A Modular Approach for Trajectory Generation in Biped Robots

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Abstract. Robot locomotion has been a major research issue in the last decades. In particular, humanoid robotics has had a major breakthrough. The motivation for this study is that bipedal locomotion is superior to wheeled approaches on real terrain and situations where robots accompany or replace humans. Some examples are, on the development of human assisting device, such as prosthetics, orthotics, and devices for rehabilitation, rescue of wounded troops, help at the office, help as maidens, accompany and assist elderly people, amongst others. Generating trajectories online for these robots is a hard process, that includes different types of movements, i.e., distinct motor primitives. In this paper, we consider two motor primitives: rhythmic and discrete. We study the effect on a bipeds robots' gaits of inserting the discrete part as an offset of the rhythmic primitive, in synaptic and diffusive couplings. Numerical results show that amplitude and frequency of the periodic solution, corresponding to the gait *run* are almost constant in all cases studied here.

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

INTRODUCTION

There has been an increase interest in the study of animal and robot locomotion. Many models for the generation of locomotion patterns of different animals have been proposed [3, 7, 14]. The main goal is the understanding of the neural bases that are behind animal locomotion and then use this information to generate online trajectories on robots. In vertebrates, goal-directed locomotion is a complex task, involving the Central Pattern Generators (CPGs), located in the spinal cord, the brainstem command systems for locomotion, the control systems for steering and control of body orientation, and the neural structures responsible for the selection of motor primitives [8]. CPGs are networks of neurons that are responsible for the locomotion movements in animals [13, 3, 7, 14]. Mathematically, CPGs are modeled by coupled nonlinear dynamical systems.

In Robotics, dynamical systems are a valuable tool 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 [16, 5, 14, 11]. Schöner *et al* [15] propose a set of organizational principles that allow an autonomous vehicle to perform stable planning. Dégallier *et al* [5] use a dynamical systems' approach yielding the online generation trajectory in a robot performing a drumming task. These trajectories have both rhythmic and discrete parts. Nakamura *et al* [12] present a reinforcement learning method allowing a biped robot not only to walk stably, but also to adapt to environmental changes. Matos *et al* [11] propose a bio-inspired robotic controller able to generate locomotion and to easily switch between different types of gaits.

In this paper, we assume a modular generation of a biped robot movements, supported by current neurological and human motor control findings [1, 8]. Our study is based in the work by Golubitsky *et al* [7, 14]. We consider the CPG model biped-robot (Figure 1) for biped robots' movements, which has the same architecture as a CPG for biped animals' movements [14]. The main difference is that here each neuron/cell is considered a CPG-unit, composed of two motor primitives: rhythmic and discrete. Both primitives are modeled by nonlinear dynamical systems. We study

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the variation in the amplitude and the frequency values of a periodic solution produced by the CPG model biped-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. Amplitude and frequency may be identified, respectively, with the range 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 FOR BIPEDAL ROBOTS' LOCOMOTION

In this section, we review the work done by Pinto and Golubitsky [14] on the CPG model biped-robot. We write the general class of systems of ODEs that model CPG biped-robot resume the symmetry techniques that allow classification of periodic solutions produced by this CPG model and identified with biped locomotor patterns.

Figure 1 shows the CPG model biped-robot for generating locomotion for bipeds 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.

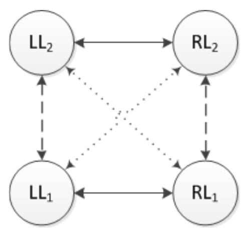

FIGURE 1. CPG biped-robot for biped robots locomotion. LL_i (left leg cells), RL_i (right leg cells), where $i = 1, 2$.

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

$$\begin{array}{rcl} \dot{x}_{LL_1} & = & F(x_{LL_1}, x_{RL_1}, x_{LL_2}, x_{RL_2}) \\ \dot{x}_{RL_1} & = & F(x_{RL_1}, x_{LL_1}, x_{RL_2}, x_{LL_2}) \\ \dot{x}_{LL_2} & = & F(x_{LL_2}, x_{RL_2}, x_{LL_1}, x_{RL_1}) \\ \dot{x}_{RL_2} & = & F(x_{RL_2}, x_{LL_2}, x_{RL_1}, x_{LL_1}) \end{array} \tag{1}$$

where $x_i \in \mathbf{R}^k$ are the cells i variables, k is the dimension of the internal dynamics for each cell, and $F : (\mathbf{R}^k)^4 \rightarrow \mathbf{R}^k$ 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

Network biped-robot has

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

symmetry. biped-robot has the bilateral symmetry of animals ($\mathbf{Z}_2(\kappa)$), that allows for signals sent to the two legs to be interchanged. The translational symmetry ($\mathbf{Z}_2(\omega)$), forces the signals sent to the two cells in each leg to be the same, maybe up to a phase shift.

The Theorem H/K classifies all possible symmetry types of periodic solutions for a given coupled cell network [6]. These periodic solutions are then identified with bipedal rhythms. Let $x(t)$ be a solution of an ODE $\dot{x} = f(x)$, with period normalized to 1. Its periodic solutions are characterized by two symmetry groups: spatio-temporal symmetry group H and spatial symmetry group K. Spatio-temporal symmetries H fix the solution up to a phase shift, i.e., let $\gamma \in \Gamma$, then $\gamma x(t) = x(t-\theta) \leftrightarrow x(t+\theta) = x(t)$, where θ is the phase shift associated to γ. Spatial symmetries' action in the solution is trivial, i.e., $\gamma x(t) = x(t)$. If $\theta = 0$, then γ is a spatial symmetry. The pair (H, K) is a symmetry of a periodic solution $x(t)$ iff H/K is cyclic. There are twelve pairs of symmetry types (H, K) such that H/K is cyclic. In Table 1, we show, as an example four of those pairs, the corresponding periodic solutions and their identification with primary biped locomotor patterns. For more information see [14]. We explain how the gait *jump* is identified with the periodic solution $((x_{LL}, x^S_{LL}), (x_{LL}, x^S_{LL}))$ of system (1), that has symmetry pairs $(H, K) = (\Gamma_{\text{biped-robot}}, \mathbf{Z}_2(\kappa))$. Permutation

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

H	K	**Left leg**	**Right leg**	**Gait**
$\Gamma_{\text{biped-robot}}$	$\Gamma_{\text{biped-robot}}$	(x_{LL}, x_{LL})	(x_{LL}, x_{LL})	*two-legged hop*
$\Gamma_{\text{biped-robot}}$	$\mathbf{Z}_2(\omega\kappa)$	(x_{LL}, x_{LL}^S)	(x_{LL}^S, x_{LL})	*walk*
$\Gamma_{\text{biped-robot}}$	$\mathbf{Z}_2(\kappa)$	(x_{LL}, x_{LL}^S)	(x_{LL}, x_{LL}^S)	*jump*
$\Gamma_{\text{biped-robot}}$	$\mathbf{Z}_2(\omega)$	(x_{LL}, x_{LL})	(x_{LL}^S, x_{LL}^S)	*run*

κ switches signals sent to the cells in the two legs. Applying κ to the *jump* does not change that gait since LL_i and RL_i, $i = 1,2$ receive the same set of signals. The permutation κ is called a *spatial* symmetry for the *jump*. Symmetry $\Gamma_{\text{biped-robot}}$ forces the signals sent to the two cells in each leg to be the same, up to a phase shift of $1/2$.

The observed symmetry of CPG models for locomotion of animals or robots is fairly accepted by most researchers. See [16, 9] for CPG models of biped robots.

NUMERICAL SIMULATIONS

We simulate the CPG model biped-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. We vary $T \in [0,25]$, in steps of 0.1, for a given periodic solution, identified with the *run*. We start from a stable purely rhythmic periodic solution, identified with the bipedal *run*. Then, we fix T, and simulate the periodic solution, with this new offset, until a new stable solution is found. In the case of a periodic solution, we compute its amplitude and frequency values, that are then plotted. Values of the offset T such that the achieved stable solution is an equilibrium are not plotted.

The system of ordinary differential equations that models the discrete primitive is the VITE model given by [2]:

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

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.

The equations for the rhythmic motor primitive are known as the modified Hopf oscillators [10] 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 [5, 11].

The coupled systems of ODEs that model CPG biped-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}, $a = 50.0$, $G = 1.0$, $\delta = 10.0$. Figure 2 depicts amplitude and frequency values of the periodic solutions produced by CPG biped-robot and identified with the bipedal *run*. The charts above reveal that the amplitude and frequency values

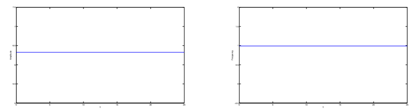

FIGURE 2. Amplitude (left) and frequency (right) of the periodic solutions produced by CPG biped-robot and identified with *run*, for varying $T \in [0, 25]$ in steps of 0.1, in cases of diffusive and synaptic couplings.

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 biped robots, since varying the joint offset will not affect the required amplitude and frequency of the resultant trajectory, nor the gait.

CONCLUSION

We study the effect on the periodic solutions produced by a CPG model for biped robots movements of superimposing two motor primitives: discrete and rhythmic. These periodic solutions are identified with the bipedal *run*. The CPG model biped-robot has the same architecture as a CPG model for biped animals, developed in [14]. There is, however, an important distinction: here, each neuron/cell (CPG-unit) combines two motor primitives, discrete and rhythmic. We simulate the CPG model biped-robot considering the discrete primitive as an offset of the rhythmic primitive, and two distinct coupling functions. We compute the amplitude and the frequency values of the periodic solutions identified with *run*, 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. Future work includes the development a biped robot experiment, in which these findings may be replicated.

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