Energy Efficiency Analysis of the Tegotae Approach for Bio-inspired Hopping

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1 Introduction

In bio-inspired robotic control, CPGs (Central Pattern Generators) architectures have been extensively adopted to generate periodic patterns in the actuation, due to the interesting properties of nonlinear oscillators which they make use of [1]. Although sensory feedback in CPGs is not necessary for the generation of the patterns, it plays a central role guaranteeing adaptivity to the environmental conditions [2]. Nonetheless, its inclusion greatly modifies the dynamics of the CPG architecture [3], often leading to bifurcations. For instance, force feedback can be exploited to derive information about the state of the system. In particular, the Tegotae approach, as presented in [4], can be adopted by coupling a proprioceptive information with the state of oscillation itself in the CPG model. We discuss how such policy, with respect to other sorts of feedbacks, provides higher adaptivity and an optimal energy efficiency for the actuation [5]. We believe it is a first attempt on the analysis of energy efficiency along with apaptivity of the Tegotae approach.

2 Case Analysis

A mono-dimensional hopping robot is taken into account, being characterized by a mass connected to a massless spring and damper system. A linear actuator is in parallel to the spring and the damper and determines a vertical thrust. The *Kuramoto model* for phase oscillators is used as a model for the CPG oscillator, simplifying the analysis of the effects of the feedback. The integration of the ODEs is done via the LSODA routine in Python scipy.integrate.odeint method, which automatically switches between nonstiff and stiff solvers depending on the behaviour of the problem.

2.1 Mathematical Model

The evolution of the phase of the oscillator ϕ and of the vertical height of the mass y is described by the ODE,

$$\dot{\phi} = \omega + f_i(t,y,\phi) \tag{1}$$

$$\ddot{y} = \frac{1}{m}\left(F_c(\dot{y}) + F_k(y) - mg + F_a(t,y,\phi)\right) \tag{2}$$

In Eq. (1) $f_i(t,y,\phi)$ is the sensory feedback in the *Kuramoto model*, while in Eq. (2) $F_k(y)$, $F_c(\dot{y})$ and $F_a(t,y,\phi)$ are the elastic, the viscous and the actuation force due to the spring, the damper, and the actuator respectively. These three components will be absent during the flight phase, assuming no forces acting from the environment. As described in [4], the Tegotae sensory feedback f_1 is defined directly by the Tegotae function $T(t,y,\phi)$,

$$T(t,y,\phi) \triangleq (-\sigma\sin(\phi))F_k(y) \tag{3}$$

$$f_1(t,y,\phi) = \frac{\partial}{\partial\phi}T(t,y,\phi) = -\sigma\cos(\phi)F_k(y) \tag{4}$$

with σ being a proportionality factor. By the nature of Eq. (3), it follows that this sensory feedback will be absent during the flight phase as well.

2.2 Control Policy

The neuro-mechanical coupling will force a secondary dynamics in the phase oscillator [6] and our goal is to analyze and possibly exploit such effect. Therefore, in case of a constant actuation force of value A, the force will be injected only when the phase of the oscillator ϕ will be inside a certain interval containing a critical point of the dynamics:

$$F_a(t,y,\phi) = A \iff \phi \in (\phi_0, \phi_0 + \Delta) \tag{5}$$

3 Simulations and Results

3.1 Learning Transient and Energy Efficiency

The goal of the simulations was to analyze the effects of different feedbacks in terms of stability, transient periods and power injection by the actuator. We took into account four different instances as a sensory feedback dynamics, as reported in Figure 1. While f_2 corresponded to the height of jump, f_4 was the force passing through the spring. Then, f_1 and f_3 were respectively the Tegotae feedback and the feedback proposed in [6]. Interestingly, both of these shared a neuro-mechanical coupling. It was evident that all of them

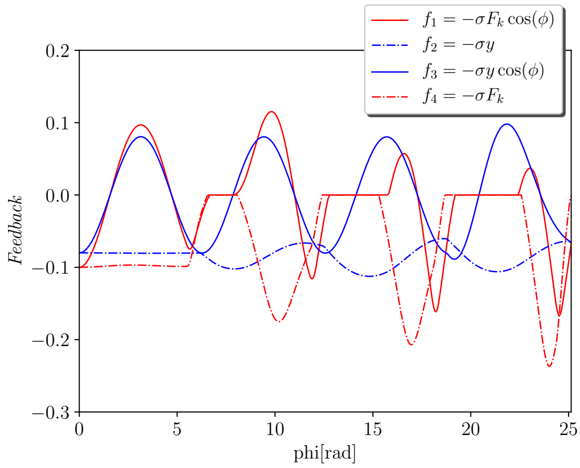

Figure 1: Feedback dynamics over the phase ϕ

were introducing a strong polarization with critical points, with which we defined ϕ_0. The mechanical parameters and the natural length of the spring were $m = 0.1$ kg, $k = 5$ N/m, $c = 0.2$ Ns/m, $l_0 = 1$ m respectively. The parameters of the oscillator were $\omega = 8$ rad/s and $\sigma = 2$, whose dimensionality was determined on the basis of the feedback law. The actuation parameters and the results of the simulations were worked out on oscillations in the steady state and they are reported in Table 1. The transient period Δt was defined as when a limit cycle was reached. It followed that the case f_4 was not able to provide a stable orbit. Finally, it was evident that the introduction of the Tegotae feedback was optimal in terms both of the transient period of the synchronization and of the energy efficiency E_e, defined on a limit cycle of period $T^\star$ with an actuation force F_{act}, as:

$$E_e = \frac{h_{max,T^\star} - h_{min,T^\star}}{E}, \; E = \int_{T^\star} F_{act}(t)\dot{h}(t)dt \quad (6)$$

Interestingly, to obtain similar hopping in terms of height the cases f_2,f_3 required higher amplitude of the actuation force.

3.2 Robustness and Adaptivity

Secondly, we considered the case of the Tegotae approach f_1 and the case f_3 presented in [6] and we tested them with a dynamical change in the environment. In particular, at $t = 5$ s the ground level was lowered from 0 to -0.6 m. The results are shown in Figure 2. It was evident that our approach was able to cope with these variations by a proper re-polarization of the oscillator, even without an adaptation of σ, ϕ_0 or Δ. It was possible to notice how the Tegotae approach was able to quickly react to such variations, by a modification in the power injection,

Table 1: Simulation results

FeedBack	f_1	f_2	f_3	f_4
A [N]	4	12	12	4
ϕ_0, Δ [rad]	1.75π,0.1π	1.96π,0.1π	1.96π,0.1π	1.75π,0.1π
h_{max} [m]	1.16	1.05	1.08	1.57
Δt [s]	3	4	5	$\nexists$
E_e [m/Ws]	1.50	1.16	1.15	1.25
J [W]	5.49	17.69	20.15	10.56

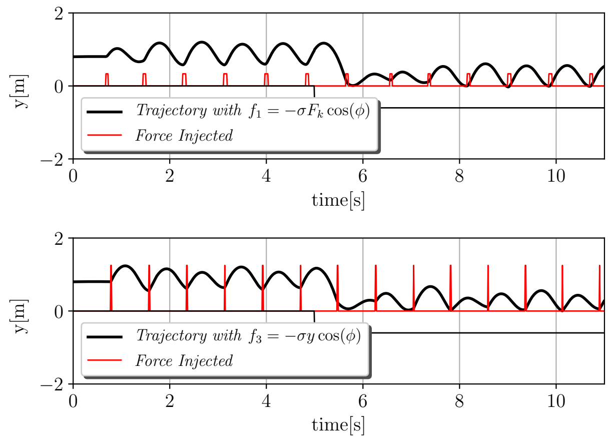

Figure 2: Dynamic environment and adaptation process

4 Conclusions and Future Work

We have integrated a particular typology of sensory feedback, the Tegotae feedback, in a *Kuramoto oscillator* and analyzed its effect in terms of the pattern generation, the energy efficiency and the adaptivity to a sudden change in several properties of the global system. It will be interesting to extend such architecture in more complex topologies of oscillators, in order to verify the effect on the coupling terms between oscillators as well. A further extension of the adaptivity in terms of the design parameters will be tackled as well. Interestingly, the Tegotae feedback and the *Kuramoto model* share a common structure with the adaptive frequency Hopf oscillators described in [6], which are able to reproduce Hebbian learning. In future, the characteristics of the emergent learning processes induced by the Tegotae approach will be further studied.

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