Enhancing Serpentine Motion and Obstacle Avoidance in Snake Robot Locomotion: Design, Simulation, and Analysis

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Abstract— Snake robots offer unique capabilities for navigating complex environments, inspired by the locomotion of their biological counterparts. This research examines how serpentine motion and obstacle evasion can be incorporated into the design of snake robots, using V-Rep (CoppeliaSim) as the simulation software. Drawing inspiration from snake locomotion principles, a novel snake robot prototype was meticulously crafted to emulate the fluid movements essential for traversing various terrains. Sophisticated control algorithms have been implemented to facilitate seamless serpentine motion and dynamic obstacle avoidance. Through extensive simulation trials, the effectiveness of the proposed approach is demonstrated, showcasing the navigation of the snake robot through cluttered environments and the successful circumvention of obstacles. This study not only advances snake robot technology, but also underscores its potential across diverse domains, including search and rescue operations, surveillance missions, and exploration endeavours.

Keywords— snake robot, serpentine motion, obstacle avoidance, simulation study, control algorithms

I. INTRODUCTION

Snake robots, inspired by the remarkable locomotion of their biological counterparts, offer unparalleled versatility in navigating complex terrain. By mimicking the fluid movements of real snakes, these robotic systems have immense potential for applications in search and rescue operations, exploration missions, and environmental monitoring. However, achieving precise serpentine motion and effective obstacle avoidance remains a significant challenge in the development of snake robots.

The primary problem faced in obtaining the correct serpentine motion lies in reconciling the complex interplay between the multiple actuators and segments within the snake robot's body. The intricate coordination required to produce undulating waves along the length of the robot requires precise control algorithms and a meticulous mechanical design. Furthermore, integrating obstacle avoidance mechanisms adds another layer of complexity that necessitates real-time sensing and decision-making capabilities to navigate through cluttered environments.

To address these challenges, this study employs a multidisciplinary approach, drawing upon insights from robotics, biomechanics, and control theory. Through a series of design iterations and simulation experiments, research aims to refine the serpentine motion generation process and optimize obstacle avoidance strategies.

II. LITERATURE REVIEW

Research on snake robots has been driven by the enduring goal of replicating the efficient and versatile locomotion of biological snakes for diverse applications. Studies by Desai and Kumar [1] provide a comprehensive survey of kinematic control strategies for snake-like robots, highlighting the crucial role of control algorithms in achieving desired movement patterns and navigating complex environments. Notably, advancements in bio mimetic control strategies are fostering the development of robots that directly mimic the neural control systems of their biological counterparts [5].

Simulations have become an indispensable tool for developing and testing control strategies for snake robots. Works by Rohmer et al. [2] demonstrate the utility of physics simulation environments like CoppeliaSim (V-REP) in analyzing snake robot locomotion and evaluating control algorithms. These simulations enable researchers to explore a wide range of scenarios, including diverse terrains, obstacles, and sensor configurations, in a controlled environment before real-world implementation. Furthermore, the burgeoning field of soft robotics simulation allows for the incorporation of more realistic material properties and sensor interactions, leading to simulations that more closely mirror real-world behavior [6].

Obstacle avoidance remains a critical aspect for enabling autonomous operation of snake robots in dynamic environments. Research by Marques et al. [3] investigates the use of proximity sensors for reactive obstacle detection and avoidance maneuvers. Likewise, Guo et al. [4] explore the integration of LiDAR sensors for more comprehensive obstacle mapping and path planning. Beyond these reactive approaches, advancements in planning algorithms are paving the way for robots that consider their entire body configuration and future movements when navigating obstacles [7]. These developments are crucial for enabling snake robots to navigate complex and cluttered environments with greater autonomy and efficiency.

III. KINEMATICS

The kinematics describes the geometrical aspect of motion. The DH convention provides a systematic approach to describe the relative transformations between frames attached to each link. For each joint (j1, j2...j8), a set of four DH parameters are defined:

$\boldsymbol{\alpha_n}$ is the twist angle about the common z-axis between consecutive frames (in degrees). $\mathbf{a_n}$ is link length along the common normal between consecutive z-axes (in millimeters). $\boldsymbol{\theta_n}$ is the joint angle variable representing the rotational DoF about the common x-axis (in degrees). $\mathbf{d_n}$ is link offset along the common z-axis of consecutive frames (in millimeters).

$$
{}^{n-1}T_n = \left[\begin{array}{cccc}
\cos\theta_n & -\sin\theta_n\cos\alpha_n & \sin\theta_n\sin\alpha_n & r_n\cos\theta_n \\
\sin\theta_n & \cos\theta_n\cos\alpha_n & -\cos\theta_n\sin\alpha_n & r_n\sin\theta_n \\
0 & \sin\alpha_n & \cos\alpha_n & d_n \\
\hline
0 & 0 & 0 & 1
\end{array}\right]
$$

$$
= \left[\begin{array}{ccc|c}
 & R & & T \\
\hline
0 & 0 & 0 & 1
\end{array}\right]
$$

The upper left 3x3 sub-matrix of the final transformation matrix T^8_0 represents the rotation matrix (R^8_0).

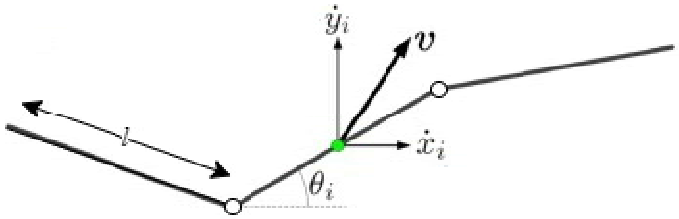


Fig 1.1 The serpenoid curve

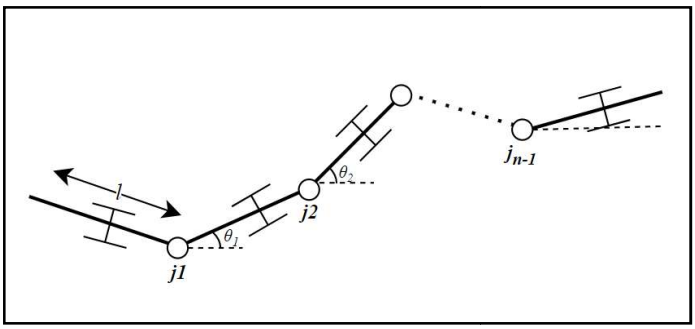


Fig 1.2

This snake robot is comprised of *N* rigid links with identical lengths of *l*. The links are connected by *N-1* motorized joints, allowing for movement. Each link has a mass of m and a moment of inertia of *I = (1/3)ml^2*. The mass distribution within each link is uniform, placing the center of mass (CM) at its midpoint, which is *l/2* distance away from the joints on either side.

IV.SIMULATION AND ANALYSIS

The snake robot's slithering motion is accomplished through a series of coordinated bending movements in its numerous joints, which closely resemble a **sinusoidal wave**. Each body segment exhibits lateral undulation relative to its neighbours, allowing the robot to generate wave-like propagation along its body length. By strategically controlling the actuation of individual joints, the robot is able to propel itself forward without the need for limbs or external support.

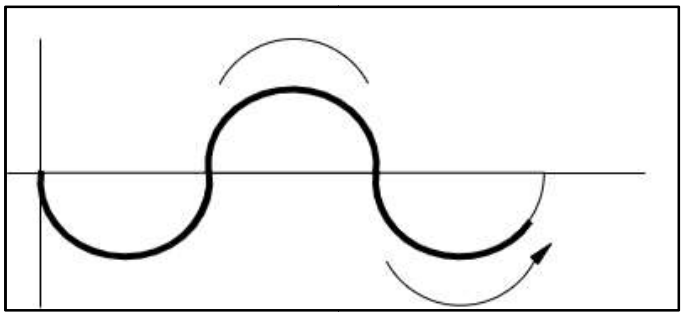


Fig 1.3 The serpentine curve

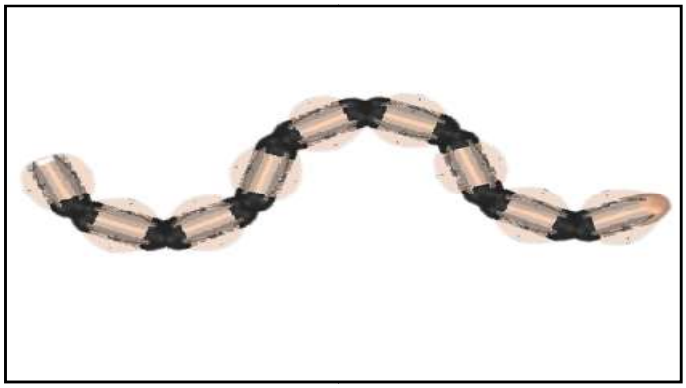


Fig 1.4 ACMR snake robot forming the serpenoid curve

The kinematic modelling described in the previous section provides a framework for analyzing and controlling this serpentine motion. By specifying a desired wave pattern, including amplitude and wavelength, and translating it into corresponding joint angle trajectories, the robot's movement can be precisely orchestrated. This approach enables the snake robot to navigate through complex environments and adapt its gait based on terrain variations.

A. SERPENTINE MOTION

The simulation utilizes the built-in ACM-R5 snake robot model available in CoppeliaSim (V-REP). This model provides a realistic representation of a snake robot with N rigid links and N-1 motorized joints. It consists of 9 links and 8 revolute joints. A virtual environment was created within CoppeliaSim to simulate the robot's movement.

The ACM-R5 snake robot features a modular design, which allows for the customization of its overall length based on specific requirements. Each segment has a typical diameter of 80mm and a length of 170mm. By connecting a variable number of these modules, the robot's total length can be adjusted. A configuration with nine modules achieves a total length of 1.75 meters. Furthermore, each segment possesses a single degree of freedom (1 DoF), enabling independent rotary motion between segments. This modularity and independent movement capability contribute to the robot's manoeuvrability. Moreover, the integration of passive wheels within each segment's body enhances the robot's ability to traverse flat and rough terrains smoothly.

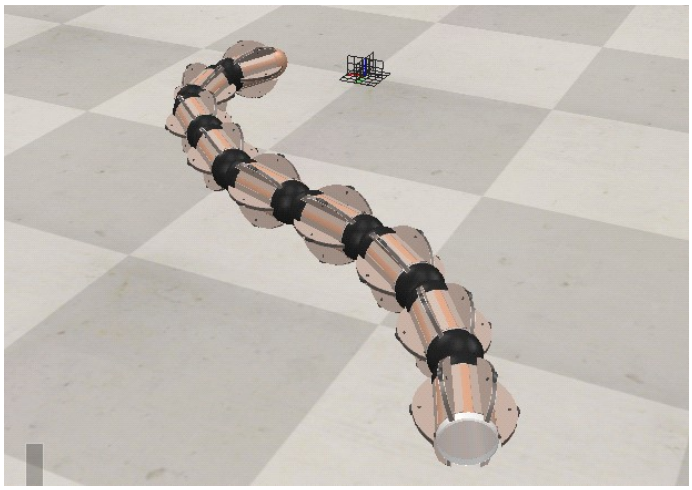


Fig 1.6 Snake Robot during serpentine motion simulation

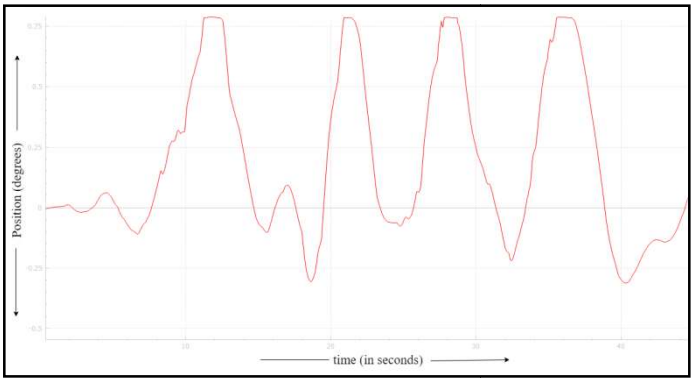
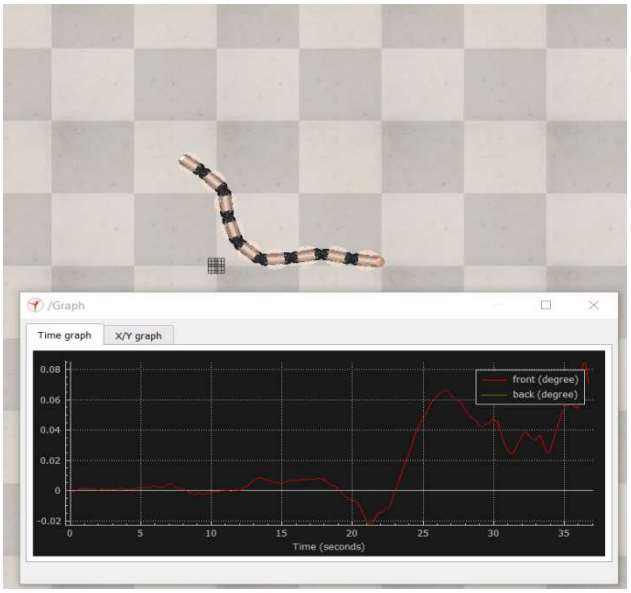


Fig 1.7 Position of Joint 8 during lateral undulation on a flat plane

Figure 1.7 depicts the plotted trajectory of the snake robot's joint positions during the head-driven locomotion simulation. As observed, the pattern closely resembles a sinusoidal wave. This behaviour is attributed to the control strategy employed, where only the first joint (head) was actively controlled dynamically, while the remaining joints operated as free joints. The head's movement dictated the configuration of the subsequent joints, resulting in the wave-like motion characteristic of snake locomotion.



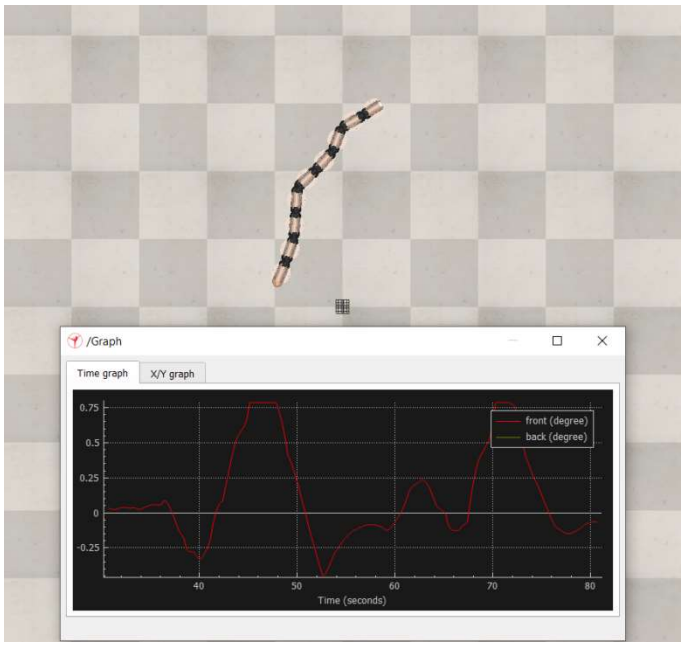


Fig 1.8 (a), (b) Top view of Serpentine motion during simulation

B. OBSTACLE AVOIDANCE

The sensors, configured for real-time obstacle detection, facilitated navigation adjustments and enhanced the robot's performance. These sensors operate within a specific detection range of 20 centimetres, allowing the robot to perceive the immediate presence of obstacles in its path. Proximity sensors were chosen due to their effectiveness in detecting a wide range of obstacles, including objects with varying textures and reflectivities.

Three sensors were positioned at the head of the robot. One sensor faced forward, whereas the remaining two were angled slightly outward, providing a comprehensive field of view for multidirectional obstacle detection.

Forward Sensor: Primarily responsible for detecting obstacles directly in the path. Upon detection, the robot calculated the distance and adjusted its movement to prevent collisions.

Left and Right Sensors: Assisted in obstacle detection at oblique angles.

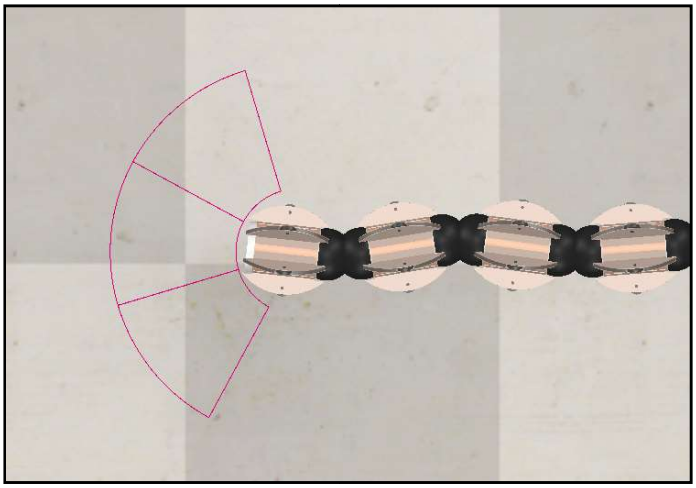


Fig 1.9 Proximity sensors' positioning in the snake robot

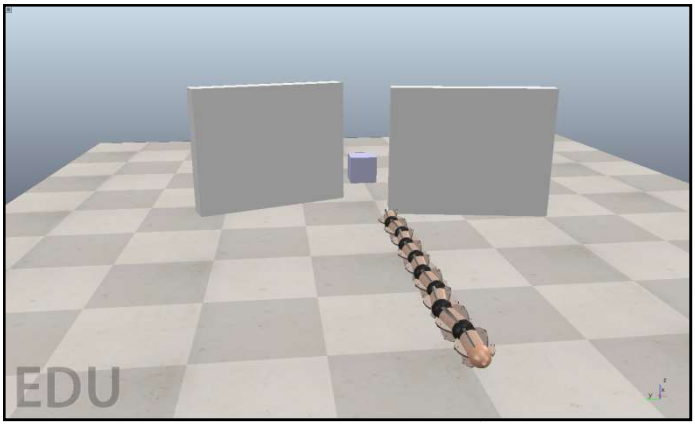


Fig 2.0 Side view of snake robot during simulation

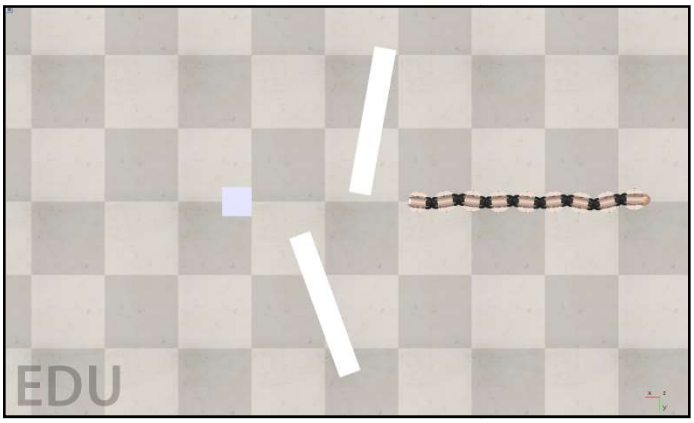


Fig 2.1 Top view during obstacle avoidance simulation(at t=0s)

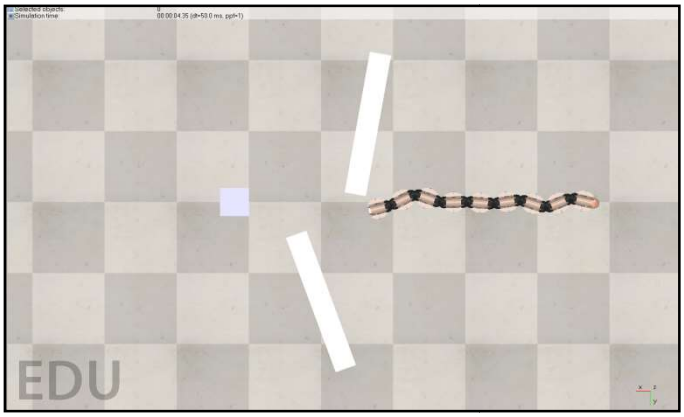


Fig 2.2 Top view during obstacle avoidance simulation (at t=4.0s)

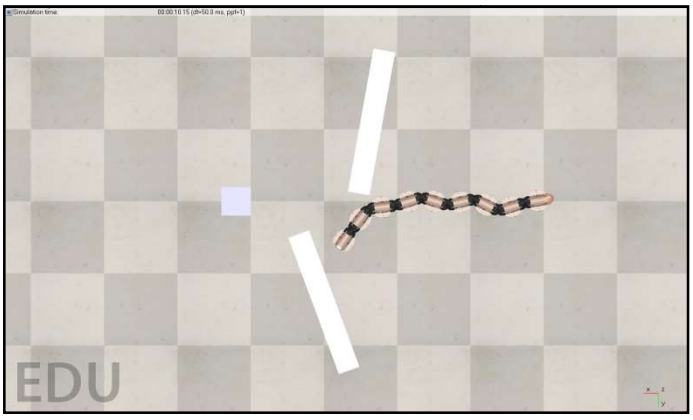


Fig 2.3 Top view during obstacle avoidance simulation(at t=10.0s)

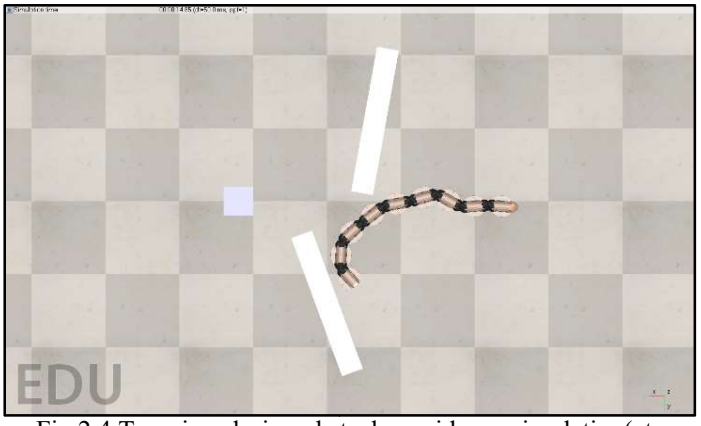


Fig 2.4 Top view during obstacle avoidance simulation(at t=14.0s)

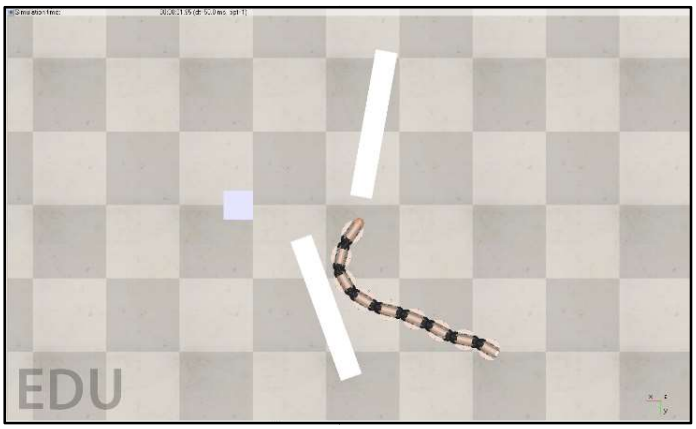


Fig 2.1 Top view during obstacle avoidance simulation(at t=32.0s)

V. CONCLUSION AND FUTURE WORK

The selected method of obstacle avoidance, which is reactive and utilizes proximity sensors, has had a significant influence on the robot's efficiency, manoeuvrability, and ability to navigate obstacles successfully. The success of obstacle avoidance largely depends on the control algorithm selected. Reactive methods enable quick obstacle detection in real-time but may have limited planning capabilities, while path planning algorithms can optimize routes by utilizing accurate environmental information but require knowledge of the surroundings. Future work would include the use of advanced soft robotics simulation techniques to incorporate more realistic material properties and sensor interactions for snake robots with soft bodies.

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