Bio-Inspired Locomotion via a Sensorless Kuramoto-Based Central Pattern Generator

Abstract

This project implements a bio-inspired locomotion controller for a quadruped robot using a Kuramoto-based Central Pattern Generator (CPG). The model reproduces rhythmic limb coordination similar to that found in vertebrate spinal networks, achieving a trot gait without any sensory feedback. The system consists of four coupled oscillators, one per leg, that synchronize their phases according to biologically inspired phase relationships. Simulation results show stable phase locking and consistent gait patterns, demonstrating how complex locomotor behaviors can emerge from simple oscillator dynamics.

1. Introduction

In biological systems, rhythmic behaviors such as walking, swimming, and breathing are controlled by Central Pattern Generators (CPGs) — neural circuits in the spinal cord that produce coordinated muscle activations even without sensory input. In robotics, CPGs allow smooth locomotion using mathematical models. The Kuramoto oscillator captures synchronization between coupled oscillatory units. This project develops a sensorless CPG using the Kuramoto model to coordinate four oscillators representing a quadruped robot's legs, producing a trot gait where diagonal legs move in phase.

2. Methodology

The phase dynamics of the i-th oscillator are described by the Kuramoto equation: $d\theta_i/dt = \omega_i + (K/N) \Sigma \sin(\theta_j - \theta_i - \phi_{ij})$ where θ_i is the phase, ω_i is the natural frequency, K is coupling strength, N is the number of oscillators, and ϕ_{ij} is the desired phase offset. By selecting specific phase offsets, different gaits can be encoded. In this implementation, LF–RH and RF–LH are in phase, while lateral legs are anti-phase. The code simulates 4 oscillators with 1 Hz rhythm and coupling K=6. Each generates sine waves for hip and knee joints, producing gait diagrams and trajectories.

3. Results

The oscillators converged to stable phase relationships matching the trot pattern. Diagonal legs (LF–RH, RF–LH) remained in-phase, while lateral pairs were anti-phase ($\sim\pi$). The stance/swing pattern alternated consistently, replicating diagonal coordination of a trot. Hip and knee angles followed smooth oscillations with stable amplitude and frequency.

4. Discussion

This experiment demonstrates how complex coordinated motion can emerge from simple coupled nonlinear systems. The Kuramoto-based CPG replicates the timing relationships of biological gait patterns without sensory feedback — a hallmark of vertebrate locomotion circuits. Extensions include other gaits, robustness studies with noise, or implementation using Hopf oscillators with amplitude dynamics.

5. Conclusion

This bio-inspired CPG shows how synchronization principles from neuroscience can be applied in robotics. Using the Kuramoto model provides a compact and interpretable mathematical foundation for gait generation, bridging biological motor control and autonomous robotics.

References

1. Kuramoto, Y. (1975). Self-entrainment of a population of coupled non-linear oscillators. In International Symposium on Mathematical Problems in Theoretical Physics. 2. Ijspeert, A. J. (2008). Central pattern generators for locomotion control in animals and robots: a review. Neural Networks, 21(4), 642–653. 3. Cohen, A. H., Holmes, P. J., & Rand, R. H. (1982). The nature of the coupling between segmental oscillators of the lamprey spinal generator for locomotion. Journal of Theoretical Biology, 95(4), 747–777.