Robot Phase Entrainment on Quadruped CPG Controller

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Abstract: Central Pattern Generators are used in several kinds of robot locomotion, from swimming and flying, to bipeds, quadrupeds and hexapods. It is thought that this approach can yield better results in dynamical and natural environments. In this work we expand a previous quadruped locomotion controller and propose a method to couple the step cycle phase onto the locomotor CPG of a quadruped robot, creating a feedback pathway to coordinate the phases of each leg to the phase of the step cycle. This approach is tested in a simulated quadruped robot and the performed locomotion is evaluated. Results demonstrate that the proposed phase coupling synchronizes the swing step phase of ipsilateral legs to the respective step phase of the cycle and show an improvement in stability of the performed walk gait.

1 INTRODUCTION

Motor control is a complex problem in robotics, highly relevant in tasks such as manipulation and grasping, environment exploration and navigation, human-robot interaction and locomotion, all in demanding dynamical environments. Several processes must be addressed to achieve an acceptable level of performance and autonomy in motor control, as perception, planning, execution, feedback and mechanics.

We endeavor to achieve general and autonomous quadruped locomotion on natural environments. In this work we explore further contributions in the feedback process, ubiquitous for short and long-term adaptation of any kind of legged locomotion.

Legged locomotion can be achieved using typical model based planning algorithms (Buchli et al., 2009), or limit-cycle based control, such as Central Pattern Generators (CPGs) (Fukuoka et al., 2003). CPG controllers are well suited for locomotion because: 1) produce stable rhythmic patterns, providing robustness against transient perturbations; 2) enable the design of distributed implementations; 3) are generally easier to modulate through control parameters that may be used as higher level command signals; and 4) due to its stability, CPGs are appropriate for the integration of sensory feedback signals and to achieve entrainment with the mechanical body (Ijspeert, 2008).

CPG systems can be designed starting from different conceptual approaches. They can be designed firstly from the CPG model as a feedforward generator, and only then the effect of feedback signals is included and the loop is closed; endorsing what kind of information should be considered and how will affect the final behaviour (Righetti and Ijspeert, 2008; Fukuoka et al., 2003). Or can be designed from the beginning with the closed-loop goal in mind, using feedback signals to tightly generate trajectories (Maufroy et al., 2010; Buchli and Ijspeert, 2008).

Systems of coupled oscillators are widely used for modeling CPGs, and while there exists extensive work and methods for analyzing these dynamical systems, less work has been carried out on methods and frameworks for synthesizing oscillators that have to exhibit a specific desired behavior. For instance, in (Buchli et al., 2006) it is presented a framework for characterizing and designing oscillators, as well as defining desired perturbations in order to achieve frequency-locking, phase-locking or any specific output signal shape.

Step phase feedback plays an important role in locomotion, allowing the adaptation of the onset of the swing and stance phases (Pearson, 2008). These were explored in legged robots, whether through phase resetting (Aoi and Tsuchiya, 2006) or phase transitions depending on load/unloading of the legs (Righetti and Ijspeert, 2008; Maufroy et al., 2010)

In this paper, we explore a different approach for phase feedback. We devise a phase feedback inspired in (Fukuoka et al., 2003) and try to entrain the CPG oscillators with the phase of the robot's periodic dynamics, coordinating the phase of the step cycle of each leg with the sensed body motion.

The goal of this contribution is to include step phase feedback onto a previous developed locomotor system and study its influence on locomotion's performance. It is based on past work for modeling a limb-CPG (Matos and Santos, 2010). This previous work only considered the CPG network as a rhythmic open-loop controller. In this paper, we discuss the effects of the addition of feedback on the rhythmogenic ability of the CPGs, and propose a methodology to explore the possibilities of physical entrainment with the system.

The proposed feedback couples the CPG system to the pendulum rolling motion of the projected Center of Gravity (pCOG). Robot's sensory information regarding body angle, joint position and foot touch sensors are used to calculate pCOG, which modulates the frequency of the leg oscillator through the feedback mechanism. The goal of this feedback is to avoid the swinging of a leg before the robot pCOG is transferred to the opposite support polygon, and this is achieved by synchronizing the oscillator's phase with the performed step phase.

The inclusion of feedback is expected to improve robot performance, herein measured by the Support Stability Margin (SSM), an adequate measure for a static stable. Besides, the proposed feedback should not affect the required duty factor and phase relationships of a crawl gait.

Simulations are conducted on a simulated environment with the model of an AIBO quadruped robot. We study the robot's performance regarding velocity, SSM and the correct execution of the step phases. We also explore the influence of integrating this phase feedback along with the coupling network of CPGs (Matos and Santos, 2010). Simulation results show an improvement on robot performance regarding SSM, maintaining the desired general features of the crawl gait such as duty factor and interlimb phase relationships.

2 LOCOMOTOR SYSTEM

The locomotor system generates the trajectories for the leg joints, producing the locomotor motions of the robot. Similarly to previous work, the locomotor system is composed by a network of four Central Pattern Generators (CPGs) modeled as nonlinear oscillators (Matos and Santos, 2010). Each CPG is able to endogenously output the rhythmic signals that will control each joint on a single leg.

2.1 Central Pattern Generator

The concept of biological locomotor CPG includes the idea of hierarchical organized unitary oscillators, the unit-CPG. A single unit-CPG controls and activates the antagonistic muscle pairs, controlling the movements of a single joint.

The hip unit-CPG is modeled using a nonlinear oscillator:

$$\dot{x}_i = \alpha\left(\mu - r_i^2\right)(x_i - O_i) - \omega_i z_i \tag{1}$$

$$\dot{z}_i = \alpha\left(\mu - r_i^2\right) z_i + \omega_i (x_i - O_i) \tag{2}$$

$$\omega_i = \frac{\frac{1-\beta}{\beta}\omega_{\mathrm{sw}}}{\mathrm{e}^{-az_i}+1} + \frac{\omega_{\mathrm{sw}}}{\mathrm{e}^{az_i}+1}, \tag{3}$$

with $r_i = \sqrt{(x_i - O_i)^2 + z_i^2}$.

$x(t)_i$ solution is the angle of the hip joint of leg i at instant t. This rhythmic solution has an amplitude of $\sqrt{\mu}$, an offset O_i and an angular frequency ω. Frequency is modulated according to the current phase of the oscillator, enabling the generation of a trajectory with stance and swing phase of different durations (Righetti and Ijspeert, 2008). We want to achieve a 0.75 duty factor for the walk gait, setting $\beta = 0.75$. Parameter α controls the relaxation of the solution to the stable orbit and a the toggling speed of ω.

The modulation of the generated trajectories with respect to their amplitude, frequency and offset, is carried out explicitly and smoothly through the specification of a set of parameters, and allows for a distributed organization due to its entrainment properties.

Knee joints are controlled according to the corresponding hip swing joint in a simple fashion. When the leg performs the swing phase, the knee flexes to a fixed angle θ_{sw}. During the stance phase, the knee extends to θ_{st}.

This motion is generated by applying the following second order system:

$$\dot{y}_i = v_i,\ \dot{v}_i = -\frac{b^2}{4}(y_i - g_i) - b v_i \tag{4}$$

$$g_i = \frac{\theta_{\mathrm{st}}}{\mathrm{e}^{-az_i+1}} + \frac{\theta_{\mathrm{sw}}}{\mathrm{e}^{az_i+1}} \tag{5}$$

whose stable solution y converges to a goal fixed point g, changing between θ_{sw} and θ_{st} depending on the step phase. Relaxation is controlled by parameter b.

2.2 Interlimb Coordination

In order to generate the desired quadruped gait, we couple the four CPGs in a network with variable phase

Table 1: Phase relationships for walking gait.

i	LF	LF	LF	RF	RF	LH
j	RF	LH	RH	LH	RH	RH
ϕ_i^j	$-\pi$	$-\frac{3\pi}{2}$	$-\frac{\pi}{2}$	$-\frac{\pi}{2}$	$\frac{\pi}{2}$	π

relationships. Coupling between two oscillators is achieved by applying a rotation matrix $\mathbf{R}\left(\phi_i^j\right)$, where ϕ_i^j is the desired relative phase between oscillator i and j. Eqs (1,2) are extended with the rotation matrix members:

$$\dot{x}_i = \ldots + k_{\text{osc}} \sum_{j \neq i} \left(x_j \cos\phi_i^j - z_j \sin\phi_i^j \right) , \quad (6)$$

$$\dot{z}_i = \ldots + k_{\text{osc}} \sum_{j \neq i} \left(x_j \sin\phi_i^j + z_j \cos\phi_i^j \right) , \quad (7)$$

where i and j specifies the CPG of leg $\in \{\text{LF}, \text{RF}, \text{LH}, \text{RH}\}$. Parameter k_{osc} determines the strength of the interlimb coupling in the network, where every connection has equal weight. Phase relationships for the walk gait are presented in table 1, note that $\phi_i^j = -\phi_j^i$.

The achieved coordination among the CPGs is stable and flexible through the modulation of the desired phase relationships. It is also stable and robust to perturbations of phase, making the system return to the desired phase relationships, depending on the coupling strength k_{osc} and assuming a limited range in the perturbation magnitude.

2.3 Robot Phase Coupling

The goal of using phase coupling in our CPG approach is to synchronize the phases of the CPG network to the dynamics' phase of the robot. The act of walking exhibits periodic motions, from which we extract the phase of the robot's locomotion or robot phase. We use the periodic motion of the projected Center of Gravity to calculate the robot's phase, considering the body angle, joint positions and touch sensors. The proposed coupling tries to synchronize the generated swing phase of the CPGs with the measured point in the step cycle in which the robot has its projected Center of Gravity (pCOG) over the contralateral support polygon during the walk gait (fig. 1).

If this phase coupling is achieved correctly, the swing phase of each leg will happen when the pCOG is over the contralateral support side, ensuring that the weight is not over the swinging leg, and thus the robot does not fall over it. This feedback mechanism by coordinating the swing phases with the correct support polygon presents the potential of improving the walk, by increasing the stability, forcing the pCOG to be over the side with most legs supporting the body. This

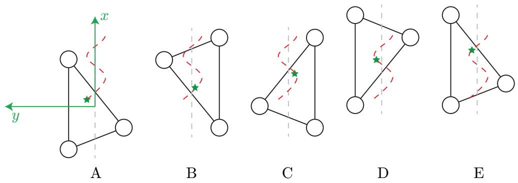


Figure 1: Oscillatory movement exhibited by the projected Center of Gravity during the walk gait. The pCOG moves between the contralateral triangular support polygons. Open circles denote feet ground contact.

improvement on stability is specially desired when the body weight goes from one side to the other (A to B in fig. 1). The normal tendency is to fall over the swing leg. The proposed feedback is expected to improve this.

To achieve this kind of entrainment between our oscillators and the robot dynamics we follow the general guidelines from (Buchli et al., 2006). We specify the desired perturbation effect on the oscillator's phase using its polar representation and transform it back to its cartesian representation.

Consider the oscillator from eq.(1,2) in polar coordinates and consider the movement of pCOG in the frontal plane due to the robot's rolling motion as a simple oscillatory motion with its phase described by $\phi_{\text{r}} = \arctan 2\left(\frac{\text{p}\dot{\text{C}}\text{OG}_y}{\text{pCOG}_y}\right)$. We couple the robot's phase (ϕ_{r}) with the oscillator's phase (ϕ_i) with a desired phase difference of ϕ_{r}^i and coupling constant k_{r}, as follows:

$$\dot{\phi}_i = \omega_i + k_{\text{r}} \sin\left(\phi_{\text{r}} - \phi_i - \phi_{\text{r}}^i\right) , \quad (8)$$

$$\dot{r}_i = \alpha\left(\mu - r_i^2\right) r_i . \quad (9)$$

In cartesian coordinates this phase coupling becomes

$$\dot{x}_i = \alpha\left(\mu - r_i^2\right)(x_i - O_i) - z_i \overline{\omega}_i , \quad (10)$$

$$\dot{z}_i = \alpha\left(\mu - r_i^2\right) z_i - (x_i - O_i)\, \overline{\omega}_i , \quad (11)$$

$$\overline{\omega}_i = \omega_i - \frac{k_{\text{r}}}{r_i}\left[z_i \cos\left(\phi_{\text{r}} + \phi_{\text{r}}^i\right) - x_i \sin\left(\phi_{\text{r}} + \phi_{\text{r}}^i\right) \right] . \quad (12)$$

We choose the desired phase differences to respect the following rules (fig. 2): i) when the robot leans left with its pCOG over the left support polygons, $\phi_{\text{r}} = 0$, the right legs should perform the swing phase, $-\pi < \phi_i < 0$; ii) when the robot leans right and the pCOG is to the right side, $\phi_{\text{r}} = \pi$, the left legs should swing while the right legs perform the stance phase, $-\pi < \phi_i < 0$; and iii) the oscillators should reflect the phase relationship and sequence of the walk gait and exhibit a relative phase difference of $\frac{\pi}{2}$ among themselves. Phase relationships are: $\phi_{\text{r}}^{\text{LF}} = \frac{\pi}{4}$, $\phi_{\text{r}}^{\text{RF}} = \frac{-3\pi}{4}$, $\phi_{\text{r}}^{\text{LH}} = \frac{3\pi}{4}$, $\phi_{\text{r}}^{\text{RH}} = \frac{-\pi}{4}$.

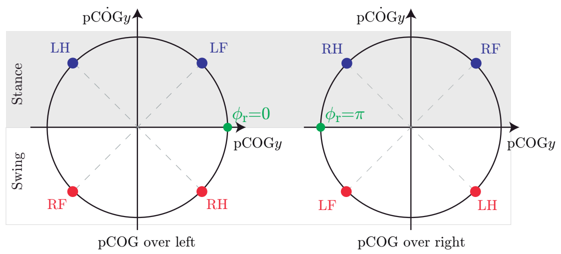


Figure 2: Limit cycle of the pCOG oscillation on the frontal plane ($pCOG_y$). When the pCOG is on the left side ($pCOG_y > 0$) the robot's phase is $\phi_r = 0$, and $\phi_r = \pi$ when is on the right side $pCOG_y < 0$. Each CPG performs the swing phase when $-\pi < \phi_i < 0$.

3 SIMULATIONS

A series of simulations were performed in a simulated environment with the model of Sony AIBO quadruped robot in Webots[1].

First we study the coupling of interlimb coordination and robot phase by changing the values of the coupling weights k_{osc}, k_r. We make a systematic parameter exploration on the parameter tuple $\langle k_{osc}, k_r \rangle$ in the range $[0, 9.5]$, in steps of 0.5. In each run the robot locomotes with a desired nominal gait, a statically stable walk gait ($\beta = 0.75$) for 10 s and the required information is recorded. We then compare and discuss the obtained average Support Stability Margin (SSM) and the achieved velocities. SSM is the smallest distance of the pCOG to the edge of the polygon defined by the supporting feet projection onto the plane with the gravitational acceleration as its normal. SSM is an indicator that tells if the pCOG is inside the support polygon at all times, when considering statically stable gaits as the walking gait.

We then choose and use the $\langle k_{osc}, k_r \rangle$ values that result in the best walk in terms of trade-off between the average SSM and the achieved velocity, to compare and quantify the improvement of the walk without and with robot phase coupling. We analyze the robot's performance regarding velocity, SSM and discuss improvements over the execution of the step phases.

Parameter exploration Interlimb coupling, k_{osc}, and robot phase coupling, k_r influence the walk in different ways. While interlimb coupling simply coordinates the phase relationships between the CPGs, robot phase coupling tries to coordinate the phase of each CPG to the phase of the robot.

From fig. 3(a) we can see that velocity does not change when we increase or decrease the strength of interlimb coupling, k_{osc}. However, when changing the strength of phase coupling, k_r, the achieved velocity is influenced, decreasing when the coupling increases. This is a possible indicator that the oscillators are being adapted to respect the current step phase of the walk, being slowed down to match the robot dynamics. For $k_r > 4.5$ the velocity decreases greatly, suggesting that beyond this point the influence and strength of this phase coupling is no longer adequate and tries to stop the robot.

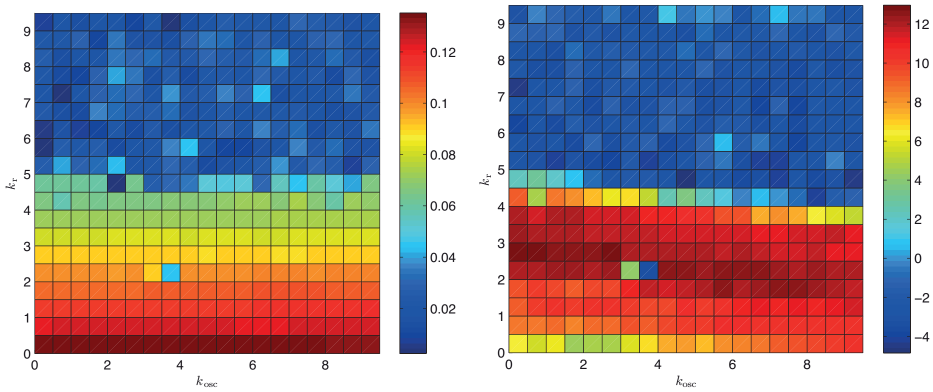
Similarly, SSM shows no major variation for a changing interlimb coupling strength, k_{osc} (fig. 3(b)). The major determinant of the achieved SSM is the phase coupling strength, k_r. There is a range of k_r where the SSM shows higher values, $[1; 3.5]$. It suggests that the CPGs are being coordinated according to the robot dynamics, correcting the execution of the step phases. However, above 3.5 the SSM decreases to low values, similarly to the velocity.

The velocity achieved without phase coupling was 0.134 m.s^{-1} ($k_{osc} = 1, k_r = 0$) and the obtained SSM was 6.14 mm. The highest obtained SSM was 12.97 mm, when using $k_{osc} = 2.5, k_r = 2.5$, with achieved velocity 0.098 m.s^{-1}. We consider this result to be a fair trade-off between the achieved SSM and velocity for a walk gait.

Locomotion comparison With phase coupling ($k_{osc} = 2.5, k_r = 2.5$) it is expected that the left legs' swing phases are performed when the pCOG is over to the right side of the support polygon. We can verify this is true in fig. 4 (right) since the swing phase of both left legs (ascending trajectories) are performed when $pCOG_y < 0$. These results show that the proposed phase coupling synchronizes the swing step phase of ipsilateral legs to the respective step phase of the cycle. The nominal step period is 0.8 s, from a swing period of 0.2 s and a duty factor of 0.75. When we employ phase coupling the interaction of the CPGs with the robot's phase changes slightly the achieved average step period, from 0.8 s to 1.2 s, while maintaining the chosen duty factor, adapting the swing period to 0.3 s. This adaptation did not change the relative phases among the CPGs, maintaining the desired interlimb coordination of the nominal walk gait.

Let us verify the overall effect on the achieved step cycle duration and compare the achieved SSM. Fig. 5 shows the achieved SSM over the two runs. The dotted (solid) lines show the achieved SSM without (with) phase coupling. Positive values denote that the pCOG lies inside the support polygon, while negative values denote a position outside the support polygon, with a distance to the nearest edge correspondent to

[1]Webots mobile robot simulator: http://www.cyberbotics.com/



(a) Velocity achieved on each run.

(b) Mean Support Stability Margin (SSM) on each run.

Figure 3: k_{osc}, k_r parameter exploration, and its effects on velocity (m.s^{-1}) and phase coupling. Velocity and SSM are mostly influenced by the value of k_r.

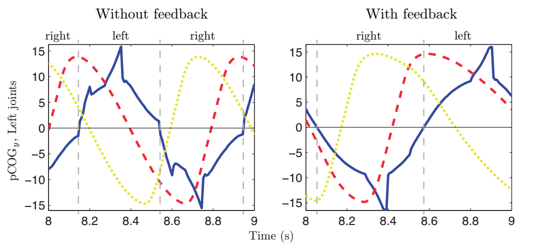


Figure 4: pCOG position in the frontal plane (solid blue) and left hip joints' trajectories (dashed red:fore and dotted yellow:hind). Swing phases correspond to the ascending parts of the trajectories. Without phase coupling the hind leg (dotted yellow) swing onset happens while the pCOG is in the ipsilateral side (left panel), meaning pCOG$_y > 0$. With phase coupling (right panel) the swing phases on both left legs happen when the pCOG is in the contralateral side, pCOG$_y < 0$.

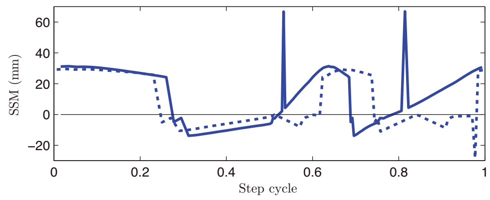


Figure 5: SMM without (dotted) and with (solid) robot phase coupling. The average SSM is 6.14 mm without phase coupling and 12.97 mm with phase coupling. Using phase coupling, increases the chance of brief four feet support (solid).

the absolute value.

We can verify in fig. 5 that the performed SSM increases when phase coupling is employed. Negative values of SSM indicate the robot may fall over the swinging leg. The moments of the step where pCOG falls outside the support polygon (negative values) are reduced from 66% of the step phase without feedback (dotted), to 29% of step phase when feedback is employed (solid). The average value of SSM also increases due to the maintenance of the pCOG inside the support polygon.

The walk gait sequences from the two simulations are shown in fig. 6. We can see that without phase coupling (top) the pCOG is generally closer to the edge of the support polygon than with phase coupling (bottom). pCOG also is in the same side in the onset of some swing phases when phase coupling is not employed, at 9.10 s and 9.50 s, which was solved when phase coupling is employed (bottom, at 9.10 s and 9.60 s). The concerning point of contralateral swing onset was dealt with by the proposed feedback mechanism and the result was to achieve brief four feet support between these contralateral phases (bottom, at 9.00 s and 9.50 s).

Results also show that front feet touching the ground incorrectly during the swing phase decreased from 12.60% to 11.90% of the swing phase period, and hind feet from 1.30% to 0.07%. The unwanted lifting of the feet occurring during stance phase decreased in the fore legs from 23.40% to 5.09% of the stance period.

4 CONCLUSIONS

In this contribution we try to take advantage of the properties of oscillators, typically used to model CPGs on legged robots. We investigate and propose a method to couple the CPG rhythmic activity to the step phase of a quadruped robot, trying to create a link between the robot dynamics and the walking motion of the locomotor controller.The goal of the proposed

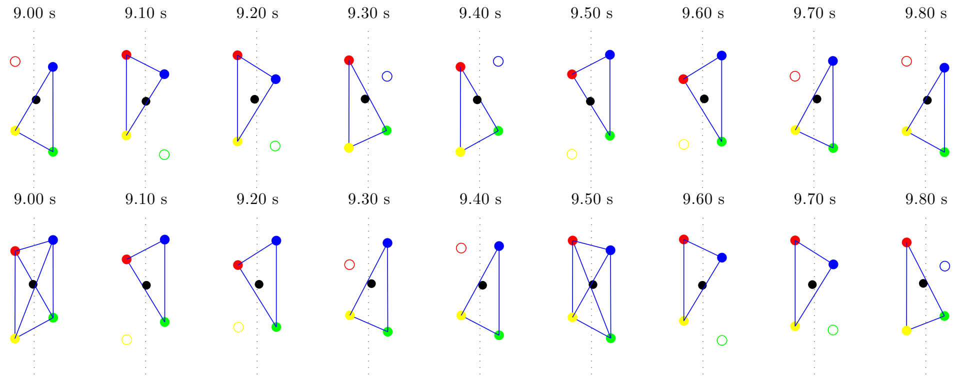


Figure 6: Performed gait sequence of the walk gait without (top) and with (bottom) phase coupling. Black dot is the position of the projected Center of Mass. Colored filled dots represent stance trajectories and empty dots swing trajectories. (red:left fore, blue: right fore, yellow:left hind, green: right hind) In this figure, the reference frame is centered on the robot.

feedback is to maintain the pCOG over the contralateral side of the current swinging leg, in order to improve stability and avoid the swinging of a leg which is supporting the body weight.

Results show that the phase coupling adapts the generated trajectories and performs what is proposed. A systematic exploration of coupling parameters was conducted to study the influence of interlimb coupling and the proposed phase coupling onto the CPG and final walk gait, and the best parameters were used to conduct further comparisons. The obtained measurements indicate an improvement of the walk gait, doubling the SSM.

However,further work should be performed in evaluating its effect on different walking conditions, such as in inclined planes, irregular terrains and small perturbations. We will also study the integration with other kinds of feedback within the same framework, such as phase transition (Righetti and Ijspeert, 2008) and postural control (Sousa et al., 2010), as well as on other legged robots, including robots with compliant actuators.

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