Experimental Observations and Robophysical Models of Snake Lateral Undulation, Sidewinding, and Proto-Sidewinding

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Abstract

Snakes are complex and versatile locomotion platforms. We analyze lateral undulation and sidewinding gaits of snakes using motion-capture technology and curvature analysis in the horizontal and vertical planes. We also perform this analysis on a "proto-sidewinding" variation of sidewinding which is exhibited on hard surfaces. It is shown that this curvature analysis shows striking similarities between lateral undulation, sidewinding, and proto-sidewinding. Finally, a protosidewinding-like gait is implemented on a snake robophysical model.

1 Introduction

Snakes are fascinating animals because they have a huge number of degrees of freedom in their bodies, leading to an incredible amount of flexibility. Hirose says "The simple cordlike body of the snake becomes a leg when it moves among rocks, a body when it moves from branch to branch, and a hand when it coils around a prey" [1]. This amount of flexibility creates a large space of complex gait patterns which can operate over diverse terrain types. There is thus much to study in the snake field.

Presently, we study the lateral undulation gait observed in the Western shovel-nosed snake (*Chionactis occipitalis*), as well as a strange sidewinding-like gait that is observed only when this species is placed on a hard (non-yielding) surface. We then build a robophysical model of this proto-sidewinding gait to demonstrate our understanding of it.

2 Methods

To obtain kinematic data from *C. occipitalis*, an Opti-track system was utilized to track infra-red markers placed 1cm apart along the snake spine. Two snake subjects were observed. The Opt-track system tracked 3D position data for each marker at 120Hz. Data was collected from 2 runs of each snake subject over a whiteboard surface, which was hard and had low friction.

Kinematic data were obtained for *C. occipitalis* lateral undulation over sand, as well as a rattlesnake sidewinding, but was not collected directly by the author or (lab partner) Lucas Isbill.

Data was post-processed in Matlab to fit the raw data with a cubic spline curve. Horizontal and vertical curvature information as well as velocity information was extracted from the data using custom Matlab scripts.

For sidewinding data, in order to account for what appeared to be sloped ground, the vertical height of the snake was defined to be the shortest distance from each point of the body to the plane which is fitted to all points along the body (by minimizing least-squares error).

Static contact regions were determined by thresholding velocity to below about 50% of average velocity values and applying temporal and spatial smoothing.

In addition to anyalzing kinematic data, a robophysical snake model was constructed out of 13 Dynamixel XL-320 servomotors, as shown in Fig. 1. This robot was used to replicate the porto-sidewinding gait observed in the real *C. occipitalis*.

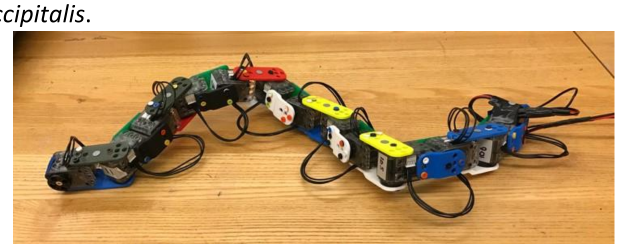


Figure 1: 13-DoF snake robot capable of lateral and vertical bending.

3 Results

Figure 2 shows horizontal (medio-lateral) curvature (gray shaded regions), vertical curvature (blue and pink), and static contact regions (white overlay), for a sidewinding gait in a rattlesnake. This type of superimposed curvature plot was constructed for *C. occipitalis* for its lateral undulation and proto-sidewinding gaits in Figs. 3 and 4.

The robophysical snake model was controlled in a manner similar to [2], where horizontal and vertical waves of curvature were simultaneously present along the body. Eqs. (1) and (2) show the curvature commands given to the robot, where parameter α parametrizes the gait from pure lateral undulation ($\alpha = 0$) to sidewinding ($\alpha = 1$). s is arc length parameter, ω represents the speed of the traveling wave, and A_H,A_V are horizontal and vertical curvature amplitude, respectively.

$$\kappa_H = A_H \cos(2\pi s - \omega t) \quad (1)$$

$$\kappa_V = (1-\alpha) A_V \cos(4\pi s - 2\omega t) + \alpha A_V \cos(2\pi s + \pi/2 - \omega t), \quad (2) \quad s,\alpha \in [0,1]$$

Fig. 5 shows real curvature data obtained from our robophysical model executing the gait of Eqs. (1) and (2) with $\alpha = 0.3$.

4 Discussion

Analysis of the vertical and horizontal curvature data provides an interesting way to look at sidewinding, lateral undulation, and proto-sidewinding gaits. As shown in Figs. 2 to 4, the boundary line between positive and negative lateral curvature lies consistently over regions of positive vertical curvature. Additionally, the peak of positive or negative lateral curvature coincides with a peak of negative vertical curvature. Thus, from a curvature perspective, sidewinding, lateral undulation, and proto-sidewinding, all appear to share a vertical wave of curvature with double spatial and temporal frequency of the horizontal wave of curvature, and with precise phase alignment in space and time. Thus, it appears as if these three gaits were really one, but the only thing different between them is the region(s) of static contact.

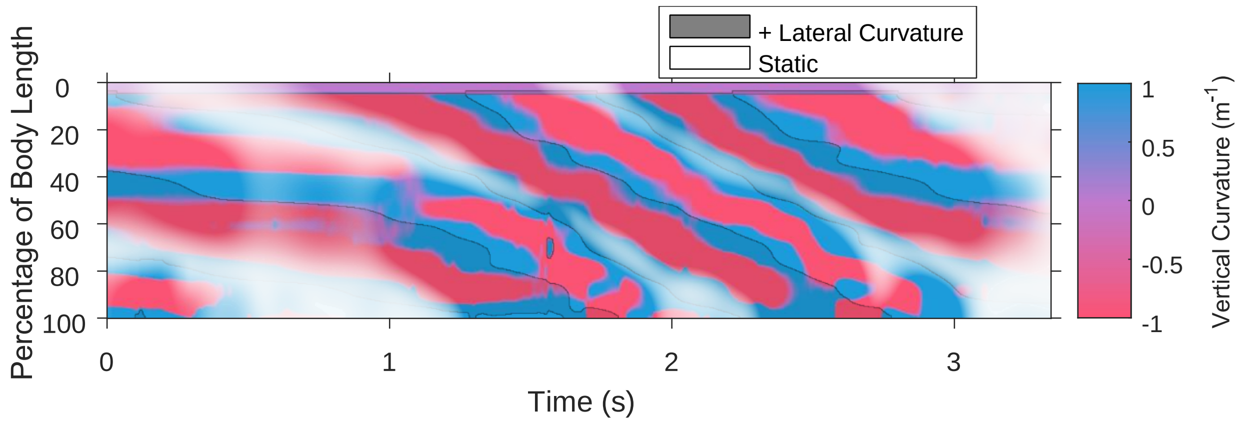


Figure 2: A superimposed plot of horizontal (medio-lateral) curvature (gray shaded regions), vertical curvature (blue and pink), and static contact regions (white overlay), for the sidewinding gait in a rattlesnake.

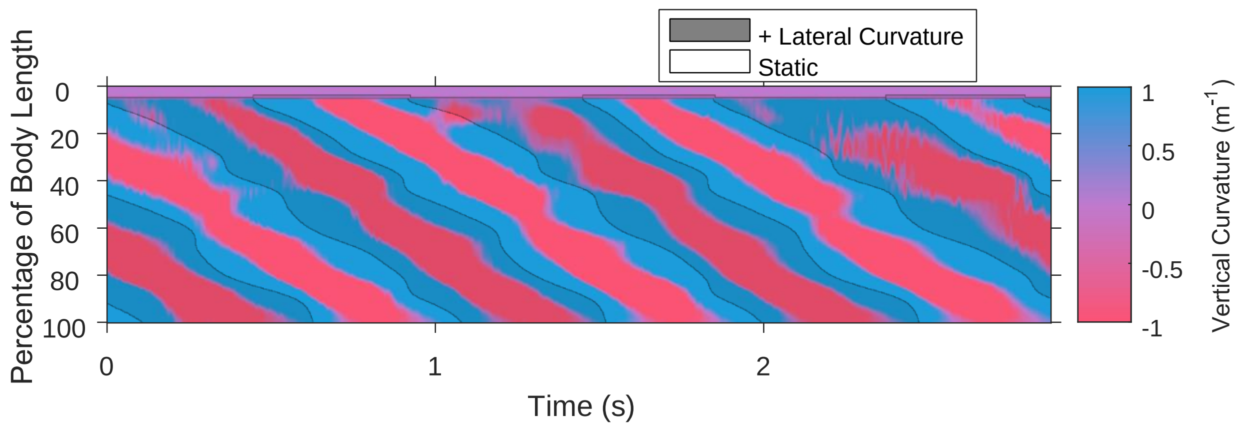


Figure 3: Plot similar to Fig. 2 for lateral undulation of *C. occipitalis*.

We hypothesized that only a small, perhaps imperceptible, change in curvature would be enough to change the snake contact pattern, as shown in Fig. 6. We tested this hypothesis on the snake robophysical model, by setting α in Eqs. (1) and (2) to a small value (0.3). The result is shown in Fig. 5. Sidewinding (sideways) motion was observed on the robot, and Fig. 5 shows many similarities to the other superimposed curvature plots, confirming the hypothesis that small changes in curvature can change the contact pattern enough to induce sidewinding locomotion.

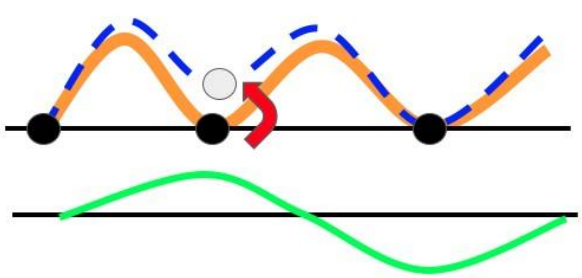


Figure 6: A small change in curvature given by the green wave (bottom) induces a significant change in ground contact area (top).

However, there is more to the picture than only local curvature. If we instead look at body lifting height (Fig. 7), rather than curvature, we can see that the curvature picture may be slightly misleading: small deviations in height can lead to a large curvature value, without representing the true shape of the snake. For example, for the time instant shown in Fig. 7, the shape vertical lifting would be better characterized as a wave of wavelength 0.8m rather than a wavelength of 0.15m, because this lower-frequency wave is larger in amplitude. However, a curvature analysis would likely only show the wave of smaller wavelength since its higher-frequency peaks dominate the curvature value.

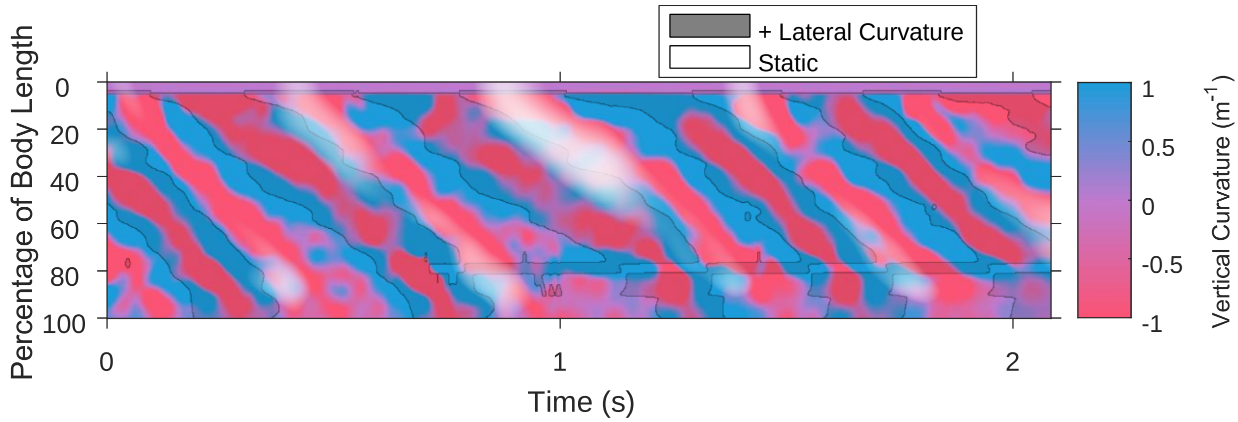


Figure 4: Plot similar to Fig. 2 for proto-sidewinding of *C. occipitalis*.

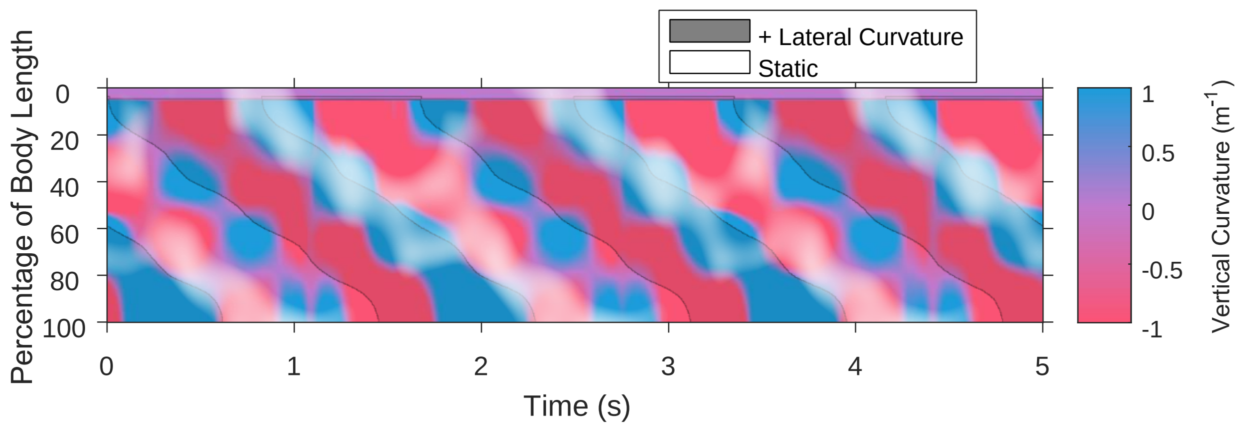
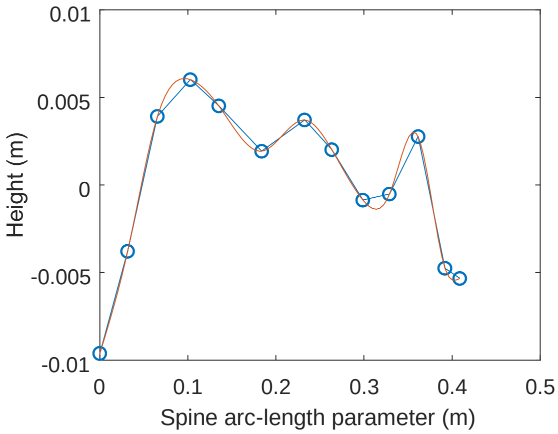


Figure 5: Plot similar to Fig. 2 for robophysical model.



5 Future Work

Better experimental techniques are needed to accurately measure the lifting height of snake subjects. As demonstrated, even small changes in lifting height can result in large changes in contact pattern and thus locomotor behavior. Sub-millimeter precision is probably necessary, which is difficult to resolve with the Opti-track system used in this work.

Additionally, more robust and reliable techniques than curvaFigure 7: Fitting continuous cubic splines to discrete vertical position data from a sidewinding rattlesnake.

ture analysis are necessary in order to extract high-level principles of snake locomotion.

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