the water, further minimising drag. The arm is actuated through a seven-way pneumatic valve system, enabling complex 3D manipulations. An innovative feature of this system is incorporating an angle correction model, which compensates for deformations caused by the weight of the soft material and external loads.

Another robot with a soft structure and fibre-reinforced actuators is presented by Gong et al. [64], which introduces an opposite bending and extension design comprising two bending segments, one elongating segment, and a soft gripper at the end. Each bending segment has three individual chambers with a multi-channel pneumatic system to control the pressure, enabling bidirectional bending and allowing the robot to achieve complex movements in underwater environments. The fibreglass-reinforced elastomer actuators make the manipulator both lightweight and flexible. The underwater manipulator designed by Emet et al. [65] is inspired by the tentacles of squids and cuttlefish, with four soft, tendon-actuated limbs. Two of the limbs function as manipulating arms for tasks such as reaching, gripping, and pulling, while the other two function as tentacles for visual feedback and navigation and contain an underwater camera and lighting system. The limbs are constructed using Ecoflex 00−30 elastomer, a soft, flexible material with a low Young's modulus and high elasticity. The actuators consist of four tendons passing longitudinally through each limb, contained in silicone tubes to protect the soft limbs from wear. Electromechanical systems inside the robot's head actuate the tendons within each limb. The four-tendon configuration simplifies control strategies while allowing sufficient dexterity for underwater manipulation tasks like gripping.

A unique and hybrid underwater manipulator is presented by Zheng et al. [66], inspired by the octopus arm and features a continuum robotic arm structure consisting of multiple flexible segments. Each segment contains both longitudinal and radial actuators, mimicking the anatomy of an octopus arm, allowing for bending, elongation, and contraction in various directions. The arm is entirely built with soft/flexible materials, capturing the octopus's ability to perform dexterous movements. The longitudinal actuators are tendon-driven, with 12 tendons of different lengths attached to three locations along the arm, driven by external servomotors housed outside the water tank. The radial actuators use SMA springs inside the body at 18 locations along the arm. These SMAs replicate the radial muscle contraction found in an octopus, enabling the arm to change its diameter and perform complex movements.

4.4 Tethered robots' final remarks

Tethered underwater manipulators offer various advantages depending on their mechanical structure, ranging from high flexibility in continuum arms to precision and strength in rigid-joint structures. Their design reflects specific operational needs, where the balance between compliance, manoeuvrability, and payload capacity drives the design choices. Continuum robotic arms offer high manoeuvrability but suffer from tendon routing friction and modelling continuum mechanics, while rigid-joint designs provide better payload capacity but are less flexible. Soft robotic arms, although good for delicate object interactions, are limited in load-bearing capacity and control accuracy. Many of these manipulators have modular segments, allowing customisation and easy replacement of damaged parts. However, coordinating the movement of numerous segments and actuators can be challenging, requiring advanced control systems and high computational resources. Some manipulators are designed with particular environments or tasks in mind, such as deep-sea applications, where pressure resistance is emphasised, while others are more specialised for precise detection tasks. The rigid segments of snake-arm manipulators provide greater structural robustness than purely soft-actuated designs or smart material structures, making them more durable in harsher underwater conditions. However, this robustness comes at the cost of increased weight and reduced energy efficiency.

5 Modelling

The modelling of underwater snake-like robots is important for understanding and predicting their behaviour, allowing their design, control, and optimisation for various underwater tasks. This section presents the various modelling methods considered in different categories of underwater snake-like robots, providing an analysis of the techniques used to describe their kinematics, dynamics, and actuation mechanisms. Table 3 summarises the different kinematic and dynamic modelling methods for each category of robots, providing also an example reference in which the specific method is detailed.

Table 3 Modelling methods identified for each underwater snake-like robot category

	TRRJ	SRRJ	SRCJ	SRSJ	SRSM	RJRA	SRA
Kinematic modelling methods							
D-H convention and Jacobian matrix	[67]	[68]				[61]	
Sine wave function	[43]	[37]	[42]	[45]	[24]		
Beam theory			[69]	[69]			
Piecewise constant curvature							[65]
Dynamic and hydrodynamic modeling methods							
Newton–Euler equations		[31]				[53]	[54]
Euler–Lagrange and hydrodynamic effects	[5]						
Morison equation		[70]	[69]	[69]			
Continuum mechanics				[47]			
Electro-thermo-mechanical modelling					[24]		

5.1 Kinematic modelling

The Denavit-Hartenberg (D-H) convention was often used for robots with multi-joint and rigid structures, like TRRJ, SRRJ, and RJRA, for the calculation of joint angles and positions [27, 67]. This method represents the robot's kinematics through transformation matrices, mapping out the complete configuration of the robot in space. The piecewise constant curvature (PCC) model was used for more complex robots, representing the body as a series of constant curvature arcs [32, 71]. Gautreau et al. [72] improved the PCC approach by including adaptive curvature parameters that change with the robot's speed and swimming mode, allowing the model to represent different gaits more effectively. This hybrid approach allows a more accurate representation of the transition between straight and bending motions. Regarding SRAs, the PCC model and the Denavit-Hartenberg (D-H) convention were the most commonly used kinematic modelling methods. The PCC approach provided an accurate representation of bending behaviours [65], while the D-H convention was used to map joint transformations [52].

For modelling undulatory motion, sine wave functions were used to represent the undulatory swimming patterns, imitating the serpentine or eel-like body waves [22]. In tendon-driven manipulators, the Jacobian matrix was frequently used to relate tendon lengths to joint movements, mapping actuation inputs to end-effector positions and orientations [60, 62].

5.2 Dynamic and hydrodynamic modelling

The Newton-Euler and Euler-Lagrange equations are used to model the forces acting on each segment, especially in rigid-joint robots like TRRJ, SRRJ, and RJRA, often with internal actuation and external hydrodynamic forces [53, 54, 73]. The Newton-Euler equations describe the motion of each link by considering both linear and angular components of forces and torques. The dynamic behaviour of TRRJ can be represented using the Euler-Lagrange equations, which consider the kinetic and potential energies, as well as external forces such as hydrodynamic drag [5]. Sverdrup-Thygeson et al. [74] presented a unique dynamic modelling method for underwater snake robots using multi-body dynamics combined with hydrodynamic coefficients derived from experimental testing. This model represents added mass effects, where the inertia of the water surrounding the robot contributes to the overall dynamics and hydrodynamic drag forces that vary with velocity and curvature.

Hydrodynamic modelling is critical in propulsion-driven robots, as water resistance plays a significant role in their performance. The Morison equation and slender body theory are commonly used to calculate drag, lift, and added mass effects. Kelasidi et al. [70] and Chen et al. [75] offered hydrodynamic models by applying computational fluid dynamics (CFD) simulations to validate the force coefficients. T1he authors emphasised the importance of accurately modelling vortex-shedding effects, having a streamlined geometry for reducing drag, and their impact on the robot's propulsion efficiency. Meng et al. [76] also used simulation to analyse the dynamics of a snake-like robot, replicating how a biological snake moves underwater to generate data that can guide the design, material selection, and actuation strategies for real-world applications. Kelasidi et al. [77] also presented a closed-form dynamic model for planar underwater snake-like robots, focusing on the hydrodynamic effects of drag, added mass, and fluid moments. The model uses Morison's equations for the fluid forces acting on each link, accounting for linear and nonlinear drag in the tangential and normal directions. The model also includes the added mass effect and introduces fluid torques to improve accuracy in simulating the robot's power consumption and movement efficiency. The Morison formulation is also used for modelling and simulation in a 3D serial eel-like robot using recursive Newton–Euler equations, proposed by Khalil et al. [67]. The dynamic model considers both direct and inverse dynamics, calculating the joint torques and head accelerations based on joint positions and velocities. Jiang et al. [78] developed a novel dynamic model that uses the sliding-layer laminate approach, which allows real-time stiffness adjustments to the robot's body segments. This method takes into account how stiffness variation affects thrust generation and shows the influence of material properties on swimming efficiency for a robot. Boyer et al. [69] presented a dynamic model for a swimming eel-like robot using geometrically exact beam theory combined with the Newton-Euler approach. The fluid-structure interaction is modelled using an adapted Morison equation, taking into account drag, lift, and added mass effects. Kelasidi et al. [70] included vortex shedding effects in their hydrodynamic modelling, providing an understanding of how these effects influence undulatory motion. McIsaac et al. [79] presented a geometric approach for modelling the dynamics of an eel-like swimming robot using a combination of viscous drag models and reduced dynamics. The method separates shape variables from the position and orientation of the robot, allowing motion planning based on shape space trajectories.

A different swimming method was proposed by Takayama et al. [80], which presented a dynamic and kinematic model for an amphibious snake-like robot using helical propulsion dynamics. The model focuses on a helical distortion mechanism, where the robot's body revolves around its axis to generate thrust.

Finally, another different model was presented by Wiens et al. [81] to represent the undulatory swimming in a hyper-redundant mechanism. The model uses a resistive-reactive approach to simulate swimming at intermediate Reynolds numbers. The fluid forces acting on each segment are modelled using a combination of drag and added mass effects, integrated into a computational framework.

5.3 Electromechanical and thermomechanical modelling

In SRSM, electromechanical and thermomechanical modelling is often needed to model the behaviour of smart material actuation. In light-responsive robots, thermomechanical modelling represented the hydrogel deformation induced by light using heat transfer equations and phase transition properties [24].

5.4 Continuum mechanics

In SRSJ, continuum mechanics is often used to model the complex deformations that occur under actuation. This approach treats the robot as a continuum, allowing for a precise representation of how each material point deforms under applied forces or pressures. The pseudo-rigid-body model was also used to approximate the soft segments as rigid links with rotational springs, simplifying the analysis while maintaining reasonable accuracy [46, 47]. This approach is particularly useful for real-time control applications.

5.5 Final remarks on modelling methods

Modelling approaches vary significantly across robot categories, with rigid systems often using classical kinematics and dynamics, while compliant and soft structures require more advanced continuum or simulation-based models. The analysis highlights the complexity of modelling the underwater fluid-structure interactions, especially in soft and hybrid systems.

6 Discussion

This review presented the innovative design and modelling solutions found in the literature across various types of robotic systems, which were classified into two families: untethered underwater robots, which represent the majority with 55.3% of the total, and tethered underwater robots, with 44.7%. Characterised by multiple joints coupled with thrusters, untethered underwater robots can be fast and able to travel for long distances, which is ideal for rapid inspections or investigations across large underwater areas. This is especially true for TRRJ. However, their rigidity and bulkiness compared to the other robots of this survey compromise their confined space accessibility or adaptability in complex environments. Propeller-driven designs might cause drag that would reduce the general swimming efficiency, especially for a robot with rigid joints. Also propulsion-driven robots generally have more mechanical parts, like several thrusters and propeller shafts. Therefore, they have a larger possibility of mechanical failure. Combining swimming and propeller-driven motion, as seen in some designs, provides a versatile approach, allowing the robots to adapt their movement based on task requirements. Conversely, swimming robots must depend on a design capable of realising undulatory motions typical of natural organisms like eels or snakes. While flexible, their propulsion power and speed are sacrificed for this capability, meaning that such robots are generally slower compared to propulsion-driven ones. Furthermore, repeated flexing and joint activity, especially in soft or hybrid designs, will induce wear over time. This may result in periodic maintenance needs and may even reduce the robot's operational life expectancy.

Swimming robots with soft joints are adaptive and compliant with either fluidic elastomer actuators or pneumatic nets; hence, they safely interact with fragile underwater structures. However, controlling their nonlinear deformations remains difficult, and often, their force output is insufficiently large for heavy-duty applications. They are also less suited to rapid deployment or travel over a long distance, as they generally lack the speed and thrust supplied by propeller-based systems. Swimming robots actuated with smart materials like hydrogels offer a high degree of flexibility and are often lightweight while changing shape and movements in real-time. This makes them suitable for operation in complex and narrow underwater conditions and for applications requiring delicate interactions that may be difficult for rigid-link robots. However, their low force output confines their applications to tasks that do not require much propulsion power or heavy lifting. Besides, the performance of the smart materials may change with some environmental parameters such as temperature, salinity, and light intensity.

Tethered snake-arm underwater robots allow precise movements, making them ideal for tasks such as inspection, maintenance, or exploration in intricate underwater structures like pipelines, coral reefs, or shipwrecks. These manipulators behave well when performing precision-requiring tasks. The majority of snake-arm underwater robots are tendon-actuated. Tendon-driven robots reduce the coupling effect with underwater vehicles since having the actuators at the base does not affect the vehicle's stability and control by creating reactive forces and moments, causing challenges in maintaining position and orientation. However, unlike propulsion-driven robots, snake-arm manipulators lack the propulsion power for high speeds and/or long-distance travel. In contrast, they perform best in stationary tasks or when precise manipulation is required.

This survey also analysed the modelling techniques employed by the presented works and additional works focusing only on modelling, with the majority of the research papers focusing on dynamic and hydrodynamic modelling, with the 52% of the total works, 26% on kinematic modelling, and another 18% on continuum mechanics, and only one work on more specific analysis on electro and thermomechanical modelling.

Regarding kinematic modelling, the Denavit-Hartenberg (D-H) convention is frequently used for rigid structures, providing a systematic way to represent joint movements. Piecewise constant curvature models and continuum mechanics methods are more applicable for flexible designs; these can capture complex bending and undulatory movements.

Dynamic modelling often uses Euler-Lagrange and Newton-Euler equations by integrating hydrodynamic forces along with drag and lift. Advanced methods, including the Morison equation and computational fluid dynamics simulations, provide further insight into the interaction between fluids and structures, especially in vortex shedding and its effect on propulsion efficiency. Additionally, robots actuated by smart materials benefit from electromechanical and thermomechanical models, which represent material responses to environmental changes such as temperature and light. However, accurate modelling of fluid-structure interaction remains challenging, especially for robots with complex, flexible bodies.

Further work is needed to enhance the durability and reliability of soft materials and tendon-driven systems in underwater environments. Exploring new materials with greater resistance to wear and harsh conditions, and advancements in waterproofing dynamic components, could significantly improve robot longevity. Lightweight, compact actuation units remain a critical area for improvement, as current designs often impose constraints on the overall system size and payload. From a functional perspective, modular and reconfigurable designs could offer greater versatility, allowing robots to adapt to a broader range of tasks and environmental conditions. Integration of adaptive stiffness mechanisms, inspired by biological systems, could improve locomotion and manipulation capabilities, particularly for navigating complex geometries. Other issues were identified within tendon-driven snake-arm manipulators. Actuator size in said systems needs optimisation since it usually requires a big and bulky actuation unit. This way, an ROV can be integrated with the actuation unit, obtaining the hybrid of a thruster-actuated unit and a snake-arm manipulator, which could be propelled to reach remote environments, remaining in place while the robot arm performs the related inspection or maintenance tasks. Furthermore, waterproofing of the interface between tendon-driven manipulators and the actuation unit is challenging since the constant linear movement of the tendons going in and out of the actuation box makes it difficult. Modelling fluid-structure interactions, especially for flexible and hybrid designs, is still a challenge. More robust integration of hydrodynamics with structural and kinematic models is necessary to accurately predict robot performance under varying underwater conditions. Additionally, many existing designs prioritise either propulsion efficiency or dexterity, but hybrid systems combining undulatory swimming with thruster-based propulsion could achieve a better balance between speed, energy efficiency, and manoeuvrability. Continuous development keeps improving the capabilities of these robots for several underwater applications.

7 Conclusion

This paper surveyed underwater snake-like robots concerning their designs, actuation, and modelling techniques. The key points addressed in this review article are the following:

- Snake-like underwater robots can be grouped into tethered and untethered systems, each suited to specific tasks.
- Design trade-offs exist between flexibility, manoeuvrability, speed, and actuation force.
- Modelling approaches vary widely and are often not unified, especially for soft and compliant robots.

In the untethered class, which refers to mobile robots not fixed to a platform, two categories were identified: thrusted robots and swimming robots, which include thrusted robots with rigid joints, thrusted robots with soft joints, swimming robots with rigid joints, swimming robots with compliant joints, swimming robots with soft joints, swimming robots actuated by smart materials, and hybrid systems. Likewise, the tethered robots class, which refers to underwater manipulators, was divided into three categories: compliant joint robotic arms, rigid joint robotic arms, and soft robotic arms. This review aims to inform future underwater robot design, highlighting the importance of integrated, efficient, and adaptable solutions. Despite various approaches, many systems still depend on bulky or inefficient actuators, and integrated modelling approaches remain a challenge. In conclusion, while progress has been substantial, future developments should prioritise integrated modelling frameworks, compact and efficient actuators, and robust designs specific for complex underwater operations.

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Declarations

Conflict of interest The authors declare no competing interests.

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