An adaptive 3D bipedal locomotion model

Stability and efficiency analysis of an entrained motion primitive

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Introduction

- We present an adaptive 3D bipedal model for adaptive locomotion.
- The *uncontrolled manifold hypothesis* asserts that neural control applies only to high level, spatio-temporal aspects of task performance — e.g. keeping the head steady while running — while the mechanics of the body and Central Nervous System resolve the remaining degrees of freedom through activation patterns, called *motion primitives*.
- The *equilibrium point hypothesis* states that the body completes the task with limited input from neural system, provided the specified motion is stable and completes the objectives.
- These principles are implemented via two adaptive controllers: a neural oscillator coupled with the mechanical system to achieve entrainment, and symmetry controllers which adapt phase space to changes in the environment [3].
- We analyse the efficiency and and stability of entrainment as a control strategy for this model.

Objectives

1. Motion synthesis through integrating the current state of knowledge from diverse fields such as motor control, robotics and bio-mechanics.
2. Extend these principles to the 3D bipedal model of [1].
3. Develop tools to evaluate the influence of entrainment by numerical analysis to find the relationship between stability, cost of transport and changes in slope.

Methods

Mechanical Model

- Ames and Gregg [1] describe the continuous phase manipulator equation and hybrid dynamics as the instantaneous equation of the dynamics.
- They decoupled frontal-plane and sagital-plane dynamics.
- This 3D compass gait has a stable limit cycle walking on flat surface in R^3.

Environment Adaptation using Control Symmetry

- The Lie Group Symmetry Control *offset action* has been used in [2, 3, 4]. This control strategy shapes the potential energy of bipedal walker to stable walking on a flat surface.
- We adapt this method to satisfy new environmental constraints. Given a transformation $m' = g(m)$ a controller is found which satisfies the motor invariant I, i.e.

$$I(g(m)) = I(m), g \in G; m \in M \tag{1}$$

  where G and M represent the action and motion spaces, respectively, and I is a desired *motion invariant*.
- Applied to [1], this provides the local controller

$$u = K^{\alpha}_{3D}(\theta) := B_{3D}\frac{\partial}{\partial\theta}(V_{3D} - V_{3D}(\Psi_{\gamma}(\theta)) + \frac{1}{2}\frac{\alpha^2\dot{\phi}^2}{m_{3D}(\theta)}). \tag{2}$$

- The new control scheme implicitly utilizes the Lie group control symmetry

$$u = K^{\alpha}_{3D}(q) + (1 \quad 0 \quad 0)^T v$$

  A standard nonlinear SISO control system is used to drive the walker's frontal plane dynamic response to 0 as seen in Fig 1.

Global Control with Entrainment

- Entrainment between the mechanical system and a neural oscillator have been shown to enhance structural stability [3].
- We combine controller from previous local Control Law resulting into our final system

$$\begin{aligned}\dot{\boldsymbol{x}} &= F(\boldsymbol{x}, h_{out}u_{out}(\boldsymbol{x}_c)) + Bu_{local}(\boldsymbol{x})\\ \dot{\boldsymbol{x}}_c &= S(\boldsymbol{x}_c, h_{in}u_{in}(\boldsymbol{x}))\end{aligned} \tag{3}$$

  .
- We couple the Matsuoko oscillator as in [3].
- Perturbations (see Fig. 3) are handled by the entrainment with the neural oscillators providing the necessary structural stability to adapt to a new limit cycle.
- The neural oscillator input is given by the angle between two legs.

Results

- State stability improved by combination of local and global controllers.

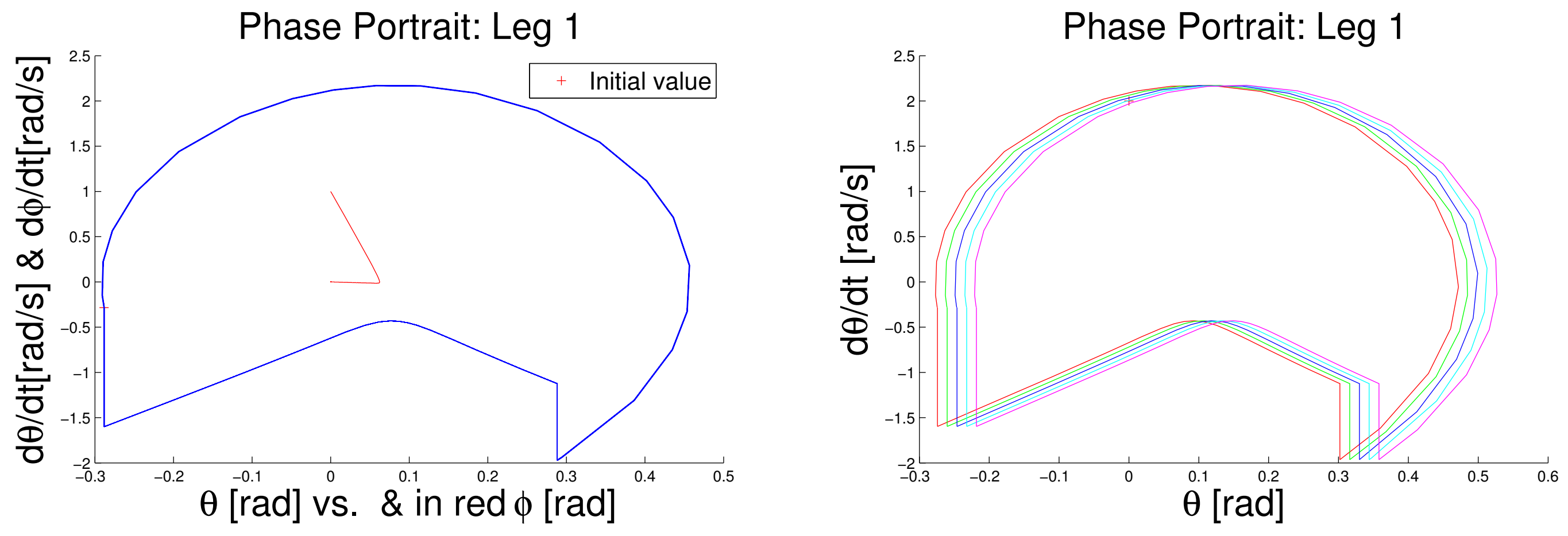

Figure 1: Local Control Law based adaptation at 5 different slopes in range $\gamma = (0, -0.0628)$ radians. This demonstrates the ability of this model to walk on uneven terrain.

- The global controller enables the adaptation to perturbations at rate of -0.015 per 10 steps. The strength of coupling between the systems correlates with the rate of convergence towards a stable periodic orbit.

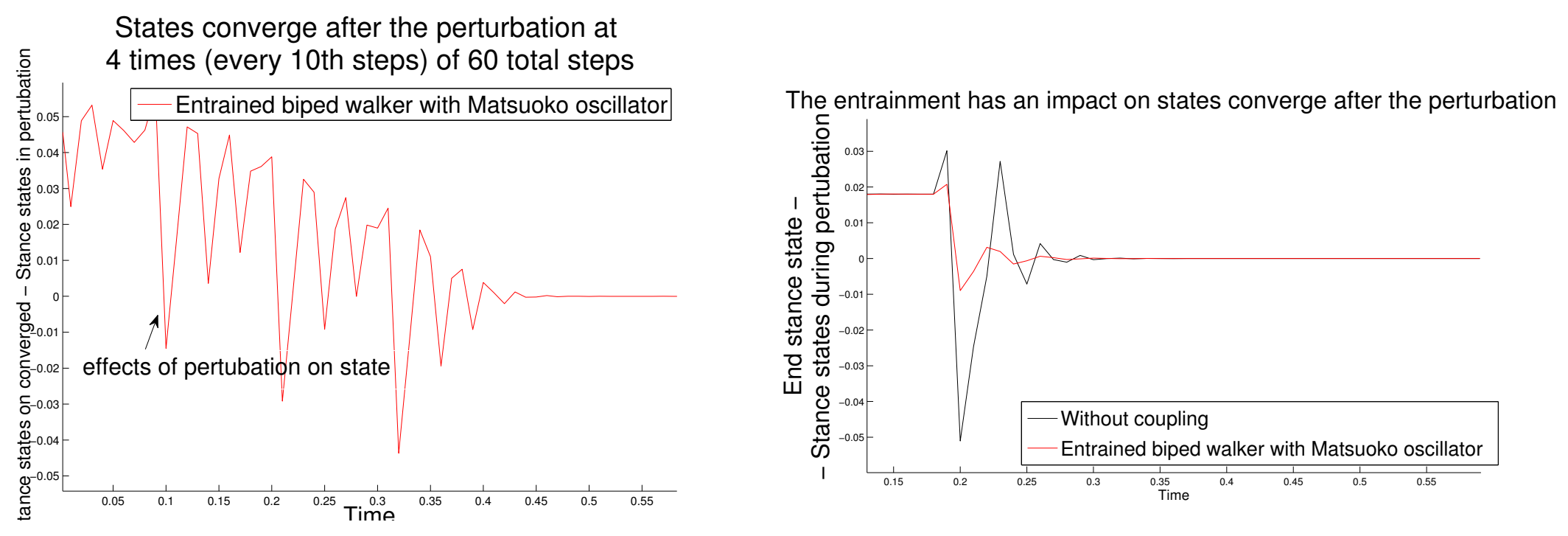

Figure 2: Convergence of the stance phase after a perturbation. The states regain periodic limit cycle after the perturbation at 10th step on coupled oscillator.

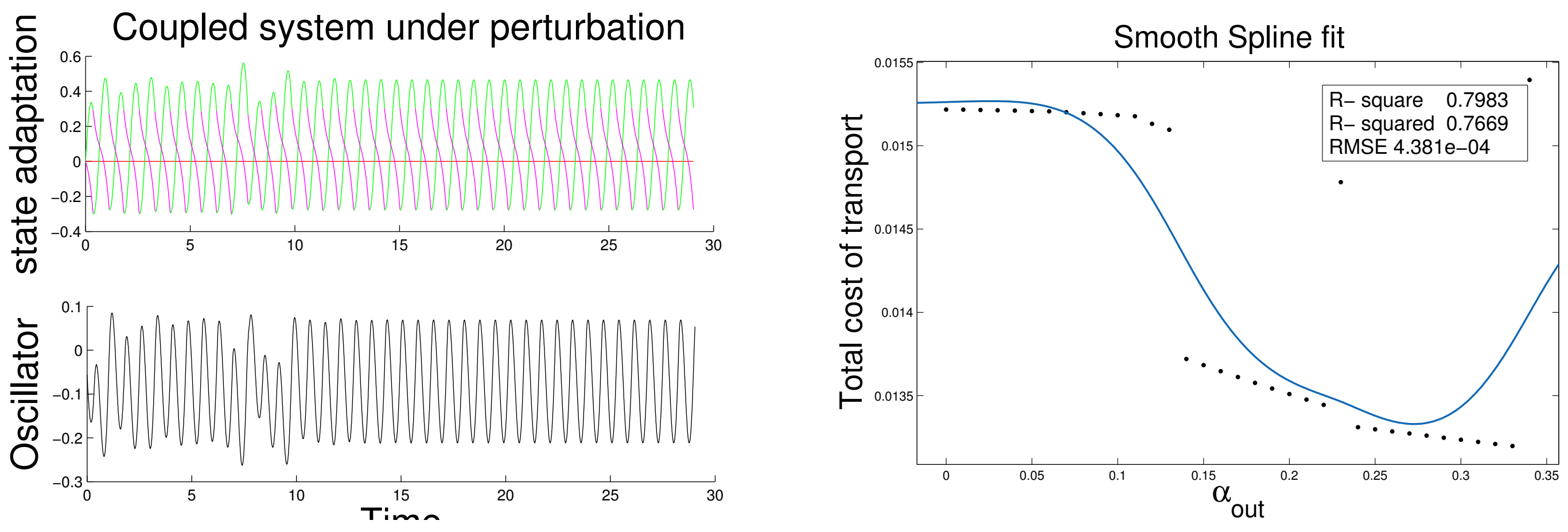

Figure 3: On the left, the global controller improves stability at instantaneous slope change of -0.02 rad(s). On the right, we evaluate the effect of the coupling coefficient h_{out} on the cost of transport.

- In Fig.3 we propose a method to choose the optimal coupling coefficient to minimise the cost of transport with stable control.

Future Work

In the future we intend to

- develop an on–line method to identify optimal control parameters for uneven terrain;
- derive a motion planning method which accounts for adaptation costs;
- develop smooth and effective switching between motion primitives, such as of between running, walking and balancing in $\mathbb{R}^3$; and
- leverage underpinning biological principles of locomotion in the development of robotic models which are stable and energy efficient.

References

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