A Review on Perception-driven Obstacle-aided Locomotion for Snake Robots*

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***Abstract*—Biological snakes can gracefully traverse a wide range of different and complex environments. Snake robots that can mimic this behaviour could be fitted with sensors and also transport tools to hazardous or confined areas that other robots and humans are unable to access. To carry out such tasks, snake robots must have a high degree of awareness of their surroundings (i.e. *perception-driven* locomotion) and be capable of efficient obstacle exploitation (i.e. *obstacle-aided locomotion*) to gain propulsion. These aspects are important to realise the large variety of possible snake robot applications in real-life operations such as fire-fighting, industrial inspection, search-and-rescue and more. In this paper, an elaborate review and discussion of the state-of-the-art, challenges and possibilities of perception-driven obstacle-aided locomotion for snake robots is presented for the first time. Pertinent to snake robots, we focus on current strategies for obstacle avoidance, obstacle accommodation, and obstacle-aided locomotion. Moreover, we put obstacle-aided locomotion into the context of perception and mapping. To this end, we present an overview of relevant key technologies and methods within environment perception, mapping and representation that constitute important aspects of perception-driven obstacle-aided locomotion.**

I. Introduction

In nature, snakes are capable of performing an astounding variety of tasks. They can locomote, swim, climb and even glide through the air in some species [1]. One of the most interesting features of biological snakes is their ability to exploit roughness in the terrain for locomotion [2], which allows them to adapt to different types of environments. Biological snakes may push against rocks, stones, branches, obstacles, or other environment irregularities. They can also exploit the walls and surfaces of narrow passages or pipes for locomotion.

Building a robotic snake with such agility is one of the most attractive steps to fully mimic the movement of biological snakes. The development of such a robot is motivated by the fact that different applications may be realised for use in challenging real-life operations, pipe inspection for oil and gas industry, fire-fighting operations and search-and-rescue. Snake robot locomotion in a cluttered environment where the snake robot utilises walls or external objects, other than the flat ground, for means of propulsion can be defined as *obstacle-aided locomotion* [3], [4]. This challenging control scheme requires a mathematical model that includes the interaction between the snake robot and the surrounding operational environment. This model can take into account the external objects that the snake robot uses in the environment as push-points to propel itself forwards. In this perspective, the environment perception, mapping and representation is fundamental for the model. We use the term *perception-driven obstacle-aided locomotion* as locomotion where the snake robot utilises a sensory-perceptual system to perceive the surrounding operational environment, for means of propulsion. Consequently, we can provide a more comprehensive characterization of the whole scientific problem considered in this work. The underlying idea is shown in Fig. 1. The snake robot exploits the environment for locomotion by using augmented information: obstacles are recognised, potential push-points are chosen (shown as cylinders), while achievable normal contact forces are illustrated by arrows.

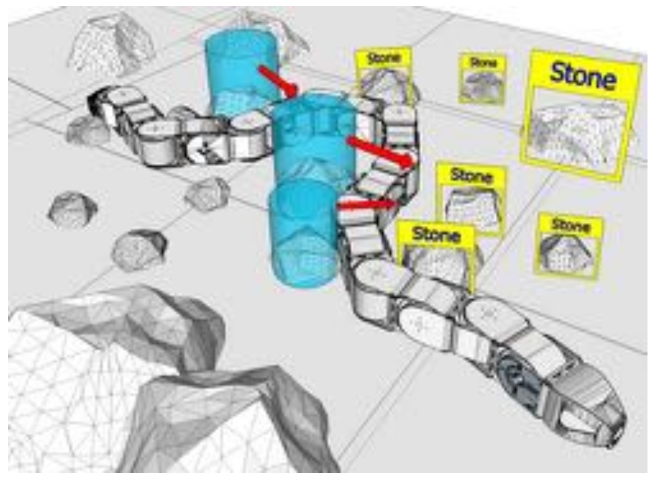

Fig. 1: The underlying idea of snake robot perception-driven obstacle-aided locomotion.

In this paper, we present an elaborate review and discussion of the state-of-the-art, challenges and possibilities of perception-driven obstacle-aided locomotion for snake robots. To this end, we review current strategies for snake robot locomotion in the presence of obstacles. Moreover, we discuss

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and present an overview of relevant key technologies and methods within environment perception, mapping and representation which constitute important aspects of perception-driven obstacle-aided locomotion. The goal of this paper is to further raise awareness of the possibilities with perception-driven obstacle-aided locomotion for snake robots and provide an up-to-date reference to new research and development within this field.

The paper is organised as follows. A review of the state-of-the-art concerning control strategies for obstacle-aided locomotion is described in Section II. Challenges related to the environment perception, mapping and representation are described in Section III. Finally, conclusions and future work are outlined in Section IV.

II. Control strategies

The greater part of existing literature on control of snake robots considers motion across smooth, usually flat, surfaces. Different research groups have investigated this particular operational scenario. Various approaches to mathematical modelling of snake robot kinematics and dynamics were presented as a means to simulate and analyse different control strategies [5]. In particular, many of the models presented in the early literature focus purely on kinematic aspects of locomotion ([6], [7]), while more recent studies also include the dynamics of motion ([8], [9]).

Among the different locomotion patterns inspired by biological snakes, lateral undulation is the fastest and most commonly implemented locomotion gait for robotic snakes in literature [10]. This particular pattern can be realised through phase-shifted sinusoidal motion of each joint of the robotic snake [11]. This approach was investigated for planar snake robots with metallic ventral scales [12] placed on the outer body of the robot, passive wheels [13], or for snake robots with anisotropic ground friction properties [14].

Even though these previous studies have provided researchers with a better understanding of snake robots dynamics, most of the past works on snake robot locomotion have almost exclusively considered motion across smooth surfaces. However, many real-life environments are not smooth, but cluttered with obstacles and irregularities. When the operational scenario is characterised by a surface that is no longer assumed to be flat and obstacles are present, snake robots can move by sensing the surrounding environment. In existing literature, not much work has been done to develop control tools specifically designed for this particular operational scenario. Next, we analyse and group relevant literature for snake robot locomotion in environments with obstacles, as shown in Table I.

Obstacle avoidance

A traditional approach to dealing with obstacles consists in trying to avoid them. Collisions may make the robot unable to progress and cause mechanical stress or damage to equipment. Therefore, different studies have focused on obstacle avoidance locomotion. For instance, principles of Artificial Potential Field (APF) theory [15] have been adopted to effectively model imaginary force fields around objects that are either repulsive or attractive on the robot. The target position generates an attractive force field while obstacles, other robots or the robot itself emits repulsive force fields. The strength of these forces may increase as the robot gets closer. Based on these principles, a controller capable of obstacle avoidance was presented in [16]. However, the standard APF approach may cause the robot to end up trapped in a local minima. In this case, the repulsive forces from nearby obstacles may leave the robot unable to move. To escape local minima, a hybrid control methodology using APF integrated with a modified Simulated Annealing (SA) optimization algorithm for motion planning of a team of multi-link snake robots was proposed in [17]. An alternative methodology was developed in [18], where Central Pattern Generators (CPGs) were employed to allow the robot for avoid obstacles or barriers by turning the robot body from its trajectory. A phase transition method was also presented in the same work utilising the phase difference control parameter to realise the turning motion. This methodology also provides a way to incorporate sensory feedback into the CPG model allowing for detecting possible collisions.

Obstacle accommodation

By using sensory feedback, a more relaxed approach to obstacle avoidance can be considered. Rather than absolutely avoiding collisions, the snake robot may collide with obstacles, but collisions must be controlled so that no damage to the robot occurs. This approach was first investigated in [19], where a motion planning system was implemented to provide a snake-like robot with the possibility of accommodating environmental obstructions. In [20], a general formulation of the motion constraints due to contact with obstacles was presented. Based on this formulation, a new inverse kinematics model was developed that provides joint motion for snake robots under contact constraints. By using this model, a motion planning algorithm for snake robot motion in a cluttered environment was also proposed.

Obstacle-aided locomotion

Even though obstacle avoidance or obstacle accommodation are useful features for snake robots when locomoting in unstructured environments, these control approaches are not sufficient to fully exploit obstacles for means of propulsion. As observed in nature, when locomoting through lateral undulation, biological snakes exploit the terrain irregularities and push against them so that a more efficient locomotion gait can be achieved. In particular, the entire snake's body bends itself and all sections consistently follow the path taken by the head and neck [2]. Snake robots may adopt a similar strategy. A key aspect of practical snake robots is therefore obstacle-aided locomotion [3], [4]. However, to the best of our knowledge, little research has been done in the past literature concerning the possibility of applying this locomotion approach to snake robots.

For instance, a preliminary study aimed at understanding snake-like locomotion through a novel push-point approach was presented in [21].

Remark 1. *In [21], an overview of the lateral undulation as it occurs in nature was first formalised according to the following conditions:*

- *it occurs over irregular ground with vertical projections;*
- *propulsive forces are generated from the lateral interaction between the mobile body and the vertical projections of the irregular ground, called push-points;*
- *at least three simultaneous push-points are necessary for this type of motion to take place;*
- *during the motion, the mobile body slides along its contacted push-points.*

Based on Remark 1, the authors of the same work considered a generic planar mechanism and a related environment that suit to satisfy the fundamental mechanical phenomenon observed in the locomotion of terrestrial snakes. A simple control law was applied and tested via dynamic simulations with the purpose of calculating the contact forces required to propel the snake robot model in a desired direction. Successively, these findings were tested with practical experiments in [22], where closed-loop control of a snake-like locomotion through lateral undulation was presented and applied to a wheel-less snake-like mobile mechanism. To sense the environment and to implement this closed-loop control approach, simple switch sensors located to the side of each module were adopted. A more accurate sensing approach was introduced in [23], where a design process for the electrical, sensing, and mechanical systems needed to build a functional robotic snake capable of tactile and force sensing was presented. Through manipulation of the body shape, the robot was able to move in the horizontal plane by pushing against obstacles to create propulsive forces. Instead of using additional hardware, an alternative and low-cost sensing approach was examined in [24], where robot actuators were used as sensors to allow the system to traverse an elastically deformable channel with no need of external tactile sensors.

Some researchers have focused on asymmetric pushing against obstacles. For instance, a control method with a predetermined and fixed pushing pattern was presented in [25]. In this method, the information of contact affects not only adjacent joints but also a couple of neighbouring joints away from a contacting link. Furthermore, the distribution of the joint torques is empirically set asymmetrically to propel the snake robot forward. Later on, a more general and randomised control method that prevents the snake robot to get stuck in crowded obstacles was proposed by the same research group in [26].

When locomoting through environments with obstacles, it is also important to achieve body shape compliance for the snake robot. Some researchers have focused on shape-based control approaches, where a simple motion pattern is propagated along the snake's body and dynamically adjusted according to the surrounding obstacles. For instance, a general motion planning framework for body shape control of snake robots was presented in [27]. The applicability of this framework was demonstrated for straight line path following control, and for implementing body shape compliance in environments with obstacles. Compliance is achieved by assigning mass-spring-damper dynamics to the shape curve defining the motion of the robot.

TABLE I: Snake locomotion in unstructured environments

Obstacle avoidance	Obstacle accommodation	Obstacle-aided locomotion
[15]–[18]	[19], [20]	[3], [21]–[26] [27], [4]

Remark 2. *Most of the previous studies highlight the fact that lateral undulation is highly dependent on the actuator torque output and environmental friction.*

Based on Remark 2, interesting approaches were discussed in [4], [28]. In [4], the main focus was on how to use optimally the motor torque inputs, which result in obstacle forces suitable to achieve a user-defined desired path for a snake robot. As the authors pointed out, there are two main issues to practically use their method for obstacle-aided locomotion. The first is the definition of an automatic method for finding the desired link angles at the obstacles. The second is the automatic calculation of the desired path. However, an interesting result is that one could use the approach in [4] to check the quality of a given path, i.e. checking if useful forces could be generated by the interaction with a number of obstacles for that path.

III. Environment perception, mapping and representation

In order for robots to be able to operate autonomously and interact with the environment in any of the ways mentioned in Section II (obstacle avoidance, obstacle accommodation or obstacle-aided locomotion), they need to acquire information about the environment that can be used to plan their actions accordingly. This task can be divided into three different challenges that need to be solved:

1) *sensing*, on using the adequate sensor or sensor combinations to capture information about the environment;
2) *mapping*, which combines and organises the sensing output to create a representation that can be exploited for the specific task to be performed by the robot;
3) *localisation*, which estimates the robot's pose in the environment representation according to the sensor inputs.

These topics are well studied for different types of robots and environments, and tackled by the Simultaneous Localisation And Mapping (SLAM) community which as been the foremost research area for the last years in robotics. However comparatively little work has been done in this field for snake robots, as research has been focused on understanding the fundamentals of snake locomotion, and on the development of the control techniques.

Table II summarises the sensors most commonly found in the robotics literature for environment perception aimed at navigation. The table also contains some basic evaluation on the suitability of the specific sensor or sensing technology for the requirements and limitations of snake robots. For the sake

TABLE II: Sensors for environment perception

Sensor/Sensing technology	Pros	Cons	Refs
Proprioceptive	No need for additional payload.	Depends on accuracy of the robot's model. Low level of detail. Does not allow to plan in advance.	[29], [30]
Contact/Force	Bioinspired. Suitable for simple obstacle-aided locomotion.	Low level of detail. Reactive, does not allow to plan in advance.	[31]–[37]
Proximity (US and IR)	Suitable for simple obstacle-aided locomotion. Allows for some lookahead planning.	Low level of detail. Additional payload.	[38]–[41]
LiDAR	Well-known sensor in robotics community. Provides dense information about environment.	Usually requires sweeping and/or rotating movement for full 3D perception.	[41]–[44]
Laser triangulation	Provides high accuracy measurements.	Very limited measurement range. Requires sweeping movement. Limitations in dynamic environments.	[45]
ToF camera	Provides direct 3D measurements.	Low resolution, low accuracy. Not suitable for outdoor operation.	[46], [47]
Structured light - Temporal coding	Provides direct 3D measurements. High accuracy, high resolution.	Limited measurement range. Not suitable for outdoor operation. Limitations in dynamic environments. Sensor size.	Non-snake: [48]
Structured light - Light coding	Provides direct 3D measurements. Small sensor size.	Noisy measurements. Not suitable for outdoor operation.	Non-snake: [49]
Stereovision	High accuracy, high resolution, wide range.	Measuring range limited by available baseline. Computationally demanding. Dependent on texture.	Non-snake: [50]
Monocular - SfM	Small sensor, lightweight, low power. Wide measurement range. No active lighting.	Computationally demanding. Dependent on texture. Scale ambiguity.	Non-snake: [51]
Radar (e.g. UWB)	Sense through obstacles.	Mechanical or electronic sweeping required. Computationally demanding.	Non-snake: [52]

of completeness, we have included references to representative robots different from snake robots for those technologies where we were not able to find examples of applications involving snake robots.

The classification of sensors in Table II takes into account both the measuring principles and sensing devices involved. A review on the sensors and their operating principles can be found in [53], [54].

Many of the snake robots found in the literature are equipped with a camera located in the head of the robot, and pointing in the same direction as the navigation direction. However, in most cases the images captured by the camera are not used for visual feedback for the robot's control, but just sent to the operator for her/him to plan the robot's trajectory, or to solve the high level applications, which in the case of snake robots are usually inspection or search-and-rescue operations.

One way a snake robot can have a very simple perception of the surrounding environments is by using *proprioception*, i.e. using the robot's own internal state (e.g., joint angles, motor current levels, etc.) to derive some properties of the environment. As an example [30] showed that the tilt angle of a slope can be inferred by only using the snake robot's state estimated from the joint angles, and used this information to adapt the behaviour of sidewinding and maximise the travelling speed. In [29] a heavily bioinspired method is developed based on the mechanics and neural control locomotion of a worm which also uses a serpentine motion. The objective in this case is to react and adapt to obstacles in the environment.

The sensing modality that is most commonly explored in snake robots for environment perception is *force* or *contact* sensors. The first snake robot in 1972 [31] already used contact switches along the body of the snake robot, and demonstrated lateral inhibition with respect to external obstacles. Apart from reacting to contact with obstacles, the main use of force sensors is to adapt the body of the snake robot to the irregularities of the terrain [34], [36]. The authors in [32] claim to feature the first full body 3D sensing snake. The robot is equipped with 3 DOF force sensors integrated in the wheels, which are also actuated, and uses this data to distribute equally the weight of all the segments, apart from moving away from obstacles at the sides. In [33], a different application of contact sensors is shown, in which lateral switches distributed along the body of the snake are used as touch sensors to guarantee that there are enough push-point contacts so that propulsion can be performed. In case the last contact point was lost, the robot performs an exploratory movement. The snake robot in [35] is already designed aimed at obstacle-aided locomotion, by including two main features: a smooth exterior surface, that allows the robot to glide, and contact force sensing, by using four force sensing resistors in each side of the joint module, and assuming that in locomotion on horizontal surfaces, it is enough knowing in which side of the robot the contact happens. In [37], the same research group uses strain gauges measuring the deformation in the joint actuators to measure the contact forces of a waterproof snake robot.

Robots that base their environment perception in contact-based sensors exclusively allow for limited motion planning. For example, when aiming at obstacle avoidance, it is impossible to achieve full avoidance, as the robot needs to make contact with the obstacle to realise its presence. However, in [55], [56], it is demonstrated that environment representation can be achieved by purely contact sensors. In this case, whisker like contact sensors were used in a SLAM framework to produce an environment representation that could potentially be used for planning and obstacle-aided locomotion purposes.

The use of range or *proximity* sensors allows snake robots not to rely on contact in order to perceive the environment, and thus perform obstacle avoidance. The works in [39] and [40] feature active infrared sensors used to implement reactive behaviours for avoiding obstacles, either by selecting an obstacle-free trajectory in the first case, or by adapting the undulatory motion for narrow corridor-like passages in the second one. It is worth noting that the snake robot in [39] is equipped with actively driven tracks for propulsion in slippery terrains. Ultrasound sensors are used in a similar fashion, and their data can also be used to estimate the snake robot's speed in case it is approaching an obstacle [38]. A combination of ultrasound sensors for mapping and obstacle avoidance, and passive infrared sensors for the detection of human life in urban search-and-rescue applications is proposed in [42], though details on how the sensor information is exploited is not provided. A more detailed and accurate representation of the environment can be achieved by the use of LiDAR sensors, sometimes combined with ultrasound sensors as in [41]. The use of LiDAR even allows for the generation of richer and more complete maps. The use of such sensors in a SLAM framework is demonstrated in [43]: the snake robot is equipped with a LiDAR sensor in the head, a camera and infrared sensors in the sides. The camera is used to provide position information to the remote operator who controls the desired velocity of the snake robot using a joystick. The snake then uses the LiDAR to perform SLAM, producing a map and an estimated position of the robot itself in that map. The robot then uses the output from the SLAM to navigate the environment, while using the infrared sensor information in a reactive way to avoid obstacles not detected by the LiDAR and overcome the errors in the SLAM. A rotating LiDAR is used in [44] to scan the environment and generate a 2.5 dimensional map, that then can be used to perform motion planning in 3D. The main objective of this system is to overcome challenging obstacles such as stairs, for which the robot also relies on active wheels. The point clouds generated by the LiDAR are also matched across time, estimating the relative localisation that is then used to correct the robot odometry.

The use of onboard *vision* systems to perceive the environment and influence the snake robot's motion is limited in the literature. In a simplified example [57], a camera mounted in the head of the snake robot is adopted to detect a black tape attached on the ground and then use that information as the desired trajectory for the snake. Time-of-flight (ToF) cameras provide 3D information of the environment in the form of depth images or point clouds, without requiring any additional scanning movement. A modified version of the Iterative Closest Point (ICP) algorithm is used in [46] to combine the information of an Inertial Measurement Unit (IMU) with a ToF camera. The ICP [58] is a well-known algorithm that calculates the transformation (translation and rotation) to align two point clouds that minimises the mean squared error between the point pairs of the point clouds. The modifications proposed for the ICP are intended to speed up and increase the robustness. The objective of this process is to perform localisation and mapping. Localisation is demonstrated at 4 fps, while map construction was done offline. The concept is demonstrated in a very challenging scenario, which is the Collapsed House Simulation Facility, and adopting the *IRS Souryu* snake robot which uses actively driven tracks for propulsion. The use of ToF cameras is also demonstrated in [47] in a pipe inspection snake robot. The camera is used to detect key aspects of the pipe geometry, such as bends junctions and pipe radius. The snake robot's shape can then be adapted to the pipe's features, and navigate that way efficiently even through vertical pipes.

Laser triangulation is a well-known sensing technology in industry, providing very high resolution and high accuracy measurements. The work in [45] focuses on increasing the snake robot's autonomy, which is demonstrated by autonomous pole climbing. This is a complex behaviour to be achieved by teleoperation. The authors have custom designed a laser triangulation sensor to fit into the size and power constraints of the snake robot. The robot adopts a stable position with the head raised, and rotates the head to perform a environment scanning. The resulting point cloud is filtered and processed to detect pole-like elements in the environment that the snake robot can climb. Once the pole and relative positioning is calculated, the robot pose is estimated by using the forward kinematics and IMU data.

For the sake of completeness, we can refer to vision systems *offboard*, which might not be applicable to more realistic applications such as exploration, search-and-rescue or inspection. In [59], two cameras with a top-down view of the operating area are used to detect the obstacles and calculate the snake robot's pose. The pose estimation is simplified by placing fiducials in the snake robot (10 orange blocks along the snake robot's length). In [60], a similar setup uses a stereovision system to measure the head's position of the robot and target coordinates.

Remark 3. *Knowledge about the environment and its properties, in addition to its geometric representation, can be successfully exploited for improving locomotion performance for obstacle-aided locomotion.*

While knowledge about the environment's geometry might seem an obvious requirement for obstacle avoidance, other kinds of interaction with the environment, including obstacle-aided locomotion, require some further task-relevant knowledge about the environment. From a cognitive perspective, this has been acknowledged by the robotics community by the creation of *semantic maps* [61], which capture higher level information about the environment, usually linked or grounded to knowledge from other sources. For the T^2 Snake-2s robot [43], the authors also claim that for planning the trajectory, they require to consider the nature of the surrounding obstacles, as contact with some elements (e.g. fragile, high heat, electrically charged, or sticky obstacles) might pose a safety risk to the robot and must then be completely avoided. But safety is not the only reason. The biologically inspired hexapod robot in [62] represents a good example of how knowledge about the environment is exploited for enhanced navigation. Information about certain terrain characteristics is captured in the environment model, and later adopted as part of the cost function used by the RRT* planner [63]. This way, the trajectory planned takes into account factors such as terrain roughness, terrain inclination or mapping uncertainty.

IV. Conclusions and future work

In this paper, we have reviewed and discussed the state-of-the-art, challenges and possibilities with perception-driven obstacle-aided locomotion. This includes snake robot locomotion in the presence of obstacles, as well as methods and technologies for environment perception, mapping and representation.

Perception-driven obstacle-aided locomotion is still at its infancy. However, there are strong results which can be used to build further upon from both the snake robot community in particular, and the robotics community in general. One of the fundamental targets of this paper is to further increase efforts world-wide on realising the large variety of application possibilities offered by snake robots and to provide an up-to-date reference as a stepping-stone for new research and development within this field. This effort is also supported by our ongoing research [64], [65].

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