Attitude Analog CNN Control for a Hexapod Robot

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Abstract — **In this paper the core of the control of a biologically inspired walking robot is presented. An analog distributed system acts as Central Pattern Generator for the locomotion control, while the attitude control is performed by integrating in the central pattern generator a proportional integrative controller for each leg. This can also be formulated in terms of a CNN. Thus, the whole control system can be viewed as an analog control system realized by CNNs generating the locomotion pattern as a function of the sensorial stimuli from the environment. Some preliminary results obtained with a 18 DOF walking robot prototype are presented.**

1 Introduction

Recently, great interest has been devoted to the study of biologically inspired robots [1]. This category comprises a large variety of robots presenting different degrees of biological inspiration and involves synergies from various disciplines (robotics, neuroscience, biology, ethology). The term biologically inspired robot often indicates both robotic animal models, that can be useful to a major understanding of biological behaviors and to criticize the hypotheses of the starting biological model, and more abstract robotic models.

This paper is focused on the possibility to have a biologically inspired analog control system to solve the task of attitute stabilization and locomotion control.

An earlier version of the six legged walking robot investigated in this paper has been presented in [2]. In this prototype a Reaction-Diffusion Cellular Neural Network (RD-CNN) acts as Central Pattern Generator (CPG) for the robot. This constitutes an analog distributed control system based on a simple CNN-based neuron model. In [3] the extension of the network of CNN neurons to networks with both inhibitory and excitatory synapses is illustrated also with some guidelines to generate the CPG for a given locomotion pattern.

The focus of this paper is to investigate how to include in the biologically inspired CPG an attitude control. This leads to a reformulation of the problem in terms of a 18 Degrees Of Freedom (DOF) legged structure. This step is mandatory for the attitude control problem and offers further advantages. A lot of different locomotion patterns can now be implemented in the structure. Moreover, the added degree of freedom for each leg enables us to consider a more realistic and efficient trajectory in the stance phase (namely, the phase in which the leg is on the ground and moves in the opposite direction with respect to the direction of the robot movement). On the other hand the weight of the whole system grows up, mainly for the presence of six further servomotors actuating the third degree of freedom for each leg. Moreover, the leg controller, that in [2] is basically constituted by a CNN neuron, has to be designed to include the driving signals for the third joint as discussed in the following.

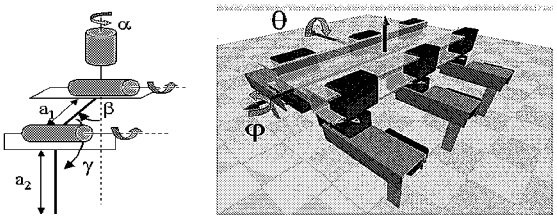
The structure of the leg and the whole system are briefly described in Section II. The control system is described in Section III. A discussion on the results of our approach is presented in Section IV that concludes the paper.

2 Structure of the robot

The prototype of the 18 DOF legged hexapod robot has been realized by designing a carrying structure in aluminium and by using servomotors as actuators. The structure of each leg has three rotational joints orthogonally displaced as shown in Fig. 1(a).

The structure of the whole robot is shown in Fig. 1(b). It is similar to the one we used for the 12 DOF legged hexapod robot.

For the attitude control task a 2-axis accelerometer, the ADXL202, has been used as inclinometer sensor. It has been used to detect the roll and pitch of the robot. It is a low cost sensor that integrates two analog measurements on a chip. It was located on the bottom middle side of the aluminium carrying structure.



(a) (b)

Figure 1: (a) Leg model. (b) Structure of the robot.

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3 The Control System

3.1 Leg controller

The configuration assumed for the leg is the one of the well known anthropomorphic manipulator [4]. This allows us to find the trajectories of the joint variables for a given trajectory of the tip point in the operative space by using the inversion of the kinematics matrix for this manipulator.

A CNN is assumed to constitute the leg controller by generating the joint variables and then driving the servomotors using a Pulse Width Modulation. This CNN has been designed by following the approach mainly discussed in [3] where the details on the implementation of synaptic either inhibitory or excitatory connections between two CNN neurons are discussed. The CNN neuron model is described by the following equations:

$$\begin{cases} \dot{x_1} = -x_1 + (1+\mu)y_1 - sy_2 \\ \dot{x_2} = -x_2 + sy_1 + (1+\mu)y_2 \end{cases} \tag{1}$$

where

$$y_i = 0.5(|x_i + 1| - |x_i - 1|) \quad i = \{1, 2\}$$

Its behavior for both the set of parameters

$$\mu = 0.5; s = 1; i_1 = -i_2 = -0.3 \tag{2}$$

and

$$\mu = 0.5; s = 1; i_1 = i_2 = 0.3 \tag{3}$$

is characterized by a limit cycle with a slow-fast dynamics. It models the beating behavior of a biological neuron [5].

A network of two neurons was designed in which the first neuron characterized by the set of parameters (2) excites and is inhibited by the second neuron, characterized by parameters (3). Being $y_{1,I}$ and $y_{2,I}$ the outputs of the first neuron and $y_{1,II}$ and $y_{2,II}$ those ones of the second neuron, the inhibitory synapse is realized by adding the output $y_{1,II}$ on the second equation of (1) for the first neuron, while the excitatory one adding the output $y_{2,I}$ on the first equation of the second neuron. Both the synaptic weights are $\varepsilon = 1$. This network generates four outputs, from which we take the signal to drive the joints by using the following formula:

$$\begin{cases} q_1 = y_{2,I}/2 \\ q_2 = y_{1,II} + 0.5 \\ q_3 = -y_{1,I}/5 - 0.9 \end{cases} \tag{4}$$

where q_1, q_2 and q_3 are the driving signal for the α-joint, β-joint and γ-joint, respectively.

Fig. 2 shows both the ideal tip trajectory and the one generated by using signals q_1, q_2 and q_3. As it can be noticed the agreement is good.

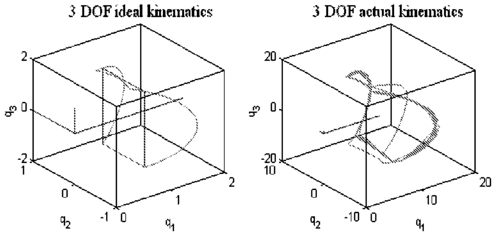

Figure 2: (a) Ideal kinematics. (b) Actual kinematics.

3.2 The Central Pattern Generator

The correlations between the legs are realized by creating synaptic connections between the group of neurons controlling each leg. These synapses have to guarantee that a given locomotion pattern is created. Thus, they depend on the desired pattern. In this paper only the CPG for the alternating tripod gait is presented. This pattern is characterized by two tripods that alternatively stay on the ground. This has been achieved by connecting the neurons of the leg controller networks into pairs of mutually inhibited neurons. As it can be noticed in Fig. 3 that shows the CPG for the alternating tripod gait, these connections are established only between the 'first' neurons of each leg controller net. In other words the approach discussed in [3] can be extended as shown to synchronize networks of neurons rather than single neurons. Other gaits can be, therefore, created as discussed in [3].

In Fig. 3 the leg controller nets are indicated with dashed boxes also with the leg that they control (L1 indicates the left front leg, R2 the right mid leg and so on).

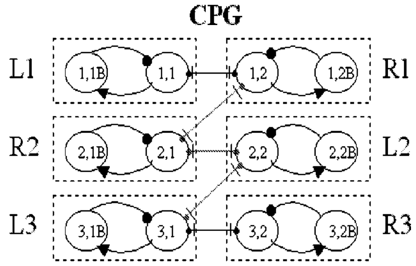

Figure 3: The Central Pattern Generator. The arrows indicate excitation, the dots indicate inhibition.

3.3 The Attitude Control

The attitude control guarantees that the robot keeps its body in horizontal position when it walks on planes with different slopes. The solution proposed to solve this task is to use traditional controllers as PIDs. The actual position of the body is revealed by using the accelerometer described in Section II. This device furnishes two signals indicating the roll and pitch rotations of the body. These signals are filtered and then used as measurements of the robot attitude error. A PID for each leg is then used to generate the signals used to correct those ones coming from the CPG and used as joint variables. It has been found that for the purpose of stability control only integrative action is needed. This solution, as discussed in the following, can be formulated as a CNN, whose inputs are the sensor signals. This aspect makes the approach particularly appealing, since the CNN paradigm can be used to generate and control the whole locomotion phase.

The 3 DOF leg allows us to perform the attitude control of the robot by applying very intuitive principles. If the robot has to go up a slope, maintaining an horizontal attitude, the front legs have to be lowered, while the hind legs have to be raised, the mid legs can be maintained at a constant distance to the ground. These results can be achieved by suitably control the β-joints and γ-joints of the front and hind legs. For the β-joints of the front legs the angle β between the femur (link a_1) and the vertical line is increased, while the angle γ of the γ-joint between the femur and the tibia (link a_2) is decreased of the same quantity. For the hind legs the opposite holds: the angle β is decreased and the angle γ increased. No action is done on the mid legs. This pattern of action can be schematized in a matrix, in which the sign of the action (+ increase, - decrease) for each leg is indicated. The legs are displaced as in Fig. 3.

$$P_\beta = \begin{bmatrix} -1 & -1 \\ 0 & 0 \\ +1 & +1 \end{bmatrix} \tag{5}$$

The pitch correction is described in Fig. 4(a) with the help of a simplified robot model emphasizing the angles of corrections, while in Fig. 4(b) a photo of the robot when the control is acting is shown. It can be seen that the body of the robot is horizontal against the slope of the ground plane. Equivalently, for the roll control purpose the action has to be performed in opposite directions for the contralateral legs, resulting thus in the pattern expressed by the matrix:

$$R_\beta = \begin{bmatrix} +1 & -1 \\ -1 & +1 \\ +1 & -1 \end{bmatrix} \tag{6}$$

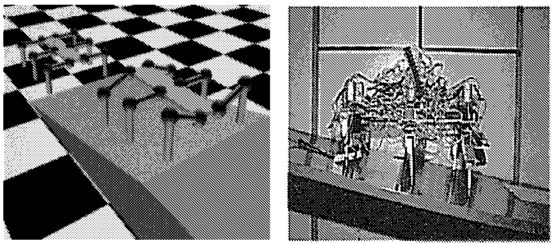
(a) (b)

Figure 4: (a) Ideal Pitch. (b) Actual Pitch.

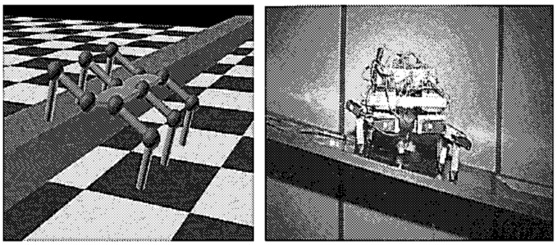
(a) (b)

Figure 5: (a) Ideal Roll. (b) Actual Roll.

Notice that the middle terms of R_β reflect the scheme of Fig. 3. In Fig. 5 both the robot prototype model and a photo of the robot are shown when the roll control is performed. In Fig. 6 the attitude control system is illustrated in some details. The signals φ and θ indicate the pitch and roll speed measurements coming from the sensor. By applying the integrative action we obtain the position error signals e_{ij} according to the following formula:

$$\dot{e}_{ij} = -\tau e_{ij} + (k_p p_{ij}\theta + k_r r_{ij}\varphi) \tag{7}$$

The error signals e_{ij} are added to the signal q_2 coming from the CPG examined in Section II and used to drive the β-joint and subtracted to the signal q_3 driving the γ-joint, according to the fact that opposite actions have to be performed on the femur-tibia and femur-coxa joints. τ is the pole of the integrative action.

It is to be outlined that an analog distributed system for both the task of locomotion pattern generation and attitude control is used. In particular the attitude control is realized by using very simple integrators.

3.4 The Attitude Control CNN

As it can be argued from the previous discussion, the approach used for the hexapod attitude control makes use of a network of distributed proportional integral linear controllers, one for each leg. The

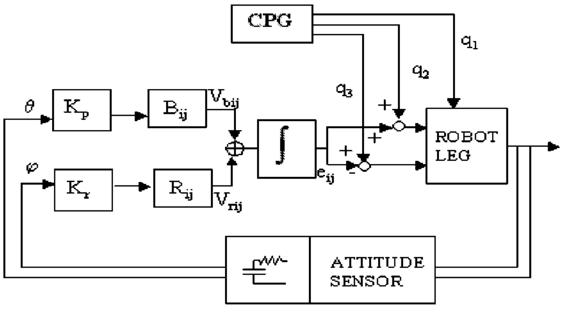

Figure 6: Attitude control.

control signal for each leg depends on a global information on the robot attitude, with respect to a virtual horizontal plane. This is in agreement with the biological case, in which central feedback signals affect local control. Of course, in biology a fundamental rule is also assured by local stimuli, that, in our case, are still under investigation. As previously outlined, the hexapod locomotion pattern generation was realized by a CNN generating autowaves and Turing patterns.

The analog distributed attitude control could also be formulated in terms of CNN structures. In fact equation (7), written for each of the six legs, can be seen in term of a CNN with the following templates:

$$A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1-\tau & 0 \\ 0 & 0 & 0 \end{bmatrix}; \quad B = \begin{bmatrix} 0 & -1/2 & 0 \\ 1 & -1 & -1 \\ 1 & -1/2 & 0 \end{bmatrix}$$

$$U = \begin{bmatrix} -k_p\varphi & k_r\theta \\ 0 & 0 \\ -k_p\varphi & -k_r\theta \end{bmatrix}$$

where U is the input pattern.

Being A_{ij} terms all zero the stability study is straightforward. In fact when the dynamics lies in the linear region, each cell is characterized by a negative eigenvalue ($\lambda_{ij} = -\tau$); when the state of the cell enters the saturation region it holds $\lambda_{ij} = -1$. Under these conditions the stability of the control law is assured. The CNN formulation is particularly suitable for practical reasons: the output saturation corresponds to the motor saturations, which cannot be neglected in the control loop. The stability of the whole control approach has been widely verified by a huge number of experiments performed on the prototype built in our laboratory. The tests performed showed the suitability of the methodology: the attitude control takes place in real time, assuring dynamical stabilization of the whole structure, when walking over unstructurated terrains. It is also surprising to verify how efficiently the structure can escape from situations in which some points, typically the γ-joints undergo saturations. Since these conditions come together with perturbations in the attitude, the feedback signal and the analog structure efficiency work so as to quickly recover to normal conditions.

Therefore, the whole motion generator and control system for the hexapod robot is realized by CNNs.

4 Conclusion

In this paper an analog spatially distributed attitude control system, realized with cellular neural networks has been introduced for the locomotion control and attitude stability task of a biologically inspired hexapod robot. The system is divided into two functional parts. The first acts as central pattern generator for the locomotion control. It has been designed to implement the alternating tripod gait, moreover the approach is general and other gait can be realized.

The attitude control is performed by considering an integrative controller for each leg. We have shown that this can be done with a cellular neural network. Thus, the whole control system can be viewed as an analog control system realized with CNNs generating the locomotion pattern as a function of the sensorial stimuli from the environment. These are now constituted by the output of the accelerometer sensor revealing the roll and pitch accelerations of the body. However, the inclusion of other stimuli as for example a local feedback in each leg is under investigation.

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