The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

A bio-inspired postural control for a quadruped robot: an attractor-based dynamics

João Sousa, Vítor Matos and Cristina Peixoto dos Santos

Abstract— **Postural stability is a requirement for autonomous adaptive legged locomotion. Neurobiological research lead to the idea that there are independent central systems for posture and locomotion, which interact when required.**

In this work we propose a posture control system focused in the standing posture context. We integrate the proposed posture system with a CPG design based on coupled nonlinear oscillators.

The proposed system generates movements for posture correction which are modulated according to sensory information. We integrate several different responses that individually contribute to the posture equilibrium. This coordination, competition and redundancy among the responses is a key element for adaptive, flexible and fault tolerant motor system.

The control system is validated through a few experiments, where the robot is subjected to different posture situations ranging from roll and pitch variations to loss of feet support.

I. INTRODUCTION

The work presented in this article takes part on a larger project which aims to design a locomotion controller capable of generating purposeful and robust locomotion in unknown, rough terrain for a quadruped robot.

Postural stability is one important requirement if we want to achieve autonomous adaptive locomotion on irregular terrains. A robot should be able to maintain its orientation in respect to gravity, keep its equilibrium and adapt the body segments to the ongoing movement. In this work we start by addressing postural control in quiet standing, considering it a first step for the design of a postural controller for locomotion.

Neurobiological research has brought interesting concepts into the field of robotics, like the concept of Central Pattern Generators (CPG) that are used in robot legged locomotion [1]–[4].

Research has also shown that the postural system of quadruped animals respond to perturbations in body orientation supervised through different sensory modalities and that closely interact with the locomotor system, generating the movements for postural corrections.

The motor responses of the limbs are coordinated resulting in a final posture task, possibly from processed and integrated characteristics of the body posture, like the Center of Mass, body geometry or even orientation of the body [5], [6].

Recent studies also have shown from complex posture tasks that the postural system is possibly composed of semi-autonomous limb controllers that receive somatosensory input and participate in the corrective movements of a limb [7], [8]. Also an interaction of limb controllers seems to exist to accurately coordinate the efforts of the individual limbs. The postural system seems to be divided in two feedback loops, in spinal and supraspinal levels. The mechanisms residing in the spinal cord are driven by limb mechanoreceptors and contribute by generating corrective responses. These may be activated and modulated by higher structures. The mechanism involving supraspinal centers receives information from the limbs, vestibular and visual information, outputting descending corrective commands. These supraspinal commands along with spinal reflexes result in the overall posture corrections.

In previous work we have proposed a locomotor system based on a network of coordinated CPGs. Now we propose a postural system that interacts with the locomotor system and corrects the posture of a standing quadruped robot.

We hypothesize that the resulting limb corrective action is the overall output of parallel responses related to sensory information. Each response may be directly influenced by sensory information or based on a processed regulated variable (e.g. Center of Mass). This way we take advantage of the two possibilities, complementing themselves. We therefore make the assumption that the integration of the parallel responses produce the final correct posture, and acts as the integration of somatosensory signals.

Some of responses that compose a limb controller have been designed based on existing reflexes observable in animals (e.g. tilt compensation), and others in requirements from a robotic point of view. Also, some responses are coordinated among the four legs, allowing joined efforts when corrective movements of full amplitude from one leg are required.

We build on previous work based on coupled nonlinear oscillators, used to generate basic rhythmic motor patterns for locomotion [9]–[11]. Additionally, it assumes that complex movement is generated from the combination of more simple movement primitives, discrete and rhythmic, modeled as dynamic systems. While standing the rhythmic movements are turned off, and the proposed postural system specifies discrete motions of hips and knees.

The dynamical systems approach has some advantages when compared to other types of implementations such as low computational cost, intrinsic stability allows for feedback integration because perturbations are quickly forgotten, smooth trajectories modulated by simple parameters change and smooth movement generation. This approach also allows an easy sum of the proposed postural responses.

There are already a few works that apply CPGs and

Industrial Electronics Department, University of Minho, Portugal, `jsousa@dei.uminho.pt`, `vmatos@dei.uminho.pt`, `cristina@dei.uminho.pt`

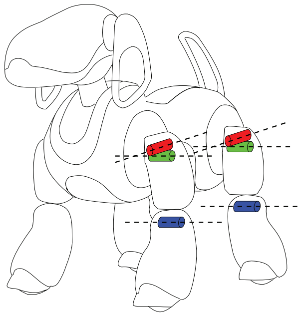

Fig. 1. Schematic view of the ERS-7 AIBO model depicting the controlled DOFs for the left side.

nonlinear dynamical systems to address locomotion and postural control. Hiroshi Kimura and colleagues [3] generate a dynamically stable gait on irregular terrains. They include a *vestibulospinal reflex* and a *tonic labyrinthine response* to adjust the pitch and rolling during locomotion.

Lewis [4] applies CPGs to generate the movement for the hip and knees robot joints. Their goal is to equalize pressure on the feet by making suitable shifts in trunk position and trunk configuration, and therefore achieve postural control. However, it is required a twist joint in the robot trunk to apply the mechanism.

Ridderström and Ingvast [12] implemented a quadruped robot postural control using force. Their goal is to follow a desired posture in height and altitude. They achieve it by distributing the applied force of the body on the legs, through hybrid control which consists in controlling the trunk's horizontal position through the feet position and controlling the vertical position using force. However, this work does not apply CPGs to generate the robot's movement which is of major importance in our work.

Zhang and Zheng [13] present a control strategy biologically inspired that allows a quadruped robot to walk smoothly up and down hill. It is a CPG based control that uses the pitch angle of the trunk as feedback to adjust the body similarly to the way that cats do. However, we are interested in exploiting the integration of different sensory modalities, creating a more robust respon8e in posture.

The proposed work strives only for standing posture control as a precursor to locomotion integrated with posture control. Our system is validated through a few experiments in an AIBO ERS-7 robot. The robot is subjected to different posture situations ranging from roll and pitch variations to loss of feet support. The system reacts promptly and smoothly in a way to recover postural control.

II. ROBOTIC SETUP

In this work we use an AIBO ERS-7 quadruped robot manufactured by Sony to demonstrate the feasibility of the proposed system. We control 12 of its degrees-of-freedom (DOFs), three for each leg: hip-swing, hip-flap and knee (fig. 1).

The AIBO has a 3-axis accelerometer built into its body. It enable us to calculate the sagittal and lateral tilt of the robot body. Each leg has a touch sensor in its foot, an encoder and PWM motor information for each joint.

III. CPGS MODELING

In previous work on locomotion, a network of coordinated Central Pattern Generators is responsible for generating the basic locomotor motions (for further details see [9]). The locomotion controller is composed by four coupled CPGs (limb-CPGs), one for each leg. A limb-CPG is formed by two unit-CPGs, controlling the hip-swing and hip-flap joints. Knee joints are not CPG controlled, but moved to the required joint angles depending on the current limb phase.

Unit-CPGs are modeled using a nonlinear oscillator, generating a periodic movement around time-varying offsets, by the following equations:

$$\dot{x} = \alpha(\mu - r^2)(x-y) - \omega z, \tag{1}$$

$$\dot{z} = \alpha(\mu - r^2)z + \omega(x-y), \tag{2}$$

with $r = \sqrt{(x-y)^2 + z^2}$. Here μ controls the amplitude of the oscillations, ω is the frequency and α controls the speed of convergence to the limit cycle ($\frac{1}{2\alpha\mu}$).

This supercritical Hopf oscillator contains a bifurcation from a fixed point $x = y$, for $\mu < 0$, to a structurally stable harmonic limit cycle with radius $\sqrt{\mu}$ and offset $x = y$, for $\mu > 0$.

In order to uniquely address the standing postural problem, we turn-off the rhythmic activity by setting $\mu < 0$. Thus, the generated solution of the unit-CPGs (x) follows the value y.

The proposed postural system outputs y for the three joints of each leg, hip swing, hip flap and knee. In this fashion we integrate both locomotor and postural systems.

IV. POSTURAL CONTROL

The postural control system generates movements for posture correction. It enables integration of sensory feedback such that movements are robustly generated and adapted to the environment. Sensory information is noisy and changes as a result of the generated robot movement. Therefore, this controller is modeled by autonomous differential equations, whose intrinsic properties provide for the required features.

We propose a postural control which depends on varied sensory modalities through the integration of several responses, each based on its own sensory input. This integration of postural responses provides the system with some aspects of coordination, competition and redundancy.

Each response individually contributes to the posture of the robot with respect to its given sensory inputs. The different responses are then integrated to produce the final corrective motions.

We propose so far the postural corrective responses and the respective sensory presented in table I.

These responses are set for each leg. Some work independently, while others are coordinated among each other, enabling the assistance when the corrective movements of full amplitude are required for one limb.

TABLE I

POSTURAL RESPONSES AND SENSORY INPUTS

Postural response	Sensory input
Roll compensation	Body roll angle
Pitch compensation	Body pitch angle
Center of Mass adjustment	Encoders and body angle
Load distribution	Joints load
Touch control	Foot touch
Leg disperser	Leg encoders

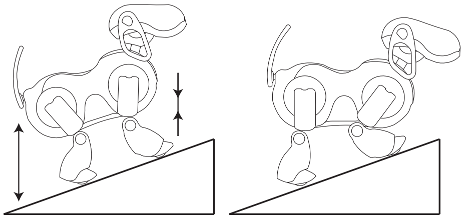

Fig. 2. Robot's pitch angle is adjusted by extending/flexing the front/rear legs in coordination.

Responses are designed as differential equations, and their integration is simply the sum of their dynamics.

$$\dot{y}_{i,p} = f_{\mathrm{roll},i,p} + f_{\mathrm{pitch},i,p} + f_{\mathrm{CoM},i,p} + f_{\mathrm{force},i,p} + f_{\mathrm{touch},i,p} + f_{\mathrm{disperser},i,p} + f_{\mathrm{reset},i,p} \tag{3}$$

The solution of eq. 3 ($y_{i,p}$) is the corrective movement for joint p on leg i.

In order to prevent the system's solution to evolve out of allowable and desirable values, and at the same time limit the range of action of each joint, we add two system limits as repellers.

$$\begin{aligned}\dot{y}_{i,p} = \ldots &+ k_{\mathrm{jl}}(y_{i,p} - M_{i,p})e^{\frac{(y_{i,p}-M_{i,p})^2}{2\sigma^2}} \\ &+ k_{\mathrm{jl}}(y_{i,p} - D_{i,p})e^{\frac{(y_{i,p}-D_{i,p})^2}{2\sigma^2}},\end{aligned} \tag{4}$$

Adding eq. 4 to eq. 3 we limit the range of solutions to be between $D_{i,p}$ and $M_{i,p}$. Parameters k_{jl} define the strength, and σ the width of the repellers.

A. Roll and pitch balance

The objective of these two responses is to adjust the body inclination, opposing to changes in terrain slope, so that the roll and pitch angles are reduced to a minimum. Slope compensation is achieved through extension and flexion of the legs, changing the legs height (fig. 2).

The following differential equation models the roll and pitch responses, for the hip swings (s) and knees (k) of each leg ($p = \mathrm{s}, \mathrm{k}$):

$$f_{\mathrm{roll},i,p} = k_{\mathrm{roll}} f_i(\phi_{\mathrm{roll}}), f_{\mathrm{pitch},i,p} = k_{\mathrm{pitch}} f_i(\phi_{\mathrm{pitch}}), \tag{5}$$

where ϕ_{roll} and ϕ_{pitch} are the actual roll and pitch angles. $f_i(\phi)$ is a linear function defining a death-zone, in order to deal with sensor noise. $f_i(\phi)$ also returns a positive or negative value as required due to the robot's joint configuration. e.g. for ϕ_{roll} it returns a negative value for the left legs and positive value for the right legs, for ϕ_{pitch} it returns the symmetric value for the fore legs and positive for the hind legs. The static gains k_{roll} and k_{pitch} define the speed of convergence to equilibrium.

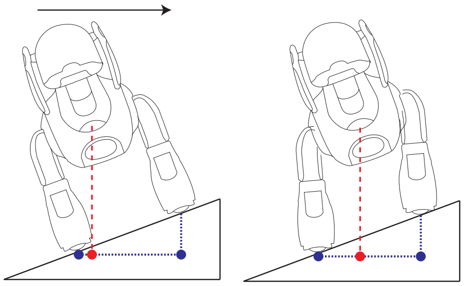

Fig. 3. The projection of the robot's Center of Mass is shifted towards the center of the support polygon, increasing the Wide Stability Margin.

1) Roll and pitch coordination: There are certain situations where corrective movements of full amplitude are not sufficient to reduce the robot's inclination. On this situations the all legs' roll and pitch responses should be coordinated, in order to work together on these more difficult postural tasks.

This coordination may also be thought for each leg as: the other legs should be flexed, when flexing own leg is not enough (same for extension). More precisely, the idea is to adjust a leg if the other diagonal legs have a $f_i(\phi_{\mathrm{pitch}}) + f_i(\phi_{\mathrm{roll}}) \neq 0$.

We add this coordination along with the roll and pitch responses to the overall system, as so:

$$\begin{aligned}\dot{y}_{i,p} = \ldots + f_{\mathrm{roll},i,p} + f_{\mathrm{pitch},i,p} + k_{\mathrm{C}}\Big(&\frac{|\phi_{roll,l} + \phi_{pitch,l}|}{2} \\ &+ \frac{|\phi_{roll,j} + \phi_{pitch,j}|}{2}\Big)e^{\frac{-(\phi_{roll,i}+\phi_{pitch,i})^2}{0.01}},\end{aligned} \tag{6}$$

where k_{C} is a static gain. l and j denote the diagonal legs.

B. Center of Mass compensation

The CoM compensation response is intended to position the robot's CoM over the center of the support polygon, increasing the Wide Stability Margin of the actual robot posture. By adjusting the hip swing (s) and hip flap (f) joints, we shift the body, shifting the CoM over the support polygon (fig. 3).

The shifting movements are generated as follows:

$$f_{\mathrm{CoM},i,\mathrm{s}} = k_{\mathrm{CoM,s}}(CoM_{\mathrm{x}} - x_{\mathrm{center}}), \tag{7}$$

$$f_{\mathrm{CoM},i,\mathrm{f}} = k_{\mathrm{CoM,f}}(CoM_{\mathrm{y}} - y_{\mathrm{center}}), \tag{8}$$

where CoM_{x} and CoM_{y} denote the Center of Mass projection position in the x and y axis, respectively, and x_{center} and y_{center} are the position of the support polygon's center. $k_{\mathrm{CoM,s}}$ and $k_{\mathrm{CoM,f}}$ are the static gains for the hip swing and hip flaps compensation movements.

C. Load distribution

This response distributes the weight of the body equally over the four legs. We estimate load information from joints by reading the PWM values and then we calculate a simple average $\overline{F}$.

Legs which are above this load average are being pushed forward then the others. Force control is applied to hip swing (s) and knees (k) joints as follows:

$$f_{\text{force},i,p} = k_{\text{force}}(F_i - \overline{F}), \tag{9}$$

where k_{force} is a static gain, F_i is the actual value read on the PWMs for leg i and $\overline{F}$ is the average force over the four legs.

D. Touch control

When the robot's feet lose ground contact, the robot loses support on that point. This response monitors the touch sensors in the foot and when it detects the lose of support, it searches for ground by extending the leg. Leg height is controlled by adjusting the hip swing and knee joints.

The response is formulated as:

$$f_{\text{touch},i,p} = k_{\text{t}}(1 - T_i)y_i, \tag{10}$$

where k_{t} is a static gain, T_i is the foot i touch sensor: 0 means that the foot is lifted and a 1 means that it has ground contact.

1) Touch coordination: Sometimes the ground is too far and a fully stretched leg is still not able of regaining support. We therefore propose a method for coordinating the touch control response, enabling the other legs to lower at the same time that the lifted leg extends.

We add the coordination to the touch response:

$$f_{\text{touch},i,p} = \ldots + k_{\text{C,touch},i}[(1 - T_j) + (1 - T_k) + (1 - T_l)], \tag{11}$$

where T_j, T_k, T_l are the foot sensors from all the other legs. Similarly, $k_{\text{C,touch},i}$ is a static gain that controls the speed of convergence.

E. Leg disperser

We have verified that in certain conditions the fore and hind knees would get very close or even collide, which caused a few stability problems since it made the robot become unbalanced and even provoked falls sometimes. In order to avoid this undesired situation we designed a leg disperser which avoids the knees from touching.

This leg disperser is activated once the distance between the knees reaches a minimum undesired value. This contribution controls the hip swings and is given as follows:

$$f_{\text{disperser},i,p} = k_{\text{disperser}}\left(1 - \frac{1}{1 + e^{-k(d_i - d_{\text{min}})}}\right), \tag{12}$$

where $k_{\text{disperser}}$ is a static gain, d_i is the actual distance between knees and d_{min} is the minimum value allowed for the distance between knees.

F. Posture reset

After a certain number of corrective movements the robot may lose its own initial posture. To force the quadruped to return to its initial position we implemented a weak attractor. The idea is to be weak enough so it does not disturb the other responses, but if allowed, it will slowly and surely return to the initial posture.

Fig. 4. Platform used to perform the various and different experiments. This platform is composed by four independent platforms, where it is possible to raise or drop each of them.

The response is given by:

$$f_{\text{reset},i,\text{s}} = k_{\text{r}}(y_{i,\text{s}} - IP_{i,\text{s}}), \tag{13}$$

$$f_{\text{reset},i,\text{f}} = k_{\text{r}}(y_{i,\text{f}} - IP_{i,\text{f}}), \tag{14}$$

$$f_{\text{reset},i,\text{k}} = k_{\text{r}}(y_{i,\text{k}} - IP_{i,\text{k}}), \tag{15}$$

where k_{r} is the static gain and has a very low value. $IP_{i,\text{s}}$, $IP_{i,\text{f}}$ and $IP_{i,\text{k}}$ are initial positions for hip swing (s), hip flap (f) and knee (k) joints.

V. RESULTS

In this section we describe experiments done on an AIBO robot. The robot stands over four independent platforms (fig. 4) which when operated together can mimic a stand-alone moveable plane, subjecting the robot to change in inclination, or can mimic the lose of foothold.

A. Sagittal and lateral inclination

This experiment is intended to verify the robot's behavior when sagittal and lateral inclination are applied. It is expected that the robot suppresses any inclination to values near zero. It is also expected that the CoM position converges to the center of the support polygon.

The four platforms start moving at $t = 8$ s, performing an inclination $-5°$ in the pitch plane (lowering the fore part of the body) and $-3°$ on the roll angle relatively to the ground (lowering the left side), during 20 s. At $t = 29$ s the platform started to return to its initial position (0°) taking 20 s.

From $t = 8$ s to $t = 28$ s the robot tries to oppose to the platform inclination (fig. 5), stretching the fore and left legs and folding the hind right leg doing a forward left move. It succeeds on suppressing it to values $|\phi| < 1°$ for the pitch and roll.

At $t = 28$ s the platform changed its movement, but despite the change the robot continued suppressing the platform inclination, slowly folding the stretched legs and stretching the folded one, resulting in an opposite movement. At the end of the platform movement, at $t = 48$ s, the roll and pitch angles of the robot are near 0°.

Based on these results it is possible to say that the inclination goals were attained.

On fig. 5 is possible to see that at the beginning of the experiment the robot does not have its CoM centered on

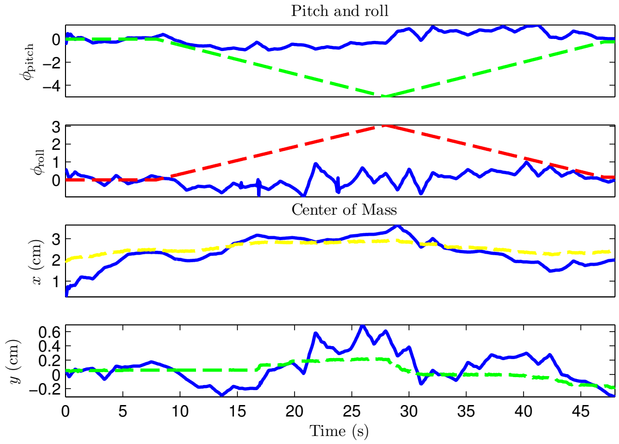

Fig. 5. The first two plots show in degrees ϕ_{pitch} (1st panel) and ϕ_{roll} (2nd panel) variation of the platform (dashed) and of the robot (solid). The bottom two show the robot center of mass position (dashed) and the intersection point (solid) evolution.

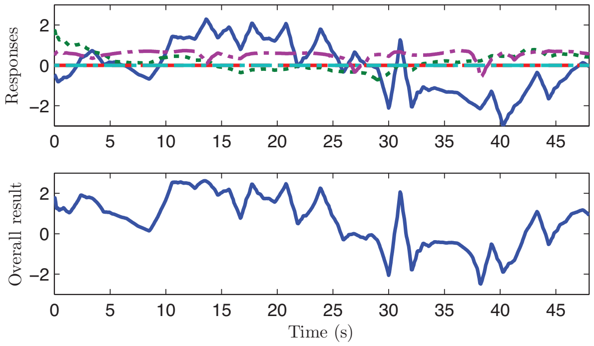

Fig. 6. The top plot shows the response of the different responses. Where the dotted line is the CoM response, the solid line is the roll and pitch response, the dash dotted line represents the leg repeller, the dashed line is the joint limits control and the leg coordination is represented by the light blue dashed line. The bottom plot shows the sum of all responses.

the support polygon. The first few seconds are used for the robot to position itself correctly. At $t = 8$ s the platform starts its movement and throughout the experiment, the CoM position stays very close to the center of the support polygon. The CoM response (fig. 6) normally opposes to the roll and pitch control, not letting it to do exaggerating moves in either direction. This competition resulted in a good performance since it was able to suppress the terrain inclination and center the robot's weight on the support polygon.

Fig. 6 shows each response for the fore left hip swing. Note that the roll and pitch balance response (blue solid line) is the dominant one, and the joint limiter and leg coordination were not activated since both are used at more demanding situations.

B. Touch and coordination

The purpose of this experiment is to demonstrate the implemented touch coordination. We dropped one of the four boxes, forcing the foot to loose ground contact. Once ground contact is lost, the robot should stretch that leg in order to regain it. At the same time, the other legs help out lowering the body to solve the problem as quickly as possible.

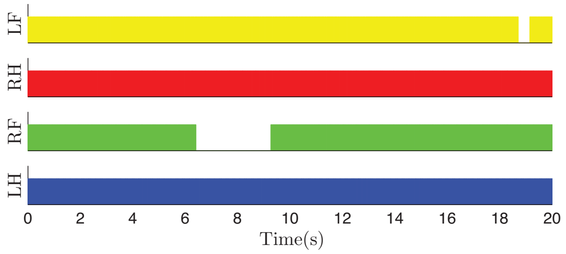

Fig. 7. Left Fore (LF), Right Hind (RH), Right Fore (RF) and Left Hind (LH) leg's touch. Filled area means that the respective foot is on the ground, otherwise is lifted.

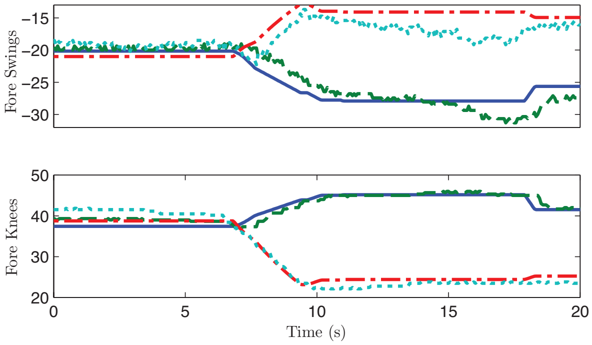

Fig. 8. Top: Desired (solid line) and real (dashed line) trajectories for Fore Left Swing, desired (dash dot line) and real (dotted line) trajectories for the Fore Right Swing. Bottom: Desired (solid line) and real (dashed line) trajectories for Fore Left Knee, desired (dash dot line) and real (dotted line) trajectories for the Fore Right Knee.

At approximately 6 s it was lowered the box beneath the right fore leg (fig. 7). On fig. 8 it is observable that to compensate the missing box the right fore leg was stretched as expected, since the swing and knee values of this leg (dash dotted red line and dotted light blue line) are decreasing. In the same scale but in opposite direction was the fore left swing lowering the body of the robot to help the fore right leg. This lack of touch was soon eliminated showing a good coordination between the legs.

Note that despite the noisy sensorial information, the resultant trajectories are smooth. Further, the joints are able to follow the planned trajectories as expected.

VI. CONCLUSION

In this article it was presented a controller for correcting standing posture. Online trajectory modulation is achieved through the inclusion of feedback loops through a set of integrated responses, adjusting the dynamics of trajectory generation. The proposed responses are included in the dynamical system equations and generate the required joint trajectories that enable a coordinated and smooth movement towards the equilibrium.

This controller was applied in a quadruped robots subjected to different kind of experiments, envisioned to demonstrate the feasibility and adequacy of the proposed system. It also showed to be efficient according to the attained results.

Future work includes the integration of this approach with locomotion, activation and modulation of the responses according to behavioral and sensory contexts. Another aspect that can be explored is the automatic learning of the response gains.

ACKNOWLEDGEMENTS

Work supported by the Portuguese Science Foundation (grant PTDC/EEA-CRO/100655/2008).

REFERENCES

[1] S. Grillner, "Locomotion in vertebrates: central mechanisms and reflex interaction.," *Physiological Reviews*, vol. 55, pp. 247–304, 1975.

[2] A. J. Ijspeert, "Central pattern generators for locomotion control in animals and robots: a review," *Neural Networks*, vol. 21, pp. 642–653, May 2008.

[3] Y. Fukuoka, H. Kimura, and A. H. Cohen, "Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts," *I. J. Robotic Res.*, vol. 22, no. 3-4, pp. 187–202, 2003.

[4] M. A. Lewis and G. A. Bekey, "Gait adaptation in a quadruped robot," *Auton. Robots*, vol. 12, no. 3, pp. 301–312, 2002.

[5] C. Maioli and R. E. Poppele, "Parallel processing of multisensory information concerning self-motion," *Experimental Brain Research*, vol. 87, pp. 119–125, oct 1991.

[6] J. Massion, K. Popov, J. C. Fabre, P. Rage, and V. Gurfinkel, "Is the erect posture in microgravity based on the control of trunk orientation or center of mass position?," *Experimental Brain Research*, vol. 114, pp. 384–389, apr 1997.

[7] T. Deliagina, I. Beloozerova, P. Zelemin, and G. Orlovsky, "Spinal and supraspinal postural networks," *Brain Research Reviews*, vol. 57, pp. 212–221, July 2008.

[8] T. G. Deliagina, G. N. Orlovsky, P. V. Zelenin, and I. N. Beloozerova, "Neural bases of postural control.," *Physiology (Bethesda)*, vol. 21, pp. 216–25, 2006.

[9] V. Matos, C. Santos, and C. Pinto, "A brainstem-like modulation approach for gait transition in a quadruped robot," in *2009 IEEE IROS*, 2009.

[10] L. Castro, C. Santos, M. Oliveira, and A. Ijspeert, "Postural control on a quadruped robot using lateral tilt: A dynamical system approach.," in *EUROS*, vol. 44 of *Springer Tracts in Advanced Robotics*, pp. 205–214, Springer, 2008.

[11] S. Degallier, L. Righetti, and A. Ijspeert, "Hand placement during quadruped locomotion in a humanoid robot: A dynamical system approach," in *IEEE-RAS International Conference on Intelligent Robots and Systems (IROS07)*, 2007.

[12] C. Ridderström and J. Ingvast, "Quadruped posture control based on simple force distribution — a notion and a trial," in *Int. Conf. on Intelligent Robots and Systems*, (Hawaii, USA), pp. 2326–2331, 2001.

[13] X. Zhang and H. Zheng, "Walking up and down hill with a biologically-inspired postural reflex in a quadrupedal robot," *Auton. Robots*, vol. 25, no. 1-2, pp. 15–24, 2008.