Hexapod Locomotion: a Nonlinear Dynamical Systems Approach

Ricardo Campos, Vitor Matos, Cristina Santos*
Industrial Electronics Department
University of Minho, Guimaraes, Portugal
* Email:cristina@dei.uminho.pt

***Abstract*—The ability of walking in a wide variety of terrains is one of the most important features of hexapod insects. In this paper we describe a bio-inspired controller able to generate locomotion and switch between different type of gaits for an hexapod robot.**

Motor patterns are generated by coupled Central Pattern Generators formulated as nonlinear oscillators. These patterns are modulated by a drive signal, proportionally changing the oscillators frequency, amplitude and the coupling parameters among the oscillators. Locomotion initiation, stopping and smooth gait switching is achieved by changing the drive signal. We also demonstrate a posture controller for hexapod robots using the dynamical systems approach.

Results from simulation using a model of the Chiara hexapod robot demonstrate the capability of the controller both to locomotion generation and smooth gait transition. The postural controller is also tested in different situations in which the hexapod robot is expected to maintain balance. The presented results prove its reliability.

I. INTRODUCTION

Hexapod robots are the most typical walking robots that imitate the limb structure and motion control of insects or arthropod animals, and that can walk in unstructured terrain with a high probability of success [1], even if a limb is lost. These important advantages make it reliable for some autonomous and high-reliability works, like field scouting, underwater searching, space exploring, disaster areas, rigs, excavations, and many other applications.

On this work we want to generate the most common hexapod gaits and also smoothly switch among these according to changes in the walking velocity to achieve stable locomotion. The generated gaits are metachronal (wave) gait that specifies a slow walking; ripple gait corresponding to a medium speed gait and the fast speed tripod gait. In order to achieve smooth walking from low speed to high speed, gait switching should take place continuously with both the duty factor and the interlimb phase relationships properly adjusted.

This gait switching issue in hexapod robots has already been addressed. [2] proposes a new gait rule named *adaptive wave gait*. The adaptive wave gait was combined with a synchronized motion control, to reproduce the gait generation and gait transition in a smooth way. Our work is based on this approach because with the proposed method it is possible to realize a smooth and effective transition between the desired gaits.

Another contribution to this issue is proposed by [3]. Three insect inspired controllers implemented on an hexapod robot are compared to verify the locomotion performance and the efficiency on gait transitions. They concluded that the controller based on Central Pattern Generators (CPGs) performed the best. Further, the robot achieved smooth transition between its three gaits.

In this contribution, we proposed a two-layer architecture. The lower level generates the movement patterns using networks of CPGs modeled by nonlinear oscillators.

The second layer models higher commands for initiating, regulating and stopping CPGs activity and therefore initiate a walking gait, switch among gaits and stop the locomotion. This layer receives a modulatory signal that regulates the CPGs activity. This signal strength is mapped onto different sets of the CPG parameters, and hence result in the different motor behaviours.

Fortuna and his group, in [4], use Cellular Neural Networks to provide a decentralized locomotion control of an hexapod robot using an approach based on locomotion control in the stick insect. They use the Walknet model proposed by Cruse [5] to implement the decentralized locomotion control.

In [6], the control of a biologically inspired robot is realized using an analog distributed system working as a CPG that performs the locomotion control. The leg controller is formed by Cellular Neural Networks (CNNs). Later they proposed the inclusion of sensory feedback in the CPG [7].

In [8], it is used a coupled nonlinear oscillator to control the Sprawlita hexapod robot. The nonlinear oscillator is a two neuron Matsuoka oscillator [9] with mutual inhibition.

The proposed controller offers multiple interesting features, including: low computational cost; intrinsic stability which allow for feedback integration; intrinsic robustness against small perturbations; smooth trajectories modulated by simple parameters change; provide for coupling/synchronization; and entrainment phenomena when coupled to mechanical systems. Therefore, it provides for an autonomous distributed controller that generates stable and robust synchronized trajectories.

Furthermore, we include sensory feedback to correct the robot body orientation with respect to lateral inclination. We propose a lateral posture mechanism in which the measured roll angle corrects the robot posture and adapts the generated locomotion on inclined terrains by generating discrete trajectories for the femur and tibia.

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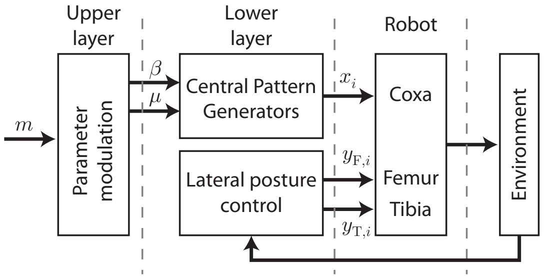
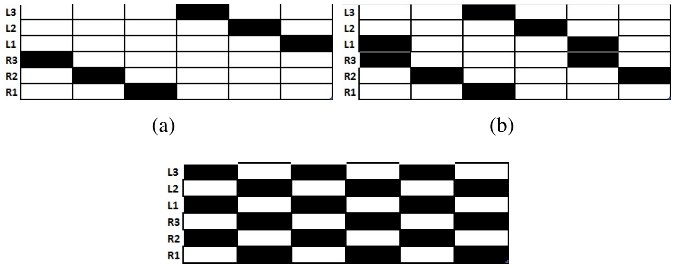


Fig. 1. System's overall architecture. The network of CPGs generate the motions of locomotion for the coxa joints. The posture control mechanism generates the necessary discrete movements on the femur and tibia, to correct the robot's body orientation.



(a) (b)

(c)

Fig. 2. Gait diagram depicting event sequences for three different hexapodal gaits. White color indicates that the foot is in ground contact. a) Metachronal (low - speed) Gait. b) Ripple (medium - speed) Gait. c) Tripod (fast - speed) Gait.

The proposed system is implemented in a simulated environment with a model of the hexapod robot Chiara. Results demonstrate the robot performing three hexapodal gaits individually and demonstrate a smooth transition between these three gaits correctly adjusting the interlimb phases. The postural controller is also tested in different situations in which the robot must keep balance. The presented results prove its reliability and robustness.

II. SYSTEM OVERVIEW

We present a two-layer architecture (fig. 1). The lower layer generates the required motions of the limbs for locomotion, using a network of CPGs, on-line generating coordinated trajectories for the coxa joints, which we can modulate through simple and predictable parameter changes.

These parameter values are set by the upper layer, according to the value of a single descending command, m. We change between three basic hexapodal gaits, controlling the velocity and behaviour of the robot, as locomotion initiation, gait switching and stopping.

Parallel to the network of CPGs, a lateral posture mechanism acts on the limbs to correct the body's orientation through the value of roll displacement of the body, correcting the posture and adapting the locomotion on inclined terrains by generating discrete trajectories for the femur and tibia.

III. HEXAPOD LOCOMOTION GENERATION

A. *Gait Description*

During animal locomotion one of the most important actions is the coordinated cyclic manner of lifting and placing the legs on the ground. This action, called a gait, is a periodic relationship among the movement of all limbs during locomotion.

A gait can be characterized by the concepts of cycle time (T), duty factor (β) and relative phase [10].

The duty factor, $\beta \in [0, 1]$, for a leg is the ratio between that leg stance phase duration and the cycle time,

$$\beta = \frac{T_{\mathrm{st}}}{T_{\mathrm{st}} + T_{\mathrm{sw}}}. \tag{1}$$

Animals increase their locomotion velocity by decreasing the step cycle duration, increasing the number of steps per second, through the decrease in the stance phase duration, T_{st}. While the swing phase duration, T_{sw}, remains practically constant throughout all velocities of locomotion.

The relative phase of leg i is the time elapsed from the setting down of a chosen reference foot until the foot of leg i is set down, given as the fraction of the cycle time. It is considered the start of the stride as the set down of the right rear limb.

Many of the usual hexapod gaits possess a degree of symmetry, which can in general be described according to the two following assumptions [11]: 1) no leg moves forward until the one behind is placed in a supporting position; and 2) legs of the same girdle are always in strict alternation, performing the step cycle out of phase from each other (0.5 out of phase).

We focus our work in the most common hexapodal gaits, used for straightforward walking [12]. We follow usual limb conventions [13], the limbs of the left (L) and right (R) sides of the insect are numbered from front to back. The subindexes stand for the limb number: 1 is the front leg, 2 is the middle leg and 3 is the rear leg.

Figures 2 and 3 depict the gait diagrams and the relative phases for the most common hexapodal gaits [13].

The Metachronal gait, illustrated in Fig. 2(a), is adopted when moving slowly, usually with a a duty factor of $\beta = \frac{3}{4}$. This gait can be described as a back to front propagating *wave*, first moving the limbs on the right side and then the limbs on the left side.The adjacent limbs of each half of the hexapod body (R3 and R2, R2 and R1) are 60° out of phase and contralateral limbs (e.g. R3 and L3) are half a period (or 180°) out of phase (Fig. 3(a)).

The Ripple Gait (Fig. 2(b)) is used to move at a medium speed, with $\beta = \frac{5}{8}$. L1 (left front leg) and R3 (right rear leg), L3 (left rear leg) and R1 (right front leg) move together in phase.

When an hexapod moves rapidly, it normally uses the tripod gait (Fig. 2(c)), with $\beta = \frac{1}{2}$. At each move, ipsilateral anterior and posterior legs, and the contralateral middle leg move together in phase.

B. *Locomotor Model*

In this article we use CPGs modeled by nonlinear dynamical equations, as a paradigm to generate the rhythmic locomotor movements to the robot legs.

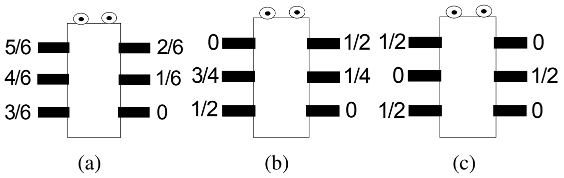


Fig. 3. Relative phases for the most common hexapodal gaits.a) Metachronal gait.b) Ripple gait .c) Tripod gait.

1) CPGs: The movements for each leg are generated by a single nonlinear Hopf oscillator, as follows

$$\dot{x_i} = \alpha(\mu_i - r_i^2)(x_i - y_i) - \omega z_i \tag{2}$$

$$\dot{z_i} = \alpha(\mu_i - r_i^2)z_i + \omega(x_i - y_i) \tag{3}$$

where x_i and z_i are the state variables, $r_i = \sqrt{(x_i^2 + z_i^2)}$, amplitude of the oscillations is given by $A = \sqrt{\mu_i}$, ω specifies the oscillations frequency and relaxation to the limit cycle is given by $\frac{1}{2\,\alpha\,\mu_i}$.

This oscillator contains an Hopf bifurcation from a fixed point at $x_i = 0$ (when $\mu_i < 0$) to a structurally stable, harmonic limit cycle, for $\mu_i > 0$.

This oscillator generates smooth trajectories due to the stable solutions of the dynamical solutions, despite small changes in the parameters.

The generated x_i solution of this nonlinear oscillator is used as the control trajectory for a i coxa joint of the robot limbs. These trajectories encode the values of the joint's angles and are sent online for the lower level PID controllers of each coxa joint (see Fig. 1).

This oscillator generates an x_i oscillatory trajectory in which the ascending and descending parts have equal durations. In order to achieve an independent control of the duration of these parts, we employ the following equation proposed by [14],

$$\omega \quad = \quad \frac{\omega_{\mathrm{st}}}{\mathrm{e}^{-az_i} + 1} + \frac{\omega_{\mathrm{sw}}}{\mathrm{e}^{az_i} + 1}, \tag{4}$$

where ω alternates between two different values, ω_{sw} and ω_{st}, depending on the step phase.

The control of the durations of the step phases is achieved by setting $\omega_{\mathrm{sw}} = \frac{\pi}{T_{\mathrm{sw}}}$ (swing frequency) and $\omega_{\mathrm{st}} = \frac{\pi}{T_{\mathrm{st}}}$ (stance frequency). It is thus possible to generate gaits with a desired duty factor, β, by keeping the swing frequency constant and specifying the stance frequency according to the duty factor value as follows,

$$\omega_{\mathrm{st}} = \frac{1-\beta}{\beta}\omega_{\mathrm{sw}}. \tag{5}$$

The femur joints are controlled as simple as possible: by flexing the femur to a fixed angle during swing phase, and extending to a fixed angle during the stance phase.

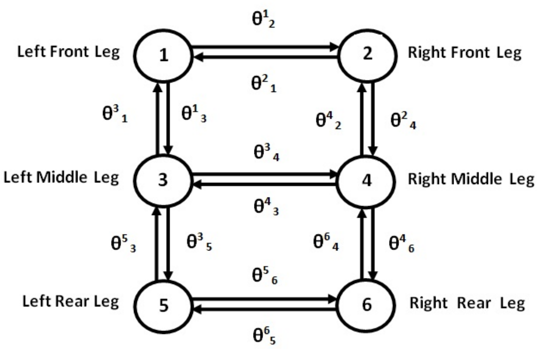


Fig. 4. Coupling Network to achieve interlimb coordination.

Gait	θ_2^1	θ_3^1	θ_4^2	θ_4^3	θ_5^3	θ_6^4	θ_6^5
Metachronal	π	$\frac{\pi}{3}$	$\frac{\pi}{3}$	π	$\frac{\pi}{3}$	$\frac{\pi}{3}$	π
Ripple	$-\pi$	$-\frac{3\pi}{2}$	$\frac{\pi}{2}$	π	$\frac{\pi}{2}$	$\frac{\pi}{2}$	π
Tripod	π	π	$-\pi$	$-\pi$	$-\pi$	π	π

TABLE I
RELATIVE PHASES BETWEEN OSCILLATORS.

2) Interlimb coordination: Interlimb coordination is achieved by coupling, in a given manner, the dynamics of the six CPGs, each controlling a coxa joint (Fig. 4). These couplings ensure that the limbs stay synchronized, and are given by:

$$\begin{bmatrix}\dot{x}_i\\ \dot{z}_i\end{bmatrix} = \begin{bmatrix}\alpha\left(\mu - r_i^2\right) & -\omega\\ \omega & \alpha\left(\mu - r_i^2\right)\end{bmatrix}\begin{bmatrix}x_i\\ z_i\end{bmatrix} + \sum_{j\neq i}\mathbf{R}(\theta_j^i)\begin{bmatrix}0\\ \frac{x_j + z_j}{r_j}\end{bmatrix} \tag{6}$$

where $i, j \in \{\mathrm{L1, L2, L3, R1, R2, R3}\}$. The linear terms are rotated onto each other by the rotation matrix $\mathbf{R}(\theta_i^j)$, where θ_i^j is the required relative phase between the i and j coxa oscillators to perform the gait (we exploit the fact that $\mathbf{R}(\theta) = \mathbf{R}^{-1}(-\theta)$).

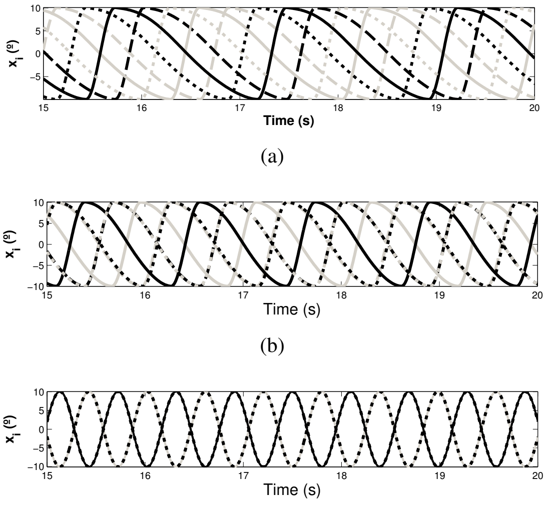
Table I lists the relative phases (θ_j^i) between the oscillators of the coupling network for metachronal, ripple and tripod gaits.

Using this approach to interlimb coordination we obtain a network of oscillators with controlled phase relationships, able to generate any type of behavior such as locomotion with stable and smooth trajectories.

C. Gait Generation

All experiments presented in this paper were done in simulation using the Webots simulator based on ODE, an open source physics engine. We have developed a model for the Chiara Robot, a new, open source educational hexapod robot, developed at Carnegie Mellon University's Tekkotsu lab [15]. We control 3 degrees-of-freedom (DOFs) for leg, coxa, femur and tibia joints, meaning a total of 18 DOFs.

Parameters for experiments were chosen in regard to stability during the integration process and to feasibility of the



(a)

(b)

(c)

Fig. 5. Generated coxa joint trajectories for: a) Metachronal gait. b) Ripple gait. c) Tripod gait. Dashed light line represents the left front leg trajectory, dashed dark line for right front leg trajectory, solid light line for left middle leg trajectory, solid dark line for right middle leg trajectory, dotted light line for left rear leg trajectory and dotted dark line for right rear leg trajectory.

desired trajectories. In these experiments, the robot walks over a plain surface and a $T_{sw} = 0.3s$ is set for the three generated gaits.

1) Metachronal Gait: In this experiment, for a $\beta = \frac{5}{6}$, the robot moves with a velocity of ≈ 0.058 m/s. Coxa joint trajectories are depicted in fig. 5(a).

2) Ripple Gait: In this experiment, we set $\beta = \frac{3}{4}$. The robot moves with a velocity of ≈ 0.09 m/s, slightly faster than in the metachronal gait. Fig. 5(b) depicts the generated real coxa joint trajectories.

3) Tripod Gait: In the tripod gait, with a $\beta = \frac{1}{2}$, a final faster velocity of ≈ 0.19 m/s was achieved. Coxa trajectories are illustrated in Fig. 5(c)

IV. GAIT TRANSITION

A modulatory drive signal, m, is used to regulate the activity of the CPGs. Its strength initiates, stops and switches among gaits, by adjusting the needed parameters of the oscillators. These parameters are the amplitude μ, the frequency ω_{st} of the stance phase and the gait phases (θ^i_j). Both the value of the stance frequency and the gait phases can be expressed as functions of the duty factor β. The m values were chosen arbitrarily as well as its range.

A. Initiating/stopping locomotion

By modifying the μ parameter the system switches between a stable fixed point at $x_i = 0$ $(\mu < 0)$ and a rhythmic movement $(\mu > 0)$, meaning the μ parameter sets whether or not there are oscillations generated by the CPG. For a m below $m_{low} = 0.2$ the oscillators are shut down and the robot stops its movement.

B. Duty factor modulation

As the modulatory drive increases in strength, the duty factor linearly decreases (from $(\frac{5}{6})$ until $(\frac{1}{2})$), and is defined as a piecewise linear function of the modulatory drive

$$\beta = \begin{cases} -0.083m^2 + 0.166m + 0.749 & , m_{low} < m \leq 3 \\ 0.5, m \geq 3 \end{cases} . \tag{7}$$

C. Gait phases modulation

In order to modulate the gait phases we use the rule from [2]. This rule states that: 1) in consecutive legs, each leg motion has $1 - \beta$ phase shift fast to fore side leg; and 2) legs of the same girdle perform the step cycle 0.5 out of phase from each other.

According to these indications, (θ^i_j) can be mathematically defined by

$$\theta^i_j = \begin{cases} (1-\beta)2\pi, & \text{lengthwise legs} \\ (0.5)\pi, & \text{bilateral legs} \end{cases} . \tag{8}$$

Different values of the drive signal mean different behaviors, that is, locomotion initiation, speed change and gait change. These different behaviors correspond to adjustments of the CPG parameters, namely: amplitude, stance frequency and coupling parameters.

D. Experiments

The aim of this experiment is to demonstrate the smoothness and performance on gait transition when interlimb phase relationships are progressively adjusted following the previously presented solution.

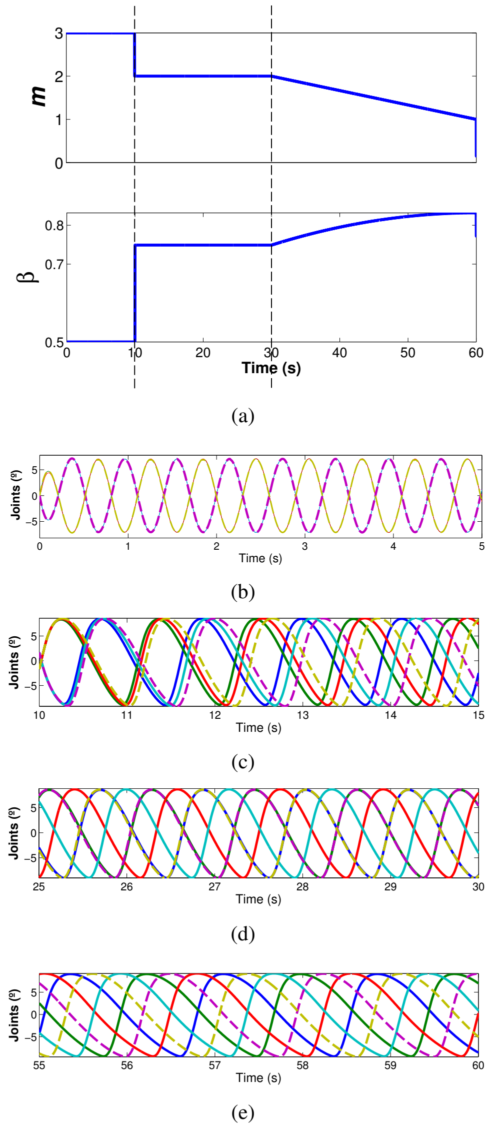
The modulatory drive m starts at 3 (top fig. 6(a)), such that the robot walks with a tripod gait(fig. 6(b)) $(\beta = \frac{1}{2})$. At instant $t = 10$ s m drops to 2, $\beta = \frac{3}{4}$, forcing a quick change from tripod to ripple gait (fig. 6(c)). m is maintained at 2, from 10 s to 30 s, such that the robot performs a ripple gait (fig. 6(c)). m is gradually reduced down to 1 from 30 s to 60 s, with a corresponding increase of β towards $\frac{5}{6}$ (top fig. 6(a)). In fig. 6(e) are shown the last moments of the transition to metachronal gait.

The duty factor value during the gait transitions is demonstrated in the bottom of fig. 6(a).

V. LATERAL POSTURE CONTROL

Postural control has been intensively investigated in hexapod robots. In [16], they propose and demonstrate a simple algorithm for controlling the posture of a complex robot with several DOFs. In order to maintain static posture and generate body motion the algorithm avoids inverse kinematics by issuing feedforward force commands.

Paolo Arena et al. [6] presented a biologically inspired solution to control an hexapod locomotion using an analog distributed system that makes the role of a CPG for the locomotion control. The attitude control is realized by integrating in the CPG a proportional integrative controller for each leg. In [17] they propose two new controllers, one for climbing



(a)

(b)

(c)

(d)

(e)

Fig. 6. a)Top:Modulatory drive. *m* is abruptly changed to 2 at 10 s and 30s when the robot is performing the transition between tripod gait and ripple gait. From 30 s *m* is gradually decreased in order to achieve the metachronal gait. a)Bottom: resulting duty factor. b) coxa joint trajectories between 0 s and 10 s when the robot is in tripod gait. c) coxa joint trajectories between 10s and 15 s where the robot is starting the transition to ripple gait. d) coxa joint trajectories between 25 and 30 s when the robot is in ripple gait. e) coxa joint trajectories between 55 s and 60 s when the robot is already performing the metachronal gait.

constant slope inclinations where the posture control is a very important factor and one for achieving higher speeds using a gait that incorporates a substantial aerial phase.

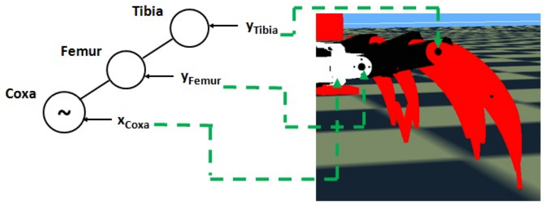


Fig. 7. Posture control architecture for one leg (similar to the other legs).

TABLE II
PARAMETER VALUES USED IN THE POSTURE CONTROL EXPERIMENTS.

$k_{j,i}$	α	σ	$M_{\mathrm{F},i}$	$D_{\mathrm{F},i}$	$M_{\mathrm{T},i}$	$D_{\mathrm{T},i}$
15	5000	0.1	100^o	-100^o	160^o	-60^o

In our approach we compensate lateral displacement of the body by increasing or decreasing leg height on both sides, performed by changing the angles of the femur and tibia joints (fig. 7). These angles are controlled by discrete movements, generated by a nonlinear dynamical system designed to find the neutral point of lateral posture of the robot, reducing the roll to a minimum. The dynamical system is given by

$$\begin{aligned} \dot{y_{o,i}} &= k_{o,j,i} f(\phi) + \alpha(y_{o,i} - M_{o,i}) e^{-\frac{(y_{o,i}-M_{o,i})^2}{2\sigma^2}} \\ &\quad + \alpha(y_{o,i} - D_{o,i}) e^{-\frac{(y_{o,i}-D_{o,i})^2}{2\sigma^2}}, \qquad (9) \end{aligned}$$

applied to the femur (F) and tibia (T) joints ($o = \mathrm{F}, \mathrm{T}$) where $k_{o,j,i}$ (j =left,right) is a static gain, set symmetrically for the right and left legs. Function $f(\phi)$ defines a dead zone for the robot's roll angle ϕ, given by

$$f(\phi) = \begin{cases} 0, & -0.2 < \phi < 0.2 \ (^\circ) \\ \phi, & \text{elsewhere} \end{cases} . \qquad (10)$$

The limits of operation for the system are given by the values M_i (maximum) and D_i (minimum).

The main aim of this posture control is, by measuring the lateral tilt of the robot body, ϕ, we want to stretch the legs towards which the robot is tilted, and fold the other legs, thus reducing the robot lateral tilt and keeping the body parallel to the ground.This aim is achieved modulating and adjusting the femur and tibia joints values that are controlled by the discrete dynamical system, changing the height of the leg, reducing the lateral tilt to a minimum. Only the coxa joints perform a rhythmic motion, provided by the six coupled CPGs.

A. *Experiments*

To demonstrate the role of the lateral posture control, we realize an experiment where the simulated Chiara robot walks with a metachronal on top of a moveable platform, subject to lateral inclinations, reacting to changes in its lateral tilt. In table II the chosen configuration parameters are presented.

The robot must counteract the effects of the platform inclination on the robot's body, reducing the sensed roll angle to values belonging to a small region around zero as defined by the dead-zone.

Top panel of fig. 8 shows the change in inclination on the platform in dashed red. The robot walks forward during the first 10s without any lateral tilt change. From $t = 10$ s to $t = 20$ s, the platform is gradually inclined to the left up to 7°, while the robot remains walking without loss of balance counteracting the body's lateral tilt, stretching the left legs and folding the right legs. We can see that the robot successfully

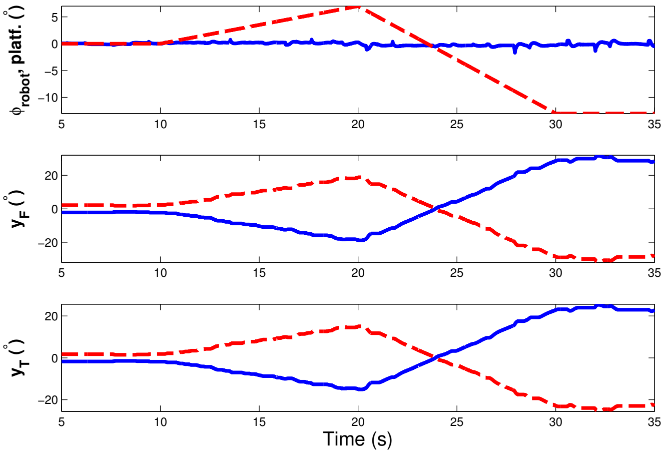
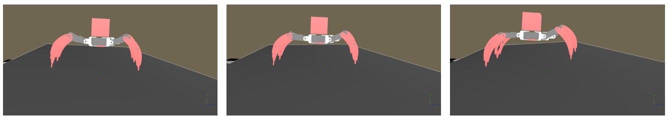
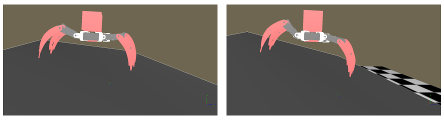


Fig. 8. Posture control experiments: a)Top:Lateral tilt ϕ of the robot; Middle: y_F trajectories for L1 (solid blue line) and R1 (dashed red line); Bottom: y_T trajectories for L1 (solid blue line) and R1 (dashed red line).



(a) t=10 s (b) t=14 s (c) t=20 s



(d) t=26 s (e) t=30 s

Fig. 9. Robot behavior during posture control.

counteracts the platform inclination, maintaining the body roll angle close to 0°.

Between $t = 22$ s and $t = 30$ s the platform is gradually shifted to 15°. Again, the robot successfully maintains its lateral tilt near 0°, this time, by stretching the right legs and folding the left.

The two bottom panels of fig. 8 show the trajectories in the femur and tibia joints of both front legs, exhibiting symmetric trajectories, as expected.

Snapshots of the experiment are presented in fig. 9, showing the inclination that the robot is subjected and its reaction in order to maintain the body orientation.

VI. Conclusion

In this contribution we applied nonlinear oscillators to model CPGs and to generate the most common hexapodal gaits. Further, a simple command, a drive signal, allows velocity control and a smooth switching between three different gaits.

Results are demonstrated in simulation, where the robot successfully switches between the three gaits.

Additionally, we propose a lateral posture control based on the use of dynamical systems. The idea is to make it possible to correct the robot posture and keep its balance when subjected to changes in its lateral tilt. Results show that the lateral posture controller is able to maintain the roll angle around zero, even when the robot walks in planes with a lateral inclination.

Future work includes to achieve more complex postural control; omnidirectional locomotion; partially injured legs; homing and learning in hexapod robots.

Acknowledgment

This research was supported by the Foundation for Science and Technology (FCT) in Portugal under the project PTDC/EEA-CRO/100655/2008, and under the grant SFRH/BD/62047/2009.

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