

Collisional Diffraction Emerges from Simple Control of Limbless Locomotion

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Abstract. Snakes can utilize obstacles to move through complex terrain, but the development of robots with similar capabilities is hindered by our understanding of how snakes manage the forces arising from interactions with heterogeneities. To discover principles of how and when to use potential obstacles, we studied a desert-dwelling snake, *C. occipitalis*, which uses a serpenoid template to move on homogeneous granular materials. We tested the snake in a model terrestrial terrain—a single row of vertical posts—and compared its performance with a robophysical model. Interaction with the post array resulted in reorientation of trajectories away from the initial heading. Combining trajectories from multiple trials revealed an emergent collisional diffraction pattern in the final heading. The pattern appears in both the living and robot snake. Furthermore, the pattern persisted when we changed the maximum torque output of the robot motors from 1.5 N-m to 0.38 N-m in which case local deformation of the robot from the serpenoid curve appears during interaction with the posts. This suggests the emergent collisional diffraction pattern is a general feature of these systems. We posit that open-loop control of the serpenoid template in sparse terrains is a simple and effective means to progress, but if adherence to a heading is desired more sophisticated control is needed.

Keywords: Locomotion · Snakes · Complex terrain

1 Introduction

Principles governing movement in heterogeneous terrains remain largely undiscovered. During terrestrial locomotion, contacts with the surroundings are often intermittent and can lead to unexpected emergent behavior [1]. Snakes are remarkable in their ability to use a seemingly simple morphology—a limbless, elongate trunk—to navigate many habitats including a wide range of terrestrial environments. Previous research on terrestrial snake locomotion focused on so-called generalist snakes which encounter a variety of terrain (forest, grassland, wetland, etc.) consisting of many different materials. These snakes use posteriorly-propagating body bends to push the trunk laterally against obstacles and generate the forces needed for forward movement [2, 3]. The versatility and simplicity of this scheme makes it an attractive model for robots [4]. However, the challenge of controlling the many degrees of freedom to effectively

manage interaction with obstacles can stymie robotic implementation of slithering locomotion.

Locomotor templates [5] can simplify control and aid understanding. We previously found the desert-dwelling sand-specialist Mojave Shovel-nosed snake (*Chionactis occipitalis* Fig. 1a) uses a highly-stereotyped waveform which adheres to a sinusoidal curvature in both time and arclength along the body (a “serpenoid” curve [6], Eq. 1) when moving on the surface of homogeneous sand. Given the observed stereotypy of the waveform both between individuals and trials, we hypothesized that *C. occipitalis* uses open-loop control, where the muscle activation is not modified in response to perturbation from the terrain.

Therefore, to begin a systematic search for principles of slithering movement in terrestrial environments, we studied *C. occipitalis* navigating a model terrestrial terrain—a single row of vertical, rigid posts embedded in a homogeneous substrate (Fig. 1d)—inspired by the omnipresent sand substrate and sparse obstacles in their natural habitat (Fig. 1b). We compared the performance of the living snake to a multi-link snake robot in a similar model terrain (Fig. 1c). The robophysical model provided the benefit of behaving in a controlled way which facilitated understanding both of the control strategy of the animal as well as the benefits and drawbacks of using the simple open-loop serpenoid template scheme in multi-modal terrain.

2 Living Snake Experiments

A schematic of our terrain model is shown in Fig. 1d. A carpet with long fibers mimicked the yielding properties of sand without the experimental challenge of using granular materials, namely hysteresis. We verified that the snake used the sand-swimming serpenoid template to move on the carpet. A single row of six 0.64 cm diameter polyurethane rods was placed perpendicular to the direction of motion of the snake. The open space between the posts was 1.7 cm. The rubber rods would deform slightly ($\sim 5 \times$ less than the body width) at the point of contact of the snake. This deformation was measured at 200 Hz using a high-speed camera (X-PRI, AOS) and used to calculate the force applied. A seventh rigid post was included at the end of the row to act as a fiducial.

Nine *C. occipitalis* were used in our trials. To simplify comparison with the robot, we “blindfolded” the snakes by obscuring the spectacle scale with water-based face paint. Snakes were tested individually and the trials captured at 200 Hz using a high-speed camera (S-Motion, AOS) and digitized using custom MATLAB (R2015b, MathWorks) code.

Because the living and robotic snakes are different sizes (Fig. 1 caption) we chose to use as a unit of measurement of length the average distance travelled in one undulation, $v_o T$. For the living snake we calculated $v_o T$ as the average center-of-mass speed times the average temporal period of *C. occipitalis* moving freely when no obstacles were present.

The scattering angle, θ , was measured as the angle between a point on a snake’s trajectory and the z-axis as the snake passed through a circular arc centered between the 3rd and 4th posts and in line with the row (Fig. 1d). We chose to measure the angle

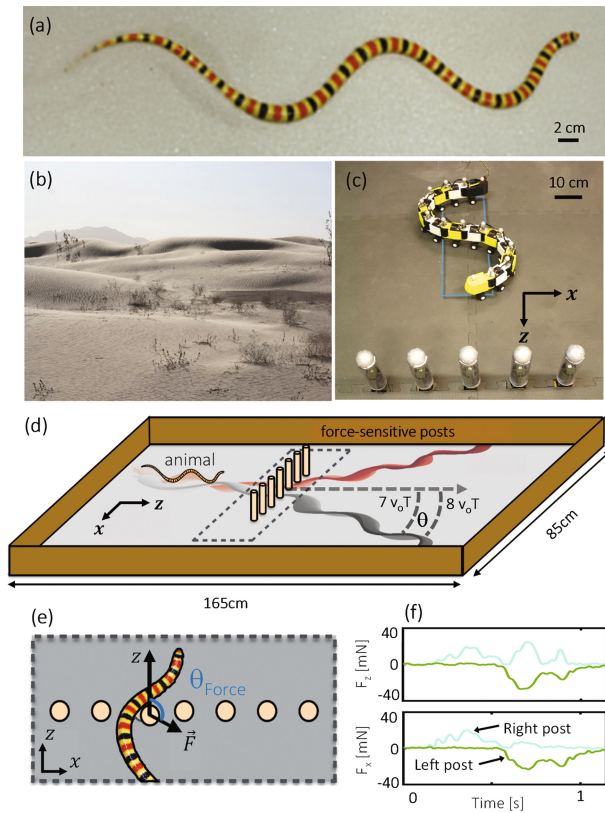


Fig. 1. *C. occipitalis* and robotic snake in heterogeneous terrain. (a) The Mojave Shovel-nosed snake, *Chionactis occipitalis*, is a small desert-dwelling Colubrid specialized to move on and within sand (9 individuals; Mass: 21 ± 3 g; Length: 38.4 ± 2.3 cm) (b) An example of the natural habitat of *C. occipitalis*. The sand substrate is omnipresent. Obstacles are sparse and include small plants, twigs, and rocks. (c) The 12-joint robot snake. (Mass: 1.1 kg; Length: 80 cm) Local joint angles were commanded to vary sinusoidally both along the arclength and in time according to Eq. 1. The array of 5 evenly-spaced posts is seen at the bottom of the image. In order to sample all initial conditions, the robot CoM was placed throughout the initial conditions box indicated by the blue rectangle. (d) Snake experiments were carried out in a 165 cm $\times$ 85 cm arena. The substrate was a high-pile carpet. Six force-sensitive posts and one fiducial post were oriented perpendicular to the direction of travel. Red and black traces are example snake trajectories. The scattering angle θ was calculated by averaging the angle between the trajectory and the dashed line indicating the z-axis between the dashed arcs at seven and eight $v_0 T$. (e) Schematic of a snake interaction with a post. The snake applied a force vector $\vec{F} = \langle F_x, F_z \rangle$ to the post. $\theta_{\text{Force}} = \text{atan}(F_x/F_z)$ is the angle between the positive z-axis and $\vec{F}$. θ_{Force} is always less than 180° . $F_x > 0$ yields positive θ_{Force} and $F_x < 0$ yields negative θ_{Force} . (f) Example time-resolved forces from a single living snake trial. The snake contacted two posts and applied forces in both x and z. (Color figure online)

with respect to all points on the first half of the body. We found this measurement was a fair representative of the path of the snake given the noise introduced by tracking as well as differences between the waveforms of individuals. The drawback of this method was that close to the array the tracks from trajectories which ultimately diverge overlapped, obscuring the pattern. Therefore, we found the peaks in the histogram did not become obvious to the eye until the snake was 5–6 undulations from the array and continued to become more clear as we measured further away. At 7–8 undulations from the array the angles have discernable peaks. These peaks would likely become increasingly distinct further away from the posts, however the tracks begin ending past $8 v_0 T$. That is, at 7–8 $v_0 T$ the number of data points included in the histogram is comparable to the number of points included at, for example, 1 to 2 $v_0 T$.

3 Robotic Snake Experiments

We constructed a robophysical model [7] of the snake from 13 rigid, 3D printed segments actuated by 12 servo motors (Dynamixel AX-12A) (Fig. 1c). The robot moved on rubber mats and LEGO wheels on the underside of the robot facilitated low-slip locomotion comparable to that of *C. occipitalis* in granular media [8]. A row of five rigid 4.5 cm diameter posts with a 5.7 cm opening between posts was placed perpendicular to the direction of travel of the robot. The force applied to the posts was measured via strain gauges bonded to the square Aluminum-rod base.

Interaction with the array was dependent on the phase and position of the robot when it contacted the posts. Therefore, to explore all possible initial conditions, we varied the initial placement of the center-of-mass (CoM) of the robot within a rectangle whose width was set by the periodicity of the posts and length by the wavelength of the waveform (blue rectangle, Fig. 1c). The x and z coordinates of each segment were captured at 120 Hz by a system of four OptiTrack cameras (Flex 13, Natural Point) tracking infrared reflective markers on the robot.

The robot was controlled using a Robotis CM-700 controller and powered using an external supply. The actuator positions were determined by the equation for a serpenoid curve (Eq. 1).

$$\zeta_i = \zeta_{Max} \sin(ks_i + 2\pi ft) \quad (1)$$

ζ_i is the angular position of actuator $i = [1, \dots, 12]$ with a set maximum angular excursion $\zeta_{Max} = 0.62$ rad, spatial frequency $k = 1$, and temporal frequency $f = 0.15$ Hz. The waveform seen on the robot in Fig. 1c is this serpenoid curve at time $t = 0$. The control signal sent to the robot was open-loop such that these parameters were not changed at any point in any of the trials and the control signals would continue to be sent as a function of time and position on the body regardless of external forces or tracking accuracy of the actuators.

We tested two versions of this control on the robot. The first case was high-torque (HT). In this case the maximum torque each actuator could produce was 1.5 N-m. The HT robot could accurately track the desired waveform in most cases. We verified the tracked robot positions using the OptiTrack data and found the tracking error was $< 5\%$.

For the limited-torque (LT) case we kept all other aspects of the robot and controller the same but limited the torque output of each actuator to 25% of the overall maximum (0.38 N-m). For reference, the largest torque measured in the robot moving on the rubber mats alone was 20% max, or 0.3 N-m. In the LT case the actuator would track the commanded trajectory up until the torque exceeded 0.38 N-m. At this point the motor continued attempting to track the commanded angles but did not exert more than 0.38 N-m of torque. The motor resumed successful tracking of the commanded trajectory once this was possible with ≤ 0.38 N-m of torque. The inability of one actuator to achieve the desired position did not change the commands to it nor to the other actuators. The observed result of the LT condition was that local deformations from the serpenoid curve appeared during interaction with the post array. The distribution of tracking error during interaction with the posts had a similar mean to the HT case but the tails of the distribution were longer and asymmetric with a greater number of large positive errors (maximum tracking error measured was 34%) than seen in the HT case. This reflects the observed local deviations from the commanded angles. We compared the kinematics of the HT to the LT case for the robot moving in a steady state with no pegs present to verify that decreasing the maximum torque available to the actuators did not otherwise change their behavior.

4 Results

The array acts to scatter the snakes. Two example trajectories are shown in the schematic in Fig. 1d (black and red tracks). The action of the array is further illustrated when all trajectories from all trials are combined as in Fig. 2d. The snakes move from bottom to top, in the direction of positive z . The units are normalized by v_0T , the average CoM velocity times the period of the motion, i.e., the average distance travelled in one undulation. The trajectories are colored according to the scattering angle θ . To calculate θ we averaged the polar angle of the trajectory with respect to the z -axis as it passed through a band between seven and eight v_0T from the array (see Fig. 1d for a schematic).

The trajectories of the LT and HT robot trials are shown in Fig. 2e and f, respectively. The trajectories are colored by scattering angle as before, and as in the trials with *C. occipitalis* some trajectories were deflected away from the z -axis by the interaction with the array. The LT robot generally scattered at smaller angles than the HT robot. We note that the largest scattering angles of *C. occipitalis* were greater than those of the robot, but we cannot say whether this is of any significance. During these trials we found that the scattering angle was sensitive to a number of factors related to the various dimensions of the system, and it is as of yet unclear which of these drove the differences between *C. occipitalis* and the robot, or if it was to a greater degree due to differences in the neuromechanical systems (e.g. the use of bilateral muscle versus a single servo to actuate the trunk).

The emergent pattern of the trajectory re-orientations was further illustrated in a histogram of the scattering angle. These histograms are above their corresponding trajectory maps in Fig. 2. It is clear that both the living and robotic snakes are more

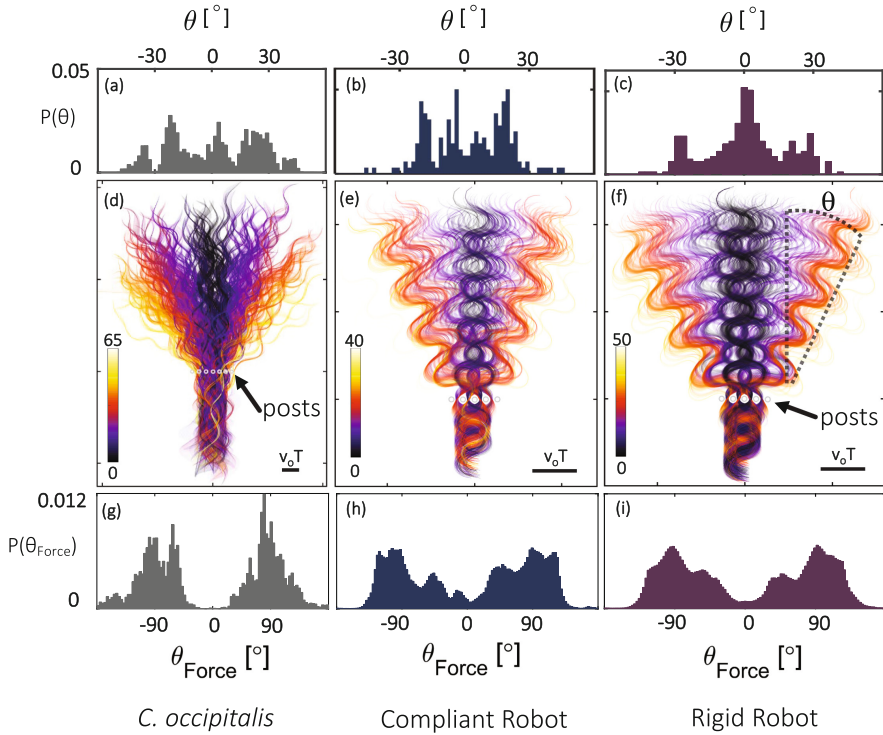


Fig. 2. Emergent collisional diffraction pattern (a–c) Scattering angle θ for the snake (181 trials), limited-torque (LT) robot (216 trials), and maximum-torque (HT) robot (366 trials), respectively (left to right). Snake scattering angles are calculated as the mean polar angle of a trajectory when it is a distance between 7 and $8 v_0 T$ from the center of the post array (see diagram in Fig. 1d and discussion in Sect. 2). As the robot waveform has less natural variation, scattering angle is calculated by fitting a line to the maxima/minima of the trajectory for all body segments and calculating the angle between these lines and the vertical. θ is taken to be the average of all of these values. (d–f) Trajectories for the snake, LT robot, and HT robot, respectively (left to right). To help differentiate trajectories each run is colored according to the absolute value of its scattering angle. Light gray circles indicate the position of the posts. Prior to the posts the group of trajectories is “collimated” whereas after interacting with the array some trajectories deflect away from the vertical z-axis. (g–i) Force orientation angle θ_{Force} for the snake, LT robot, and HT robot, respectively (left to right). θ_{Force} is calculated for each contacted post throughout each run by finding the angle between the force vector and the z-axis. A value of zero corresponds to the snake pushing directly forward (+z) while 180° is the snake pushing directly opposite the direction of motion (−z). The peaks in the distributions occur around $\pm 90^\circ$, meaning the snakes are most likely to push left/right on the posts.

likely to travel in certain directions than others upon exiting the array, and this pattern is qualitatively similar for the three systems tested.

The forces applied to the obstacles revealed a similar emergent pattern. The angle θ_{Force} is the angle between the force vector and the positive z-axis, i.e. $\text{atan}(F_x/F_z)$

(Fig. 1e). The bottom row of Fig. 2 shows histograms of θ_{Force} for all trials. We find that both the living and robotic systems are more likely to push left/right against the array. It seemed reasonable to expect that θ_{Force} and θ would be correlated. However, we did not find any relationship between the two. This may be attributed to the complexity of the interactions acting simultaneously between the posts, the body, and the substrate; perhaps in combination with the highly dissipative nature of the surroundings.

5 Discussion

This study highlights the benefits and repercussions of using an open-loop template during limbless locomotion in multi-modal terrain. Control of the serpenoid-template was easy to implement, and we note that it was exceedingly rare ($\sim 1\%$ of trials) for the rigid robot to become wedged in the array, while the compliant robot and living snake always transited the array. We therefore argue open-loop control of the serpenoid template is an effective strategy for transit of sparse terrain which requires no external sensors, with the caution that the pattern of trajectory reorientation appears to be a general feature of these systems. A more sophisticated control scheme which can correct the heading changes caused by collision with obstacles may be necessary if a specific trajectory is desired.

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