IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 8 September 2022, accepted 6 October 2022, date of publication 17 October 2022, date of current version 28 October 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3215162

SURVEY

A Survey on Snake Robot Locomotion

G. SEEJA[1], AROCKIA SELVAKUMAR AROCKIA DOSS[2], (Senior Member, IEEE), AND V. BERLIN HENCY[1]

[1]School of Electronics Engineering, Vellore Institute of Technology, Chennai, Tamil Nadu 600127, India
[2]School of Mechanical Engineering, Vellore Institute of Technology, Chennai, Tamil Nadu 600127, India

Corresponding author: V. Berlin Hency (berlinhency.victor@vit.ac.in)

This work was supported in part by the Department of Science and Technology-Tamil Nadu State Council for Science and Technology (DST-TNSCST) under Award TNSCST/STP/PRG/17/2019-2020; and in part by the Vellore Institute of Technology, Chennai, Tamil Nadu, India, to develop an autonomous snake robot for earthquake rescue applications.

ABSTRACT Snake robots have been a topic of discussion among researchers for decades. They are potentially strong enough to bring substantial contributions to the fields which are unsafe/ narrow/ dirty/ hard reachable to human operators, such as inspections, rescue missions, firefighting, etc. Though the inventions of the wheel and legged mechanisms are amazing, they often fail when coming to these scenarios. Terrain adaptability is the vital essence of locomotion over constrained surfaces in biological snakes. But how this natural adaptability is accomplished in snake-like robots? Therefore, this paper focuses a study on factors behind the recreation of a physical snake, like the kinematics and dynamics modelling, mechanical design, and locomotion control approaches from existing literature. With their feature comparison, the simulators available for verifying the mathematical model and the feasibility of the mechanical design are also made for researchers new to the field.

INDEX TERMS Snake-robots, locomotion control, mathematical modelling, kinematics, dynamics, mechanical design, perception, simulators.

I. INTRODUCTION

The world suffers many natural and man-caused catastrophic disasters like massive earthquakes, fire breakouts, floods, aeroplane crashes, tsunamis, building collapses, etc. Disaster management is vital in minimizing/avoiding the losses these calamities create. Table 1 indicates the mortality statistics for building collapse due to earthquakes and other reasons around the globe over the last ten years. According to [1], there are four disaster management phases: prevention, preparedness, response, and recovery. The complete accomplishment of the preparedness phase of a disaster management cycle includes taking preventive measures to avoid the disaster and being prepared to face it. Many projects and research works have been carried out to understand the benefits and problems of mobile robots in Urban Search and Rescue (USAR). This work focuses on the second preventative measure, i.e., being prepared with emergency assistance for search and rescue. SAR operations in the urban disaster scenario are complex and of high risk due to the uncertainties in the environmental conditions, which restrict the rescue team from accessing the spot, making the mission delayed. According to USAR, the probability of saving a victim is high only within the first 48 hours of the rescue operation, and the prospect tends to be almost zero.

The rescue teams currently have no higher-order processing to analyze the scene and estimate the location of the victims trapped and an efficient robot design that can traverse the collapsed environment with suitable mechanical design. There are developments in rescue assisting legged and wheeled robots. Though they are amazing inventions, they fail to perform as required in uncertain environments. The snake locomotion inspired by biology shows the significance of exploring uncertain environments with versatile motion abilities. This is the inspiration behind studying deeper snake-like robots (snake robots or snakebot). Of course, snake robot application is not restricted to USAR operations. They also perform magnificently in other areas like firefighting, pipeline inspections in gas and power plants, and surgical applications.

The associate editor coordinating the review of this manuscript and approving it for publication was Amjad Gawanmeh.

TABLE 1. Recent statistics of building collapse due to earthquakes and other reasons around the globe. [Courtesy: NGDC statistics, times of India, BBC].

Date	Location	Total damages/notes	Mortality Scale
2022	Changsha building collapse, China	Building destroyed	53 dead, 10 injured
2022	Abadan Metropol building collapse, Iran	Building destroyed	41
2021	Champlain Towers South, US	Building destroyed	98 dead, 11 injured
2020	Juxian Restaurant, China	Building destroyed	29 dead, 28 injured
2020	Kep building collapse, Cambodia	Building destroyed	36 dead, 26 injured
2020	Bhiwandi, Maharashtra- India	Building damage	41
2019	Dharwad building collapse, India	Building destroyed	19 dead, 82 injured
2019	Mumbai (age-related instability)	Building destroyed	10
2019	Lagos school collapse. Nigeria	3-story school	20 dead, over 60 injured
2018	Ponte Morandi collapse, Italy	Bridge collapsed	43 dead, 16 injured
2018	Indonesia Stock Exchange floor collapse	Suspended walkway collapsed	72 injured
2016	Fengcheng power station collapse, China	Cooling tower under construction	74 dead, 2 injured
2016	Afghanistan, India, Pakistan	NA	399 dead, 2536 injured
2015	Dharahara Earthquake-Nepal, India	$10 billion	218
2015	Nepal, India	$10 billion	8,964
2014	Chennai	11-story building	61 workers
2013	Mumbai, India	5 story building destroyed	61

The concept of snake robots started in the 1940s. Snake robots are basically hyper-redundant snake-like biomorphic mechanisms that mimic the morphology of natural snakes. A qualitative study on snake locomotion was first done by J. Gray in 1946 [2]. He described the types of movements snakes possess. Then, Professor Shigeo Hirose developed the world's first snake robot (Figure. 1) at the Tokyo Institute of Technology, Japan, in 1972 [3]. Since that time, numerous

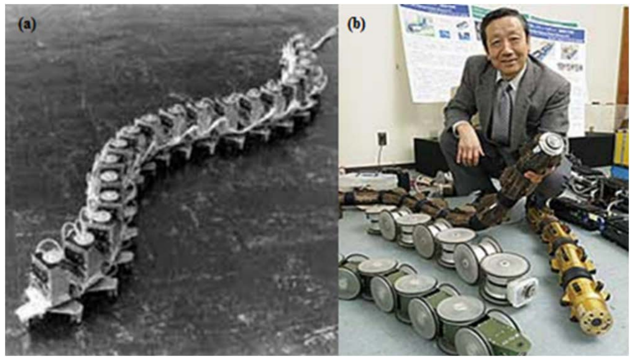


FIGURE 1. (a) World's first snake robot developed by Professor Shigeo Hirose [1] (b) Professor Shigeo Hirose with a series of his developed snakebots.

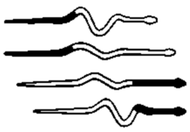
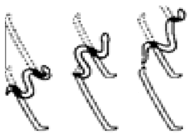
snake-inspired robot designs have been conceived and prototyped. Although many of the designs mimic the movement of snakes, they may have different physical configurations and purposes. For instance, some robots are redundant, while others have no redundancy. Some robots use powered wheels or treads, while others use passive wheels or no wheels. Some designs are even amphibious, travelling effortlessly between ground and water environments. The slender, elongated body with a thin cross-section is perfect for narrow space/ pipe exploration. The more the ground contact points (traction properties), the more will be the distribution of mass minimizing the center of mass [4], [5]. This makes them stable compared to other limped, wheeled, or multipedal robots [4], [6]. The terrain adaptability of snake robots is a highly noticeable feature that makes them move mostly on surfaces. They use the ground roughness or obstacles to gain enough friction to move forward without slipping [7]. This terrain adaptability and stability make them robust to mechanical failure making them suitable for exploring uncertain environments.

Overall, this paper is divided into five sections. Section one details the physiology of biological snakes, their locomotion patterns, and how they accomplish these motion patterns. Further, various mathematical modelling approaches, factors, and constraints are explained in detail in section 2. For any robot locomotion, environmental sensing plays a vital role in control autonomy and hence a study on perception is done in section 3. Then comes the reality, the mechanical structure of the robot! The two key design aspects of locomotion in the 2D plane and 3D space are studied based on snake robots in section 4. Before going with the prototype, it is always advisable to understand the correctness and feasibility of the design with simulation. Hence, the last section of this study introduces the existing dynamic simulator platforms with their features which help readers choose simulators for their application.

II. BIOLOGICAL SNAKES: ANATOMY, GAITS, AND PRINCIPLES OF LOCOMOTION

Snakes are limbless reptiles consisting of a long backbone made with many vertebrae. This backbone

TABLE 2. Locomotion patterns/gaits exhibited by the biological snake and their employing principles.

Gaits	Motion pattern	Principle	Reference
Lateral undulation		• Obtains movement by utilizing ground roughness and parallelly propagating sinusoidal waves from head to tail (serpanoid curve). • The entire body passes through the same part of the ground leaving a sinusoidal pattern on the ground (max speed: 11 km/hr).	[14],[15],[16],[17], [18],[19],[20], [21],22],[23], [24],[25],[26], [27]
Concertina		• Gain forward propulsion by a combination of stretching and folding of the body. The folded portion is kept fixed, and the rest is pulled or pushed. The two parts switch this role to achieve continuous locomotion. • Used while moving through narrow pipes or passages. • Snakes cannot move when the passage is too narrow, concerning the snake's curving capacity.	[28].[38]
Side winding		• While moving inclined, these snakes make parallel marks on the ground by lifting and curving its body. • Used mainly by dessert snakes (max speed: 3 km/hr)	[29], [25], [31]
Rectilinear progression		• The motion is carried out by propagating an expansion and contraction wave through the ventral skin toward the tail. • The body anchors the ground at the points where the ventral skin contracts.	[32],[33],[34],[35], [36],[37]

(100-400 vertebras), a skull, and ribs form the skeleton of a snake. Each vertebra allows slight movements in horizontal and vertical directions but no twisting and hence works as compliant universal joints. The snake curves its body with small angular motions (10-20 degrees in the H-plane and 2-3 degrees in the V-plane) of each vertebra [7]. Their long, slender body covered with scales protects the skin from wear and tear and helps gain enough propulsive force for forwarding motion [8]. A study by mathematician David Hu [9] says that snake scales are like wheels of ice skates, which slide much faster and smoother in one direction than in the opposite. However, it will be rough if rubbed in the opposite direction due to the overlapping arrangement.

According to Hu, scale roughness is the secret behind the forward propulsion in snakes [11]. To test this statement by avoiding scale contact from the ground, the team designed a unique jacket to cover the snake scale. They discovered that the friction was high and equal in all directions making the snake immovable. Hence, the directionality of the scale is the key. Though it was not fully addressed in their mathematical models how fast the snake slithers, they observed that the entire snake body was not pressed-flat against the ground. But in fact, they lift part of their bodies above the ground and found that the friction and weight distribution help the snake slither. To be scientific, snakes exhibiting isotropic friction are uncontrollable [8], whereas anisotropic friction promotes movement [12], [13]. Therefore, for snake robot control designs, anisotropic friction is always considered where the frictional coefficient in the normal direction is too large than that in the tangential direction. With these basic biological features, snakes perform different locomotion patterns called gaits or serpentine movements, such as lateral undulation, concertina locomotion, rectilinear progression, sidewinding, etc., to adapt to different terrains and situations. The ways by which each gait is performed by the biological snake in real life (Prof. Gray's classification of snake locomotion) and their principles of motion are shown and listed in Figure. 2 and Table 2, respectively. Many researchers also considered similar locomotions in other creatures like inch worms/caterpillars (vertical wave locomotion), eel(amphibious snake-like), and elephant trunk/ octopus arm movement (backbone curvature) for the model study. But this review focuses purely on explorations of snake locomotions on land (not the inchworm, caterpillar, or other amphibious movements).

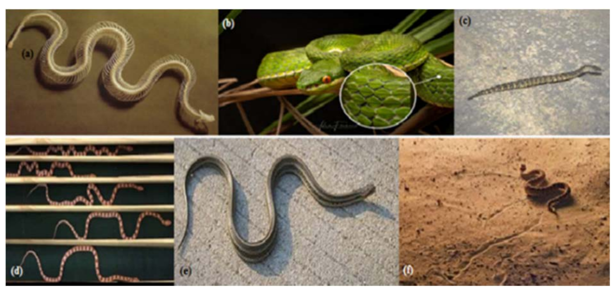


FIGURE 2. (a) Skeleton, (b) Scales and major locomotion gaits exhibited by biological snakes [(c) rectilinear motion, (d) concertina, (e) Lateral undulation and (f) side winding] [10].

III. GENERAL MATHEMATICAL APPROACHES

This section seeks the mathematics behind snake locomotion. In mapping the snake body anatomy to an artificial snake, most studies made the physical structure of the snake using a combination of links connected with joints. Design parameters (like link length, joint angles, offsets, etc.) play a key role in any modelling approach. Many researchers have approached this with kinematic and dynamic modellings, whereas most authors have concentrated on either kinematics or dynamics alone. Similarly, many researchers have approached the control of terrain adaptiveness as the terrain contour adaption, while others dealt with it as obstacle avoidance. This section briefs the available methods and considerations in modelling and focuses more on the recent updates in snake modelling, which came after the existing literature presented in [37]. The section is majorly divided into two; the first is the studies on the kinematics dealing with the snake robots' locomotion, and the second is the dynamics involved in the snake robot locomotion in the 2D plane and 3D environments. The structure of the mathematical modelling used in this section is shown in the below block diagram (Figure: 3).

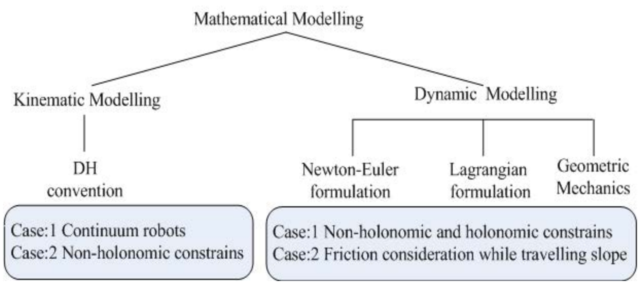


FIGURE 3. Illustration of the structure of snake robot mathematical modelling handled in this section.

A. KINEMATICS

Kinematics describes the geometrical aspect of motion. It considers only a link's motion or relative motion, not the force or torque causing it. Different modelling techniques have been employed, ranging from classical methods such as the Denavit–Hartenberg (DH) convention to specialized methods for hyper-redundant structures (structures with a high number of DOF). In kinematics, the DH convention is an engrained technique for describing the position and orientation of the links of a robot manipulator concerning a (usually fixed) base frame. Many solutions have been presented considering some of the tail segments as the snake robot's base for the smooth application of the DH convention (refer to textbook [38] for DH convention by Murray). The base of a snake robot is considered not fixed in works by [31] and [39]. Consecutive front links were considered like a manipulator, where the first motionless link was the base frame, whereas the links in a motion described the inertial frame [39]. Hence, only four or five links took part in movement giving the position and orientation with respect to the base frame (motionless link); the need for traversing the entire robot length to obtain the final head position and orientation was eliminated. By employing a virtual orientation and position (VSOP) structure in the DH convention, Pal Liljeback found the position and orientation of each joint in an inertial coordinate system [25]. A control system is developed based on forward kinematics using DH convention in [40] for the motion and trajectory tracking of flexible surgical robots. While deploying passive wheels, an explicit assumption is considered, which restricts the sideways slipping, and the constraint is called the non-holonomic constraint. Snakes achieve locomotion by changing their body shape, relating the change in internal position to the net change in the position of the entire body. This can be expressed in a local form, 'A', of a connection as below.

$$g^{-1}\dot{g} = -A(r)\dot{r} \tag{1}$$

where the parameters are, r: shape variable, $g \in SE(2)$: gives the overall position and orientation of the snakebot [16]. The connection / local form is the controlling factor that maps the shape change to the displacement (locomotion) of the robot [41]. ACM III uses this modelling technique to define motion for the first three segments. The rest of the segments follow the path generated by these segments to achieve net movement. Passive wheels are mostly considered free-motion enablers without considering friction. Though the wheels significantly reduce the longitudinal friction (usually considered for kinematic modelling), making the snake capable of achieving lateral undulation, a few of the literature deals with passive castor wheels. The kinematic non-holonomic constraint (Refer to (2)) realized by the addition of passive wheels can be expressed as:

$$\dot{x}_i \sin(\phi_i) - \dot{y}_i \cos(\phi_i) = 0 \tag{2}$$

where $(\dot{x}_i, y_i)$: velocity of CM (centre of mass), ϕ_i: joint angle of the attached wheel. No-slip wheel condition is assumed to exhibit ideal frictional properties. In contrast, another study with holonomic constraints found that the joint torque is difficult to control when slip-condition is considered [20]. A mathematical model of a non-holonomic locomotion system using fibre bundle theory for undulatory movement is introduced in [42]. From holonomic to non-holonomic robotic systems, the concept of the dynamically consistent Jacobian inverse was extended by [43]. This new inverse is based on a conceptual similarity between holonomic and non-holonomic systems and is built around a Riemannian metric in the configuration space. This dynamically consistent Jacobian inverse can address the snake robot's rolling ball motion planning problem. Kinematic models for creeping, rolling and serpentine gaits for the unstructured environment were established by [44].

Apart from the DH convention, head lifting in a snake can be categorized under continuum motion (resembling the elephant trunk and octopus arms movements). Continuum robots have a high degree of freedom resulting in hyper redundancy of the structure. This motion is defined with a curve describing the spine's shape without utilizing the DH convention. An approach called Frenet–Serret apparatus [45] is employed in the classical handling of the geometry of curves. But it exhibited certain limitations: *1) the Frenet–Serret frames* *assigned along the curve are not defined for straight-line segments. 2) the vector function describing the spatial curve requires a numerical solution of a cumbersome differential equation.* Backbone curves eliminate these limitations. The backbone curve is defined as "a piecewise continuous curve that captures the important macroscopic geometric features of a hyper-redundant robot", and it typically runs through the spine of the snake robot. To specify the actual snake configuration, a set of orthogonal reference frames is set along the spine at each joint. Readers can avail more information on the design, actuation methods, and challenges in continuum robots from [46].

B. DYNAMICS

The dynamics deal with studying forces and the moments causing them. It utilizes various modelling techniques such as the Newton–Euler formulation, the Lagrangian formulation, and geometric mechanics.

The first two methods deal with the 2D rigid body dynamics model. The final answers for rigid body dynamics are the same, using the Lagrangian and Newton–Euler formulas. In Lagrangian, the snake robot is treated using a Lagrangian function that contains system energy [39], [47], [71]. The Newton–Euler formula is the most appropriate method to obtain the torque required for the desired motion. At the same time, the Lagrangian formula describes the time evolution of the system's generalized coordinates [48]. Newton–Euler formula was used in conjunction with the set-valued force law for deriving a non-smooth 2D model [7], [49], [50].

Moreover, no contact force consideration is required when lifting the snake head. But it is not the case when the snake creeps along a surface. This is where the significance of snake robots with and without wheels comes into the picture. All dynamic models presented for wheelless bots can also be applied for wheeled bots. Dynamic modelling becomes vital because the friction between the lower body and the ground is huge. There are majorly two cases for friction consideration as follows:

- *Non-holonomic and holonomic constraints*
- *Friction considerations while traversing slopes and climbing*

Holonomic constraints develop when the joint torque is difficult to control under slip consideration. The normal contact force (a spring-damper-compliant model) other than a frictional force for 3D models can be studied in detail in [25]. The 2D anisotropic friction [23] can be described using Equation 3:

$$\begin{aligned} f_i &= H_i v_i \\ H_i &= c_{i,n}^{(2)}\left[\left(1-\frac{c_{i,t}^{(2)}}{c_{i,n}^{(2)}}\right)e_t^{Bi}(e_t^{Bi})^T - I_{2\times 2}\right] \\ I_{2\times 2} &\in R^{2\times 2} \end{aligned} \tag{3}$$

And, f_i = *[fxi fyi] T* $\in R^2$ is the friction forces that act on the CG of link *i*. H_i is the anisotropic friction coefficients' matrix and finally $I_{2\times 2} \in R^{2\times 2}$ is a unit matrix. Denote the unit vectors tangential $e_t^{Bi} \in R^2$ the link i in the horizontal xy-plane. $c_{i,n}^{(2)}$ and $c_{i,t}^{(2)}$ are the coefficients of friction normal and tangential to link *i*, respectively. The total viscous friction torque (from Equation 4) due to rotational velocity around the centre of mass of link i is found to be:

$$\tau_i = -c_{i,n}^{(3)} J_i \dot{\theta}_i \in R \tag{4}$$

Equation 5 represents the friction force based on Coulomb's law for translational motion is found for $\theta i = 0$ by [12] is as:

$$\begin{aligned} f_i = -m_i g \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} c_{i,t}^{(3)} & 0 \\ 0 & c_{i,n}^{(3)} \end{bmatrix} \\ \times \text{sign}\left(\begin{bmatrix} (e_t^{Bi})^T v_i \\ (e_n^{Bi})^T v_i \end{bmatrix}\right) \end{aligned} \tag{5}$$

A musculoskeletal system by a simple mass–spring–damper model is designed to study its dynamics in a two-dimensional plane where the ground frictional force acting on the backbone particles is modeled by the Coulomb friction [10]. Further, sidewinding has been implemented with an isotropic friction model (C i,t = C i,n) by [2] and as a purely kinematic case by [29]. In another study [31], travelling wave locomotion utilizing friction as the dominant propulsive force for a one-dimensional n-linked crawler is discussed.

A fusion of Coulomb friction forces with the ground's normal contact forces for non-smooth dynamics is described in [52]. The property $C_{\ i,t} < C_{i,n}$ has been implemented to realize the anisotropic friction property for lateral undulation in most simulated gaits using friction models. Designing a snake robot with $C_{i,t} < C_{i,n}$ on a general surface may be difficult. Special gaits for planar motion based on an isotropic friction model are detailed by [53].

Similarly, a snake robot WHEEKO [54] was developed (with passive wheels) to generate anisotropic friction property. The passive wheels here have the same effect as the edges of ice-skate plates. Pushing the skate plate sideways moves forward because the sharp edge gives high sideways and minimal forward friction. With this anisotropic friction property, it is found that lateral undulation produces forward motion. Undulations always propagate backward along the snake's body. Hence, from mathematical analysis and biology, it is found that lateral undulation is required to move the robot forward, ensuring that it has the required friction properties. This can be achieved by making each link follow the reference signal θi, as given in Equation:6.

$$\theta\text{i, ref} = \alpha\text{g (i)} \sin\{\omega\text{t} + (\text{i} - 1)\,\delta\} + \varphi_0 \tag{6}$$

Lateral oscillations and body compliance help snake robots achieve stable traversal [55]. Where α is the amplitude of oscillation, ω is the frequency, δ is the phase shift between joints, and φ0 is the joint offset which depends on the direction of locomotion. This is also known as the travelling wave locomotion/ serpenoid curve locomotion. Locomotion using undulation mainly consists of relative link displacements sideways with respect to the direction of motion. This observation can simplify the mathematical model making it better suited for control design. In addition, the friction considerations while traversing slopes and climbing in snake robots must be addressed. For any inclined surface, the friction coefficient depends on the surface's inclination angle and the surface's condition. To achieve maximum stability, different adaptive methods are utilized by systems. ACM-1 utilized self-contained terrain adaptability for traversing the slope. The adaptive control method determines the winding angle depending on the frictional coefficient ratio. For smooth upward movement along a slope, the relation between the slope gradient and winding angle in the case of lateral undulation is studied by [56]. An adaptive slope control using feedback CPG network by varying speed and winding angle is proposed in [57]. Another CPG model for effective terrain exploration is discussed on various slopes and terrain in [58]. The concept of climbing comes where the snake robot must lift its body to traverse some obstacles. This lifting can be done either by the snake itself or with external support (mostly by exploiting the obstacle). As the output joint torque is limited, the action of lifting the segments should have to be designed carefully to avoid joint breakage due to the load of the segments being lifted. A control approach for semiautonomous snake robot step climbing based on mixed-integer quadratic programming to produce the snake robot's head's reference trajectory is suggested in [56]. The approach identifies appropriate places and time durations to detect the environment, among other things.

Furthermore, the method considers the snake robot's velocity and acceleration limitation when following the created route. [55], [59] created a snake robot with lateral undulation, cantilever gait, and snake-like anisotropic friction that can climb stairs up to one-third of its body length fast and steadily. When ascending a short route, snake robot modules can use friction to sustain the robot's whole weight if both modules' ends exert adequate pressure on the passage wall. This self-locking phenomenon is employed in [136] to maximize joint torque in an ascending concertina action. Dynamic modelling and control of motion in a vertical plane for an unstructured environment are discussed in [47]. Environmental sensing becomes inevitable to control or make the robot move efficiently in an unstructured / obstacle environment. The control is more dependent on sensing when it comes to uninterrupted motion. Hence, the following section deals with locomotion in an obstacle environment by integrating it with sensors, as they are inevitable in terrain exploration.

IV. SENSING AND MOTION CONTROL SCHEMES

To have high locomotion adaptability to the environment, snake robots require a high degree of awareness of their surroundings (i.e. *perception*) and the capability of efficient obstacle exploitation [61]. Hence, this section focuses on sensors and the available literature study of snake robot locomotion in obstacle environments. We will now glance at the major sensors and technologies used in obstacle exploration and avoidance for perception-aided locomotion. Readers can find a detailed study on perception-driven locomotion from [61].

Based on what the sensors do, they are categorized as proprioceptive sensors, which measure values internal to the system (like motor speed, wheel load, robot arm joint angle, and battery voltage) and exteroceptive sensors, which acquire information from the robot's environment (quantities such as distance, light intensity, sound amplitude). A study by [79] used joint angle to estimate the slope's tilt angle and then utilized it for speed control and sidewinding behaviour. Based on how they (sensors) perform, sensing sensors are of two types: active and passive sensors. Active sensors emit energy into the environment and then measure the environmental reaction (like ultrasonic sensors and laser rangefinders), whereas passive sensors measure the ambient environmental energy by receiving signals from the source (like microphones and temperature sensors). Force/contact sensors are widely used in adapting to terrain irregularities [80], [81]. These contact-based sensors usually permit limited motion planning as they can only provide touch information. A whisker-based contact sensor was integrated with a SLAM framework for mapping and obstacle-aided locomotion [82], [83]. In [84], the distribution of contact switches along the snake body is utilized to find the push points for propulsion. Proximity / range sensors are used as obstacle detection sensors. Integration of passive IR sensors for human detection and ultrasound sensor for obstacle avoidance and mapping in rescue applications is introduced in [85]. More accurate and detailed 3D map information on the environment can be obtained using LiDARs.

A combination of LiDAR for mapping and ultrasound sensor for obstacle avoidance with a SLAM framework could successfully navigate a snake robot by state estimation [86]. Another high-resolution and accurate estimate can be done with laser triangulation. A custom-designed laser triangulation sensor for a pole climbing autonomous snake robot that fits the robot head's size and power constraints was developed in [87]. First, the relative position is estimated using IMU data and forward kinematics. Other offboard vision systems like stereovision systems [88] and cameras [89] are also used for the head position state and obstacle coordinates. A detailed survey on visual and inertial odometry can be found in [90]. Autonomous decentralized controls used for highly adaptive functioning are mentioned in [91] and [92]. Also, an automated sensing system can be found in [69], with the integration of a camera unit, thermal and PIR-based imaging, processor, and a GPS module to aid rescue operations after an earthquake.

With the knowledge of the environment, locomotion can be performed in two ways: Locomotion by avoiding obstacles and locomotion by accommodating obstacles. The conventional way to manage obstructions comprises attempting to avoid them (obstacle avoidance). Otherwise, the collision might restrict further motion imparting mechanical stress or damage to the equipment. Various investigations have concentrated on motion dealing with obstacle avoidance. One such locomotion is the Artificial Potential Field (APF) concept [62], where an imaginary force field is assigned to each object in the plane. The target attracts the robot with the positive potential field, whereas the other objects (obstacles) repel it from hitting it. As the robot gets closer, the strength of these forces may increase. A new controller for obstacle avoidance using APF theory is presented in [63]. While using the APF approach, there is a probability that the repulsive forces from adjacent obstacles may leave the robot unable to move and eventually make the robot stuck and end up in local minima. In [64], a hybrid control methodology by integrating APF with a modified Simulated Annealing (SA) optimization algorithm is proposed to avoid local minima. Another algorithm known as the Central Pattern Generator (CPG) [65] allow the robot to avoid obstacles or barriers by turning the robot body from its trajectory. The CPG model also allows collision detection using sensory feedback. The same work also discussed a phase transition method using a phase difference control parameter to realize the turning motion. This CPG algorithm based on a neural oscillator is applied to generate rhythmic rectilinear and lateral undulation gaits [33].

The second method of obstacle accommodation can be easily understood by observing biological snakes. Snakes utilize the terrain unevenness (bumps and obstacles) to achieve an efficient motion pattern/ gait. Snakes push against these unevenness/ irregularities and make bends in the body, and all consecutive body parts follow the same pattern from head to tail to achieve better motions [8]. Adopting this strategy in snake robots leads to obstacle-aided locomotion [67] (see Figure 4). Such an approach makes use of obstacles/ accommodates the obstacle rather than completely avoiding them. A motion planning system for a snake-like robot that accommodates barriers was first investigated in [68]. The robot uses its contact with the obstacles to establishing forward motion. The obstacle avoidance using sensory data allows collision in a controlled way by reducing the damage it causes to the robot. A general formula for motion constraints due to obstacle contact is presented in [69], where an inverse kinematics model is developed based on this formula for finding the joint angles of a snake robot under contact constraints. Using this model, a motion planning algorithm is also proposed for a cluttered environment.

In [70], a framework of non-smooth dynamics and convex analysis is used to systematically and accurately incorporate both unilateral contact forces (from the obstacles) and isotropic friction forces based on Coulomb's law using set-valued force laws. A simple control law was developed using a novel push-point approach to determine the contact forces required to propel a snake robot through a path/ direction [71]. The findings were experimentally validated for a wheelless snakebot, with closed-loop control for the lateral undulation.

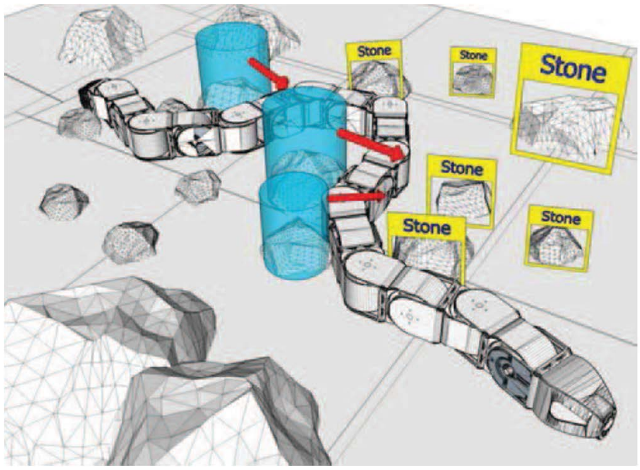


FIGURE 4. Concept of a snake robot exploring terrain with obstacles [61].

Both obstacle accommodation and avoidance locomotion help robots move in undefined environments considerably. However, these control approaches are not enough to fully exploit obstacles for means of propulsion. Only a few pieces of research have been conducted to see the feasibility of applying this approach to snakebots. A few researchers have focused on asymmetry in pushing against obstacles, like control methods for fixed and predetermined pushing patterns. In most studies, the lateral undulation depends on the environment friction and the actuator's output torque. To achieve a user-defined path for snakebot by generating suitable obstacle forces, [72], [73] investigated the effects of using optimal motor torque. According to the study, the method faced two significant issues while practically implementing it for obstacle-aided locomotion. The first issue is in the automatic link angle calculations, and the other is in the automatic path generation. The exciting thing about this approach is that it helps check the quality of a given path, i.e., one can use useful forces for a path if they exist from the set of forces generated by interacting with the obstacles [74]. For obstacle-aided locomotion, besides the geometric representation, knowledge about the environment and its properties should be successfully explored for effective locomotion. Several studies have been carried out aiming at obstacle-aided locomotion control approaches. We will now go through the majors among them briefly.

Adaptive control schemes: This approach aims at the direction of locomotion and joint angle tracking [75].

Sliding model control: Deals with planar snakebots' head angle control and velocity tracking [51], [76].

Manoeuvring control method: To converge the centre of mass with the desired path and traverse it with the desired velocity for planar snakebots [77].

Genetic algorithm: With the help of sensory information, the robot analyses its internal state by learning appropriate responses. Accordingly, the robot adjusts its gait to the environment.

The complexity in controlling and coordinating the high DOF of a snake robot is overcome by Choset by developing a directional compliance approach which moderates the effective stiffness of the robot to decide whether to stick on or not to a particular direction based on proprioceptive sensing to react to unknown / non-predefined environment. Along with the perception of the environment, the knowledge of the robot's body shape is equally crucial in analyzing the state acquisition, especially when it comes to surgical applications. Due to the miniaturized size of the minimally invasive surgical robot, it is not possible to equip the conventional encoders or position sensors. [93] developed a micro-sensing sensor, a fusion of inertial and gravitational sensors for finding the difference of states in two consecutive universal joints of a surgical robot.Along with the knowledge of motion control mathematics and environment, the mechanism/ prototype with which the studies are being validated is equally essential to understand. Hence the next section tries to provide a detailed review of the electro-mechanical aspects of the mechanical design of the snake robot literature.

V. MECHANICAL DESIGN

A snake robot body comprises linearly connected modules through joints (like links and joints mechanism of a manipulator). The combination of different joint orientations reflects in the robot's relative head position (the same as the end-effector position in a manipulator). Generally, almost all snake robots have a modular structure where the entire body comprises segments connected in series through joints. Based on the structure of the module/ how the segments are joined, snake robots can be divided into three: 1,2 and 3-DOF modular structures (see Table 3 for details). Two-DOF and three-DOF modules can reduce the number of robot modules while maintaining the same operating conditions. However, they are advantageous when used for 3D terrain, but the number of modules required increases. Minimizing the cross-sectional size while ensuring the output torque becomes challenging. Whereas aligning two motors orthogonal to achieve 2-DOF makes the module bulky due to the small diameter-length ratio. It is commonly placed parallel with several other motors to reduce the cross-sectional size. The rotation axis is then transmitted through worm gears or a combination.

The selection of actuators for a snake robot depends on several factors, such as the operating surface roughness, the minimum dimension of the tunnel, and the maximum gap to cross. Table 4 compares the types of major actuators studied in this paper. Generally, DC motors have the advantages of digital controllability, extensive joint bending range, and integrated gear-box control circuitry. Pneumatic actuators exhibit high transmission force and simple linear deformation design. One module can even achieve 3-DOF motion (e.g., the Slim Slime Robot can rotate about two axes, and the linear motion

TABLE 3. Details of the three existing modular structures found in snake robots.

DOF	General features	Robot
1-DOF module	• Used planar snake robots to reduce tangential friction and are mostly equipped with passive wheels. • Easy to implement dynamics modelling and control. • Can perform planar obstacle avoidance and path planning [106, 107] • Terrain adaptability is restricted to exploring tunnels and climbing slopes. • An assembled bot can have three DOF by arranging three 1-DOF modules perpendicular.	• Amphibot [108] connects two adjacent modules with a perpendicular axis of rotation. • Modsnake [109], with a customized design, uses a U-shaped frame to connect two modules. • Polybot, ACM III [110, 95]
2-DOF module	• Achieved in two ways: ▪ Orthogonally assembling two revolute motors ▪ Parallelly arranging two motors with the help of worm/bevel gears.	• In Kulko [111], all 2-DOF modules were spherical shapes comprising two intersecting semi-circle rings driven by servo motors via chain drive and worm gear. • In ACM-R4 [112], one DOF is utilized for bending and the other for driving wheels
3-DOF module	• Short in size compared to 1-DOF [113, 105]. • Due to the complexity of integrating 3-DOFs in a single module, these types of robots are of only two kinds ▪ Reconfigurable snake robots [105],[70] ▪ Hyper redundant manipulator mechanism [113]	• Perambulator-II,

TABLE 4. Mostly used actuators, their features and application details in different snake robots.

Actuator	Advantages	Disadvantages	Applications found in articles
DC motor	• Large bending range • Easy to design and control	• Limited torque • Miniaturization issues • Mechanical friction	• Coupled with gear train/mechanical linkage, which helps drive a module to bend/rotate [123, 124]. • Accurate turning control and torque were achieved using spur gear with high reduction gear [95, 112], and DC motor speed control is done in [78]. • RC servos are already fitted with reduction gears, encoders, and control units [11, 96, 45].
Pneumatic	• Linear expansion motion • High force trans-mission • Simple, Low-cost design	• Lack of accurate control • Limited joint bending range	• A novel pneumatic soft snake robot that utilizes traveling wave locomotion for exploring complex and narrow environments is discussed in [41]. • A fluid-driven mechanism in [90] has three identical metal bellows arranged parallel for controlled locomotion in an inclined plane. • [125] used a variable stiffness actuator to study the adaptive stiffness control and motion optimization of a snake robot by controlling the actuator.
Hybrid Motor	• Large propulsion surface • Stiffness control	• Limited joint bending range • Low DOF • Efficient motion	• The major type is the combo of DC motor and pneumatic actuators [126,127,97]. The DC motor provides forward propulsion by driving tracks over the bot. Joints' connection and bending angle connecting two modules are accomplished with a pneumatic actuator (Omni Tread, MOIRA).
Artificial Muscles	• Combination of lightweight, low power requirements agility for locomotion and manipulation • Can produce sizeable bending displacement	• Independent of the voltage polarity • Slow response • Produces monopolar actuation due to the electrostriction effect associated.	• Fabricated paper-based bilayer actuator combining the hydro and thermal expansion with a simple printing method [128]. • This actuator exhibits large anisotropic deformation and features like low cost and superior stability. • More articles on artificial muscle modules, piezoelectric motor modules, and shape memory alloy modules can be found in [129-134].
Bio-inspired soft actuators	• Highly deformable materials can be used for a variety of innovative applications (SMA, FEA, SMP, DEAP)	• Deformations usually need multiple independently activated actuators	• [135, 94] discusses a comprehensive study on everything related to soft actuation. • Deformable structures can be made using several techniques like pop-up, rapid prototyping and origami. • Deformable skin with directional friction properties can be created with the Kirigami principle, which can be used for soft robots, even with a single extended actuator. [137-138]

TABLE 5. Existing snake robots and their design specifications and features.

Robots	Body /joint DOF	Joint / Joint Actuation	Wheels/ Gaits achievement	Modelling and control	Other features
ACM III (Hirose-Fukushima Robotics Lab)	2/1	• Parallel joint connection • Servo motor actuation for rotary joint	• Passive wheels • Serpentine gait (2D lateral undulation) is used for forward propulsion	• Serpanoid curve based • A curve describing the spine of a snake is controlled using joint actuation	• Length: 2000mm & weight: 28 kg. • Each link length: 102 mm, height 162 mm, width: 144 mm, • Used limit switch as a tactile sensor for obstacle detection • Forward velocity: 400 mm/s • Smooth surface and tunnels
ACM-R3 (Hirose-Fukushima Robotics Lab)	2/1	• Orthogonal joint connection: Joints connected to provide an orthogonal axis of rotation on each end of the links • Servo motor (19.1 Nm)	• Passive wheels (110 mm dia) • It can roll against contacted obstacles, and the design could lift eight units up	• Tendon-driven actuation for manipulation • Remote controlled	• Total length: 1755 mm and weight: 12.1 kg, joint twist angle: 62.5 deg • Length and width are equal (110 mm)
ACM-R4 (Hirose-Fukushima Robotics Lab)	2/1	• a novel ball-bearing cam system to compress an O-ring as the joint exerts a torque	• Active wheels • 3D gaits, sharp turning climbing	• Serpanoid curve based	• Total length: 1100 mm and a cross-section:135mm x 135mm, weight: 9.5kg. • Seep: 0.4m/s both on land and in water
ACM-R5 (Hirose-Fukushima Robotics Lab)	3/2	• Amphibious • Universal joint and bellow • Actuated with a pair of servo motors (9Nm) with spur gear connection	• Passive wheels • 3D gaits, lateral undulation, and swimming	• Passive propeller	• Total length: 1750 mm, diameter: 80 mm, Weight: 7.5kg • Each segment was a modular unit (equipped with a CPU, battery, and motor)
Slim slime (Hirose-Fukushima Robotics Lab)	2/1	• Continuum robot with internal pneumatic actuator	• Passive wheels • Capable of achieving rectilinear progression and rolling	• Backbone curve without DH-convention • Achieves compliant actuation using a bellow-like actuator	• Length: 730mm, cross section: 0.013sqm, weight: 12kg, velocity 60mm/s
Amphibot-1 (Hirose-Fukushima Robotics Lab)	2/1	• DC motor (0.75W, 1.2Nm) drives a set of reduction gears • Propeller less	• Without wheels • Achieves 2D gaits, lateral undulation, crawling, turning	• Adaptive controller based on Central Pattern Generator • Dexterous locomotion controlled by Neural Networks	• Length:70mm, cross-section: 5mm x 33mm, total length: 490 mm appx. Speed: 33mm/s • Amphibious
Amphibot-II (Hirose-Fukushima Robotics Lab)	2/1	• DC motor (2.3W, 4.2Nm) drives a set of reduction gears • Propeller less	• Passive wheels • Can achieve 2D gaits, lateral undulation, swimming	• Central Pattern Generators (CPGs) for online trajectory generation for crawling and swimming	• Length: 94mm, cross-section 55mm x 37mm; Total length: 772 mm • 400mm/s speed on land; 230 mm/s speed in the water
GMD snake-II (German National Research Center for Information Technology)	3/2	• 3 DC Motor to control the Universal joint via a rope	• Active wheels over the body help in crawling over obstacles and in-ground • Lateral undulation, rectilinear motion • 2D gaits which can lift head	• Travelling wave locomotion and frictional constraints • Curvature control with a second-order function • Adaptive stiffness control and motion optimization were done by controlling the actuator.	• Length: 1500 mm, diameter: 180mm, weight: 15Kg • Camera for image recognition. LED lights for lighting. Acceleration sensor for observing motion, mechanical-optical sensors
Omnitread-8,4 (University of Michigan)	2/2	• Pneumatic bellow actua tion for universal joint • Hybrid motor: Combo of DC motor with pneumatic actuator	• Treads instead of wheels • Motor controls active treads through a worm gear mechanism • 3D gaits, crossing gaps, passing holes, rectilinear gait • Can also climb stairs, drill pipes and crawl in a vertical pipe.	• Joystick controlled • Achieves compliant actuation using pneumatic bellows-like actuators	• Can go over obstacles whose height equals twice its length and go across the gap whose width is equal to half its size. • Motion range is restricted due to physical shape and forces exerted by the robot due to pneumatic actuation
Koryu-I (KR-I) By Hirose	3/2	• Servomotor actuation	• Active wheel (crawlers at the bottom)	• Coordination control of the body articulation	• Length: 1391, height: 393 mm., weight: 27.8 kg • Utilized force sensor based on photo detective technology.

TABLE 5. *(Continued.)* Existing snake robots and their design specifications and features.

Uncle Sam (Biorobotics Lab at CMU)	3/ 2	• PR universal joint connection	• Without wheels • Capable of climbing poles, lateral rolling	• Joystick controlled	• Length: 94cm • Capable of climbing poles, lateral rolling
Anna Konda (Norwegian University of Science and Technology)	3/1	• Hydraulic actuation system (actuated by two double-acting water hydraulic cylinders and 20 hydraulic motors)	• Without wheels • Side winding gait	• Operator controlled joint coordination	• Developed for fire fighting • Length: 3m, weight: 70kg
Kulko (Norwegian University of Science and Technology)	2/2	• Ten identical ball-shaped joint modules connected in series with spherical uni versal joints and DC motors, worm gears	• No wheeled snake-like robot • Able to realize multi-gait sidewinding, rolling	• Curvature control for snake motion. • Obstacle-aided locomotion by controlling contact force	• They provide the foundation for studying Auxiliary locomotion gait intensely.
S1 to S7 series of robots (Dr. Gavin Miller at the University of Glasgow)	2/2	• Simple revolute joints	• S7 is with no-wheel drive • S1-S5 with passive wheels on the bottom to achieve lateral serpentine gait	• S1, S2, S4, S5, S6: achieved lateral undulation using basic servo motor control where S4 & S6 achieved locomotion using joint control through gear train set along the length of the body using a single servo motor. • S3: Achieved both lateral undulation & side winding (Joystick controlled) • S7: Rectilinear motion	• S7 integrates a wide variety of sensors for distance detection, motion measurement, image acquisition, rotation, and other functions
Perambulator-II (CAS Shenyang Institute of Automation Robotics Research Laboratory)	3/3	• DC motors, worm gears	• Without driven wheels (series of Passive wheels over the module) • Rolling, lateral undulation	• Second-order functions are used for joint control.	• Amphibious • Applicable for 3D terrain surfaces
Polybot	3/1	• Servo motor	• Without wheels • Rolling	• Rolling chain theory of locomotion	• The first and last segments can loop to form a continuous chain

about the 3rd axis). A miniature endoscopy mobile robot, Heart-Lander, has a module cross-section smaller than DC motor modules (8mm in diameter).

Nevertheless, the pneumatic modules' bending range is small (30 degrees), limiting the potential motion type of the whole robot. Besides, the response time and the control accuracy are worse than DC motor-based modules. Hybrid actuators integrating DC motors and pneumatic joints have the advantages of stiffness control and a large propulsion surface. Applying tracks on the module surface gives the robot maximum propulsion contact in rough terrain. However, the hybrid actuators can only bend about one axis in a limited range. Therefore, the motion efficiency of such snake robots is higher than pneumatic and DC motor modules. Major actuation modules for selected snakebots are shown in Figure 5. Nowadays, more soft actuators are used for more sophisticated snake robotic / surgical applications. Shape Memory Alloy (SMA), Fluid elastomer actuators (FEA),

Shape morphing Polymers (SMP), and Dielectric Electro-Activated Polymers are such novel actuators being used for soft robotic applications [94].

The existing snake robots design is found to be categorized into five groups based on the type of locomotion: i) with passive wheels [like ACM III, ACM-R3, ACM-R5, AmphiBot I, AmphiBot II], ii) with active wheels [Koryu-II (KR-II), GMD-SNAKE2 [95], ACM-R4], iii) robots with active treads (OmniTread OT-4, OmniTread OT-8 [96], [97]) iv) robots based on undulations using vertical waves [Inchworm robot developed by Kotay in 1996, Dowling's snake robot in 1997, PolyBot, CMU's Modular Snake Robots], v) robots based on undulation using linear expansion [Slim Slime Robot, Telecubes [47]]. Certain snakebots are modular to reconfigure their bodies to perform different tasks and adapt to environmental conditions. [91], [92], [93], [94], [104]. It was Hirose [3] who introduced the first recorded snake robot (ACM) in 1972, which was 2m long with 20 single DOF joints. It performed the left-right movement to achieve forward locomotion. He introduced the concept of a snake robot with passive wheels to achieve lateral undulation by utilizing the serpenoid curve for a series of sinusoidal patterns transferred from head to tail [105]. Among the ten snake robots Hirose developed, some were employed with passive wheels over joints (ACM-III and R5). In contrast, some robots were equipped with active wheels as the primary actuators (ACM-R4) and a few with pneumatically driven joints (Slim Slime). Chowset of Carnegie Mellon University is another renowned researcher in this field. From snoopy [105] to Greasefire (the latest among his Modesnake series

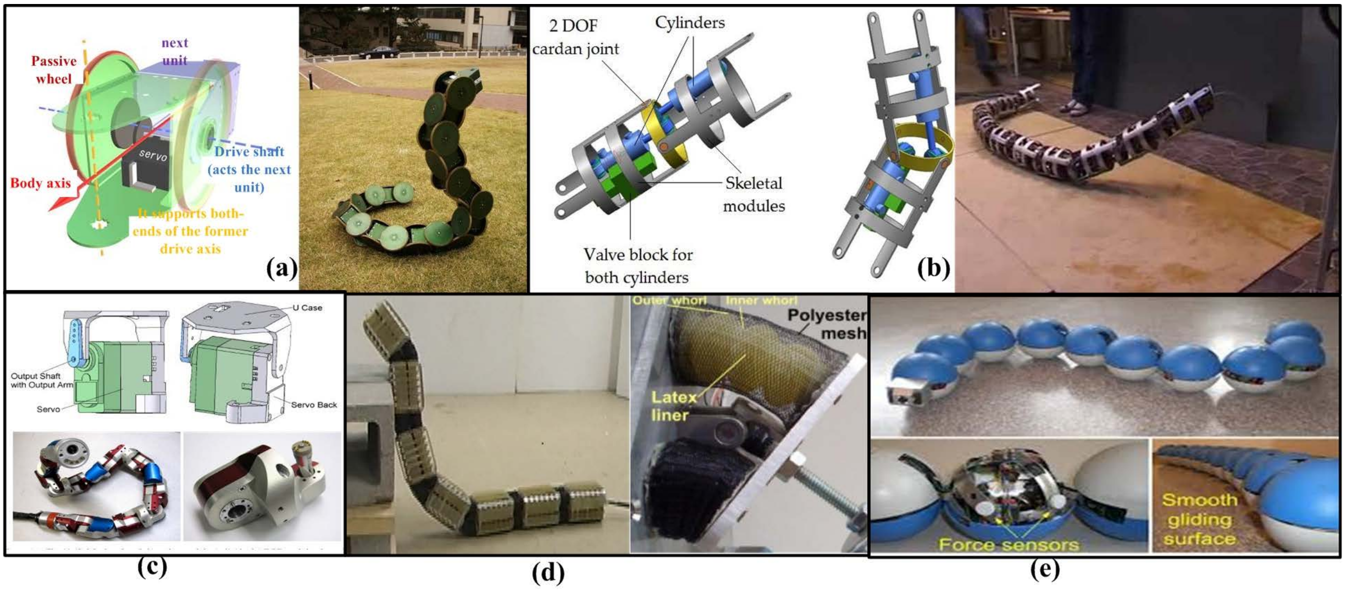


FIGURE 5. Major snakebots with their joint module in close. (a) Wireless controlled ACM-R1 by Hirose and its single DOF joint module (b) World's largest snake robot Anna Konda by Hirose (c) Carnegie Mellon University's Modesnake/ Uncle sam by Prof. Choset (d) Onmitread-4 by Johann Borenstein, The University of Michigan (e) Kulko by Hirose.

is capable of 3D locomotion, including swimming, climbing, and crawling), the group developed a series of robots by modifying the joint configurations [116].

The University of Michigan utilized active treads and joints designed using pneumatic bellows (OT-8 and OT-4). The key features of these robots are a high propulsion ratio and versatile terrain adaptability. Later many researchers came up with different ideologies like smart material-based flexible snake robots [117], modular snake robots based on series elastic actuators [118], and cable-actuated snake robots [119]. Two versions of HITSZ-Snakebot with their kinematic models for creeping, rolling, and serpentine gaits were established [44]. In the next year, remote-controlled, ground-based surveillance and inspection robot were developed on a commercial basis by Sarcos. The robot named 'Guardian' claims to offer live video feed, 3D mapping, and two-way communications with real-time data transferability from challenging environments and terrains. The snakebot is commercialized for a prize of $60,000. In 2020, the creators of Kulko came up with two new designs for unstructured environment exploration. The first was a design approach for sensing environment contact forces based on the measured joint constraint. The second design approach allowed the cylindrical surface of each snake segment to rotate by an embedded motor to generate the forward propulsive forces on the robot from its environments [120].

The mechanical design thus helps the system's smooth control using the modelling equations. More details on the design specifications of major snake robots, including the joints, actuators, DOF, modelling, and control, are listed in Table 5. The snake robot body is usually custom-made by 3D printing or simple assembly. Generally, these snakes used polycarbonate plastics, aluminum, or steel, as their body material. Snake robot, MAMBA has all modules sealed with rubber for waterproofing capable of protecting it till at water depths down to at least 2 m [66]. A series elastic actuator-based precision torque-controlled low-cost robot named serpent was introduced in 2019, which utilized Fused Deposition Modelling (FDM) manufacturing technology for 3D printing the modules using polycarbonate plastics [121]. Recently, to withstand higher traverse force and for the screw-less assembly mechanism, the elastic joint was redesigned with the addition of a damper element [122].

VI. SIMULATORS FOR ROBOTS

Compared to virtual character animation, dynamic robot simulations have more strict requirements. The physical reality, time complexity, and computational burden are all challenging for dynamic simulations. As the law of physics can be violated for cartoons, video games, and other entertainments, unrealistic forces will not become a problem for their animation. Simulators can be used offline to analyze or generate behaviours in mechanical and biomechanical studies. Most snake robot studies are done by validating the mathematical model with the experimental prototype alone. The need for whole-body movement control for complex structures is still challenging even though the field of dynamic simulations has matured in the last decades [23], [30]. The challenges include:

- Numerical instability comes during real-time control [21], [22].
- Lack of performance (high computational time requirement) when used as predictive engines in real-time control loops.

TABLE 6. Existing simulation platforms used by robotics research communities.

Simulator	Features	OS shared & Main API	Real robots simulated in software
Gazebo	• A multi-robot simulator for outdoor environments • Developed by Open-Source Robotics Foundation. • It is the official software tool for the DRC. Supports multiple physics engines (ODE, Bullet).	• LINUX/GNU • API- C++	• Atlas custom platform • Wheeled vehicles • Quadrotor • Turtlebot, PR2
ARGoS	• A multi-robot, multi-engine simulator for swarm robotics • Initially developed within the Swarmanoid project4	• GNU/Linux • MAC OSX • API: C++	• Khepera • E-puck, Thymio • marXbot, Footbot quadrotor
ODE (Open Dynamics Engine)	• An open-source library for simulating rigid body dynamics • Used in many computer games and simulation tools • It is used as physics engines	• GNU/Linux • API: C++	• Multi-legged robot • iCub
Bullet	• An open-source physics library; mostly used for computer graphics and animation. • The latest release5 also supports Featherstone's articulated body algorithm and a Mixed Linear Complementarity Problem solver, which makes it suitable for robotics applications.	• Windows • MAC OSX • GNU/Linux • API: C++	• Multi-legged robots • Humanoid robotics • Numerical simulation of physical systems • Industrial manipulators • Human motion analysis
V-Rep (Virtual - Robot Experimentation Platform)	• A robot simulator software with an integrated development environment produced by Coppelia Robotics • Like Gazebo, it supports multiple physics engines (ODE, Bullet, Vortex).	• Windows • GNU/Linux • API: C++, LUA	• Nao, thymio • Wheeled vehicle • e-puck, Khepera • Bioloid • Quadrotor
Webots	• Webots is a development environment used to model, program and simulates mobile robots developed by Cyberbotics Ltd.	• GNU/Linux • MAC OSX, Windows • API: C++, LUA	• KUKA LWR • Lego Mindstorm • Wheeled vehicle
OpenRave	• An environment for simulating motion planning algorithms for robotics.	• GNU/Linux • API: python	• PR2
Robotran	• A software that generates symbolic models of multibody systems, which can be analyzed and simulated in Matlab and Simulink. • It is developed by the Center for Research in Mechatronics, Universit'e Catholique de Louvain.	• Windows • GNU/Linux • API: C	• Coman • iCub

- Solvers may converge to physically feasible solutions at a certain time [14].

Table. 6 shows the details of existing robotic simulators used by researchers, which would help future researchers to choose their simulation platform. It is always preferable to study the feasibility of the mechanism with any of the platforms mentioned. Among these simulators, snake robots are widely studied with Gazebo, V-rep, and Webots.

VII. CONCLUSION AND FUTURE SCOPE

Snake robots have been a topic of discussion among researchers for decades. Starting from Hirose, many researchers have made several studies that contributed substantially to the field. Although these researches were motivated by the potential adaptability to an unstructured environment, the practicality of a complete real-time snake robot is still challenging due to its design and control complexities, as mentioned below.

- Obtaining a smooth surface combined with contact force sensing at articulated parts of the robot represents a significant design challenge.
- Developing a joint mechanism to maximize the actuator strength to robot weight ratio is critical in head-lifting snakebots.
- Researchers are still in a clean laboratory environment which is not the scenario of the real applications. Hence waterproofing, dust-proofing, and body covering are essential.
- When the elongated body with the small cross-sectional area helps manoeuvre narrow passages, the higher degrees of freedom allow it to explore spaces lifting its body. However, this higher DOF makes the body configuration redundant. This makes the system difficult to control.
- The complexity in coordinating the high degree of freedom to generate the required motion.

Soft robots exhibit safe contact and environmental adaption compared to traditional rigid robots. But the advancements in the actuation of these soft materials are restricted due to two reasons which make traditional motion planning, dynamic modelling and controls computationally expensive:

- Limitations in internal sensing
- The difficulty of precise modelling is due to the continuous deformable characteristics, which in turn can result in infinite DOF and non-linear dynamic response.

Apart from pipeline inspection, all other applications of snake robots require high environmental sensing and adaptability of their body shape according to the environmental conditions/
uncertainties. From the control point of view, path planning and navigation, optimal control-intelligent gait selection, and

compatible control based on gait improve robot motions [139], [140], [141], [142], [143], [144], whereas compatible perception devices, visual systems [110], [145], [146] from the point of perception driven obstacle avoidance have to be explored more for highly adaptive functionality. It is found that almost all research was concentrated on planar motions, and very few studies have made obstacle avoidance. Hence a deeper focus must be made on adaptive motion behaviours in unstructured environments.

Whereas, in continuum robots, when the backbone curve concept is employed, the problem of hyper redundancy gets reduced to determine the proper time-varying behaviour of the backbone reference set. Once the backbone reference set is determined, a fitting procedure may allow it to align the manipulator with the backbone curve.

A few available works have employed locomotion in unstructured environments using simulation platforms; the background dynamics are not available, making the controller analysis challenging to comprehend. Hence, more researchers must address this with easily analyzable models.

Though there are better designs, almost all prototyped snake-inspired robots face other issues like compromises in cross-sectional sizes, lack of multi-gait functionality, low-speed operation, longer operational time, and lack of waterproofing and dust proofing. These practical challenges needed to be resolved for effective USAR operations. However, the developments achieved by Carnegie Mellon University's snake robot are appreciable because it has assisted the red cross rescuers after a meter 7 earthquake hit Mexico City in 2017 [94]. They could find that the building was unoccupied with any victims. This accomplishment inspires researchers enthusiastic about the development of rescue assistance snake robots. Overall, researchers must put a significant concentration on the adaptive motion behaviour in debris/ uncertain environments.

In brief, this paper has started with the principles of locomotion behind biological snakes and then goes to the existing works of literature on mathematical modelling involved in the recreation of this biology. The kinematics-dynamics motion controls are studied in detail, followed by the factors for the mechanical design. Finally, the existing dynamic robotics simulator platforms are also discussed to choose simulator platforms for readers.

ACKNOWLEDGMENT

Dr. V. Berlin Hency is the primary investigator and Dr. Arockia Selvakumar Arockia Doss is the co-primary investigator for the project.

REFERENCES

[1] D. E. Alexander, *Principles of Emergency Planning and Management*. Oxford, U.K.: Oxford Univ. Press, 2002.

[2] J. Gray, "The mechanism of locomotion in snakes," *J. Experim. Biol.*, vol. 23, no. 2, pp. 101–120, Dec. 1946.

[3] S. Hirose, *Biologically Inspired Robots: Snake-Like Locomotors and Manipulators*, P. Cave and C. Goulden, Eds. Oxford, U.K.: Oxford Univ. Press, 1993.

[4] J. K. Hopkins, B. W. Spranklin, and S. K. Gupta, "A survey of snake-inspired robot designs," *Bioinspiration Biomimetics*, vol. 4, no. 2, Jun. 2009, Art. no. 021001.

[5] R. Webster, A. Okamura, and N. Cowan, "Toward active cannulas: Miniature snake-like surgical robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2006, pp. 2857–2863.

[6] M. Li, B. H. Kim, and A. I. Mourikis, "Real-time motion tracking on a cellphone using inertial sensing and a rolling-shutter camera," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 4712–4719.

[7] K. J. Dowling, "Limbless locomotion: Learning to crawl with a snake robot," Ph.D. dissertation, Robotics Inst., Carnegie Mellon Univ., Pittsburgh, PA, USA, Dec. 1997.

[8] S. Ma, Y. Ohmameuda, K. Inoue, and B. Li, "Control of a 3-dimensional snake-like robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, Sep. 2003, pp. 2067–2072.

[9] D. L. Hu, J. Nirody, T. Scott, and M. J. Shelley, "The mechanics of slithering locomotion," *Proc. Nat. Acad. Sci. USA*, vol. 106, no. 25, pp. 10081–10085, Jun. 2009.

[10] T. Kano, H. Date, and A. Ishiguro, "Simple decentralized control scheme can reproduce versatile gait patterns of snakes," in *Proc. Int. Symp. Nonlinear Theory Appl. (NOLTA)*, 2014, pp. 3–20.

[11] C. Gong, M. J. Travers, H. C. Astley, L. Li, J. R. Mendelson, D. I. Goldman, and H. Choset, "Kinematic gait synthesis for snake robots," *Int. J. Robot. Res.*, vol. 35, nos. 1–3, pp. 100–113, Jan. 2016.

[12] M. Saito, M. Fukaya, and T. Iwasaki, "Modeling, analysis, and synthesis of serpentine locomotion with a multilink robotic snake," *IEEE Control Syst. Mag.*, vol. 22, no. 1, pp. 64–81, Jan. 2002.

[13] I. Grabec, "Control of a creeping snake-like robot," in *Proc. 7th Int. Workshop Adv. Motion Control.*, 2002, pp. 526–531.

[14] P. Wiriyacharoensunthorn and S. Laowattana, "Analysis and design of a multi-link mobile robot (serpentine)," in *Proc. IEEE Int. Conf. Ind. Technol.*, Dec. 2002, pp. 694–699.

[15] S. Ma, "Analysis of snake movement forms for realization of snake-like robots," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 1999, pp. 3007–3013.

[16] J. Ostrowski and J. Burdick, "Gait kinematics for a serpentine robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 2, Apr. 1996, pp. 1294–1299.

[17] S. Ma, N. Tadokoro, B. Li, and K. Inoue, "Analysis of creeping locomotion of a snake robot on a slope," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 2, Sep. 2003, pp. 2073–2078.

[18] H. Ohno and S. Hirose, "Design of slim slime robot and its gait of locomotion," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. Expanding Societal Role Robot. Next Millennium*, Nov. 2001, pp. 707–715.

[19] S. Ma, "Analysis of creeping locomotion of a snake-like robot," *Adv. Robot.*, vol. 15, no. 2, pp. 205–224, 2001.

[20] P. Prautsch and T. Mita, "Control and analysis of the gait of snake robots," in *Proc. IEEE Int. Conf. Control Appl.*, vol. 1, Aug. 1999, pp. 502–507.

[21] E. Drumwright and D. A. Shell, "An evaluation of methods for modeling contact in multibody simulation," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2011, pp. 1695–1701.

[22] E. Drumwright and D. A. Shell, "Extensive analysis of linear complementarity problem (LCP) solver performance on randomly generated rigid body contact problems," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 5034–5039.

[23] L. A. De and W. Book, "Robots with flexible elements," in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Cham, Switzerland: Springer, 2008, pp. 287–319.

[24] K. A. McIsaac and J. P. Ostrowski, "Motion planning for anguilliform locomotion," *IEEE Trans. Robot. Autom.*, vol. 19, no. 4, pp. 637–652, Aug. 2003.

[25] P. Liljeback, Ø. Stavdahl, and K. Y. Pettersen, "Modular pneumatic snake robot: 3D modelling, implementation and control," *Model., Identificat. Control*, vol. 29, no. 1, pp. 21–28, 2008.

[26] K. A. Melsaac and J. P. Ostrowski, "A geometric approach to anguilliform locomotion: Modelling of an underwater eel robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 1999, pp. 2843–2848.

[27] Z. Y. Bayraktaroglu, F. Butel, P. Blazevic, and V. Pasqui, "A geometrical approach to the trajectory planning of a snake-like mechanism," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. Hum. Environ. Friendly Robots High Intell. Emotional Quotients*, Oct. 1999, pp. 1322–1327.

[28] Y. Shan and Y. Koren, "Design and motion planning of a mechanical snake," *IEEE Trans. Syst., Man, Cybern.*, vol. 23, no. 4, pp. 1091–1100, Jul./Aug. 1993.

[29] J. W. Burdick, J. Radford, and G. S. Chirikjian, ''A 'sidewinding' locomotion gait for hyper-redundant robots,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, Jan. 1993, pp. 101–106.
[30] A. Jain, *Robot and Multibody Dynamics: Analysis and Algorithms*. Berlin, Germany: Springer, 2010.
[31] H. Marvi, J. Bridges, and D. L. Hu, ''Snakes mimic earthworms: Propulsion using rectilinear travelling waves,'' *J. Roy. Soc. Interface*, vol. 10, no. 84, Jul. 2013, Art. no. 20130188.
[32] H. W. Lissmann, ''Rectilinear locomotion in a snake (boa occidentalis),'' *J. Experim. Biol.*, vol. 26, no. 4, pp. 368–379, Feb. 1950.
[33] S. Manzoor, U. Khan, and I. Ullah, ''Serpentine and rectilinear motion generation in snake robot using central pattern generator with gait transition,'' *Iranian J. Sci. Technol., Trans. Electr. Eng.*, vol. 44, no. 3, pp. 1093–1103, Sep. 2020.
[34] A. H. Chang and P. A. Vela, ''Shape-centric modeling for control of traveling wave rectilinear locomotion on snake-like robots,'' *Robot. Auto. Syst.*, vol. 124, Feb. 2020, Art. no. 103406.
[35] E. Foo and T. T. Le, ''STARCLY robot—A novel compact stair climbing robot,'' in *Proc. 2nd Int. Conf. Mech. Electron. Eng.*, Aug. 2010, pp. 2–75.
[36] S. Yu, S. Ma, B. Li, and Y. Wang, ''An amphibious snake-like robot with terrestrial and aquatic gaits,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2011, pp. 2960–2961.
[37] A. A. Transeth, K. Y. Pettersen, and P. Liljebäck, ''A survey on snake robot modeling and locomotion,'' *Robotica*, vol. 27, no. 7, pp. 999–1015, Dec. 2009.
[38] R. M. Murray, Z. Li, and S. S. Sastry, *A Mathematical Introduction to Robotic Manipulation*. Boca Raton, FL, USA: CRC Press, 1994.
[39] G. Poi, C. Scarabeo, and B. Allotta, ''Traveling wave locomotion hyper-redundant mobile robot,'' in *Proc. IEEE Int. Conf. Robot. Automat.*, vol. 1, May 1998, pp. 418–423.
[40] O. M. Omisore, S. Han, Y. Al-Handarish, W. Du, W. Duan, T. O. Akinyemi, and L. Wang, ''Motion and trajectory constraints control modeling for flexible surgical robotic systems,'' *Micromachines*, vol. 11, no. 4, p. 386, Apr. 2020.
[41] S. D. Kelly and R. M. Murray, ''Geometric phases and robotic locomotion,'' *J. Robotic Syst.*, vol. 12, no. 6, pp. 417–431, Jun. 1995.
[42] T. Lipták, I. Virgala, P. Frankovský, P. Šarga, A. Gmiterko, and L. Baločková, ''A geometric approach to modeling of four-and five-link planar snake-like robot,'' *Int. J. Adv. Robotic Syst.*, vol. 13, no. 5, 2016, Art. no. 1729881416663714.
[43] K. Tchon and J. Ratajczak, ''Dynamically consistent Jacobian inverse for non-holonomic robotic systems,'' *Nonlinear Dyn.*, vol. 85, no. 1, pp. 107–122, Jul. 2016.
[44] F. Sanfilippo, E. Helgerud, P. Stadheim, and S. Aronsen, ''Serpens: A highly compliant low-cost ROS-based snake robot with series elastic actuators, stereoscopic vision and a screw-less assembly mechanism,'' *Appl. Sci.*, vol. 9, no. 3, p. 396, Jan. 2019.
[45] P. Liljebäck, Ø. Stavdahl, K. Y. Pettersen, and J. T. Gravdahl, ''Two new design concepts for snake robot locomotion in unstructured environments,'' *J. Paladyn Behav. Robot.*, vol. 1, no. 3, pp. 154–159, Jan. 2010.
[46] J. Whitman, N. Zevallos, M. Travers, and H. Choset, ''Snake robot urban search after the 2017 Mexico city earthquake,'' in *Proc. IEEE Int. Symp. Saf., Secur., Rescue Robot. (SSRR)*, Aug. 2018, pp. 1–6.
[47] M. J. Koopaee, C. Pretty, K. Classens, and X. Chen, ''Dynamical modelling and control of snake-like motion in vertical plane for locomotion in unstructured environments,'' in *Proc. Int. Design Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, vol. 59292, 2019, Art. no. V009T12A004.
[48] M. J. Koopaee, C. Pretty, K. Classens, and X. Chen, ''Dynamical modeling and control of modular snake robots with series elastic actuators for pedal wave locomotion on uneven terrain,'' *J. Mech. Des.*, vol. 142, no. 3, Mar. 2020, Art. no. 031120.
[49] A. A. Transeth, R. I. Leine, C. Glocker, and K. Y. Pettersen, ''3-D snake robot motion: Nonsmooth modeling, simulations, and experiments,'' *IEEE Trans. Robot.*, vol. 24, no. 2, pp. 361–376, Apr. 2008.
[50] A. A. Transeth, R. I. Leine, C. Glocker, K. Y. Pettersen, and P. Liljeback, ''Snake robot obstacle-aided locomotion: Modeling, simulations, and experiments,'' *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 88–104, Feb. 2008.
[51] A. Mohammadi, E. Rezapour, M. Maggiore, and K. Y. Pettersen, ''Maneuvering control of planar snake robots using virtual holonomic constraints,'' *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 3, pp. 884–899, May 2016.
[52] A. A. Transeth, R. I. Leine, C. Glocker, and K. Y. Pettersen, ''Non-smooth 3D modeling of a snake robot with frictional unilateral constraints,'' in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Dec. 2006, pp. 1181–1188.
[53] F. L. Chernousko, ''Modelling of snake-like locomotion,'' *Appl. Math. Comput.*, vol. 164, no. 2, pp. 415–434, May 2005.
[54] E. Rezapour, K. Y. Pettersen, P. Liljebäck, J. T. Gravdahl, and E. Kelasidi, ''Path following control of planar snake robots using virtual holonomic constraints: Theory and experiments,'' *Robot. Biomimetics*, vol. 1, no. 1, pp. 1–15, Dec. 2014.
[55] Q. Fu, S. W. Gart, T. W. Mitchel, J. S. Kim, G. S. Chirikjian, and C. Li, ''Lateral oscillation and body compliance help snakes and snake robots stably traverse large, smooth obstacles,'' *Integrative Comparative Biol.*, vol. 60, no. 1, pp. 171–179, Jul. 2020.
[56] X. Wu and S. Ma, ''CPG-controlled asymmetric locomotion of a snake-like robot for obstacle avoidance,'' in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2009, pp. 69–74.
[57] T. Sato, T. Kano, and A. Ishiguro, ''A decentralized control scheme for an effective coordination of phasic and tonic control in a snake-like robot,'' *Bioinspiration Biomimetics*, vol. 7, no. 1, Mar. 2012, Art. no. 016005.
[58] K. Kon, M. Tanaka, and K. Tanaka, ''Mixed integer programming-based semiautonomous step climbing of a snake robot considering sensing strategy,'' *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 1, pp. 252–264, Jan. 2016.
[59] F. Barazandeh, B. Bahr, and A. Moradi, ''How self-locking reduces actuators torque in climbing snake robots,'' in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, Sep. 2007, pp. 1–6.
[60] M. P. Do Carmo, *Differential Geometry of Curves and Surfaces*. Englewood Cliffs, NY USA: Prentice-Hall, 1976.
[61] F. Sanfilippo, J. Azpiazu, G. Marafioti, A. A. Transeth, O. Stavdahl, and P. Liljeback, ''A review on perception-driven obstacle-aided locomotion for snake robots,'' in *Proc. 14th Int. Conf. Control, Autom., Robot. Vis. (ICARCV)*, Nov. 2016, pp. 1–7.
[62] A. J. Davy, ''12 establishment and manipulation of plant populations and communities in terrestrial systems,'' in *Handbook of Ecological Restoration*. Cambridge, U.K.: Cambridge Univ. Press, 2008, p. 223.
[63] C. Ye, D. Hu, S. Ma, and H. Li, ''Motion planning of a snake-like robot based on artificial potential method,'' in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Dec. 2010, pp. 1496–1501.
[64] D. Yag, J. Ren, and R. Liscano, ''Motion planning for multi-link robots using artificial potential fields and modified simulated annealing,'' in *Proc. IEEE/ASME Int. Conf. Mech. Embedded Syst. Appl.*, Jul. 2010, pp. 421–427.
[65] N. M. Nor and S. Ma, ''CPG-based locomotion control of a snake-like robot for obstacle avoidance,'' in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 347–352.
[66] P. Liljeback, O. Stavdahl, K. Y. Pettersen, and J. T. Gravdahl, ''Mamba—A waterproof snake robot with tactile sensing,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 294–301.
[67] C. Holden, O. Stavdahl, and J. T. Gravdahl, ''Optimal dynamic force mapping for obstacle-aided locomotion in 2D snake robots,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 321–328.
[68] Y. Shan and Y. Koren, ''Obstacle accommodation motion planning,'' *IEEE Trans. Robot. Autom.*, vol. 11, no. 1, pp. 36–49, Feb. 1995.
[69] K. Gupta, N. Jaiswal, and V. B. Hency, ''Development of automated sensing system to aid rescue operations after an earthquake,'' *Internation J. Civil Eng. Technol.*, vol. 8, no. 8, pp. 1430–1440, 2017.
[70] G. Seeja, ''A survey on swarm robotic modeling, analysis and hardware architecture,'' *Proc. Comput. Sci.*, vol. 133, pp. 478–485, Jan. 2018.
[71] J. J. Fernandes, ''Kinematic and dynamic analysis of 3PUU parallel manipulator for medical applications,'' *Proc. Comput. Sci.*, vol. 133, pp. 604–611, Jan. 2018.
[72] S. Ma, Y. Ohmameuda, and K. Inoue, ''Dynamic analysis of 3-dimensional snake robots,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2004, pp. 767–772.
[73] B. C. Jayne and J. D. Davis, ''Kinematics and performance capacity for the concertina locomotion of a snake (Coluber constrictor),'' *J. Experim. Biol.*, vol. 156, no. 1, pp. 539–556, Mar. 1991.
[74] B. Moon and C. Gans, ''Kinematics, muscular activity and propulsion in gopher snakes,'' *J. Experim. Biol.*, vol. 201, no. 19, pp. 2669–2684, Oct. 1998.
[75] J. Mukherjee, S. Mukherjee, and I. N. Kar, ''Sliding mode control of planar snake robot with uncertainty using virtual holonomic constraints,'' *IEEE Robot. Automat. Lett.*, vol. 2, no. 2, pp. 1077–1084, Apr. 2017.
[76] G. S. Chirikjian and J. W. Burdick, ''A modal approach to hyper-redundant manipulator kinematics,'' *IEEE Trans. Robot. Autom.*, vol. 10, no. 3, pp. 343–354, Jun. 1994.

[77] K. Ito and Y. Fukumori, "Autonomous control of a snake-like robot utilizing passive mechanism," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2006, pp. 381–386.
[78] G. Seeja, V. Saisudha, G. Manikutty, R. R. Bhavani, and V. R. Pillay, "Speed analysis of DC motor under load and no load condition using CHR based PID and LQR optimal controller," *Int. J. Control Theory Appl.*, vol. 9, no. 15, pp. 7387–7394, 2016.
[79] J. Gonzalez-Gomez, J. Gonzalez-Quijano, H. Zhang, and M. Abderrahim, "Toward the sense of touch in snake modular robots for search and rescue operations," in *Proc. ICRA*, Anchorage, AK, USA, May 2010, pp. 63–68.
[80] X. Wu and S. Ma, "Development of a sensor-driven snake-like robot SR-I," in *Proc. IEEE Int. Conf. Inf. Autom.*, Shenzhen, China, Jun. 2011, pp. 157–162.
[81] S. R. Taal, H. Yamada, and S. Hirose, "3 axial force sensor for a semi-autonomous snake robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2009, pp. 4057–4062.
[82] C. Fox, M. Evans, M. Pearson, and T. Prescott, "Tactile SLAM with a biomimetic whiskered robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2012, pp. 4925–4930.
[83] M. J. Pearson, C. Fox, J. C. Sullivan, T. J. Prescott, T. Pipe, and B. Mitchinson, "Simultaneous localisation and mapping on a multi-degree of freedom biomimetic whiskered robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, Karlsruhe, Germany, May 2013, pp. 586–592.
[84] P. Chavan, M. Murugan, E. V. V. Unnikkannan, A. Singh, and P. Phadatare, "Modular snake robot with mapping and navigation: Urban search and rescue (USAR) robot," in *Proc. Int. Conf. Comput. Commun. Control Autom.*, Pune, India, Feb. 2015, pp. 537–541.
[85] M. Tanaka, K. Kon, and K. Tanaka, "Range-sensor-based semiautonomous whole-body collision avoidance of a snake robot," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 5, pp. 1927–1934, Sep. 2015.
[86] H. Ponte, M. Queenan, C. Gong, C. Mertz, M. Travers, F. Enner, M. Hebert, and H. Choset, "Visual sensing for developing autonomous behavior in snake robots," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Hong Kong, May 2014, pp. 2779–2784.
[87] M. Yamakita, M. Hashimoto, and T. Yamada, "Control of locomotion and head configuration of 3D snake robot (SMA)," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 2, Taipei, Taiwan, Sep. 2003, pp. 2055–2060.
[88] X. Xiao, E. Cappo, W. Zhen, J. Dai, K. Sun, C. Gong, M. J. Travers, and H. Choset, "Locomotive reduction for snake robots," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Seattle, WA, USA, May 2015, pp. 3735–3740.
[89] S. Ma, N. Tadokoro, and K. Inoue, "Influence of the gradient of a slope on optimal locomotion curves of a snake-like robot," *Adv. Robot.*, vol. 20, no. 4, pp. 413–428, Jan. 2006.
[90] Y. Alkendi, L. Seneviratne, and Y. Zweiri, "State of the art in vision-based localization techniques for autonomous navigation systems," *IEEE Access*, vol. 9, pp. 76847–76874, 2021.
[91] T. Kano and A. Ishiguro, "Obstacles are beneficial to me! Scaffold-based locomotion of a snake-like robot using decentralized control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 3273–3278.
[92] T. Kano and A. Ishiguro, "Decoding decentralized control mechanism underlying adaptive and versatile locomotion of snakes," *Integrative Comparative Biol.*, vol. 60, no. 1, pp. 232–247, Jul. 2020.
[93] J. Seetohul and M. Shafiee, "Snake robots for surgical applications: A review," *Robotics*, vol. 11, no. 3, p. 57, May 2022.
[94] P. Boyraz, G. Runge, and A. Raatz, "An overview of novel actuators for soft robotics," *Actuators*, vol. 7, no. 3, p. 48, Aug. 2018.
[95] B. Klaassen and K. L. Paap, "GMD-SNAKE2: A snake-like robot driven by wheels and a method for motion control," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 4, May 1999, pp. 3014–3019.
[96] J. Borenstein, M. Hansen, and A. Borrell, "The OmniTread OT-4 serpentine robot—Design and performance," *J. Field Robot.*, vol. 24, no. 7, pp. 601–621, 2007.
[97] J. Borenstein, G. Granosik, and M. Hansen, "The OmniTread serpentine robot: Design and field performance," in *Proc. SPIE*, vol. 5804, pp. 324–332, May 2005.
[98] T. Kano, R. Yoshizawa, and A. Ishiguro, "Tegotae-based decentralised control scheme for autonomous gait transition of snake-like robots," *Bioinspiration Biomimetics*, vol. 12, no. 4, Aug. 2017, Art. no. 046009.
[99] T. Kano, T. Sato, R. Kobayashi, and A. Ishiguro, "Local reflexive mechanisms essential for snakes' scaffold-based locomotion," *Bioinspiration Biomimetics*, vol. 7, no. 4, Dec. 2012, Art. no. 046008.
[100] A. Morishima and S. Hirose, "Impedance control of articulated body mobile robot 'Koryu,'" in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Jul. 1993, pp. 1786–1790.
[101] J. Liu, X. Zhang, and G. Hao, "Survey on research and development of reconfigurable modular robots," *Adv. Mech. Eng.*, vol. 8, no. 8, Aug. 2016, Art. no. 168781401665959.
[102] H. Date and Y. Takita, "Adaptive locomotion of a snake like robot based on curvature derivatives," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2007, pp. 3554–3559.
[103] T. Sato, W. Watanabe, and A. Ishiguro, "An adaptive decentralized control of a serpentine robot based on the discrepancy between body, brain and environment," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2010, pp. 709–714.
[104] T. Sato, T. Kano, and A. Ishiguro, "On the applicability of the decentralized control mechanism extracted from the true slime mold: A robotic case study with a serpentine robot," *Bioinspiration Biomimetics*, vol. 6, no. 2, Jun. 2011, Art. no. 026006.
[105] C. Wright, A. Johnson, A. Peck, Z. McCord, A. Naaktgeboren, P. Gianfortoni, M. Gonzalez-Rivero, R. Hatton, and H. Choset, "Design of a modular snake robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2007, pp. 2609–2614.
[106] M. Yim, D. G. Duff, and K. D. Roufas, "PolyBot: A modular reconfigurable robot," in *Proc. IEEE Int. Conf. Robot. Automat. Symp.*, Apr. 2000, pp. 514–520.
[107] Z. Lu, S. Ma, B. Li, and Y. Wang, "3D locomotion of a snake-like robot controlled by cyclic inhibitory CPG model," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2006, pp. 3897–3902.
[108] P. Liljebäck, Ø. Stavdahl, and K. Y. Pettersen, "Modular pneumatic snake robot 3D modelling, implementation and control," *IFAC Proc.*, vol. 38, no. 1, pp. 19–24, 2005.
[109] Y. Hiroya and S. Hirose, "Development of practical 3-dimensional active cord mechanism ACM-R4," *J. Robot. Mechatron.*, vol. 18, no. 3, pp. 305–311, Jun. 2006.
[110] E. Shammas, A. Wolf, and H. Choset, "Three degrees-of-freedom joint for spatial hyper-redundant robots," *Mechanism Mach. Theory*, vol. 41, no. 2, pp. 170–190, Feb. 2006.
[111] C. Ye, S. Ma, B. Li, H. Liu, and H. Wang, "Development of a 3D snake-like robot: Perambulator-II," in *Proc. Int. Conf. Mechatronics Autom.*, Aug. 2007, pp. 117–122.
[112] P. Berthet-Rayne, K. Leibrandt, K. Kim, C. A. Seneci, J. Shang, and G.-Z. Yang, "Rolling-joint design optimization for tendon driven snake-like surgical robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 4964–4971.
[113] M. M. Dalvand, S. Nahavandi, and R. D. Howe, "An analytical loading model for *n*-tendon continuum robots," *IEEE Trans. Robot.*, vol. 34, no. 5, pp. 1215–1225, Oct. 2018.
[114] B. Li, S. Ma, C. Ye, S. Yu, G. Zhang, and H. Gong, "Development of an amphibious snake-like robot," in *Proc. 8th World Congr. Intell. Control Autom.*, Tokyo, Japan, Jul. 2010, pp. 613–618.
[115] X. Qi, H. Shi, T. Pinto, and X. Tan, "A novel pneumatic soft snake robot using traveling-wave locomotion in constrained environments," *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 1610–1617, Apr. 2020.
[116] M. Ahmed and M. M. Billah, "Smart material-actuated flexible tendon-based snake robot," *Int. J. Adv. Robotic Syst.*, vol. 13, no. 3, p. 89, May 2016.
[117] M. J. Koopaee, S. Bal, C. Pretty, and X. Chen, "Design and development of a wheel-less snake robot with active stiffness control for adaptive pedal wave locomotion," *J. Bionic Eng.*, vol. 16, no. 4, pp. 593–607, Jul. 2019.
[118] P. Racioppo and P. Ben-Tzvi, "Design and control of a cable-driven articulated modular snake robot," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 3, pp. 893–901, Jun. 2019.
[119] P. Liljebäck, K. Y. Pettersen, Ø. Stavdahl, and J. T. Gravdahl, *Snake Robots* (Advances in Industrial Control). London, U.K.: Springer, 2013.
[120] Z. Mu, H. Wang, W. Xu, T. Liu, and H. Wang, "Two types of snake-like robots for complex environment exploration: Design, development, and experiment," *Adv. Mech. Eng.*, vol. 9, no. 9, Sep. 2017, Art. no. 168781401772185.
[121] A. Duivon, P. Kirsch, B. Mauboussin, G. Mougard, J. Woszczyk, and F. Sanfilippo, "The redesigned serpens, a low-cost, highly compliant snake robot," *Robotics*, vol. 11, no. 2, p. 42, Apr. 2022.
[122] Z. Zhang, J. Shang, C. Seneci, and G.-Z. Yang, "Snake robot shape sensing using micro-inertial sensors," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 831–836.

[123] H. Date and Y. Takita, "An electricity-free snake-like propulsion mechanism driven and controlled by fluids," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2009, pp. 3637–3642.
[124] D. Zhang, H. Yuan, and Z. Cao, "Environmental adaptive control of a snake-like robot with variable stiffness actuators," *IEEE/CAA J. Autom. Sinica*, vol. 7, no. 3, pp. 745–751, May 2020.
[125] I. Virgala, M. Kelemen, P. Božek, Z. Bobovský, M. Hagara, E. Prada, P. Oscádal, and M. Varga, "Investigation of snake robot locomotion possibilities in a pipe," *Symmetry*, vol. 12, no. 6, p. 939, Jun. 2020.
[126] M. Kelemen, I. Virgala, T. Lipták, L. Miková, F. Filakovský, and V. Bulej, "A novel approach for a inverse kinematics solution of a redundant manipulator," *Appl. Sci.*, vol. 8, no. 11, p. 2229, Nov. 2018.
[127] K. Osuka and H. Kitajima, "Development of mobile inspection robot for rescue activities: MOIRA," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2003, pp. 3373–3377.
[128] Y. Hu, A. Xu, J. Liu, L. Yang, L. Chang, M. Huang, W. Gu, G. Wu, P. Lu, W. Chen, and Y. Wu, "Multifunctional soft actuators based on anisotropic paper/polymer bilayer toward bioinspired applications," *Adv. Mater. Technol.*, vol. 4, no. 3, Mar. 2019, Art. no. 1800674.
[129] H. R. Choi, K. Jung, S. Ryew, J.-D. Nam, J. Jeon, J. C. Koo, and K. Tanie, "Biomimetic soft actuator: Design, modeling, control, and applications," *IEEE/ASME Trans. Mechatronics*, vol. 10, no. 5, pp. 581–593, Oct. 2005.
[130] R. Kornbluh, R. Pelrine, J. Eckerle, and J. Joseph, "Electrostrictive polymer artificial muscle actuators," in *Proc. IEEE Int. Conf. Robot. Automat.*, vol. 3, May 1998, pp. 2147–2154.
[131] A. Kamimura, S. Murata, E. Yoshida, H. Kurokawa, K. Tomita, and S. Kokaji, "Self-reconfigurable modular robot–experiments on reconfiguration and locomotion," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. Expanding Societal Role Robot. Next Millennium*, Oct. 2001, pp. 606–612.
[132] J. Liu, Y. Wang, S. Ma, and B. Li, "Analysis of stairs-climbing ability for a tracked reconfigurable modular robot," in *Proc. IEEE Int. Saf., Secur. Rescue Rototics, Workshop*, Jun. 2005, pp. 36–41.
[133] I. Tanev, "Incorporating learning probabilistic context-sensitive grammar in genetic programming for efficient evolution and adaptation of snakebot," in *Proc. Eur. Conf. Genet. Program.* Berlin, Germany: Springer, 2005, pp. 155–166.
[134] A. K. Tran, A. Budiyono, and K. J. Yoon, "Design and analysis of a locomotive module for snake-mimetic robots using mini-LIPCAs," in *Proc. IEEE Int. Conf. Multisensor Fusion Integr. Intell. Syst.*, Aug. 2008, pp. 131–136.
[135] N. El-Atab, R. B. Mishra, F. Al-Modaf, L. Joharji, A. A. Alsharif, H. Alamoudi, M. Diaz, N. Qaiser, and M. M. Hussain, "Soft actuators for soft robotic applications: A review," *Adv. Intell. Syst.*, vol. 2, no. 10, Oct. 2020, Art. no. 2000128.
[136] B. Liu, A. Zhang, J. Liu, Z. Han, and T. Xie, "Design and evaluation of a novel rotatable one-element snake bone for NOTES," *J. Med. Devices*, vol. 12, no. 2, pp. 1–8, Jun. 2018.
[137] N. Zhu, H. Zang, B. Liao, D. Liu, J. Tuo, T. Zhou, and Q. Wang, "The effect of different scales on the crawling rate of bionic snake robot," in *Proc. WRC Symp. Adv. Robot. Autom. (WRC-SARA)*, Aug. 2018, pp. 22–27.
[138] H. Kimura and S. Hirose, "Development of Genbu : Active wheel passive joint articulated mobile robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, vol. 1, Oct. 2002, pp. 823–828.
[139] P. Sears and P. Dupont, "A steerable needle technology using curved concentric tubes," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2006, pp. 2850–2856.
[140] W. Ouyang, W. Liang, C. Li, H. Zheng, Q. Ren, and P. Li, "Steering motion control of a snake robot via a biomimetic approach," *Frontiers Inf. Technol. Electron. Eng.*, vol. 20, no. 1, pp. 32–44, Jan. 2019.
[141] G. Wang, W. Yang, Y. Shen, and H. Shao, "Adaptive path following of snake robot on ground with unknown and varied friction coefficients," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 7583–7588.
[142] C. Li, S. Zhen, H. Sun, and H. Zhao, "Constraints following control of snake robot by leakage-type adaptive law," in *Proc. 3rd Int. Conf. Adv. Robot. Mechatronics (ICARM)*, Jul. 2018, pp. 274–279.
[143] X. Zhang, J. Liu, Z. Ju, and C. Yang, "Head-raising of snake robots based on a predefined spiral curve method," *Appl. Sci.*, vol. 8, no. 11, p. 2011, Oct. 2018.
[144] H. Matsuura, M. Mizutame, Y. Moriyama, H. Shimada, S. Hirose, and Y. Umetani, "Measuring/grinding system for water turbine runner," in *Proc. 2nd Int. Conf. Adv. Res.*, 1985, pp. 199–206.
[145] F. Saito, T. Fukuda, and F. Arai, "Swing and locomotion control for a two-link brachiation robot," *IEEE Control Syst. Mag.*, vol. 14, no. 1, pp. 5–12, Feb. 1994.
[146] J. Yan, B. Pan, Y. Qi, J. Ben, and Y. Fu, "Prior knowledge snake segmentation of ultrasound images denoised by J-divergence anisotropy diffusion," *Int. J. Med. Robot. Comput. Assist. Surgery*, vol. 14, no. 5, p. e1924, Oct. 2018.

G. SEEJA received the bachelor's degree from Kerala University, India, in 2014, and the master's degree from Amrita Vishwa Vidyapeetham, Kerala, India, in 2016. She is currently a full-time Research Scholar with the School of Electronics Engineering, Vellore Institute of Technology, Chennai, India. Her research interests include robot kinematics, autonomous robots, industrial robots, rescue robots, machine learning, and artificial intelligence.

AROCKIA SELVAKUMAR AROCKIA DOSS (Senior Member, IEEE) received the bachelor's degree in mechanical engineering from Bharathiyar University, Tamil Nadu, India, and the master's degree in computer-aided design (CAD) and the Ph.D. degree in robotics from Anna University, Tamil Nadu, India. He is currently working as a Professor with the School of Mechanical Engineering, an Assistant Director of the Career Development Centre, and In-Charge of robotics club activities at the Vellore Institute of Technology, Chennai, India. His research interests include parallel manipulators, robotics and automation, the IoT, mechanism design, and failure analysis. He is a member of the Robotic Society of India (RSI). He was the Chairperson of the Indian Rover Challenge 2020 (IRC 2020). He was the Convener of the 1st, 2nd, and 3rd International Conferences on Robotics, Intelligent Automation, and Control Technologies (RIACT 2021, RIACT 2022, and RIACT 2023).

V. BERLIN HENCY received the bachelor's degree from Manonmaniam Sundaranar University, Tamil Nadu, India, the master's degree from the Sathyabama Institute of Science and Technology, Tamil Nadu, and the Ph.D. degree in information and communication engineering from Anna University, Tamil Nadu. She is currently an Associate Professor (Senior) with the School of Electronics Engineering (SENSE), Vellore Institute of Technology, Chennai, India. Her research interests include wireless networks, the IoT, and robotics.