Modelling, Design and Kinematic Control Strategies for Snake-like Robot locomotion – A Review

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Abstract: **Research on the development of robots that mimic biological snakes has been a major trend in the past few years. This work reviews the major research efforts and contributions to snake-like robots focusing on previous research efforts on snake-like robots modelling techniques, snake-like robots physical design, the kinematic and morphological control strategies for snake-like robot locomotion and practical applications of snake-like robots. The possibility of designing locomotion control model based on Reinforcement learning for snake-like robot was also investigated. The reviewed literatures revealed that even though more research works have considered snake-like robot locomotion on environments without obstacles or lab environments, there is now a growing interest in designing and developing snake-like robots for locomotion in environments with obstacles and that could be used in real life applications rather than in the lab environment. The review also shows that application of Reinforcement Learning method in designing control model for snake-like robot locomotion rather than the traditional and conventional control methods proposed by majority of the literatures on snake-like robots is attracting a lot of research interest.**

***Keywords*: Biological snake, snake-like robot, design, modelling, control, kinematics, Reinforcement learning.**

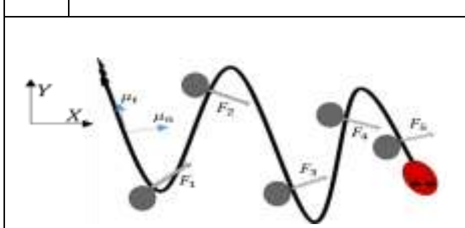
I. INTRODUCTION

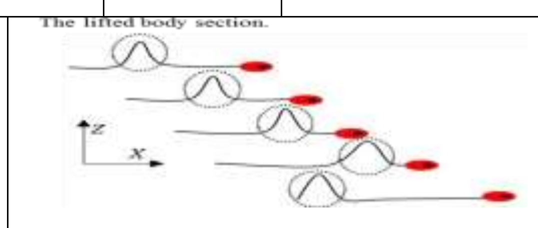
Biological snakes are astounding creatures and are optimal when on motion and their physical characteristics allow them to adapt to a wide range of natural environment. Grey who carried out early analytical and empirical study on biological snake identified four types of locomotion gaits that biological snake can exihibit at any point in time. This locomotion gaits include serpentine or lateral undulation, rectilinear, concentina and sidewinding locomotion [1]. The serpentine or lateral undulation is used by snakes for locomotion on flat surfaces and it is a very efficient locomotion and commonly used by snakes for locomotion. Snakes exhibits rectilinear locomotion gait by alternating their ribs and muscles. Rectilinear locomotion is not a very efficient gait and is usually used by snakes when trailing prey. Concentina gait is also not very efficient and is used for crawling a tree. The sidewinding is a 3D spiral gait and achieved when combine serpentine and rectilinear gait snake and it is a very efficient locomotion gait used by snakes. Figures 1 – 3 in Table 1, shows the pictorial representation of the four commonly used gaits for snake locomotion.

The advent of bionic has inspired so many researches in robust motion capabilities and behaviours of the biological snake with the view to developing snake-like robots. Snake-like robots typically consist of joint models that are serially connected together and have the ability of bending in one or more planes. Snake-like robot has several advantages over conventional wheeled, tracked or legged robots. Firstly, the body of the snake has contact with the ground when on motion and because of this, the snake has low center of gravity and this gives the snake-like robot stability during locomotion. Secondly, because of the multiple joints in snake-like robots, the robot has hyper-redundant degrees of freedom and can produce different locomotion gaits. Also because of the snake-like robot body shape, the robot find application in so many areas of human endeavour especially for locomotion in environments with irregularities and difficult terrains. However, deleoping and designing control mechanism for snake-like robot is a very challenging task because of the many degrees of freedom of snake-like robots, but this capability provides the snake-like robot the ability to traverse well in a cluthered environments compared to the ability of other types of robots with legs or wheels.

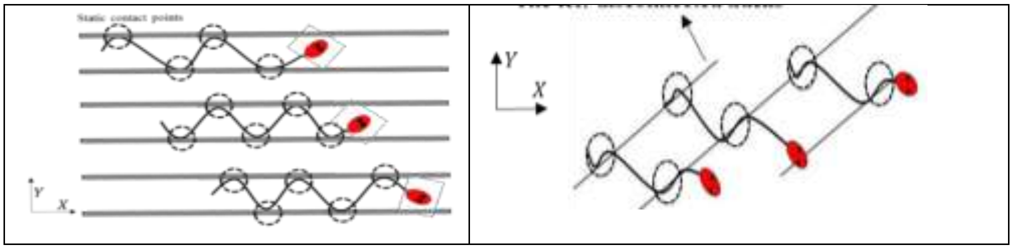
Table 1: Snake locomotion gaits

1	Serpentine/Lateral Undulation gait (Fig.1)	2	Rectilinear gait (Fig.2)





3	Concertina gait (Fig.3)	4	Sidewinding gait (Fig.4)



Snake-like robot research has been on for several decades now. As far back as 1940s, experimental and analytical studies on snake-like robot locomotion have already been reported [1], and by 1972, Hirose developed the first snake-like robot [2]. Literatures on snake-like robot motion control and modelling have thrived immensely with numerous proposed approaches on snake-like robot modelling and locomotion control models. This work reviews research efforts in this regard with the sole aim of identifying important locomotion control techniques for snake-like robot movement which will aid more research in a more complex and practical application of snake-like robot. The work also investigates the possibility of designing locomotion control model for snake-like robot based on Reinforcement learning.

II. SNAKE-LIKE ROBOT MODELLING TECHNIQUES

The work in [1] was one of the earliest research work on snake-like robot motion where the properties of the snake-like robot motion was derived mathematically to describe the forces acting on a snake-like robot. The work concluded that for a planner snake-like robot to move forward, external forces must act on the snake robot body. [2] in 1972, developed the first snake-like robot where the properties of biological snake was used to model snake-like robot body as a continuous curve. The study resulted in the formulation of serpenoid curve, which mathematically describes the locomotion gait used by most snakes during locomotion on flat surfaces known as serpentine locomotion or lateral undulation. The research also investigated the efficiency of snake-like robot in a maize. The work in [3], mathematically modelled the muscle properties of snakes and used this model to derive the kind of body shape snakes exhibit during serpentine locomotion which he called serpentine curve. The work was able to show that the locomotive efficiency of serpentine curve is higher than that of the serpenoid curve. The mechanism of the muscle activities of the snake as it interacts with the environments was studied in [4] to produce curverture and propulsion to enable snake-like robot push itself forward. As observed in [1], biological snake performing lateral undulation, the head traces a path on the ground and the entire body of the snake follows the path. This is possible because of the anisotropy friction of snake skin [7]. This could also be because of obstacles on the environment that provides a form of grip for the snake and be able to propel the snake forward. To imitate this motion capability in snake-like robots, researchers introduced nonholonoic constraints in the snake-like robust motion equation with the assumption that the snake body can only move forward [78]. This is achieved in practice by equipping the snake-like robot with passive wheels along the body.

Differential geometry was used in [22] and [5] to design wheeled snake-like robot and presented the kinematics model of the snake-like robot. Similar approaches was used by [6] and [93] where they considered the dynamics of the wheeled robot and utilized system symmetries to achieve a better result. Lagrange’s equation of motion has also been used to model a two dimensional dynamics of a wheeled snake-like robot [9] and in [10] equation of motion was modelled from first principles. In [11], a kinematics model of two dimensional snake-like robots was presented and in the work of [12], the dynamics of three dimensional snake-like robots, where some of the links are not wheeled was proposed. [111] employed the Newton-Euler equations to build a two dimensional snake-like robot dynamics model employing anisotropic ground friction properties. [17] Extended this snake model to describe snake-like robot motion on a slope. [18] Proposed a simple snake-like robot locomotion model by modelling the snake body shape changes as purely linear displacements of the snake-like robot links. [23], [24], [25] considered isotropic ground friction forces in modelling and analysing planar snake-like robots locomotion while a planar snake-like robot locomotion was described as a continuum model in [7] by treating the snake-like robot as a continuous curve.

Research has also been very active in the area of modelling snake-like robots for locomotion in rough terrains. The macroscopic structure of the snake body and their quick response to environmental forces is a major factor in snake locomotion. Because of this, [93] proposed a Backbone curve which is based on flexible shape modelling method. The result is very important due to the fact that most research on snake-like robot modeling for locomotion in environments with obstacle is attacked at a purely kinematic level. [30] Approached kinematic modelling of hyper-redundant snake-like robot on a two-step modelling process. First using the backbone curve to extract the necessary macroscopic features of a hyper-redundant snake-robot and in the second step, used the backbone curve geometry to specify the actual mechanism’s joint displacement. [26], [79] modelled a snake-like robot by imposing kinematic constraints on the robot due to external obstacles. They also analysed the effect of obstacles surrounding a snake-like robot on its degrees of freedom.

The dynamics of snake-like robots locomotion on surfaces with irregularities also was studied by [28], [32], [29], [33], [27]. [28] Performed dynamic simulation of a planar snake-like robot that interacts with obstacles around the robot using simulation software known as WorkingModel. [32] Also used Open Dynamic Engine (ODE) to design a snake-like robot that interacts with different obstacles. Autolev, a multibody dynamic simulation software was used by [29] for modelling snake-like robot motion. The underlying equations for the dynamics of the robots were not provided because of general purpose simulation software used. A nonsmooth dynamics model of snake-like robot was formulated in [33]. A worm-like locomotion was considered by [80] and presented a detailed dynamics and kinematics of a planar multi-link snake-like robots using Lagrange's method while the effect of link shape on motor torques was investigated experimentally and webots software was used for simulation. An analysis of a planar kinematics of a snake-like robot meant to overcome the nonholonomic kinematic constraints which characterizes typical wheeled robots was presented in [81]. In [82], an algorithm called Conditional Basis Array Factorization (CBAF) was used to analyze a shape trajectory data in a high dimensional data arrays onto a low dimensional representation while in [83] a modified serpenoid curve for optimal motion was presented. Snake-like robot movement is very difficult in long and narrow spaces whose diameter is very similar to that of the snake-like robot. This kind of problem was studied by [20] and a retractable snake-like robot based on 2-RRU/URR parallel module was proposed. A rectilinear locomotion gait was studied in [13], the kinematics, detailed dynamics and optimization of torque values were presented using Genetic Algorithm.

III. PHYSICAL SNAKE-LIKE ROBOT DEVELOPMENT

In 1972, Hirose built the first snake-like robot with passive wheels that used anisotropic ground friction characteristics to move well on flat surfaces [2]. Since the development of the first snake-like robots by Hirose, many other research on snake-like robot with passive wheels have been carried out as can be seen in the research works of [35], [36], [37], [38], [40], [39], [41] [42], [43], [44], [45], [46]. A common feature of robots with passive wheels is that they locomot well on a relatively flat surfaces but does badly on cluttered environments. Massive efforts have been made by researchers in an attempt to build snake-like robots without passive wheels. These types of robots are more suited for environments with obstacles compared to robots with passive wheels. [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [15], [58], [59], [60] have made great efforts in this regard. The robot in [15] employed an anosortopic ground friction properties and this allowed the robot move forward by lateral undulation. Robots in [53], [60] maintained an isotropic ground friction properties and so the robot moved forward by lifting the body from the ground or what is called sinus-lifting. However, isotropic ground friction can also be used to study other gaits such as sidewining, inchworm motion. By equipping the individual links of the robot with motorized wheels, the works in [61], [62], [63] achieved active propulsion along the snake-like robot body. In [64], [65], [66], [67], [68] a track was installed along the snake-like robot body while [69] employed screw drive mechanism.

To effectively control any robotic mechanism, smart controllers require sensors to acquire information about their surrounding environments and to effectively use this information to control the behaviour of the robot. However, equipping snake-like robots with sensors is a challenging task because snake-like robot modules move at a constant rate [91]. Snake-like robots built for environments with irregularities are usually equipped with torque, force or pressure sensors which enable them acquire information about their environment. Despite the recent progress in the development of snake-like robots without passive wheels, equipping such robots with torque/force sensing mechanism remains a challenging task. This is because available space between each snake-like robot joints is small. [71] proposed and designed a snake-like robot with a contact sensor where each module of the snake-like robot can be wrapped around the contact sensor.

IV. SNAKE-LIKE ROBOT CONTROL STRATEGIES

Several research works has been done in the area of snake-like robot locomotion control in a prearranged environments, the works in [63] and [64] considered different properties such as robustness and proposed gait patterns for snake-like robot. For instance, in environments without obstgalces, most of the controllers proposed so far are based on a sinusoidal gait pattern which generates the joint angles as can be seen in [34]. [65] Introduced a bio-inspired oscillator known as Central Pattern Generator (CPGs). In [2] a serpentine locomotion which is one of the most researched snake locomotion gait was achieved by a serpenoid curve where the snake-like robot's joints are controlled by sinusoidal reference. The work in [26], proposed a method for forward and turning motion for snake-like robot that uses solenoids. The solenoid enables the snake-like robot to attach itself to the environment. In [5], [93], the researchers showed how inputs derived from differential geometry can be be applied to wheeled snake-like robot to generate propulsion. Lyapunov function was employed by [72] to build and position a controller for a snake-like with passive wheels to achieve a path following locomotion.

Snake-like robot locomotion in environments with irregularities has also been studied. Locomotion control model based on the idea of the snake-like robot using the obstacles around its body as an aid for locomotion was proposed in the work of [33]. Control mechanism for snake-like robot that uses contact force sensing for locomotion was proposed in the works of [2], [28], [70], [27]. [70] proposed kinematic approach for the control of snake-like robot where the robot shape was determined by using curve fitting techniques with respect to the obstacles detected. Locomotion model for snake-like robots based on hybrid controllers for robot in environments with irregularities was proposed in [27]. [77] experimented with the controller proposed in [27] and result showed that the controller propelled a physical snake-like robot through various obstacles. Controllers for snake-like robot motion on surfaces with irregularities where interactions between the environment and the snake-like robot does not require sensor has also been presented. An algorithm presented in [23], a contact constraints is imposed on snake-like robot and computed the torques of the robot joints that generated the required locomotion. Climbing gaits and other locomotion models aimed at propelling snake-like robot in a cluttered environment are presented in the works of [74], [55], [75], [76]. In [95], a slithering gait for the snake-like robot for autonomous locomotion purpose was proposed. The relationship between the kinematic characteristics and the gait parameters were analyzed in detail including the stability, forward velocity and steering radius. Simulations and prototype experiments demonstrated the practicality and effectiveness of the proposed method. [111] proposed an improved serpentine locomotion control algorithm by attaching a new angular parameter to compensate for the slipping problem in the original serpentine curve. To achieve high performance in a complex environment, [98] presented a control system that utilizes STM332 as a real-time image acquisition, multisensory fusion, and wireless communication technology. The control model was based on simplified CPG model. A terrain adaptive control model that is based on torque control was proposed by [92] and the feasibility of the control model was validated through experiments and simulations. The frictional forces between snake-like robot's body and the ground was used by [94] to develop a locomotion control model for snake-like robot consisting of three links. The effectiveness and efficiency of the model was verified through simulations and experiments.

Control models have also been studied for underwater snake-like robots. In the work of [14], a control model based on coordinated drive turning was proposed. The aim was to enhance the turning performance of the snake-like robot during locomotion. The result from the simulation proved that the method proposed greatly improved the movability of the turning gait process of underwater snake-like robot. Several other control methods for underwater snake-like robots have been studied as can be seen in [84], [100], [101], [83]. Snake-like robot motion controllers based on Reinforcement learning method have been proposed in recent years. In [102], a learning method for a CPG controller was proposed known as CPG-actor-critic model. In the proposed method, CPG neurons and the controlled object were treated as a single dynamic system called CPG-coupled system and RL tried to control the CPG-coupled system. Similar research has also been carried out by [103] and [104]. In [103], an automatic control model for snake-like robot was achieved by reinforcement learning while [104] proposed a design of a robot with snake-like body based on the environment of the snake-like robot. The state-action space was explored for reinforcement learning. The work in [105] presented a Reinforcement Learning control model to generate snake-like robot locomotion gaits at different velocities, which was trained using proximal policy optimization algorithm. The RL control model exhibited acceptable and adaptive movements and conserved energy more efficiently than the gaits generated by parameterized controllers.

V. PRACTICAL APPLICATIONS OF SNAKE-LIKE ROBOT

Several studies have been carried out to investigate biological snake movements with the sole aim of replicating this biological snake movement style into a snake-like robot, but very few of these researches have resulted in practical applications. [106], studied and developed a SnakeFighter, a snake-like robot for extinguishing fire. Though the focus of the research was not on snake movement, the SnakeFighter robot was equipped with a water hose and can be utilized in putting out fire. Another area where the potentials of snake-like robot could be utilized is in the area of search and rescue missions, where other robots like legged robots might not be as optimal. A prototype snake-like robot called ACMR4.1 was developed by [92] for practical inspection applications. The robot was equipped with a torque sensing mechanism, a dust and water proof structure and a CAM system. The test outcome showed that mobility in rough terrains improved greatly. In the work of [16], a snake-like robot with a portable controller was designed. The robot developed is controlled via a smartphone to simplify the complex operation. Snake-like robots has also been proposed for pipe inspection. In the work of [8], a small envelope gait (SEG) based on the follow-the-leader method was proposed. Snake-like robot also find its application in Minimally Invasive Surgery i.e. where a medical robots devices can follow anatomical pathways to perform surgery. In [108], a minimally invasive snake-like robot was presented for radiosurgery of gastrointestinal tumor while in [109] inverse kinematics control method for redundant snake-like robot teleportation when performing minimally invasive surgery was presented. [110] proposed a Deeply-learnt damped least squares method for solving inverse kinematics (IK) of spatial snake-like robot. The proposed method had achieved a reachability measure of over 90% and was reported to be computationally efficient, fast and maneuvers singular points simultaneously.

VI. CONCLUSION

This paper reviewed research efforts on design, analysis and control of snake-like robots. The review shows that most of the works considers snake-like robot motion over environments without irregularities and therefore the need for more research in the area of developing control models for snake-like robot locomotion in real environments with irregularities than in the lab environment. It has been observed also that most of the attempts made in designing snake-like robot locomotion are based on pure heuristics where experiments and simulations are the most common approach for providing support for designed control strategies. There is therefore the need for more research on the area of designing controllers that will be based on mathematical models that can be easily analyzed and as well as established control design techniques. More researches are also required in the area of snake-like robots for environments with obstacles since most of the researches available are focused on snake-like robot locomotion on flat surfaces or lab environment. The review also showed that research efforts on methods involving the use of Reinforcement Learning algorithm in the design of control model is a very promising area but requires more research to effectively apply reinforcement learning in the design of controllers for snake-like robots outside simulation environments. From the review also, there is a growing interest in the application and use of snake-like robots in solving real life problems in the areas such as search and rescue operations, firefighting, pipe inspection, underwater exploration and most recently for minimally invasive surgery.

Finally, research towards designing snake-like robot for locomotion in environments with irregularities is increasing tremendously and to realize the capabilities and potentials of snake-like robots in the nearest future, this trend will have to be maintained and strengthened.

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