GAIT GENERATION FOR A SIMULATED HEXAPOD ROBOT: A NONLINEAR DYNAMICAL SYSTEMS APPROACH

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Abstract: The capacity 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 reproduce the different type of gaits for an hexapod robot.
Motor patterns are generated by coupled Central Pattern Generators, formulated as nonlinear oscillators. In order to demonstrate the robustness of the controller we developed a simulation model of the real Chiara hexapod robot where are described the most important steps of its development.
Results were performed in simulation using the developed model of the Chiara hexapod robot.

Keywords: Bio Control, Mobile Robots, Nonlinear Control Systems, Robot Dynamics, Robot Programming

1. INTRODUCTION

For some years, great interest has been directed to the study of biologically inspired robots (Arkin, 1998). This kind of robots include different degrees of biological inspiration and involves theories like robotics, neuroscience or biology.

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 (Jianhua, 2006) due to the existing redundant limb. Hexapod robots could continue its movement even if a limb is lost, because one of the most recognized merits of hexapod walking is robustness to recover irregular situations.

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 much others applications (Manuel S. Silva, 2001).

On this work we want to generate the most common hexapod gaits that enable the robot to achieve a stable locomotion. The physical nature extremely stable of hexapods is one of the most important motivations to continue the study of this kind of locomotion. The generated gaits are metachronal gait (”wave gait”) that specifies slow walking, ripple gait corresponding to a medium speed gait and the fast speed tripod gait.

In order to generate different gaits, we propose a control architecture that is based in the vertebrate biological motor systems (Grillner, 1975), (MacKay-Lyons, 2002).

The lower level mimics the role of the spinal cord. The generation of the movement patterns is made using networks of Central Pattern Generators (CPGs) modelled by nonlinear oscillators. Interlimb coordination is achieved by coupling six CPGs in a network. This network produces coordinated rhythms of motor activity, i.e. the correct pattern for locomotion. These systems are solved using numerical integration and sent to the lower level PIDs of the joints.

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There are several control models for hexapod locomotion that use Central Pattern Generator approaches. Central Pattern Generators (CPGs) are often modelled and built by means of coupled nonlinear oscillators (Kopell and Ermentrout, 1988; Van der Pol and der Mark, 1928) and this approach is present in the works of Rayleigh (Rayleigh, 1945), Matsuoka (Matsuoka, 1985; Matsuoka, 1987), or Fitzhugh-Nagumo.

Fortuna and his group, in (L.Fortuna, 2002), use Cellular Neural Networks (CNNs) 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 (H. Cruse and Schmitz, 1998) to implement the decentralized locomotion control.

In (P. Arena, 2001), 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 CNNs.

In (P. Arena and Patané, 2002) they propose the inclusion of sensory feedback in the CPG implemented through CNNs for an hexapod robot.

In (Kraimon Maneesilp and Sooraksa, 2004) is proposed a new design of a CNN to control hexapod robot movement.

In (Bailey, July, 2004), it is used a coupled nonlinear oscillator to control the Sprawlita hexapod robot.

In (P.Arena, 2006), CNNs play the role of an artificial CPG to the locomotion control.

There are several important features and considerations that must be addressed when implementing a controller for hexapod locomotion as stability and robustness that enable more animal-like movements.

The proposed controller overcomes these difficulties due to its intrinsic properties. It offers multiple interesting features, including: low computational cost; the intrinsic stability properties 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.

The proposed system is implemented in a simulated environment and a model of the hexapod Chiara robot is built. In this contribution, we explain the development of the simulated model and describe the most important features of the real model.

The results demonstrate the robot performing three hexapodal gaits (”wave”, ripple and tripod gait) individually. The presented results prove the reliability and robustness of the developed controller.

2. DEVELOPMENT OF CHIARA ROBOT USING WEBOTS SIMULATOR

In this work we have modeled the real Chiara robot using the Webots (Michel, 2004) simulator. Chiara was developed at Carnegie Mellon University’s Tekkotsu lab and is a open source educational robot (CMU, 2008). The Solidworks model has been made available by its developers to the student community and we have used it in the development of the robot model in the Webots platform. We want that almost all features of the simulation model are equal to the real model.

Chiara has a stable motion with a high degree of precision and is composed by a set of parts and servos. It has a 6 DOF arm with a gripper that enables to grasp and to manipulate objects. It has 25 dynamixel AX-12 servos with position and force feedback that are used, for instance, on the joints of each leg of the robot to help in their movement. In the gripper there are more three analog microservos (CMU, 2008).

The robot is composed by a dynamixel AX-S1 infrared rangefinder that is mounted directly below the camera and is used for multimodal sensing.

2.1 *Shape Simplification using Solidworks*

The ”body parts” of the Chiara Solidworks model are too complex, mainly the legs. The SolidWorks model has a lot of details. These details are not necessary for the present study and if they are used in the simulation the model of the robot becomes very heavy to render and simulate on Webots platform which could make the simulation very slow and frustrating.

Therefore, the body parts of the model were simplified on Solidworks platform by removing the minor details.

The Solidworks platform is a three dimensional mechanical software and is employed in several applications (solid, 2010). With this tool was possible model the body parts of the robot and export it to VRML (Virtual Reality Modeling Language) file format. In Webots it is possible to import the VRML format model of the robot and use it for the desired simulations.

2.2 *Webots Model of the Hexapod Robot*

The Webots platform was developed by Cyberbotics Ltd and it is a robotics simulation software for modeling, programming and simulating different kinds of robots. This simulator provides several properties very important for modeling such as shape, color, mass, friction, density. It is also possible to add many kinds of sensors, servos, etc. Further, it is possible to transfer the developed code to the real robot.

Webots simulator is based on the Open Dynamics Engine (ODE), an excellent and powerful open source physics engine that works as a library to provide more realistic simulations and improve the results (Michel, 2004).

To simplify the Chiara model, the 6 DOF arm with gripper was removed because, initially, is not necessary for the aim of the work. In Figure 1(a) and 1(b) it is possible to see the complete and final hexapod robot model rendered in Webots.

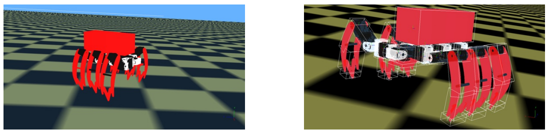

(a) (b)

Fig. 1. a) Model of the Chiara robot rendered in Webots platform. b) Chiara model rendered in Webots with its bounding objects highlighted.

3. HEXAPOD LOCOMOTION GENERATION

3.1 *Gait Description*

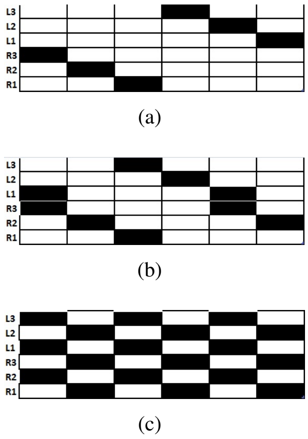
It is considered that the start of the stride, is chosen as the reference event when an arbitrary chosen reference limb is set down.

We focus our work in the most common hexapodal gaits, used for straightforward walking (Valeri A. Makarov and Ebeling, 2006). We follow usual limb conventions (J. J. Collins, 1993), the limbs of the left (L) and right (R) sides of the insect are numbered from front to back. The subindexs stand for the limb number: 1 is the front leg, 2 is the middle leg and 3 is the rear leg. The convention used here is that the reference limb is 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 (DM, 1966): 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).

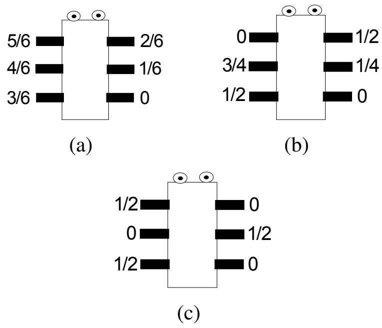
Figures 2 and 3 depict the gait diagrams and the relative phases (J. J. Collins, 1993) for the most common hexapodal gaits.

The Metachronal gait, illustrated in Fig. 2(a), is adopted by the hexapod when it moves 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 60^0 out of phase and contralateral limbs (e.g. R3 and L3) are half a period (or 180^0) out of phase (Fig. 3(a)).



(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.



(a) (b)
(c)

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

The Ripple Gait (Fig. 2(b)) is used by the hexapod to move with a medium speed and duty factor $\beta = \frac{5}{8}$. The contralateral anterior and posterior legs, *i.e.* L1 (left front leg) and R3 (right rear leg), L3 (left rear leg) and R1 (right front leg) move together in phase. Contralateral legs in each segment are half a period (180^0) out of phase and the consecutive movements of the limbs are one quarter of a period (90^0) out of phase (Fig. 3(b)).

When an hexapod moves rapidly, it normally uses the tripod gait (Fig. 2(c)), with a duty factor of $\beta = \frac{1}{2}$. At each move, ipsilateral anterior and posterior legs, and the contralateral middle leg move together in phase. On each segment, contralateral limbs are half a period (180^0) out of phase. The adjacent limbs on the right and left sides are also half a period (180^0) out of phase (Fig. 3(c)).

3.2 *Locomotor Model*

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

3.2.1. *CPGs* The movements for each leg are generated by a single nonlinear Hopf oscillator, as follows

$$\dot{x_i} = \alpha(\mu_i - r_i^2)(x_i - y_i) - \omega z_i \tag{1}$$

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

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. We motivate the choice of this Hopf oscillator because it can be completely analytically solved, which facilitates the smooth modulation of the generated trajectories with respect to their amplitude and frequency (for speed change) according to small parameter changes, while keeping the general features of the original movements.

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.

Herein, we consider that the descending phase of the x_i trajectory, in which the coxa joint value is decreasing, corresponds to the stance step phase in which the limb moves backwards, thus propelling the robot forward. The ascending phase is the movement that places the foot in a more advanced position, ready for the next step, and corresponds to the swing step phase.

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 (Righetti and Ijspeert, 2008),

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

where ω alternates between two different values, ω_{sw} and ω_{st}, depending on the step phase identified by the value of the z variable. The alternation speed between these two values is controlled by a.

By controlling the durations of the ascending and descending phase of the x trajectory, we are controlling the durations of the swing and stance step phases, respectively. This 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,

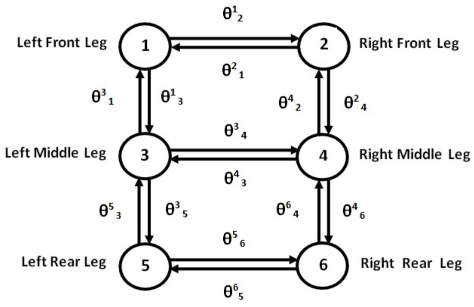


Fig. 4. Coupling Network to achieve interlimb coordination.

$$\omega_{\mathrm{st}} = \frac{1-\beta}{\beta}\omega_{\mathrm{sw}}. \tag{4}$$

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.

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

$$\begin{bmatrix}\dot{x}_i \\ \dot{z}_i\end{bmatrix} = \begin{bmatrix}\alpha\left(\mu - r_i^2\right) & -\omega \\ \omega & \alpha\left(\mu - r_i^2\right)\end{bmatrix}\begin{bmatrix}x_i \\ z_i\end{bmatrix} + \sum_{j \neq i} \mathbf{R}(\theta_j^i)\begin{bmatrix}0 \\ \frac{x_j + z_j}{r_j}\end{bmatrix} \tag{5}$$

where $i, j \in \{\mathrm{L1}, \mathrm{L2}, \mathrm{L3}, \mathrm{R1}, \mathrm{R2}, \mathrm{R3}\}$. 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 $\mathbf{R}(\theta) = \mathbf{R}^{-1}(-\theta)$).

Fig. 4 shows the resulting network of six coxa coupled Hopf oscillators, that allows interlimb coordination for each gait of the hexapod locomotion.

Table 1 lists the relative phases (θ_j^i) between the oscillators of the coupling network for metachronal, ripple and tripod gaits.

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 1. Relative Phases between oscillators.

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.

4. RESULTS

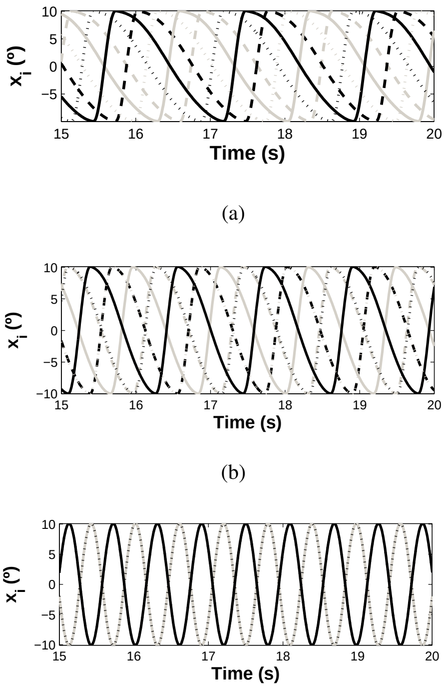
In this work we want to generate the metachronal, ripple and the tripod hexapodal gaits, according to the CPG-based locomotor generator. All experiments presented in this paper were done in simulation using the Webots (Michel, 2004) simulator. We control 3 degrees-of-freedom (DOFs) for leg, coxa, femur 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 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.

4.1 *Metachronal Gait*

In this experiment, we set $\beta = \frac{5}{6}$. The robot moves with a velocity of ≈ 0.058 m/s. The generated real coxa joint trajectories are depicted in fig. 5(a).

Note that the six oscillators have a lag of a sixth of one period (60^o) as expected.



(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.

4.2 *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.

In this gait, trajectories for the left front leg (Dashed light line) and right rear leg (dotted dark line) are in-phase, as well as the right front leg (dashed dark line) and left rear leg (dotted light line) trajectories. The consecutive legs are a quarter of a period (90^o) lagged.

4.3 *Tripod Gait*

In the tripod gait we have set a $\beta = \frac{1}{2}$. A final faster velocity of ≈ 0.19 m/s was achieved. Coxa trajectories are illustrated in Fig. 5(c)

Note that, as expected, three legs are in-phase at each time. Consecutive legs are half a period (180^o) lagged. The left middle leg (solid light line), right front leg (dashed dark line) and right rear leg (dotted dark line) trajectories are together in-phase as well as right middle leg (solid dark line), left front leg (Dashed light line) and left rear leg(dotted light line) trajectories.

5. CONCLUSIONS

In this contribution we applied nonlinear oscillators to model CPGs and to generate the most common hexapodal gaits. Further we describe the development of a robot in the Webots simulator.

The development of a simulation model allows us to equip each robot with a large number of available sensors and actuators to program these robots, simulate them and optionally transfer the resulting programs onto our real robots.

We have described a control architecture based on the vertebrate biological motor systems structure. The movement patterns are generated using networks of Central Pattern Generators that allows a stable and coordinated locomotion.

The controller properties are shown in a simulated experiment, where the robot successfully reproduces three common hexapodal gaits.

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

6. ACKNOWLEDGMENTS

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