

# 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 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 sagittal-plane dynamics.
- This 3D compass gait has a stable limit cycle walking on flat surface in  $\mathbb{R}^3$ .

#### 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  $m^l = g(m)$  a controller is found which satisfies the motor invariant  $I$ , i.e.

$$I(g(m)) = I(m), g \in G; m \in M \quad (1)$$

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

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

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

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

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

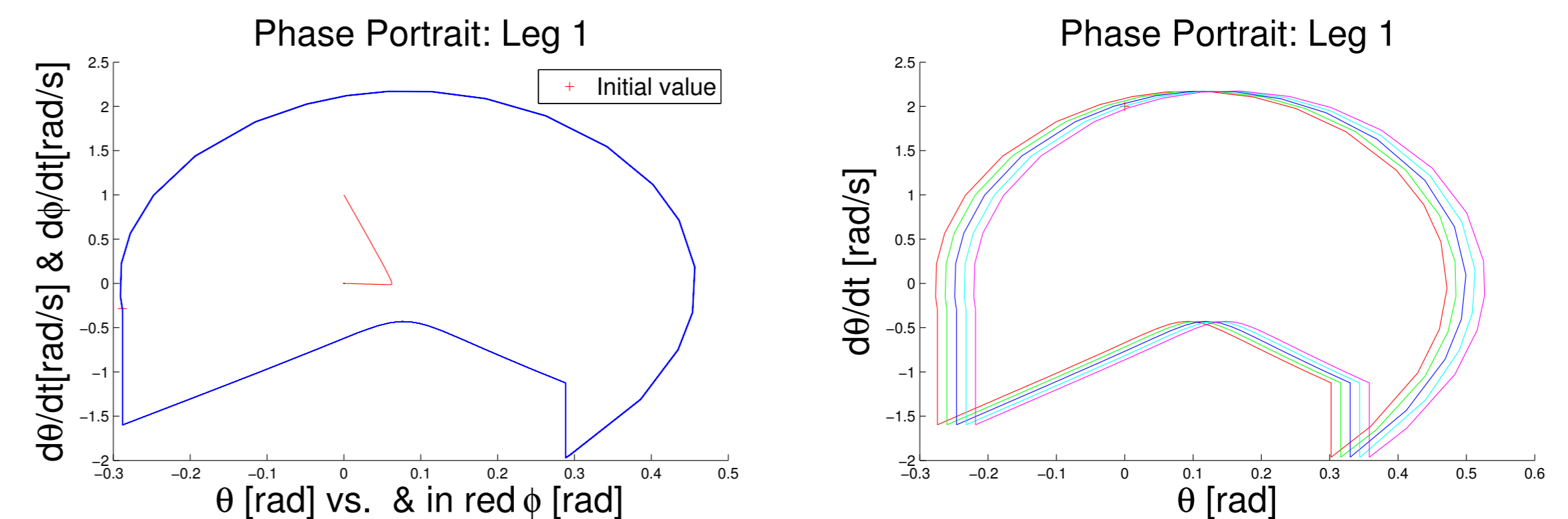
- Entrainment between the mechanical system and a neural oscillator have been shown to enhance structural stability [3].
- We combine controller from previous local Control Law resulting into our final system

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

- 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.

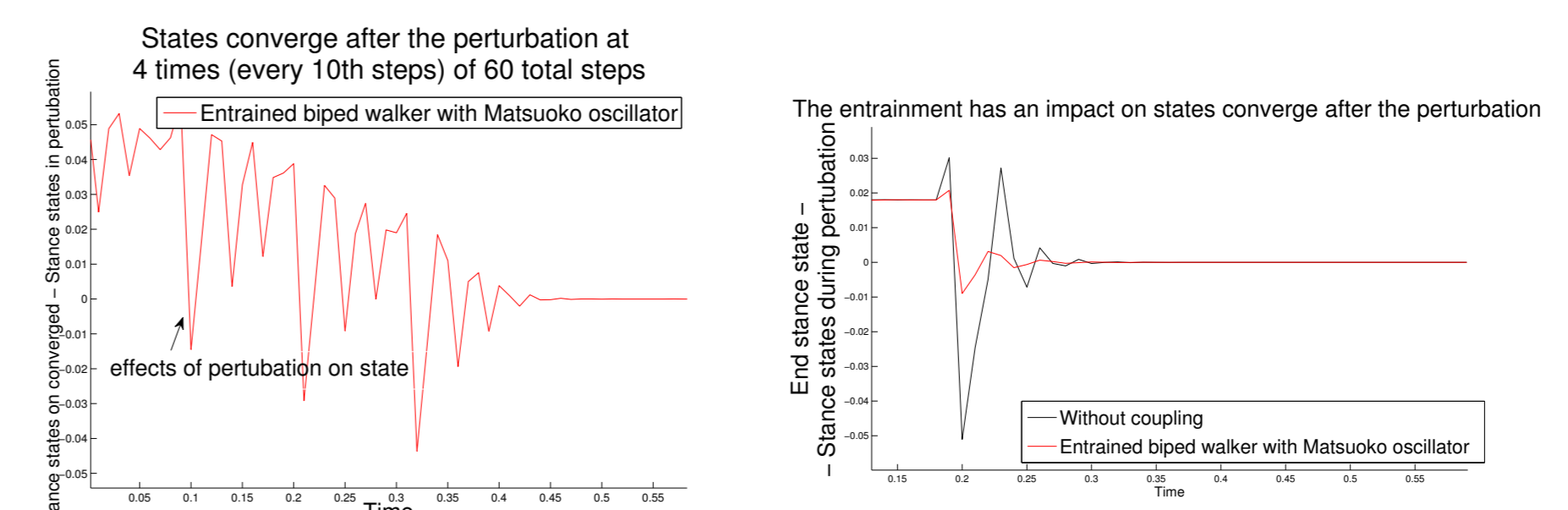
### Results

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

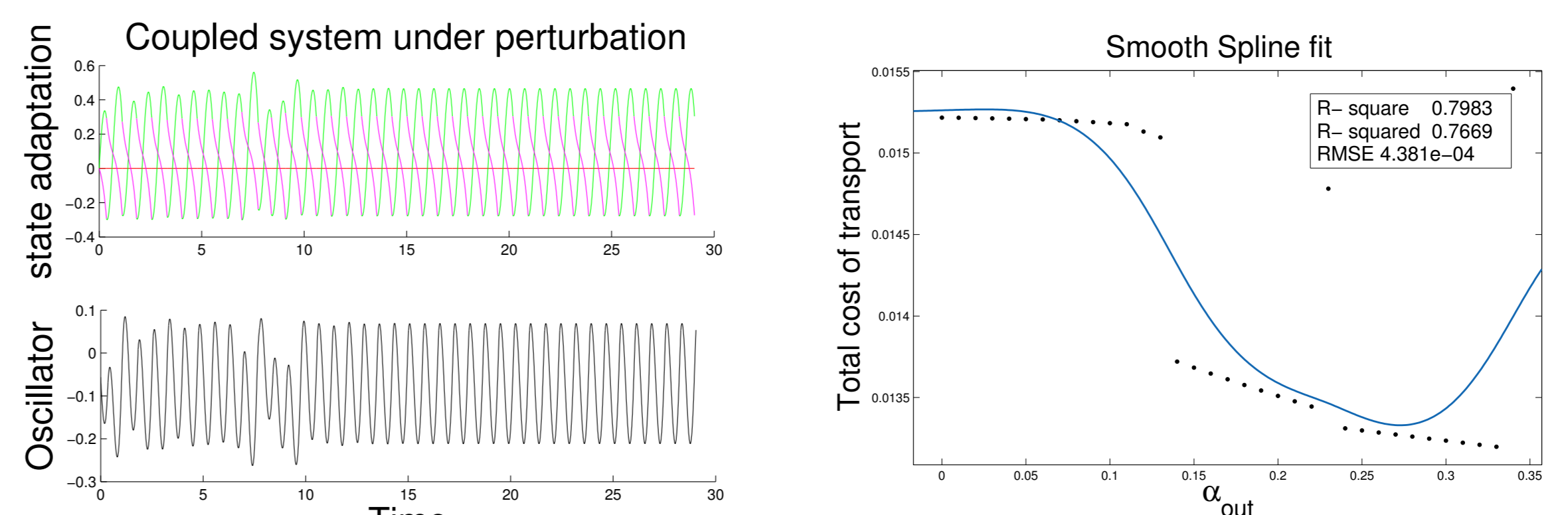


**Figure 1:** Local Control Law based adaptation at 5 different slopes in range  $\gamma = (0, -0.0628)$  radians. This demonstrates the ability of this model to walk on uneven terrain.

- 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

- [1] Aaron D Ames and Robert D Gregg. Stably extending two-dimensional bipedal walking to three dimensions. In *American Control Conference, 2007. ACC'07*, pages 2848–2854. IEEE, 2007.
- [2] Aaron D Ames, Robert D Gregg, and Mark W Spong. A geometric approach to three-dimensional hipped bipedal robotic walking. In *Decision and Control, 2007 46th IEEE Conference on*, pages 5123–5130. IEEE, 2007.
- [3] Fangde Liu, Richard Southern, Shihui Guo, Xiaosong Yang, and Jian J Zhang. Motion adaptation with motor invariant theory. *Cybernetics, IEEE Transactions on*, 43(3):1131–1145, 2013.
- [4] Mark W Spong. Underactuated mechanical systems. In *Control problems in robotics and automation*, pages 135–150. Springer, 1998.

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