

# Selecting Among Neuromechanical Control Architectures using Kinematic Phase and Perturbation Experiments

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## INTRODUCTION

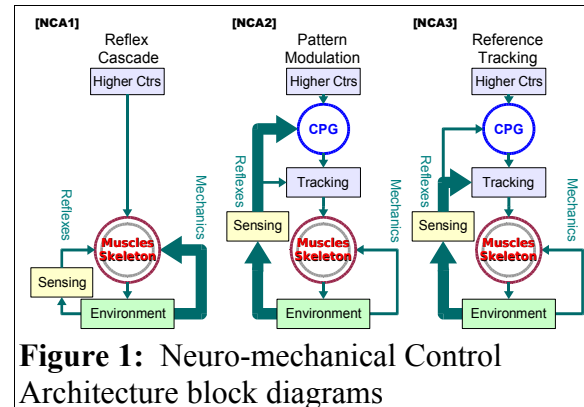
We use an experimental paradigm grounded in dynamical systems (DS) theory to select which among several competing neuro-mechanical control architectures (NCA) could be in use in a given rhythmic motor behavior by using kinematic data alone.

Our method allows us to extrapolate animal motions based on a few consecutive video frames, and compare the predicted motion to perturbation experiment outcomes.

We apply the method to the study of control of running in the cockroach *Blaberus discoidalis*, and discuss its broader utility in a variety of biomechanical problems, e.g. in potential clinical application of motor learning tasks such as [Sternad-04].

## NEURAL CONTROL FRAMEWORK

We describe neuromechanical control as occurring in the framework outlined by the block diagrams in Figure 1. The figure presents several alternative NCA that may be used to stabilize a running gait against environmental perturbations. These differ in how far up the neural control hierarchy they employ feedback, if at all. In each NCA the “Brain” specifies parameters to a pattern generator (CPG) emitting a pattern modulated by proprioceptive Tracking that applies sensory feedback to the signal before using it to drive the muscles. Mechanics generate their own feedback dynamics with the body, and motions produce sensory



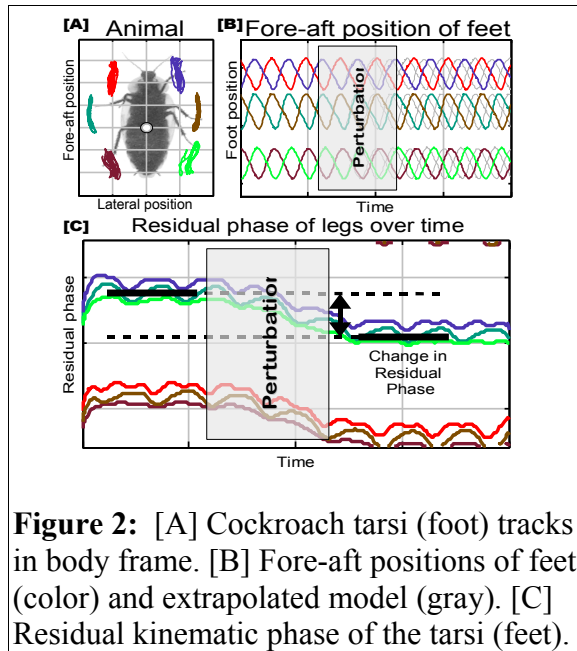
**Figure 1:** Neuro-mechanical Control Architecture block diagrams

changes that are processed through reflex pathways. [NCA1] motions cause interactions triggering subsequent motions reflexively; [NCA2] feedback strongly modulates the pattern generator; [NCA3] proprioceptive feedback makes the body track a reference signal from an immutable pattern generator.

## THEORETICAL FRAMEWORK

Dynamical systems that function as nonlinear oscillators are a natural choice of model for equations governing rhythmic behaviors such as rapid locomotion. One of the fundamental tools of the mathematical theory of such oscillators is the idea of “phase” [Guckenheimer-83].

We suggest that phase, in its strict mathematical sense, can be estimated effectively from “kinematic phase” - the phase of the kinematic state of the animal along its characteristic rhythmic cycle of poses (Figure 2 below [A,B]). Kinematic phase provides a means for predicting



**Figure 2:** [A] Cockroach tarsi (foot) tracks in body frame. [B] Fore-aft positions of feet (color) and extrapolated model (gray). [C] Residual kinematic phase of the tarsi (feet).

animal motions by extrapolating the trend of the phase variable and converting it back to a pose (Figure 2,[B] gray).

While continuous phase resetting is likely in NCA1 reflex cascade controllers like WalkNet [Cruse-98], NCA2 feed-forward control as suggested in [Jindrich-02] maintains phase or resets it in discrete jumps. Figure 2 [C] illustrates a phase change observation using our technique. Long term frequency changes provide evidence that feedback has modified the functioning of the pattern generators, possible only in NCA3 (see Figure 1).

## METHODS

Adult *B. discoidalis* cockroaches were induced to run and filmed with a high speed video camera, tracking body and tarsus motions in the horizontal plane. We collected 42 runs of animals running over a 3mm obstacle, 75 runs of a lateral impulse perturbation of 50 cm/sec and 20 unperturbed runs for validation.

The tarsus motions in the fore-aft direction were used to generate a kinematic phase

estimate, and the pre-perturbation trend fitted with a robust least squares regression line. The post perturbation residuals were used to select among the NCA alternatives.

## RESULTS

In 40 out of 42 obstacle trials significant phase changes were observed, but average frequency change was 0 and independent of phase change. All lateral impulse trials showed significant frequency changes at with a delayed onset that depended strongly on the phase at perturbation time.

## SUMMARY/CONCLUSIONS

The lateral perturbation results reconfirm the result of [Jindrich-02] that initial lateral perturbation recovery is mechanically mediated and neural feedback is evident only after times on the order of a step. The structure of the obstacle perturbation outcomes suggest a novel control model that we will briefly present.

Kinematic phase has been shown to be a useful tool for generating experimentally tractable quantitative predictions and elucidating some of the interconnections in the feedback pathways governing running in *B. discoidalis* cockroaches.

## REFERENCES

- Cruse H., Kindermann T., Schumm M., Dean J., Schmitz J. (1998). *Neural Networks*, v. 11, 7-8, 1435-1447
- Guckenheimer J., Holmes P. (1983). *Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields*. Springer-Verlag
- Jindrich D. L., Full R. J. (2002) *J. Exp. Biol.*, v. 205, 18, 2803-2823.
- Sternad D., Dijkstra T. M. H. (2004) *J. Clin. Neurophysiol.*, 21, 215–227.