

Comparative investigation of control mechanisms for turning during quadrupedal robot locomotion

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1 Introduction

Locomotion is a critical behavior that allows animals to move in the external world. The underlying neuronal control involves rhythm-generating and limb-coordinating circuits that execute commands and integrate afferent feedback to adapt to changing environments. Most studies of locomotion have been focused on the neuronal control of straight forward locomotion. How turning or the change in locomotor direction is controlled remains poorly understood. Recent neurophysiological investigations have shown that turning may result from the activation of selected neurons in the brainstem reticular formation that produces left–right asymmetries in neural control of locomotion [1, 2]. Although it is clear that different left–right asymmetries can lead to changes in movement direction, it is unknown which turning strategies optimally maintain movement stability. Here we use a quadrupedal robot simulation to compare different turning mechanisms.

2 Methods

Locomotion of the simulated quadrupedal robot is generated by four weakly-coupled oscillators (one for each limb), position controllers, and feedback (Fig. 1A). The phase of each oscillator is used by the position controller to determine the target trajectory of each foot (Fig. 1B). The ground reaction forces and hip/shoulder angles are used to generate feedback. Each limb’s feedback is phase-dependent and causes phase resetting of the oscillators. All simulations were performed in PyBullet 3.2.5.

2.1 Quadrupedal Robot

The quadrupedal robot has 13 degrees of freedom: three joints per limb and one joint within the torso that allows for lateral bending of the body. Each limb is controlled by three servos. The servos are placed at the hip/shoulder with two controlling the upper and lower leg segments, and the third controlling mediolateral limb movement.

2.2 Coupled Oscillators

Rhythm generators controlling limbs are modeled as oscillators that are weakly coupled to represent and simplify the existing commissural and propriospinal interactions in the spinal cord (Fig. 1 A) [3–7]. By varying the coupling terms, the oscillators produce phase differences characteris-

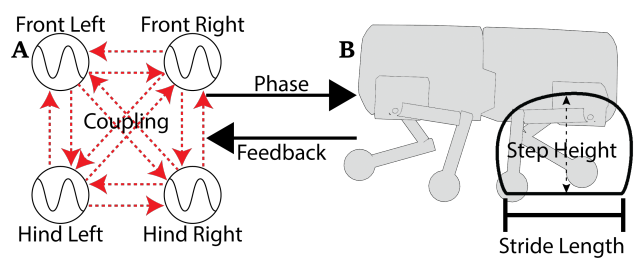


Figure 1: Overview of the robot and controller. Coupled oscillators that integrate feedback (A) input into the position controller, whose trajectory is defined by step height and stride length (B).

tic of walk, trot, gallop, and bound [4, 5].

2.3 Position Controller

A position controller transforms limb phases into target positions, where trajectories are divided into stance and swing phases (Fig. 1B). During stance phase, the target foot position follows a straight line that allows the foot to push off of the ground. After the stance phase ends, the trajectory switches to the swing phase. During swing phase the leg lifts off the ground and follows a Bezier curve to reach a target step height. Once the foot touches down the consecutive stance phase begins.

2.4 Feedback

Feedback signals from somatosensory afferents affect the timing of phase transitions [8, 9]. In particular, the feedback from Golgi tendon Ib and spindle type II afferents have been shown to regulate phase progression in a state-dependent manner and are modeled within this controller. Type II afferents are simulated by modulating phase progression when the hip/shoulder angle passes a set threshold. During stance phase the simulated type II afferents increase the speed of phase progression once past the threshold, thereby promoting a transition to swing when the limbs are overextended. Likewise, the simulated group Ib afferents receive information about the loading of the limb through recorded ground reaction forces. Loading of the limb causes a decrease in phase progression, which prolongs the stance phase. Both feedback mechanisms are modulated by static gains and thresholds that allow for optimization to determine when each feedback should be initiated and to what extent.

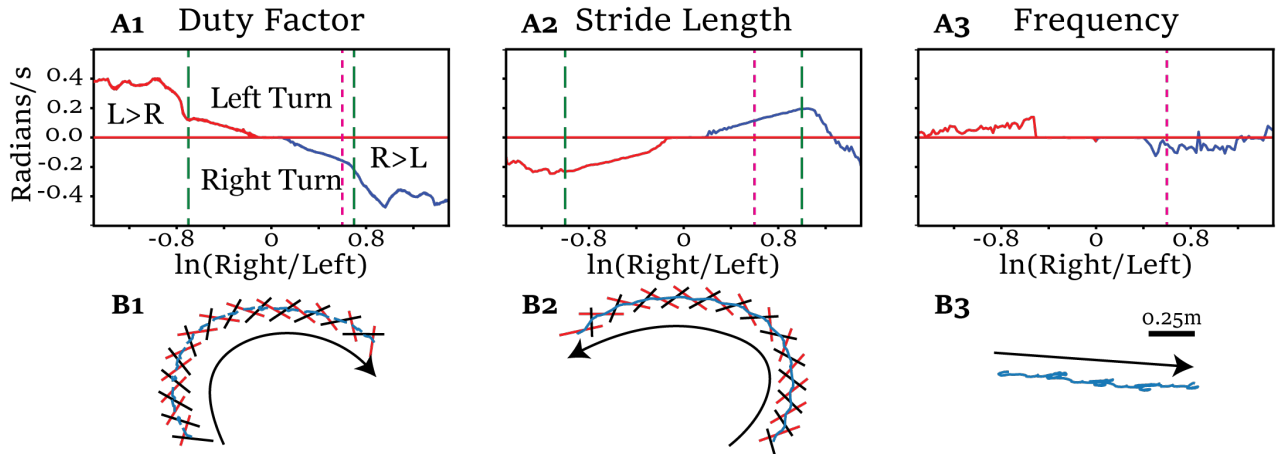


Figure 2: Turning behavior. A. The angular (turning) velocity resulting from asymmetrically changing duty factor (A1), stride length (A2), and frequency (A3). The red horizontal line represents zero turning velocity. Above the horizontal line is a left turn and below is a right turn. The x-axis shows asymmetry values where negative values represent larger values of a parameter for the left side while positive values represent larger values for the right. Green vertical dashed lines represent the limits of the asymmetric parameter before locomotion becomes unstable. B. The trajectory for duty factor (B1), stride length (B2), and frequency (B3) at an asymmetry value of 0.6. The blue line represents the center of the body, while the red and black lines connect the foot touchdown positions for the front right to back left and front left to back right diagonal limbs, respectively.

2.5 Asymmetries for Turning

To study turning, several different types of left-right asymmetries were considered. We tested stride lengths, duty factors, and step frequencies. Parameters were scaled by an asymmetry value (α) so each parameter countered the value from the contralateral side. This results in the target parameter = $P * e^{\pm\alpha}$, where P is the initial symmetric parameter value (Fig. 2A).

3 Results

The model was able to locomote at different speeds and gaits while exhibiting speed-dependent changes in stance and swing phase duration. Furthermore, the model was able to adapt to changes in the environment and external perturbations. This allowed us to study left-right asymmetric changes in locomotor frequency, duty factor, and stride length to induce turning at different speeds and gaits.

An asymmetry in duty factor resulted in a turn towards the side with the longer duty factor; a stride length asymmetry caused the robot to turn towards the side with the shorter stride length. On the other hand, we have found that an asymmetric stepping frequency does not produce stable turning (Fig. 2A). When stepping frequency was increased on one side, the robot started to step more frequently on one side but these steps were caught pushing against the slower side. This caused uncoordinated movement that is more likely to continue forward than turn. We also found that an increase of asymmetry leads to an increase of angular velocity. Stride length asymmetries allow for quicker turns than duty factor asymmetries (Fig. 2B).

4 Conclusion

Our model suggests that many strategies are needed to effectively turn while maintaining stability. The optimal strategy likely also depends on the locomotor gait and speed. Thus, control of turning likely involves task- and speed-dependent modulation of the spinal neuronal circuits at multiple levels. Currently, we are working on combinations of asymmetries to show changes in performance when combin-

ing multiple turning strategies and investigate how turning strategies depend on speed, gait and environmental conditions. It is currently unclear what constitutes as optimal turning and we plan to explore this. All of this will be validated on a physical robot that will allow us to test our simulations in real-world environments.

Acknowledgements

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