Impact of Discrete Corrections in a Modular Approach for Trajectory Generation in Quadruped Robots

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Abstract. Online generation of trajectories in robots is a very complex task that involves the combination of different types of movements, i.e., distinct motor primitives. The later are used to model complex behaviors in robots, such as locomotion in irregular terrain and obstacle avoidance. In this paper, we consider two motor primitives: rhythmic and discrete. We study the effect on the robots' gaits of superimposing the two motor primitives, considering two distinct types of coupling. Additionally, we simulate two scenarios, where the discrete primitive is inserted in all of the four limbs, or is inserted in ipsilateral pairs of limbs. Numerical results show that amplitude and frequency of the periodic solutions, corresponding to the gaits *trot* and *pace*, are almost constant for diffusive and synaptic couplings.

Keywords: stability, CPG, modular locomotion, rhythmic primitive, discrete primitive

INTRODUCTION

Online generation of trajectories in articulated robots with many degrees-of-freedom such as biped, quadruped or hexapod robots, has been an interesting and complex research issue in the last few decades. Biological inspired models to produce rhythmic movements in robots has brought new insights and developments on this issue. Central Pattern Generators (CPGs) are networks of neurons located at the spinal level of vertebrates responsible for the rhythmic patterns observed during animals' locomotion [10, 2, 9]. Mathematically, CPGs are modeled by nonlinear dynamical systems.These dynamical systems play a major role on online generation of trajectories since they allow their smooth modulation through simple changes in the parameter values of the equations, have low computational cost, are robust against perturbations, and allow phase-locking between the different oscillators [14, 5, 4].

Schöner *et al* [12] propose a set of organizational principles that allow an autonomous vehicle to perform stable planning. Matos *et al* [8] propose a bio-inspired robotic controller able to generate locomotion and to easily switch between different types of gaits. Matos *et al* [13] present a CPG design, based on coupled oscillators, generating the required stepping movements of a limb for omnidirectional motion.

In this paper, we assume a modular generation of robot movements, supported by current neurological and human motor control findings, specially considering the concepts of central pattern generators (CPGs). We continue our previous work [8, 13], considering the CPG model quad-robot (Figure 1) for quadruped robots' movements. CPG quad-robot is a network of four coupled CPG-units, each of which consists of two motor primitives: rhythmic and discrete. We study the variation in the amplitude and the frequency values of the periodic solutions produced by the CPG model quad-robot when the discrete primitive is inserted as an offset of the rhythmic part. The goal is to show that these discrete corrections may be performed since that they do not affect the required amplitude and frequency of the resultant trajectories, nor the gait, in the cases studied here. To our best knowledge, this type of study has never been addressed or explored in the literature. Amplitude and frequency may be identified, respectively, with the range

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of motion and the velocity of the robot's movements, when considering implementations of the proposed controllers for generating trajectories for the joints of real robots.

CPG LOCOMOTION MODEL

In this section, we present the CPG model quad-robot. We give the general class of systems of ODEs that model CPG quad-robot and resume the symmetry techniques that allow classification of periodic solutions produced by this CPG model, and identified with quadruped locomotor patterns.

CPG quadruped model design

Figure 1 shows the CPG model quad-robot for generating locomotion for quadrupeds robots. It consists of four coupled CPG-units. The CPG-units (or cells) are denoted by circles and the arrows represent the couplings between cells. Network quad-robot has

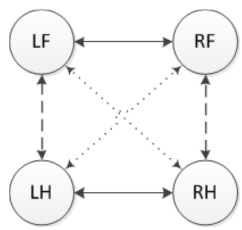

FIGURE 1. CPG locomotor model for quadrupeds, quad-robot. LF (left fore leg cell), RF (right fore leg cell), LH (left hind leg cell), RH (right hind leg cell).

$$\Gamma_{\mathsf{quad-robot}} = \mathbf{Z}_2(\omega) \times \mathbf{Z}_2(\kappa)$$

symmetry. quad-robot has the bilateral symmetry of animals ($\mathbf{Z}_2(\kappa)$) and a translational symmetry ($\mathbf{Z}_2(\omega)$), from back to front, i.e, cell RF is coupled to cell RH, and the same applies for cells LF and LH. The observed symmetry of CPG models for locomotion of animals or robots is fairly accepted by most researchers (see [14] and [11], for CPG models of legged robots).

CPG model equations

The class of systems of differential equations of the CPG model for the quadruped model quad-robot is of the form:

$$\begin{aligned} \dot{x}_{LH} &= F(x_{LH}, x_{RH}, x_{LF}, x_{RF}) \\ \dot{x}_{RH} &= F(x_{RH}, x_{LH}, x_{RF}, x_{LF}) \\ \dot{x}_{LF} &= F(x_{LF}, x_{RF}, x_{LH}, x_{RH}) \\ \dot{x}_{RF} &= F(x_{RF}, x_{LF}, x_{RH}, x_{LH}) \end{aligned} \tag{1}$$

where $x_i \in \mathbf{R}^k$ are the cell i variables, k is the dimension of the internal dynamics for each cell, and $F : (\mathbf{R}^k)^4 \to \mathbf{R}^k$ is an arbitrary mapping. The fact that the dynamics of each cell is modeled by the same function F indicates that the cells are assumed to be identical.

Symmetries and gaits

The Theorem H/K gives a method for classifying all possible symmetry types of periodic solutions for a given coupled cell network [6]. These periodic solutions are then identified with animals locomotor rhythms. Let H and K be the subgroups of spatiotemporal and spatial symmetries and let $x(t)$ be a periodic solution of an ODE $\dot{x} = f(x)$, with period normalized to 1, and with symmetry group Γ. Symmetries of spatial type K fix the solution pointwise, i.e., let $\gamma \in \Gamma$, then $\gamma x(t) = x(t)$. On the other hand, spatiotemporal symmetries H fix the solution setwise, i.e., $\gamma x(t) = x(t-\theta) \leftrightarrow x(t+\theta) = x(t)$, where θ is the phase shift associated to γ. If $\theta = 0$, then γ is a spatial symmetry. In order for (H,K) to correspond to symmetries of a periodic solution $x(t)$ to (1) for some function F the quotient H/K must be cyclic. There are twelve pairs of symmetry types (H,K) such that H/K is cyclic. In Table 1, we show six of those pairs, the corresponding periodic solutions and their identification with quadruped locomotor patterns, such as *trot*, *pace*, *transverse gallop*, *pronk*, *bound*, *rotary gallop*. The other six pairs are not yet identified with any of the known quadruped rhythms. In Table 1, we write the symmetry pairs and the corresponding periodic solutions corresponding to common quadruped gaits. We explain using the gait *pace* how its identification with one periodic

TABLE 1. Periodic solutions, and corresponding symmetry pairs, identified with quadruped gaits, where period of solutions is normalized to 1. ^{S} is half period out of phase.

H	K	**Left limbs**	**Right limbs**	**Name**
$\Gamma_{\mathsf{quad-robot}}$	$\Gamma_{\mathsf{quad-robot}}$	(x_{LH}, x_{LH})	(x_{LH}, x_{LH})	*pronk*
$\Gamma_{\mathsf{quad-robot}}$	$\mathbf{Z}_2(\omega\kappa)$	(x_{LH}, x^S_{LH})	(x^S_{LH}, x_{LH})	*trot*
$\Gamma_{\mathsf{quad-robot}}$	$\mathbf{Z}_2(\kappa)$	(x_{LH}, x^S_{LH})	(x_{LH}, x^S_{LH})	*bound*
$\Gamma_{\mathsf{quad-robot}}$	$\mathbf{Z}_2(\omega)$	(x_{LH}, x_{LH})	(x^S_{LH}, x^S_{LH})	*pace*
$\mathbf{Z}_2(\omega\kappa)$	$\mathbf{1}$	(x_{LH}, x^S_{RH})	(x_{RH}, x^S_{LH})	*rot. gal.*
$\mathbf{Z}_2(\omega)$	$\mathbf{1}$	(x_{LH}, x^S_{LH})	(x_{RH}, x^S_{RH})	*trans. gal.*

solutions, produced by (1), with symmetry $(H,K) = (\Gamma_{\mathsf{quad-robot}}, \omega)$ is done. Let ω be the permutation that switches signals sent to front and back quadruped legs. Applying ω to the *pace* does not change that gait, since the fore and hind legs receive the same set of signals. The permutation ω is called a *spatial* symmetry for the *pace*. Symmetry $\Gamma_{\mathsf{quad-robot}}$ forces the signals to be left to left and right legs to be the same, up to a phase shift of $1/2$.

NUMERICAL SIMULATIONS

We simulate the CPG model quad-robot. In each CPG-unit, the discrete part $y(t)$ is inserted as an offset of the rhythmic part $x(t)$. The coupling is either diffusive or synaptic. Additionally, we consider two possible combinations for the insertion of the discrete primitive. It may be done in the four limbs, or in the ipsilateral limbs. We vary $T \in [0,25]$, in steps of 0.1, for a given periodic solution. For a fixed T, when a stable periodic orbit is obtained, its amplitude and frequency are computed. These values are then plotted.

The system of ordinary differential equations that models the discrete primitive is the VITE model given by [1]:

$$\begin{aligned} \dot{v} &= \delta(T-p-v) \\ \dot{p} &= G\, max(0,v) \end{aligned} \tag{2}$$

This set of differential equations generates a trajectory converging to the target position T, at a speed determined by the difference vector $T-p$, where p models the muscle length, and G is the go command. δ is a constant controlling the rate of convergence of the auxiliary variable v. This discrete primitive controls a synergy of muscles so that the limb moves to a desired end state, given a volitional target position. Moreover, the brain does not encode a trajectory, that emerges from the dynamics of the motor primitive, but a desired final state.

The equations for the rhythmic motor primitive are known as the modified Hopf oscillators [7] and are given by:

$$\begin{aligned} \dot{x} &= \alpha(\mu - r^2)x - \omega z = f(x,z) \\ \dot{z} &= \alpha(\mu - r^2)z + \omega x = g(x,z) \end{aligned} \tag{3}$$

where $r^2 = x^2 + z^2$, $\sqrt{\mu}$ is the amplitude of the oscillation. For $\mu < 0$ the oscillator is at a stationary state, and for $\mu > 0$ the oscillator is at a limit cycle. At $\mu = 0$ it occurs a Hopf bifurcation. Parameter ω is the intrinsic frequency of the oscillator, α controls the speed of convergence to the limit cycle. ω_{swing} and ω_{stance} are the frequencies of the swing and stance phases, $\omega(z) = \frac{\omega_{stance}}{\exp(-az)+1} + \frac{\omega_{swing}}{\exp(az)+1}$ is the intrinsic frequency of the oscillator. With this ODE system, we can explicitly control the ascending and descending phases of the oscillations as well as their amplitudes, by just varying parameters ω_{stance}, ω_{swing} and μ. These equations have been used to model robots' trajectories [4, 11, 8, 13].

The coupled systems of ODEs that model CPG quad-robot where the discrete part is inserted as an offset of the rhythmic primitive, for synaptic and diffusive couplings, are given by:

$$\begin{aligned} \dot{x}_i &= f_2(x_i, z_i) \\ \dot{z}_i &= g_2(x_i, z_i) + k_1 h_1(z_{i+1}, z_i) + \\ &\quad + k_2 h_2(z_{i+2}, z_i) + k_3 h_3(z_{i+3}, z_i) \end{aligned} \tag{4}$$

where $f_2(x_i, z_i) = f_1(x_i, z_i, y_i)$, $g_2(x_i, z_i) = g_1(x_i, z_i, y_i)$ and $r_i^2 = (x_i - y_i)^2 + z_i^2$. Indices are taken modulo 4. Function $h_l(z_j, z_i)$, $l = 1,2,3$, represents synaptic coupling when written in the form $h_l(z_j, z_i) = z_j$, $l = 1,2,3$, and diffusive coupling when written as $h_l(z_j, z_i) = z_j - z_i$, $l = 1,2,3$. Parameter values used in the simulations are $\mu = 10.0$, $\alpha = 5$, $\omega_{\text{stance}} = 6.2832$ rads^{-1}, $\omega_{\text{swing}} = 6.2832$ rads^{-1}, $a = 50.0$, $G = 1.0$, $\delta = 10.0$. Figures 2, 3 show amplitude and frequency values of the periodic solutions produced by CPG quad-robot and identified with the quadruped rhythms of *pace*. In Figure 3 the discrete primitive is inserted only in ipsilateral pairs of limbs. The values of T not plotted in the graphs are those for which the stable solution, obtained after the insertion of the discrete part, goes to equilibrium. Note that we obtain analogous graphs for the *trot*.

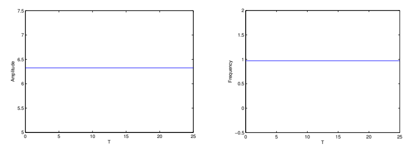

FIGURE 2. Amplitude (LEFT) and frequency (RIGHT) of the periodic solutions produced by CPG quad-robot and identified with *pace*, for varying $T \in [0, 25]$ in steps of 0.1, in cases for diffusive and synaptic couplings.

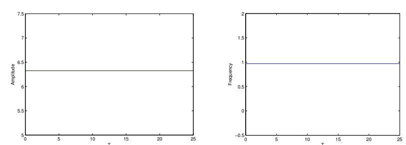

FIGURE 3. Similar to Figure 2, when the discrete primitive is inserted in ipsilateral limbs.

The graphs show that both couplings provide good results. By 'good', we mean that the amplitude and frequency values of the achieved (stable) periodic solutions, obtained after superimposing the discrete to the rhythmic primitive, are not affected. Therefore, it is possible to use them for generating trajectories for the joint values of real robots, since varying the joint offset will not affect the required amplitude and frequency of the resultant trajectory, nor the gait. Additionally, when the discrete primitive is inserted only in ipsilateral pairs of limbs, the offset is seen only in the limbs considered.

CONCLUSION

We study the effect on the periodic solutions produced by a CPG model for quadruped robots movements of superimposing two motor primitives: discrete and rhythmic. These periodic solutions are identified with the quadruped gaits of *trot* and *pace*. The CPG model consists of four coupled CPG units, where each CPG unit combines the two motor primitives, discrete and rhythmic.

We simulate the CPG model considering the discrete primitive as an offset of the rhythmic primitive, and two distinct coupling functions. Additionally, we simulate two scenarios, where the discrete primitive is inserted in all of the four limbs, or is inserted in ipsilateral pairs of limbs. For each case, we compute the amplitude and the frequency values of the periodic solutions identified with *trot* and *pace*, for values of the discrete primitive target parameter $T \in [0, 25]$. Numerical results show that amplitude and frequency values are almost constant, for both couplings. Results are also obtained in a robotic experiment using a simulated AIBO robot that walks over a ramp. The proposed controller generates movements for locomotion and posture correction which are modulated according to the measured lateral tilt of the body. Restriction on page number did not allow us to describe the experiment here.

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