Climbing Obstacles via Bio-Inspired CNN-CPG and Adaptive Attitude Control

P. Arena [*], L. Fortuna [*], M. Frasca [*], L. Patané [*], M. Pavone [§]
[*]Dipartimento di Ingegneria Elettrica Elettronica e dei Sistemi
Università degli Studi di Catania
Viale A. Doria, 6 - 95125 Catania, Italy
E-mail: lfortuna@diees.unict.it
[§] Scuola Superiore di Catania, Via S. Paolo 73, 95123 Catania, Italy

***Abstract*— In this paper a control system based on the principles used by cockroaches to climb obstacles is introduced and applied to a bio-inspired hexapod robot. Cockroaches adaptively use different strategies as functions of the ground morphology and obstacle characteristics. The control system introduced in this paper consists of two parts working in parallel. Locomotion control is performed by a Cellular Neural Network playing the role of an artificial Central Pattern Generator for the robot, while a new attitude control system has been designed. In order to reproduce the adaptative capabilities of the biological model, the attitude control system is based on a Motor Map and is aimed to regulate the posture of the robot to allow it to overcome obstacles. In fact high obstacles require the locomotion gait to be reorganized by changing the posture of the robot to be more effective during the overcoming of the obstacle. Both proprioceptive and exteroceptive information are needed to solve this problem, they constitute the input of the adaptive attitude control. Simulation results illustrating the suitability of the control system are also shown.**

I. INTRODUCTION

Explorative missions, *e.g.* to deliver a probe on a planetary surface or to inspect mined ground, represent a huge technological challenge. Major issues to be addressed are:

- rover locomotion: rover should transverse uneven terrains with large obstacles;
- rover autonomy: rover for explorative mission should maneuver on harsh terrains and unknown environments without man control.

Biology provides a wealth of inspiration: insects are able to transverse harsh terrains, to climb over obstacles or even to walk upside down. Moreover, essential aspects in unmanned missions as reconfigurability of locomotion strategies, navigation capabilities and robustness are common features between insects.

Therefore, several efforts, both from a behavioral viewpoint and from an architectural viewpoint, have been performed to design an insect-like robot.

In this paper, we propose a new approach to the control of obstacle climbing in hexapod running robots totally based on exhaustive kinematic data reported in [5]. Locomotion control is performed by a Central Pattern Generator implemented via Cellular Neural Network working in parallel with an attitude PID controller, whose references are provided adaptively by a Motor Map. On one hand the CPG provides the basic rhythmic signals needed for locomotion, on the other hand the Motor Map Controller (MMC) represents the higher level control that, basing on sensory feedback, allows the robot to climb over obstacles.

Most of the researches on locomotion control in insects reveal the presence of a hierarchical organized neural system. Most of control schemes for legged robots also use a hierarchical organization. The main focus of this work is on the higher-order level providing adaptive capabilities to the robot control system, while the low level (locomotion control) is solved by the CNN-based CPG. The first characteristics that the high level control should have is a high degree of adaptability and reconfigurability. For these reasons we choose to model the high level control by using the bio-inspired architecture of Motor Maps. In [1] it is shown how, if a high-level adaptive layer based on a MMC is introduced, controlling the locomotion gait and adapting leg coordination to a given speed reference without any supervision is possible. We now focus on the use of a MMC for posture stabilization and obstacle climbing.

To validate the control strategy we have built a simple hexapod robot model, simulated on a framework for dynamic simulation based on the DynaMechs libraries [7].

II. COCKROACH STRUCTURE AND ROBOT DESIGN

Biological data of *Blaberus discoidalis* have driven the design of the hexapod robot on which we have tested our control approach. Most important architectural issues are:

- leg structure;
- leg articulation;
- body structure.

Each cockroach leg is divided into several segments called, from the most proximal to the most distal segment, coxa, trochanter, femur, tibia and, at the end, into a series of foot joints collectively called tarsus [4]. Although front, middle and rear legs have the same segments, they are different in lengths, yielding a ratio of front:middle:rear leg lengths of 1:1.2:1.7 [6].

Cockroaches legs articulate differently with the body, with the front legs oriented almost vertically at rest and middle and rear legs angled posteriorly of about $30 \div 50$ [6]. This configuration provide an efficient passive static stability [3].

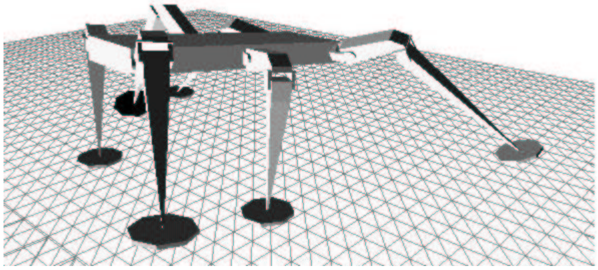


Fig. 1. Structure of the hexapod robot model (HexadynII).

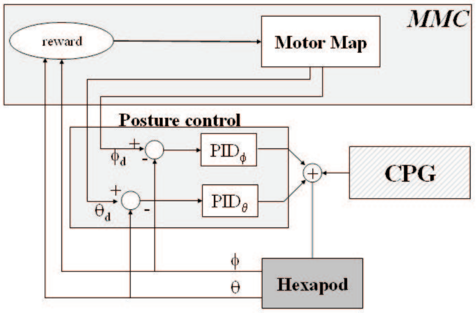


Fig. 2. Block scheme of the adaptive posture control.

Finally, body is divided in three articulated segments called prothoracic, mesothoracic and metathoracic segments.

Basing on *Blaberus discoidalis* structure, in the insect-like robot design we have considered the following guidelines:

- leg pairs with different length, that in the *Blaberus discoidalis* provide superior agility;
- leg pairs differently articulated with the body, in order to achieve the same passive static stability.

Basing on these guidelines, we have designed a robot with a single body segment to which leg pairs are symmetrically connected. Each leg is divided into three segments representing the three most important segments of *Blaberus discoidalis*: coxa, femur and tibia; nevertheless we have considered an overall leg design similar to a pantograph. Rear legs are longer, yielding a ratio 1:1:1.5 and articulate with the body with an angle of $0.63 \quad rad$, while the other legs are oriented vertically. Robot dimensions are, in u.a.:

- length: 2.2;
- height: 1;

We think that this design, inspired by the cockroach structure, can facilitate the obstacle climbing task.

III. CONTROL OF OBSTACLE CLIMBING IN THE *Blaberus discoidalis*

Watson *et al.* reported an exhaustive set of experimental data referring to kinematic changes associated with climbing in the *Blaberus discoidalis* [5]. Experimental data show that cockroaches do not deviate from normal running kinematic in surmounting obstacles whose height is smaller than one reached by front legs during swing trajectory: once one or both front tarsi are naturally placed on top of the barrier, they push downward, changing the animal's posture so that the subsequent movements of all legs drive the CoM upward; therefore for small barriers there is not an anticipatory change in running strategy. On the contrary, in climbing obstacle whose top is beyond the height of front legs during swing phase, cockroaches normally accomplish an anticipatory attitude change tilting the body upward. The animal performs this postural adjustment, *before* front legs are placed on top of the barrier, principally by rotating the middle legs in order to bring them more perpendicular to the ground. In the subsequent phase, the animal's CoM is raised upward with little or no further change in body-substrate angle.

Thus, climbing high barriers is accomplished in two stages:

- rearing stage: cockroaches generate the change in body-substrate angle *before* any leg reaches the barrier;
- rising stage: animal's CoM is raised upward.

The main point is that climbing does not require radical departures from running control mechanism, but possibly just an anticipatory rearing stage.

Since reorientation of middle legs in rearing stage is initiated only after the height of the obstacle has been evaluated, postural changes appear to be directed, at least in part, by higher centers, as *supraesophageal ganglia*, driven by sensory feedback (presumably by visual feedback and antennae) [5].

IV. CONTROL SYSTEM

A. CPG and posture control

Posture control in legged robots is fundamental to guarantee the stability of the system, to efficiently walk on uneven terrain and to overcome obstacles. In particular, as concerns obstacle climbing, several simulation tests highlighted the need of posture control during the different phases of the obstacle climbing. Otherwise, we found that a robot relying only on local reflexes was able to place its legs on the obstacle barrier, but not to overcome it.

The scheme adopted in this paper is based on two controllers acting in parallel. A CNN-based CPG generates the rhythmic leg movements needed for the locomotion gait, while a distributed networks of PID controllers deals with posture control modulating the output of the CPG. Fig. 2 shows a block scheme of the overall control system. Three layers can be distinguished. Posture control and CPG control act in parallel, a high-level adaptive layer is used to implement adaptive posture control.

Let us first focus on the low level (CPG and posture control without the MMC layer). This control scheme was successfully applied to the hexapod robot as discussed in [8], where the focus was to maintain the body in a horizontal position during walking on sloping planes or uneven terrains. This was achieved by fixing in the scheme of Fig. 2 $\theta_d = 0$ and $\varphi = 0$ (Euler roll and pitch angles, respectively). The CPG provides periodic signals which coordinate the leg movements, while the outputs of the attitude control modulate these signals so that the average values of femur-tibia and coxa-femur joints are changed to compensate for upward or downhill slopes, i.e. the attitude control acts biasing the mean values of femur-tibia and coxa-femur joints.

We now add the MMC-based adaptive layer. This layer establishes the reference Euler angles for the inner attitude control loop. The presence of this stabilizing inner loop has been found very useful in several other applications of MMC. In fact, it allows the MMC to have good performance even with a small number of neurons. Moreover, this small number of neurons has other advantages in terms of the speed of convergence of the algorithm.

B. *MMC-based attitude control*

Basing on [5] we have subdivided the task of running on uneven terrains in three main phases:

- horizontal normal running;
- rearing phase;
- rising phase.

Fictitious antennae, whose detection range is 1.2 u.a., determine the actual running phase; in particular, with d distance between obstacle edge and robot CoM and considering for sake of simplicity just one obstacle, we define:

- $d > 2.3$ cruise phase;
- $0 < d < 2.3$ rearing phase;
- $-2 < d < 0$ rising phase.

During walking on plain terrains, the MMC acts on pitch angle to have a smoother velocity control, since, for a given gait, varying pitch angle implies a slightly different velocity. This cruise MMC plays the role of adaptively determining the pitch angle that guarantees the planned reference speed; therefore the following *reward function* is taken into account:

$$Reward = -(v_{ref} - v)^2 \tag{1}$$

where v_{ref} is the reference speed and v is the actual speed (indeed the average value over three complete cycle times).

In the rearing phase, on the other hand, the MMC determines the pitch angle that allows the front leg to reach exactly the barrier top. Therefore another *reward function* should be considered as follows:

$$Reward = -((h_{obs} - \varepsilon) - h)^2 \tag{2}$$

where h_{obs} is the obstacle height as evaluated by sensors, $\varepsilon = 0.2$ is a small offset and h is the maximum height reached by front leg tarsi in swing trajectory.

Finally, in the rising stage the reference pitch angle is simply the value $5°$.

Since in the attitude control scheme there is no feedback regarding the ground contact, there is the risk that in the rising stage front legs are not well in contact with ground with a consequent bad forward thrust. Therefore, we have simply considered the shrewdness of guaranteing contact of front legs with ground for front legs in rising stage (as, indeed, cockroaches do by means of local reflexes). To close the loop with front legs ground contact we have partially modified the front legs pitch bias value:

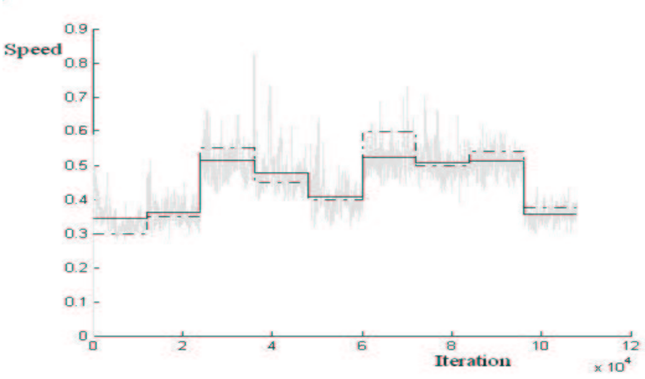


Fig. 3. Training of the MMC during walking on uneven terrains.

$$b_{pitch,front} = k\sigma b_{pitch} \tag{3}$$

where b_{pitch} is the bias value determined by the PID pitch controller, $k = 0.05$ is a parameter and σ is a counter incremented or decremented if a ground contact event has not or has happened.

V. SIMULATION RESULTS

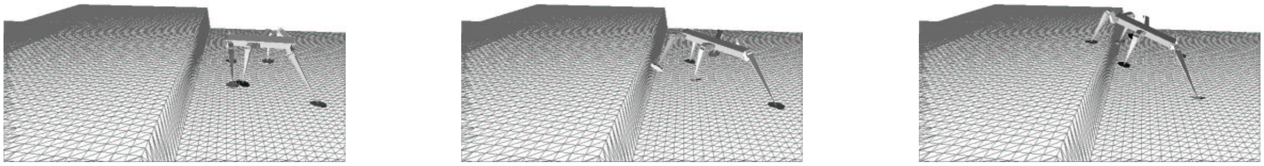
In a preliminary phase, the MMC has been trained in the two functionally different tasks (attitude control during walking and during rearing for barrier climbing).

Training phase results for the MMC during walking on uneven terrains are shown in Fig. 3. The good agreement between reference and actual speed proves the feasibility of precisely tuning robot speed by means of postural control. The discrepancy between the reference speed value 0.6 and the actual speed reached is due to the fact that the same neuron yet specialized for the reference speed value 0.5 has been activated, as it may happen in Motor Maps training.

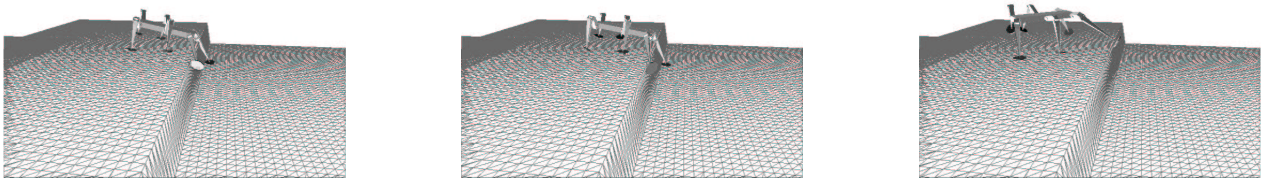
In Fig. 4 the training results during rearing are shown. Also in this case, learning algorithm guarantees a good agreement between reference and actual front legs swing; the discrepancy for the reference value 1.2 is in the same way caused by a lack of network plasticity due to the selection process.

Several simulations have been carried out in order to validate our control scheme for obstacle height varying in the range $0.6 \div 1.8$. The robot has successfully climbed over obstacle of maximum height $h = 1.5$, *i.e.* more or less 150 % of robot height (in Fig. 5 the climbing progression for a 1.4 obstacle is shown). Since *Blaberus discoidalis* is able to climb over obstacle of a maximum height of 200 % insect itself, we retain that our control scheme is adequate for the problem of obstacle climbing in hexapedal running robots.

Moreover, it is common understanding that bioinspired robot design can provide insight in biological issues inspiring further neurobiological experiments in animal locomotion; therefore our results could confirm the validity of the CPG theory of locomotion.



(a) Approach (b) Rearing phase (c) Front leg on barrier top



(d) Rising stage (e) Forward thrust (f) Cruise phase

Fig. 5. MCC controlling climbing obstacle task

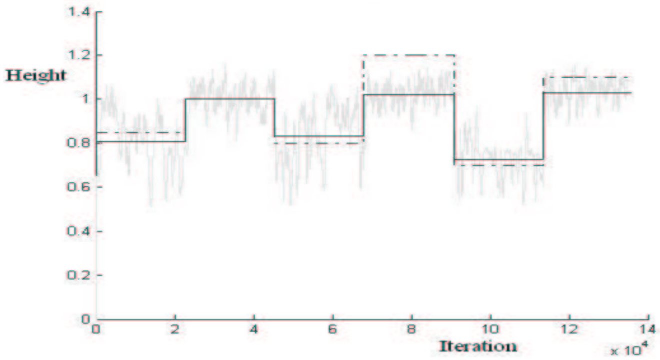


Fig. 4. Training of the MMC during rearing for barrier climbing

VI. CONCLUSIONS

In this paper a control scheme based on self-organizing dynamical systems is applied to the task of attitude control during walking and rearing to overcome a barrier.

The design of the robot model takes into account biological principles needed to efficiently overcome obstacles. The control system is based on the biological paradigm of CPG, which works in parallel with an adaptive attitude control. The CPG is implemented by a CNN, modelling a network of nonlinear oscillators which self-organize to produce an appropriate locomotion gait. The attitude control includes an adaptive layer based on self-organizing maps (Motor Maps). The presence of an inner stabilizing attitude control loop allows to speed up the initial phase in which the system self-organizes on the basis of a reward function, and at the same time allows to keep small the number of neurons needed for the task.

ACKNOWLEDGMENT

This work was supported by the Italian ”Ministero dell’Istruzione, dell’Università e della Ricerca” (MIUR) under the Firb project RBNE01CW3M.

REFERENCES

[1] P. Arena, L. Fortuna, M. Frasca and G. Sicurella, “An Adaptive, Self-Organizing Dynamical System for Hierarchical Control of Bio-Inspired Locomotion”, *IEEE Transactions On Systems, Man, And Cybernetics Part B: Cybernetics.*, 34, No. 4, pp. 1823–1837, 2004

[2] L. O. Chua and L. Yang, “Cellular neural networks: Theory”, *IEEE Trans. Circuits Syst. I*, 35, pp. 1257–1272, 1988

[3] L. H. Ting, R. Blickhan And R. J. Full, “Dynamic And Static Stability In Hexapedal Runners”, *J. exp. Biol.*, 197, pp. 251–269, 1994

[4] R. D. Quinn and R. E. Ritzmann, “Construction of a hexapod robot with cockroach kinematics benefits both robotics and biology”, *Connect. Sci.*, 10, No. 3-4, pp. 239–254, 1998

[5] J. T. Watson, R. E. Ritzmann, S. N. Zill and S.J. Pollack, “Control of obstacle climbing in the cockroach, *Blaberus disoidalis*, I. Kinematics”, *J. Comp. Physiol. A*, 188, pp. 39–53, 2002

[6] Fred Delcomyn and Mark E. Nelson, “Architectures for a biomimetic hexapod robot”, *Robotics and Autonomous Systems*, 30, pp. 5–15, 2000

[7] S. McMillan, “Dynamics for Robotic System on Land and Under Water”, *Ph.D. Thesis the Ohio State University Columbus OH*, 1994.

[8] P. Arena, L. Fortuna, M. Frasca, “Attitude control in walking hexapod robots: an analogic spatio-temporal approach”, *Int. J. Circ. Theor. Appl.*, 30, pp. 349–362, 2002.