

SAGITTAL TILT CONTROL OF A QUADRUPED ROBOT USING A DYNAMICAL SYSTEMS APPROACH

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Abstract: Autonomous adaptive locomotion over irregular terrain is one important topic in robotics research. Balance control, meaning movement generation for robot legs, is a first step in this direction. In this article, we focus on the essential issue of modeling the interaction between the central nervous system and the peripheral information in the locomotion context. This is an important issue for autonomous and adaptive control, and has received little attention so far. This modeling is based on the concept of dynamical systems whose intrinsic robustness against perturbations allows for an easy integration of sensory-motor feedback and thus for closed-loop control. In this article, balance is achieved without locomotion. The developed controller is modeled as discrete, sensory driven corrections of the robot joint values. The robot sagittal tilt information modulates the generated trajectories thus achieving balance. The system is demonstrated on a quadruped robot which adjusts its posture until reducing the sagittal tilt to a minimum.

Keywords: Robotics, nonlinear control

1. INTRODUCTION

Generating trajectories in autonomous robotics, including legged robots, is still a complex, unsatisfactory solved problem. Despite an intensive research in the field (Ijspeert *et al.*, 2003; Blickhan., 1989; Pratt *et al.*, 2001), adaptation to unpredicted changes is still an open problem. In order to develop autonomous robot systems able to deal with less knowledge of terrain irregularity, it is required a tight coupling of planning, sensing and execution.

The work presented in this article is part of a larger project which aims at developing a closed loop control architecture based on dynamical systems for the autonomous generation, modulation and planning of complex motor behaviors for legged robots with many degrees-of-freedom (DOFs). Our approach is partly inspired from the biological concept of CPGs (Delcomyn., 1980) and by the concepts of force fields (Giszter *et al.*, 1993) found in biology, as we believe this bio-inspiration enables to develop new flexible and robust technical solutions to the balance control problem. We apply autonomous differential

equations to model how behaviors related to locomotion are programmed in the oscillatory feedback systems of CPGs in the nervous systems. These systems are solved using numerical integration.

This dynamical systems approach model for CPGs presents multiple interesting properties comparatively to other methods based on finite-state machines, sine-based trajectories, ZMP-based (M Vukobratovic, 2004) or heuristic control laws such as the Virtual Model Control (Pratt *et al.*, 2001). These include: low computation cost which is well-suited for real time; the stability properties of the limit cycle behavior (i.e. perturbations are quickly forgotten); intrinsic robustness against small perturbations; the smooth online modulation of trajectories through changes in the dynamical systems parameters and phase-locking between the different oscillators for different DOFs. Further, these systems, once coupled, produce coordinated multidimensional rhythms of motor activity, under the control of simple input signals.

Our model is build using a modular approach, assuming that complex movements can be generated through

the sequencing and/or superposition of simpler movement primitives implemented as simple, stable discrete and rhythmic dynamical systems. This modular approach is supported by current neurological and human motor control findings. Further, this approach enables to tackle the complexity inherent to the design of dynamical systems.

As a main application and a first step, we address postural control without locomotion, considering robot sagittal tilt information online acquired by accelerometers. Trajectories are modulated online according to these feedback pathways thus achieving balance, i.e., movements for the robot legs are generated in order to reduce this tilt to a minimum. The controller is composed of two embedded dynamical modules: discrete and rhythmic. The discrete module specifies the offset of the rhythmic movement. In a next step, we will extend this work to the achievement of adaptive quadruped locomotion in unknown, rough terrain that we model as discrete, sensory driven corrections of a basic rhythmic motor pattern for locomotion.

We present results that show how the developed controller successfully generates the required joint movements in order to reduce the sagittal tilt.

Control approaches based on CPGs and nonlinear dynamical systems are widely used in robotics to achieve tasks which involve rhythmic motions including autonomous adaptive dynamic walking over irregular terrain (Fukuoka *et al.*, 1994; Fukuoka *et al.*, 2003), juggling (Bühler and Koditscheck., 1994), drumming (Degallier *et al.*, 2006), and basis field approaches for limb movements (Giszter *et al.*, 1993). Quadruped walking control using CPGs exploring sensory feedback integration into the locomotion control has been extensively explored by Hiroshi Kimura and his colleagues. Herein, we address postural control in the framework of dynamical systems with superposition of discrete and rhythmic movements. We build on previous work, where controllers were developed for combining discrete and rhythmic motor primitives in drumming and dancing tasks (Degallier *et al.*, 2006; Santos *et al.*, 2008). In this article, we focus the issue of modeling the interaction between the central nervous system and the peripheral information. This issue is crucial for autonomous and adaptive control, and has received little attention so far. The intrinsic robustness of the dynamical systems approach against perturbations allows for an easy integration of sensory-motor feedback and thus for closed-loop control. The proposed work tries to serve these purposes and focus on the integration of sensory-motor information in the developed dynamical architecture.

In this article, we will first present the developed Motor Pattern Generator. In Section III, we present how we control balance in an AIBO robot using sagittal tilt information by applying the developed dynamical systems. In Section IV, we present the results obtained.

We conclude by discussing the main results we obtained and the work we are currently working on.

2. DYNAMICAL SYSTEM

In this section we present our model of the MPG (Motor Pattern Generator) used to generate the trajectories for one DOF. Two motor primitives generate the rhythmic and the discrete movements. There is only balance control without locomotion generation, so the rhythmic movement is turned off. It exists because the system is conceived to generate locomotion in a posteriori phase. The rhythmic movement is generated by an Hopf oscillator. The discrete primitive is generated by a stable differential equation such that it integrates sensory information in the controller that generates the trajectories.

2.1 Architecture of the MPG

The MPG for a DOF i is divided in two dynamical subsystems, one generating the discrete part of the movement (y_i) and another generating the rhythmic part (x_i, z_i). Discrete movement is incorporated to the final trajectory as an offset of the rhythmic movement (see (Degallier *et al.*, 2006; Santos *et al.*, 2008) for details). The generated trajectories, x_i , are sent online for each DOF. The lower level control is done by PID controllers.

2.2 MPG Rhythmic Movement

To generate the rhythmic movements we apply the following dynamical system

$$\dot{x}_i = \beta (\mu_i - r_i^2) (x_i - y_i) - \omega z_i \quad (1)$$

$$\dot{z}_i = \beta (\mu_i - r_i^2) z_i + \omega (x_i - y_i) \quad (2)$$

where $r_i = \sqrt{(x_i - y_i)^2 + z_i^2}$.

These eqs. describe an Hopf oscillator, where μ_i controls the amplitude of the oscillations, ω and β controls the speed of convergence to the limit cycle. This Hopf oscillator contains a bifurcation from a fixed point (when $\mu_i < 0$) to a structurally stable, harmonic limit cycle with radius $R = \sqrt{\mu_i}$ and relaxation to the limit cycle given by $\frac{1}{2\beta\mu_i}$, for $\mu_i > 0$. The fixed point x_i has an offset given by y_i , which is the state variable of the discrete system. Thus, the resulting position x_i , modifies according to the y_i variable as specified by the discrete movement. For $\mu_i < 0$ the system exhibits a stable fixed point at $x_i = y_i$. This Hopf oscillator describes a rhythmic motion which can be switched on or off by simply setting μ_i to positive or negative values, respectively. Moreover, the amplitude of the movement is specified by μ_i and its frequency by ω_i .

Currently, rhythmic motion is switched off by setting μ_i to a negative value, so that the attractor of the Hopf oscillator is no longer a limit cycle but a fixed point specified by the offset, i.e. by y variable. Relaxation time for the rhythmic system is given by $\frac{1}{2\beta\mu_i}$ parameter. The y variable evolution will be specified and explained in the next subsection. This easy control of the different patterns generated is an advantage of the proposed architecture.

In Fig. 1, y variable (dashed line) is considered to have constant values during some time intervals. Initially $y = 9$, it is decreased to 2 at $t = 5.6s$ and at instant $t = 11.3s$ y is set to -9 . The resulting x trajectory (solid line) converges asymptotically to the current value of y (dashed line). By modifying on the fly the offset values (y variable), one can easily modulate the generated trajectories. Whatever the change is, the system converges almost immediately to the new solution of the system. Further, notice the smoothness of the trajectory when the parameters are changed.

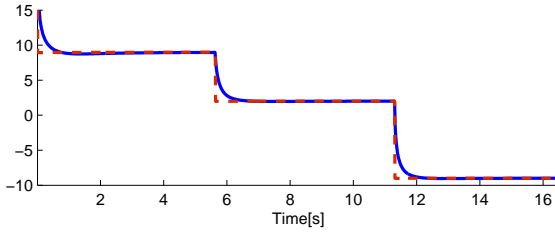


Fig. 1. Trajectory modulation through changes in the y values (offset) for dynamical system defined by eqs. 1 and 2, when rhythmic motion is turned off ($\mu_i < 0$).

2.3 MPG Discrete Movement

To generate the discrete movements, we define a non-linear dynamical system whose solution, given by y_i , is the offset of the output x_i (eq. 1). This discrete system is designed to control balance, such that by measuring the robot sagittal tilt, the controller is able to maintain the stability reducing this tilt to a minimum.

It is important that this discrete movement generator applies to the control of a real robot. Thus, the generated movement must be able to: 1) smoothly adapt to the control parameters and 2) allow trajectory modulation through changes in these control parameters. In our case, the pitch is not fixed but changes according to the robot movement during postural control. Therefore, we apply differential equations to model the discrete movement. The discrete movement is generated by the following dynamical system

$$\dot{y}_i = k_{j,i} f(\phi) + \alpha (y_i - M_i) e^{-\frac{(y_i - M_i)^2}{2\sigma^2}} + \alpha (y_i - D_i) e^{-\frac{(y_i - D_i)^2}{2\sigma^2}}, \quad (3)$$

where ϕ is the robot sagittal tilt, $k_{j,i}$ ($j = \text{fore, hind}$) is a static gain and f is defined as a linear function of the body's tilt and is given by:

$$f(\phi) = \begin{cases} 0, & -0.2 < \phi < 0.2 \text{ (degrees)} \\ 0.8 \phi, & \text{elsewhere} \end{cases} \quad (4)$$

A dead-zone was defined in order to deal with sensor noise. In this dynamical system, two repellers specify joint limits (M_i and D_i). These repellers are multiplied by a Gaussian function which delimits their range of action around the joint limits.

3. AIBO POSTURAL CONTROL USING ROBOT SAGITTAL TILT

In this section we show how we apply the presented MPG to achieve quadruped postural control using sagittal tilt of the body on a real ers-7 AIBO robot.

3.1 Robotic Setup

We use an AIBO dog robot, which is a 18 DOFs quadruped robot made by Sony. The robot stands on two platforms, one fixed and another moveable (see Fig. 2(a)). We control the hip and knee of the four AIBO legs, that is 8 DOFs of the robot, 2 DOFs in each leg: elevator and knee joints. For $i = 1, 3$

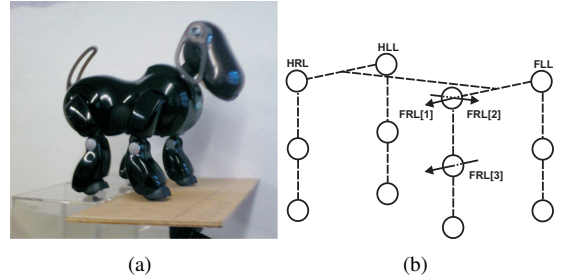


Fig. 2. (a) Real AIBO robot mounted over two platforms, one fixed and the other moveable. (b) Scheme of the AIBO controlled DOFs.

(Hip, Knee) we control FLL[i], FRL[i], for fore legs and HLL[i], HRL[i] for hind legs. The other DOFs are not used for the moment, and remain fixed to an appropriately chosen value during the experiments. Fig. 2(b) shows a schematic view of the AIBO and the controlled DOFs.

The AIBO has a set of 3-axis accelerometers, built into its body. They enable us to calculate the sagittal tilt of the robot body.

3.2 The Overall Architecture

We use one generic MPG for each controlled DOF. In order to ensure phase-locked synchronization between the different DOFs of the robot, we couple the different MPGs together. We bilaterally couple the

Hopf oscillators of the MPGs, those couplings being illustrated by right-left arrows on fig. 3 and unilaterally couple each hip MPG to the corresponding Knee MPG. For the hip joints, we modify Eqs. 1 and 2 of all the DOFs as follows:

$$\begin{bmatrix} \dot{x}_{i[1]} \\ \dot{z}_{i[1]} \end{bmatrix} = \begin{bmatrix} \beta\mu_i & \omega \\ -\omega & \beta\mu_i \end{bmatrix} \begin{bmatrix} x_{i[1]} - y_{i[1]} \\ z_{i[1]} \end{bmatrix} - \beta r_{i[1]}^2 \begin{bmatrix} x_{i[1]} - y_{i[1]} \\ z_{i[1]} \end{bmatrix} \\ + \sum_{j \neq i} \mathbf{R}(\theta_{i[1]}^{j[1]}) \begin{bmatrix} x_{j[1]} - y_{j[1]} \\ z_{j[1]} \end{bmatrix}$$

For the knee joints, we modify Eqs. 1 and 2 of all the knee DOFs as follows:

$$\begin{bmatrix} \dot{x}_{i[3]} \\ \dot{z}_{i[3]} \end{bmatrix} = \begin{bmatrix} \beta\mu_i & \omega \\ -\omega & \beta\mu_i \end{bmatrix} \begin{bmatrix} x_{i[3]} - y_{i[3]} \\ z_{i[3]} \end{bmatrix} - \beta r_{i[3]}^2 \begin{bmatrix} x_{i[3]} - y_{i[3]} \\ z_{i[3]} \end{bmatrix} \\ + \frac{1}{2} \mathbf{R}(\psi_{i[3]}^{j[1]}) \begin{bmatrix} x_{j[1]} - y_{j[1]} \\ z_{j[1]} \end{bmatrix}$$

where $r_i[k]$ is the norm of vector $(x_i[k], z_i[k])^T$ ($k = 1, 3$). The linear terms are rotated onto each other by the rotation matrices $\mathbf{R}(\theta_{i[1]}^{j[1]})$ and $\mathbf{R}(\psi_{i[3]}^{j[1]})$, where $\theta_{i[1]}^{j[1]}$ is the desired relative phase among the $i[1]$'s and $j[1]$'s MPGs and $\psi_{i[3]}^{j[1]}$ is the desired relative phase among the $i[3]$'s and $j[1]$'s MPGs ($i, j = \text{FLF, FRL, HLL, HRL}$). In our case, we set these values according to table 1, which defines the phases required for performing a walking gait (we exploit the fact that $\mathbf{R}(\theta) = \mathbf{R}^{-1}(-\theta)$). The $\psi_{i[3]}^{j[1]}$ were all set to -90° . Due to the properties of this type of coupling among oscillators, the generated trajectories are always smooth and thus potentially useful for real-world implementations such as trajectory generation in a robot.

For offset y_i specification, we measure the sagittal tilt of the body, ϕ . We want to stretch the legs towards which the robot is tilted, and fold the other legs, thus reducing the robot tilt and keeping the body parallel to the ground. This is achieved by reducing the hip and knee joint values of the former and increasing these joint values for the later.

The effect of this offset joint change should be of opposite effect on the fore and hind legs of the robot, but should also influence similarly both legs. The $k_{j,i}$ static gain ($j = \text{fore, hind}$) (eq. 3) is set symmetrically for the robot fore and hind legs, and is given by

$$k_{\text{fore},i} = -C_i \quad (5)$$

$$k_{\text{hind},i} = C_i, \quad (6)$$

where C_i is set according to the joints range of each leg such that joints change with the same velocity.

The controller architecture is depicted in fig. 3. The MPG generates discrete and rhythmic trajectories, as well as their superposition. Within the MPG, the discrete system specifies an offset for the rhythmic movement. In this particular situation, the rhythmic motion

is turned off, so that the attractor of the Hopf oscillator is a fixed point specified by the offset, i.e., by the discrete movement.

Trajectories generated by this architecture are modulated by sensory feedback, according to the sagittal tilt of the body. This tilt is linearly transformed by a f function such that it specifies a rate of change for the robot joints. A larger ϕ results in stronger rates of change, \dot{y}_i . y_i define the fixed points towards which the MPG Hopf oscillators will converge. The final trajectories x_i specify the planned joint values needed to reduce the sagittal tilt to a minimum. These are sent online for each DOF and the lower level control is done by PID controllers. Because motion is sufficiently slow there is no need to apply inverse dynamics.

4. RESULTS

In this section, we describe two experiments done in a real AIBO robot. The robot stands in a moveable platform and we forced some changes on the tilt of the robot's body. At each sensorial cycle, sensory information is acquired, dynamic equations are calculated and integrated thus specifying servo positions. The robot control loop is measured and has 8 milliseconds. The dynamics of the CPGs are numerically integrated using the Euler method with a fixed time step of 1 ms. Parameters were chosen in order to respect feasibility of the experiment and are given in table 2. We recorded the actual trajectories from the joints incremental encoders \tilde{x} and the planned trajectories x .

4.1 First Experiment

To show the behavior of the system, we start with a very simple experiment, in which the robot is initially near equilibrium ($\sim 0^\circ$), and we bent it backwards of $\sim 8^\circ$ and, after sometime, it is bent again of $\sim 7^\circ$ to the same direction. We expect the system to react to each of these tilt changes by reducing it to values belonging to a small region around zero, as defined by the dead-zone. Fore and hind legs are expected to exhibit a symmetric behavior.

In fig. 4 we can see the result of the experiment in the real dog. We depict actual trajectories $\tilde{x}_{\text{FRL}[3]}$, $\tilde{x}_{\text{HRL}[3]}$ (solid line) and the planned trajectories $x_{\text{FRL}[3]}$, $x_{\text{HRL}[3]}$ (dashed line) of the right leg knees. The controller reduces considerably the tilt in the first 2 seconds, from $\sim 8^\circ$ to $\sim 1^\circ$. When the robot is bent backwards (positive sagittal tilt), $\dot{y}_{\text{FRL}[3]}$ is positive (middle panel in the left side of fig. 4), meaning that the offset $y_{\text{FRL}[3]}$ is increased and the leg folds reducing the tilt. Because at $t = 6.6\text{s}$ the inclination is slightly smaller than at $t = 1\text{s}$, $\dot{y}_{\text{FRL}[3]}$ has a smaller

	$\theta_{FLL-FRL}$	$\theta_{FLL-HLL}$	$\theta_{FLL-HRL}$	$\theta_{FRL-HLL}$	$\theta_{FRL-HRL}$	$\theta_{HLL-HRL}$
($^\circ$)	-180	-270	-90	-90	90	180

Table 1. Phase differences between hip oscillators ($i[1]$) used to perform a walking gait.

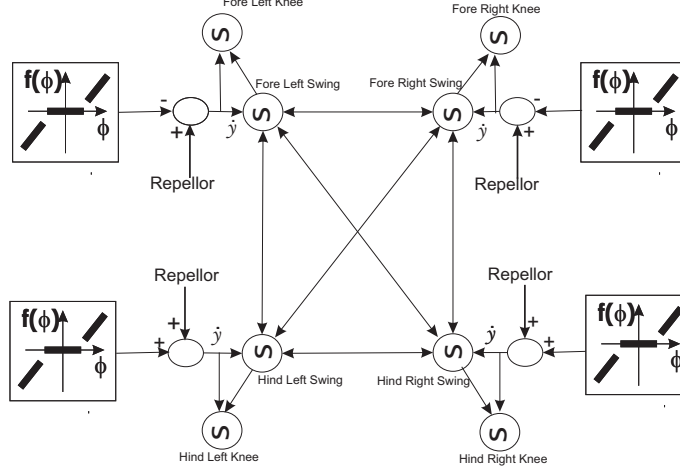
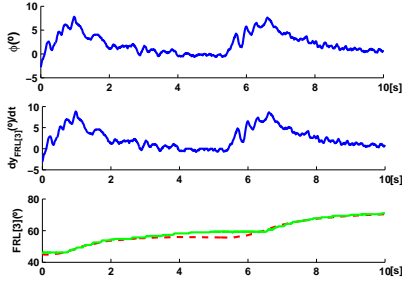


Fig. 3. Controller architecture. The sagittal tilt value and the joint limits modulate the y and x trajectories.

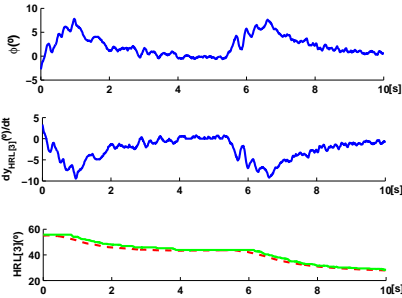
β	ω (rad s^{-1})	μ_i	$\frac{1}{2\beta\mu_i}$ (s)	α (s^{-1})	σ
1.38	1.0472	-36	0.1	5000	0.05

Table 2. Parameter values used in the experiments.

value. Comparing the fore and hind knee $x_{i[3]}$ trajectories, we see that the system behaves as expected, having symmetric trajectories.



(a)



(b)

Fig. 4. Real experiment. (a) Fore Right Knee (b) Hind Right Knee. Up panel: sagittal tilt (ϕ); Middle panel: $\dot{y}_{i[3]}$; Bottom panel: $x_{i[3]}$ (dashed line) and $\tilde{x}_{i[3]}$ (solid line) ($i = FRL, HRL$).

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

4.2 Second Experiment

In this experiment, the robot is subjected to more abrupt tilt changes and these happen during the controller recover. At $t \sim 0.5s$ we bent the robot backwards of $\sim 8^\circ$ and we expect the system to react to this perturbation by stretching the hind legs and folding the fore ones, reducing the tilt. The robot is bent forward to $\sim 12^\circ$ at $t \sim 2.4s$, but this change happens before the system had reached a balanced position. Finally, at $t \sim 5s$, the robot is perturbed again but towards the opposite direction by $\sim 8^\circ$. We expect the system to react to this change in order to reach the equilibrium. Further, hind and fore legs are expected to exhibit a symmetric behavior.

Fig. 5, depicts the obtained results. The robot successfully reacts to sagittal tilt changes by reducing this to a minimum. The trajectories are symmetric for fore and hind legs. When the robot is bent backwards (positive lateral tilt), $\dot{y}_{FRL[3]}$ is positive, thus $y_{FRL[3]}$ is increased and the robot folds this leg. At $t \sim 2.5s$, the robot is bent forward and its sagittal tilt becomes negative. Thus, $\dot{y}_{FLL[3]}$ is negative and $y_{FLL[3]}$ is decreased, meaning the fore left leg extends. Balanced position is achieved at $t \sim 7s$.

5. CONCLUSIONS

In this article, we have presented a controller for correcting posture in an irregular terrain, where a MPG implemented as two embedded dynamical systems was able to generate discrete mode of movement. Online trajectory modulation is achieved through the

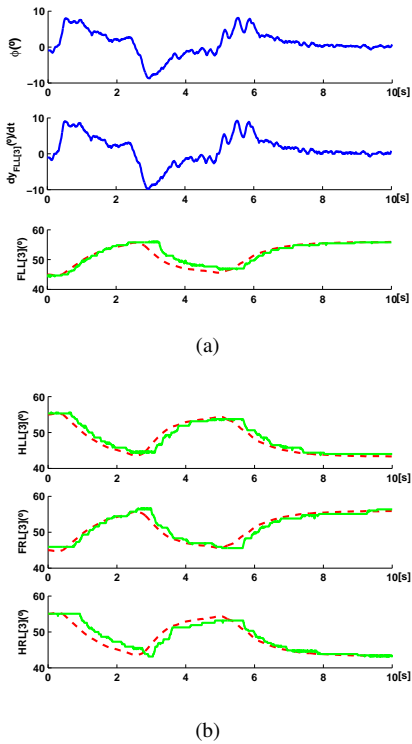


Fig. 5. a) Fore Left knee. Up panel: sagittal tilt (ϕ); Middle panel: $\dot{\phi}_{FLL[3]}$; Bottom panel: planned $\mathbf{x}_{FLL[3]}$ (dashed line) and $\hat{\mathbf{x}}_{FLL[3]}$ (solid line) trajectories. (b) Planned $\mathbf{x}_{i[3]}$ (dashed line) and actual $\hat{\mathbf{x}}_{i[3]}$ (solid line) trajectories ($i = \text{HLL, FRL, HRL}$).

inclusion of feedback loops that enable to take external perturbations into account (sagittal tilt), such that when the environment changes, the system online adjusts the dynamics of trajectory generation. Moreover, due to the properties of dynamical systems the trajectory will always remain smooth.

As an application we apply a network of MPGs coupled together to the control of a quadruped robot (an ers7 AIBO). The robot was subjected to external perturbations that change its sagittal tilt, measured by the built-in accelerometers. The MPGs network uses this information to compensate for the tilt changes and reduce them to near zero. The obtained results have been quite satisfactory. This controller showed to be fast enough since the robot can quickly recover from the induced physical inclinations. The controller also proved to be efficient according to the obtained results.

Presently, we are extending this work to control both lateral tilt and sagittal tilt, merging all in a single controller. We are also working on the integration of the touch sensors' information in order to assure contact of the robots' end effectors with the platform before performing a posture correction. Further, we are extending this work to combine this approach in order to obtain locomotion.

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