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 sagittal-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 adopt 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.

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

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

$$u = K^{eq}_d(\theta) = B_d \frac{\partial}{\partial \theta}(V_d - V_d(\Psi_d(\theta))) - \frac{1}{2m_d}(\dot{\theta})^2$$

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

$$u = K^{eq}_d(q) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \dot{q}$$

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

$$\dot{x} = F(x, h_m(x, c)) + B_m u_m(x)$$

$$\dot{c} = S(x, h_n(x))$$

• 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.

![Phase Portrait: Leg 1](image1.png)

Figure 1: Local Control Law based adaptation at 5 different slopes in range $\gamma = [0, 0.0625]$ radian. 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.

![Phase Portrait: Leg 1](image2.png)

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.

• 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 $R^3$; and
• leverage underpinning biological principles of locomotion in the development of robotic models which are stable and energy efficient.

References


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