Two new design concepts for snake robot locomotion in unstructured environments

Pål Liljebäck, Kristin Y. Pettersen, Øyvind Stavdahl, and Jan Tommy Gravdahl

***Abstract*—This communication presents and justifies ideas related to motion control of snake robots that are currently the subject of ongoing investigations by the authors. In particular, we highlight requirements for intelligent and efficient snake robot locomotion in unstructured environments, and subsequently we present two new design concepts for snake robots that comply with these requirements. The first design concept is an approach for sensing environment contact forces, which is based on measuring the joint constraint forces at the connection between the links of the snake robot. The second design concept involves allowing the cylindrical surface of each link of a snake robot to rotate by a motor inside the link in order to induce propulsive forces on the robot from its environments. The paper details the advantages of the proposed design concepts over previous snake robot designs.**

***Index Terms*—Snake robots, Sensing, Adaptation, Obstacle-aided locomotion.**

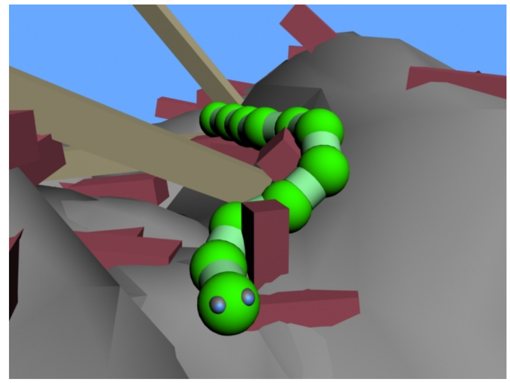

Fig. 1. Illustration of *obstacle-aided locomotion* with a snake robot.

I. Introduction

INSPIRED by biological snake locomotion, snake robots carry the potential of meeting the growing need for robotic mobility in unknown and challenging environments. These mechanisms typically consist of serially connected joint modules capable of bending in one or more planes. The many degrees of freedom of snake robots make them difficult to control, but provide traversability in irregular environments that surpasses the mobility of the more conventional wheeled, tracked and legged types of robots.

The large majority of snake robots developed so far are only able to travel across flat surfaces. As a step towards enabling these mechanisms to move in more challenging and cluttered environments, we have, over the recent years, focused on *obstacle-aided locomotion* [1], where objects in the environment of the snake robot are not avoided, but rather used as push-points to aid the propulsion (see the illustration in Fig. 1). The opinions and ideas presented in this paper are based on the experience acquired through this research activity.

This communication has three contributions. The first contribution is a set of requirements that the authors consider vital to intelligent and efficient snake robot locomotion in unknown and unstructured environments, namely environment *sensing* and *adaptation*, and a smooth robot body surface which is free of obstructive features. Along with these requirements, we present a literature review in order to show that previous research efforts that target these requirements are quite limited. The second contribution is an approach for sensing environment contact forces, which is based on measuring the joint constraint forces at the connection between the links. The advantage of this approach is that force measurements are only required at the locations of the joints, and that the sensor system can be well protected inside the snake robot. Finally, the third contribution is a design concept where the cylindrical surface of each link of a snake robot is allowed to rotate by a motor inside the link in order to produce external forces in the transversal direction of the links. These forces will propel the robot forward if the cylinder rotation is coordinated with the angle that each link forms with the forward direction. In contrast to previous snake robots with active propulsion, the proposed propulsion mechanism is both mechanically simple and maintains a smooth exterior gliding surface along the body of the snake robot.

Note that the authors are currently working towards detailed investigations of the design ideas proposed in this paper. Note also that although the proposed ideas are relatively simple and may even seem obvious, they have, to our best knowledge, not been considered in previous literature.

The paper is organized as follows. Requirements for efficient snake robot locomotion in unstructured environments are presented in Section II, while a review of previous literature that targets these requirements is given in Section III. The design concept for measuring environment contact forces is presented in Section IV, while the design concept for adding active propulsion to a snake robot is presented in Section V. Finally, Section VI presents some concluding remarks.

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II. Requirements for efficient snake robot locomotion in unstructured environments

Our research activities on snake robot locomotion are based on the following fundamental hypotheses:

Hypothesis 1: Intelligent and efficient snake robot locomotion in unknown and unstructured environments requires that the snake robot can *sense* its environment and *adapt* its body shape and movements accordingly.

Hypothesis 2: Efficient slithering (gliding) motion in unstructured environments requires that the exterior surface along the body of the snake robot is free of obstructive features that obstruct the gliding motion.

Although these two hypotheses may seem fairly obvious, it is still appropriate and useful to state them explicitly. In particular, previous research on environment sensing and robust gliding capabilities of snake robots has received limited attention in previous literature (as shown in Section III).

A theoretical justification for Hypothesis 1 follows from Newton's second law, which tells us that the acceleration of the center of mass of a snake robot is determined solely by the sum of all individual environment contact forces acting along the body of the robot (i.e. ground friction forces and contact forces from external objects). This fact enables us to conclude that the fundamental control principle of snake robot locomotion is to produce body shape changes that induce external contact forces whose sum points in the desired direction of motion. Since controlled body shape changes for inducing desired contact forces is equivalent to environment *adaptation*, and since environment adaptation is not possible without *sensing* the environment in some way, we have established a theoretical justification for Hypothesis 1.

An empirical justification of Hypothesis 1 follows from previous studies of biological snakes, which show that the sensory information transmitted by the skin of a snake influences the shape to which the body adapts in a given situation [2]–[5].

Hypothesis 2 is self-explanatory since an obstructive feature along the body of a snake robot naturally will reduce the efficiency of the gliding motion of the robot.

Remark 3: Environment sensing and adaptation is not necessary when the surface beneath the snake robot is *flat* since predetermined gait patterns, such as the *serpenoid curve* motion proposed by Hirose [3], then can be performed in open-loop without sensing the external forces. The majority of previous research on snake robot locomotion has focused on flat surface motion, even though one can argue that the main advantage of snake robots are their potential ability to move in unstructured environments.

III. Previous work on adaptive snake robot locomotion

This section provides an overview of previous work relevant to snake robot locomotion in unstructured environments. We emphasize that the majority of previous snake robot literature focuses on preprogrammed gait patterns for motion over flat surfaces (see e.g. the review given in [6]). These works are not included below since we consider them less relevant to the topic of this paper.

A. Control design for adaptive snake robot locomotion

Probably the most comprehensive work on snake robot locomotion so far is presented by Hirose in [3]. This work investigates adaptive functions of biological snakes (i.e. sinus-lifting, the α-adaptive principle, and the l-adaptive principle) and proposes mathematical descriptions of how external factors, such as ground friction and temperature, affect the shape of a snake during *lateral undulation*, which is the most common form of snake locomotion. Hirose also investigates locomotion efficiency inside a maze (i.e. when the snake touches a wall on each side) and proposes a control strategy for *lateral inhibition* that modifies the shape of a snake robot based on contact force sensing along the snake body in order to *avoid* obstacles.

The work in [7] considers a snake robot that uses solenoids for attachment to the environment and analyses how obstacles around the snake robot affect its degrees of freedom.

In [8], an algorithm is presented that takes contact constraints on a snake robot into account in order to compute the joint torques that produce the desired motion. The algorithm is applied to achieve climbing motion with a snake robot.

Lateral undulation with snake robots in an environment with obstacles is considered in [9], which proposes an inverse dynamics approach by formulating and numerically solving an optimization problem in order to, for a given set of obstacle contacts, calculate the contact forces required to propel the snake in a desired direction. A strategy for calculating the actual torque inputs to the joints from the desired contacts is, however, not presented. The same authors employ a kinematic approach in [10], where a curve fitting procedure is used to determine the shape of the snake with respect to the obstacles. Subsequently, this shape is propagated backwards along the snake body under the assumption that this will push the robot forward.

Lateral undulation in an environment with obstacles has also been investigated by the authors. In [11], the authors propose a control law for obstacle-aided locomotion aimed at resolving situations where the snake robot is jammed between obstacles. The controller employs feedback of measured contact forces in order to rotate all links in contact with obstacles so that the total propulsive force on the robot increases. Experimental results presented in [12] show that this control principle can maintain the propulsion of a physical snake robot during contact with obstacles.

Sensing the environment of a snake robot must not necessarily involve contact force sensing since the environment can be indirectly sensed through the joint angle measurements and/or the actuator torques. This approach is considered in [13], where the joint torques of a snake robot are specified solely in terms of the measured joint angles to achieve motion through a winding corridor, and in [14], which presents a control strategy that uses motor current measurements to adjust the shape of a snake robot moving through an elastically deformable channel. The approach is also employed in [15], which proposes a control strategy that takes ground friction forces into account, and in [16], where the deviations of the joint angles from their setpoints are used to modify the oscillatory joint motion, thereby enabling the robot to automatically adapt its motion to variations in the ground friction conditions.

The works in [17]–[19] propose various gaits for motion in unstructured environments, such as climbing gaits. However, the gaits do not appear to involve sensing of or adaptation to the environment.

Along with the above works, we should also mention the control strategy presented in [20], which uses range sensor measurements to center a crawling snake robot between the walls of a corridor, and the work in [21], which analyses the efficiency of earthworm-like motion on compliant surfaces motivated by biomedical applications of worm robots, and finally the fuzzy logic controller proposed in [22], which switches between various predefined gaits in order to avoid obstacles in the environment of the snake robot.

B. Hardware design for adaptive snake robot locomotion

In the following, we provide references to various hardware designs which target (adaptive) snake robot locomotion in unstructured environments. Hirose developed the world's first snake robot as early as 1972 [3]. This robot was equipped with passive wheels in order to easily achieve forward propulsion on flat surfaces. The robot was also equipped with contact switches, which enabled the robot to demonstrate the lateral inhibition motion described in the previous subsection.

The works in [23], [24] propose two novel joint mechanisms for snake robots optimized with respect to compactness and strength. A strong and light joint mechanism is important for locomotion in unstructured environments since the friction forces opposing the motion increase with the weight of the robot.

A wheelless snake robot consisting of serially connected servo motors is presented in [25]. The work considers issues related to covering the robot with compliant materials and skin to achieve certain environment contact characteristics, in particular high grip during climbing.

A snake robot with square-shaped modules covered by active tracks is presented in [26]. The modules are interconnected by pneumatic joints for compliance purposes. The active tracks give the robot excellent mobility and enable it to climb up narrow spaces and traverse rocky terrain. The robot does not have environment sensing capabilities.

A similar, but yet quite different snake robot based on skin drive is presented in [27], where the entire skin surface covering the robot is propelled backwards from head to tail in order to provide propulsion at any point where the robot contacts the environment. The skin is wrapped inside itself at the tail and propelled forward to the head in a channel inside the robot. The robot does not have environment sensing capabilities, but has an impressive mobility in unstructured environments.

A snake robot with passive wheels and strain gauge sensors is proposed in [28], where the strain gauge sensors are shown to successfully measure the constraint forces on the wheels.

A snake robot with active wheels equipped with 3-axial force sensors is presented in [29]. The force sensors, which were developed to facilitate environment adaptation, measure the translational forces on the wheel axes based on optical range measurements.

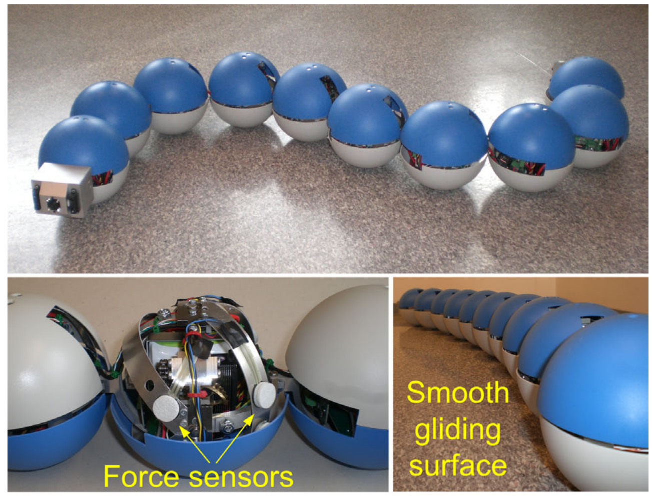


Fig. 2. A snake robot with ball-shaped modules covered by force sensors that allow environment contact forces to be measured.

Ideas related to environment sensing for snake robots are considered in [30], where the preliminary design of a capacitive contact sensor is proposed that can be wrapped around each module of a snake robot.

The work in [10] presents a wheelless snake robot with contact switches and presents experimental results where the robot is propelled forward by pushing against pegs that are detected by the contact switches. To the authors' best knowledge, this is the first reported work where a wheelless snake robot is propelled forward by active use of environment sensing.

The authors have recently developed a snake robot with ball-shaped joint modules covered by force sensors [31]. The robot, which is shown in Fig. 2, was developed to satisfy the requirements stated in Hypothesis 1 and 2. In particular, the ball-shaped modules give the robot a smooth exterior surface that allow gliding motion in irregular environments without being obstructed. Force sensing is achieved by mounting force sensors underneath the spherical shells covering the joint modules. To our best knowledge, this is the first snake robot that can measure the magnitude of external forces applied along the body of the robot. Experimental results are presented in [12], where the robot successfully demonstrates obstacle-aided locomotion on a surface with vertical obstacles.

C. Summary: The status of adaptive snake robot locomotion

The above literature review is summarized as follows:

- Previous literature presents a few demonstrations of adaptive behaviour of snake robots with respect to vertical objects/obstacles where the motion is completely planar (horizontal).
- Previous literature presents a few demonstrations of non-planar snake robot locomotion over surfaces that are not flat, but where no environment sensing or body shape adaptation is employed.
- Non-planar snake robot locomotion over surfaces that are not flat and where the controller is based on environment

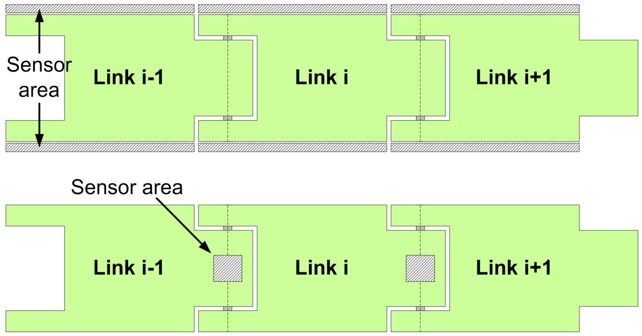
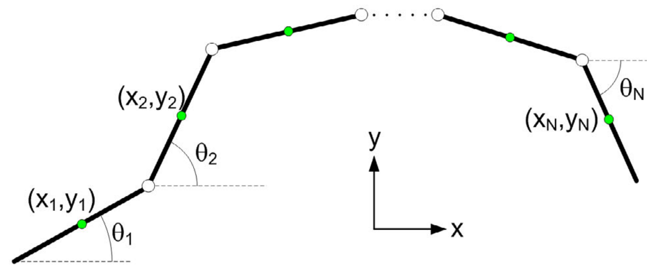
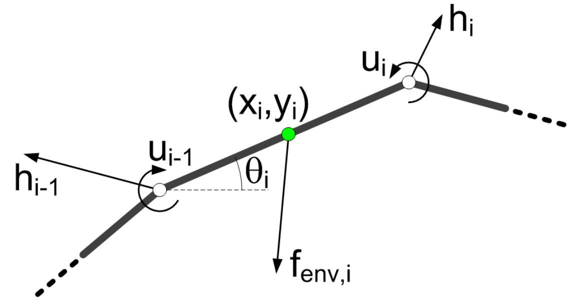


Fig. 3. Top: Sensor area required for direct measurement of external forces. Bottom: Sensor area required for calculating external forces based on internally measured joint constraint forces.



(a) A snake robot with N links.



(b) Forces and torques acting on each link.

Fig. 4. Parameters characterizing a planar snake robot.

sensing and body shape adaptation has *not* yet been demonstrated.

In the authors' opinion, the future use of snake robots requires significantly more research on adaptive behaviour during motion in unstructured environments.

IV. A Novel Approach for Environment Sensing

In this section, we propose an approach for environment sensing based on contact force measurements. The approach has several advantages over previous approaches reported in the literature, which greatly simplifies solutions to the requirements stated in Hypothesis 1 and 2.

A common feature of the snake robots with contact force sensors described in [3], [10], [30], [31] is that environment sensing is achieved by directly measuring the external forces acting on the links of the robot. This solution, which is illustrated in the top of Fig. 3, basically requires that the entire surface of the robot is covered by force sensors. As a result, the sensor and instrumentation system becomes very complex. Moreover, combining a smooth gliding surface (as required by Hypothesis 2) with such force sensing capabilities is challenging since the robot is articulated.

An alternative approach, which circumvents these drawbacks of previous force sensing solutions, is to calculate the external forces on each link of the robot based on measurements of the joint constraint forces that occur at the connection between the links. As illustrated in the bottom of Fig. 3, a major advantage of this approach is that force sensors are only required at the locations of the joints. Moreover, all the instrumentation can be well protected *inside* the joint modules. This alternative approach simplifies the development of the physical coverage of a snake robot since the coverage can be developed more or less independently of the contact force sensor system.

To verify that the external forces on a snake robot indeed can be determined from the joint constraint forces, we investigate the force balance for a single link of the robot based on the model formulation considered in [32]. As shown in Fig. 4(a), we consider a planar snake robot with N links interconnected by $N-1$ motorized revolute joints, where the links are influenced by the forces and torques illustrated in Fig. 4(b). The external contact forces from the environment, which include ground friction forces and contact forces from external objects, are all assumed to act on the center of mass of each link, and the sum of the external forces on link $i \in \{1, \ldots, N\}$ is denoted by $\boldsymbol{f}_{\text{env},i} \in \mathbb{R}^2$. The joint constraint forces which keep link i connected to link $i-1$ and link $i+1$ are denoted by $-\boldsymbol{h}_{i-1} \in \mathbb{R}^2$ and $\boldsymbol{h}_i \in \mathbb{R}^2$, respectively. Furthermore, $u_{i-1} \in \mathbb{R}$ and $u_i \in \mathbb{R}$ denote the actuator torques exerted on link i from link $i-1$ and link $i+1$, respectively. The force balance of link i can be written as

$$m\ddot{\boldsymbol{a}}_i = \boldsymbol{f}_{\text{env},i} + \boldsymbol{h}_i - \boldsymbol{h}_{i-1}, \tag{1}$$

where m and $\ddot{\boldsymbol{a}}_i = [\ddot{x}_i, \ddot{y}_i]^T \in \mathbb{R}^2$ are the mass and translational acceleration, respectively, of the link. With the proposed force sensing approach, the joint constraint forces $\boldsymbol{h}_i$ and $\boldsymbol{h}_{i-1}$ are measured. The sum of all external forces on link i can thereby be calculated as

$$\boldsymbol{f}_{\text{env},i} = m\ddot{\boldsymbol{a}}_i - \boldsymbol{h}_i + \boldsymbol{h}_{i-1}, \tag{2}$$

which is given solely from the measured joint constraint forces when the velocity of the link is zero or constant so that $\ddot{\boldsymbol{a}}_i = \boldsymbol{0}$. Moreover, since snake locomotion is usually a smooth slithering form of locomotion with slowly varying link velocities, we conjecture that (2), with $\ddot{\boldsymbol{a}}_i$ set to zero, also in general will provide a good approximation of $\boldsymbol{f}_{\text{env},i}$. Alternatively, the estimate of $\boldsymbol{f}_{\text{env},i}$ can be improved by also measuring $\ddot{\boldsymbol{a}}_i$, which is easily achieved by installing a small acceleration sensor inside each link. Note that specific techniques for measuring the joint constraint forces, of which there are many, are topics of the ongoing research efforts by the authors.

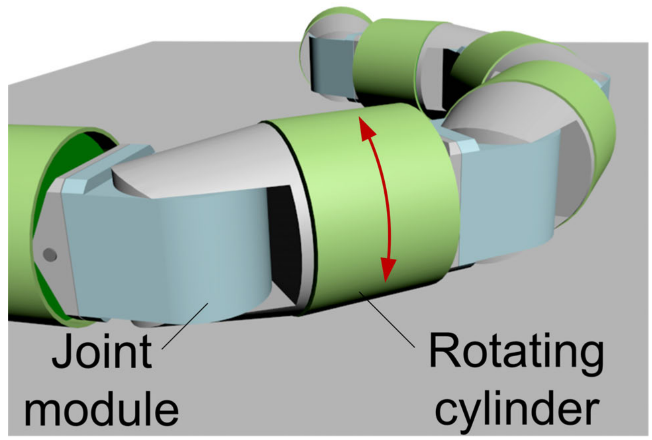
V. Combining a Smooth Gliding Surface with Active Propulsion

The efficiency of the gliding motion of a snake robot can be greatly improved by introducing active propulsion of some sort along the body of the robot, for example by equipping each link with motorized wheels [29], [33], [34], or by installing tracks along the body of the snake robot [26], [27], [35]–[37], or by employing a screw drive mechanism [38]. To the authors' best knowledge, all previous snake robots with active propulsion have been designed to produce propulsive forces in the *tangential* direction of each link. The design concept that we propose in the following, on the other hand, is based on producing propulsive forces in the transversal direction of the links. In contrast to previous snake robots with active propulsion, the resulting propulsion mechanism is both mechanically simple and maintains a smooth exterior gliding surface along the body of the snake robot.

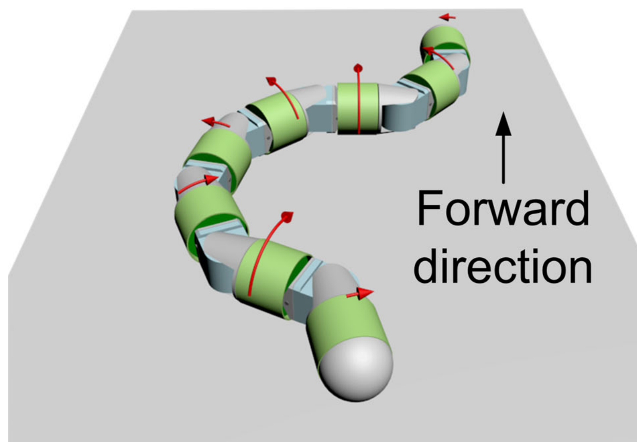
Assuming that the snake robot consists of links with a cylindrical shape, the idea is simply to let the exterior cylinder surface be allowed to rotate as illustrated in Fig. 5(a), where the cylinder rotation is controlled by a motor inside the cylinder. Due to external contact forces, each rotating cylinder will generate external forces in the normal direction of the link. By controlling the rotation of each cylinder in accordance with the angle that each link forms with the forward direction, the rotating cylinders will generate external forces that propel the snake robot forward. A possible control principle of the cylinders is illustrated in Fig. 5(b), where cylinders near orthogonal to the forward direction are rotated faster than cylinders near parallel to the forward direction.

The proposed propulsion mechanism can easily be implemented without compromising the requirement of a smooth gliding surface along the body of the snake robot. Furthermore, the propulsion mechanism can be implemented in a mechanically simple and robust way. For instance, dustproofing and waterproofing the mechanism is easy. The propulsion mechanism will also allow a snake robot to display various forms of motion that have not been demonstrated by previous snake robots. One novel type of motion is turning on the spot (e.g. while lying straight) by rotating all cylinders in the foremost half of the robot in one direction, while rotating the other cylinders in the opposite direction. The snake robot will also be able to climb a pole by curling its body around the pole and simply driving upwards by rotating all cylinders in the same direction.

Note that there are several open questions regarding this propulsion mechanism that are topics of ongoing investigations by the authors. These questions concern suitable material choices of the rotating cylinders and appropriate control strategies for the cylinders with respect to the desired motion of the snake robot.



(a) The rotating cylinder generates external forces in the normal direction of the link.



(b) Each cylinder is rotated according to its orientation with respect to the forward direction.

Fig. 5. A snake robot with a smooth gliding surface combined with active propulsion.

VI. Concluding remarks

As an attempt to increase current research efforts on snake robot locomotion in unstructured environments, this paper has highlighted requirements of snake robots that the authors consider vital to this end, namely environment *sensing* and *adaptation*, and a smooth robot body surface which is free of obstructive features. The paper has presented a literature review that shows that previous research efforts targetting these requirements are quite limited.

Moreover, we have proposed an approach for sensing environment contact forces, which is based on measuring the joint constraint forces at the connection between the links. The advantage of this approach is that force measurements are only required at the locations of the joints, and that the sensor system can be well protected inside the snake robot. We have also proposed a design concept where the cylindrical surface of each link of the snake robot is allowed to rotate by a motor inside the link in order to produce external forces in the transversal direction of the links. These forces will propel the robot forward if the cylinder rotation is coordinated with the angle that each link forms with the forward direction. In contrast to previous snake robots with active propulsion, the resulting propulsion mechanism is both mechanically simple and maintains a smooth exterior gliding surface along the body of the snake robot.

The topic of this paper is in line with current trends in robotic research, which aim at improving the cognitive abilities of robots (e.g. for grasping and object manipulation purposes) and enabling them to work in unknown and unstructured environments.

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