

Biologically-Inspired Neural Network for Walking Stabilization of Humanoid Robots

Guilherme Barros Castro¹, Kazuya Tamura², Atsuo Kawamura² and André Riyuiti Hirakawa¹

¹Department of Computer Engineering and Digital Systems, University of São Paulo, São Paulo, Brazil

²Department of Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan

Keywords: Biologically-Inspired Neural Network, Humanoid Robots, Computational Intelligence, Walking Stabilization.

Abstract: In order to accomplish desired tasks, humanoid robots may have to deal with unpredicted disturbances, generated by objects, people and even ground imperfections. In some of these cases, foot placement is critical and cannot be changed. Furthermore, the robot has to conduct the actions planned meanwhile stabilizing its walking motion. Therefore, we propose a Biologically-inspired Neural Network (BiNN) to stabilize the walking motion of humanoid robots by ankle joint control, which minimally affects the current movements of the robot. In contrast to other neural networks, which only generate walking patterns, the BiNN is adaptive, as it compensates disturbances during the robot motion. Moreover, the BiNN has a low computational time and can be used as a module of other control methods. This approach was evaluated with Webots simulator, presenting improvements in the compensation of an external force in regard to its magnitude and duration.

1 INTRODUCTION

Humanoid robots are expected not only to act in the same environment and to perform similar tasks as humans, but also to act in dangerous environments, such as those present in catastrophe or rescue scenarios, and to perform tasks that humans are not able to, such as lifting heavy weights. In these situations, humanoid robots may need to avoid objects and people and deal with irregular ground, all of which may generate disturbances and affect its balance.

There are two main alternatives to compensate external disturbances and stabilize robot motion: stepping (Stephens and Atkeson, 2010; Luo *et al.*, 2015), and postural control (Sano and Furusho, 1990; Stephens, 2007; Lee and Goswami, 2012; Lober, Padois and Sigaud, 2014; Maalouf *et al.*, 2015). Stephens and Atkeson (2010) state that humanoid robots are able to sustain larger disturbances by stepping. However, in some situations the robot may have to perform specific foot placements due to environment constraints. In these cases, postural control is the best alternative to guarantee stability without violating any constraints.

Different strategies were proposed to achieve postural control, which can be classified into two

categories: whole body control (Lee and Goswami, 2012; Lober, Padois and Sigaud, 2014) and ankle joint control (Sano and Furusho, 1990; Stephens, 2007; Maalouf *et al.*, 2015). Whilst in the whole body control strategy all actuators can be used to balance the robot motion, strategies based on ankle joint control stabilize the motion only with ankle actuators. In spite of the effectiveness of the former control method against more severe disturbances, as shown in (Stephens, 2007), this research focuses on ankle joint control, for its simplicity and efficiency.

By controlling only the ankle joints it is possible to compensate significant disturbances without changes to other joint trajectories, not interfering with the upper limb actions currently being executed or previously planned by the robot. Moreover, ankle joint control can be used with other control approaches, being activated in the cases that external disturbances are moderate.

Sano and Furusho (1990) achieved natural dynamic walking by controlling the ankle torque of the supporting leg and, thus, manipulating the robot angular momentum. Stephens (2007) analyses the disturbance compensation capacity based on the current state of humanoid robots which adopt the ankle stabilization strategy. Maalouf *et al.* (2015) proposed a model-free approach for humanoid robot

stabilization, showing improved results in comparison to the model-based approach presented in (Stephens, 2007). Nevertheless, the authors only investigated push recovery situations in which the robot was standing still, and their control objective was to maintain an upright position. Both aspects do not allow the direct application of the approach to stabilize a walking motion.

In this paper, we propose a Biologically-inspired Neural Network (BiNN) to stabilize the walking motion of humanoid robots. The approach proposed is modular, i.e., can be used in conjunction with walking pattern generation and stepping approaches, and has a low computation time, which is relevant to ensure real-time control. We investigate here the stability of NAO humanoid robot in regard to lateral disturbances (y-direction) during a walking motion, evaluating with simulations the BiNN capacity of stabilizing different external forces as well as the computation time of each control step.

In contrast to Artificial Neural Networks (ANNs), whose focus is on the learning aspect of biological neural networks, the BiNN focuses on determining its structure and parameters in order to achieve a desired behaviour. Whereas ANNs with different training methods were proposed to estimate humanoid robot models for control purposes (Liu and Li, 2003; Rai *et al.*, 2012; Sun *et al.*, 2016), the BiNN proposed does not adopt previous training and does not have a convergence period.

However, other characteristics of the BiNN proposed resemble biological neural networks, such as: inhibitory synapses, which represent negative influences between neurons; sensorial inputs, which resemble biological sensorial receptors; and different activation functions, as in the different types of biological neurons (Kandel *et al.*, 2012).

Works related to BiNNs were proposed to control different types of robots, as surveyed by Yu *et al.* (2014). In addition to the robots presented in (Yu *et al.*, 2014), which adopt BiNNs with an oscillatory behaviour inspired by the biological Central Pattern Generator (CPG) of humans, Nichols, Mcdaid and Siddique (2013) and Helgadóttir *et al.* (2013) proposed other BiNNs to control the motion of wheeled robots. Different BiNNs have different network structures, neuron models, which comprise membrane potential (activation) and neuron output determination, types of synapses and neural adaptation mechanisms.

BiNNs for humanoid robot control, such as those proposed by Taga, Yamaguchi and Shimizu (1991), Cao and Kawamura (1998), Endo *et al.* (2008) and Saputra *et al.* (2016), focus on the walking pattern

generation part of the robot motion, not being able to adaptively compensate external disturbances. Contrary to these approaches, the BiNN proposed does not focus on the walking pattern generation, but on the walking stabilization.

2 HUMANOID ROBOT WALKING STABILIZATION

Stable walking of a humanoid robot can be defined as the realization of any walking motion in which the humanoid robot achieves the final position desired without falling down. In order to guarantee the dynamical balance of the walking motion, the Zero Moment Point (ZMP) of the robot must remain inside its support polygon during its entire motion (Vukobratović, Borovac and Potkonjak, 2006). Thereby, ZMP is the point at which the resultant ground reaction force acts, whereas the support polygon is the projected area beneath the robot's feet which is formed by the convex hull of its footprints (Vukobratović and Stepanenko, 1972). Equation (1) represents this stability criterion for the y-direction, which is the focus of this paper. In the equation, y_{ZMP} represents the current ZMP, and y_{ub} and y_{lb} represent the upper and lower bounds of the support polygon in the y-direction.

$$y_{lb} \leq y_{ZMP} \leq y_{ub} \quad (1)$$

The grey area in Fig. 1a corresponds to the support polygon of NAO robot – used in this research – when both feet are on the ground. In the figure, the labels (LFsrFL, LFsrFR, etc.) indicate the position of eight Force Sensitive Resistors (FSR), which measure resistance changes according to the variation of the pressure applied. When only one foot is on the ground, the support polygon corresponds to the footprint area of that foot.

To determine the current ZMP in the y-direction, the ZMP equation rewritten by Kajita *et al.* (2003) from (Vukobratović and Stepanenko, 1972) is

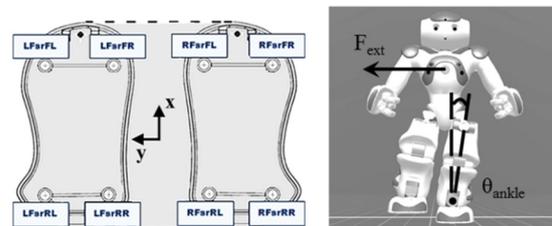


Figure 1: (a) Support polygon of NAO robot. (b) Ankle joint control.

adopted, as represented by (2). In the equation, y_{CoM} and z_{CoM} represent the center of mass position in y - and z -directions, g represents the gravitational acceleration, and \ddot{y}_{CoM} represents the center of mass acceleration in y -direction.

$$y_{ZMP} = y_{CoM} - \frac{z_{CoM}}{g} \ddot{y}_{CoM} \quad (2)$$

The approach presented in this paper controls the robot ankle motors in order to control the ZMP, guaranteeing a stable walking by satisfying the stability criterion even in scenarios with external disturbances. Thus, the BiNN influences the centre of mass position and acceleration by determining the ankle angular position θ_{ankle} (and angular velocity $\dot{\theta}_{ankle}$), as illustrated in Fig. 1b. The hip motors are also controlled, but only to maintain the robot torso vertical, reducing the overall motion range and increasing its stability.

The control cycle of the method proposed is illustrated by a block diagram in Fig. 2. The first block, ‘Walking pattern generation’, has as inputs the walking parameters that determine the motion desired, such as step height, step length and walking speed. The robot joint angles compose the outputs of this block. The second block is the control cycle plant, i.e., the robot. To accomplish closed loop control, FSR measurements, such as the ZMP, are sent as a feedback to the BiNN, which is the main contribution of this paper. The neural network processes this information and produces an output with two components, one positive (Out1) and one negative (Out2), altering the ankle and hip angles sent as references to the robot.

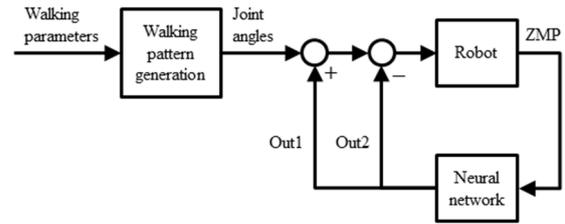


Figure 2: Control cycle.

form, as they are not the main focus of this paper.

The first fundamental movement is ‘transfer’. Its objective is to transfer the centre of mass position to the next support foot of the walking motion by changing the ankle roll angle of both legs. Equation (3) determines the ankle roll angles $\theta_{a,r}$ based on the desired centre of mass shift Δy_{CoM} and on the current support leg length L_{sl} . The support leg length, calculated by (4), is the actual length of the support leg, which considers changes in the ankle and knee pitch angles ($\theta_{a,p}$ and $\theta_{k,p}$). Constants l_K and l_H correspond to the lower and upper leg lengths, respectively. Fig. 4 illustrates all leg parameters, as well as the maximum angle values in each direction. In order to maintain the torso vertical, the hip roll angles $\theta_{h,r}$ are equal to the opposite value of the ankle roll angles $\theta_{a,r}$, as represented in (5).

$$\theta_{a,r} = \text{asin}\left(\frac{\Delta y_{CoM}}{L_{sl}}\right) \quad (3)$$

$$L_{sl} = l_K \cos(\theta_{a,p}) + l_H \cos(\theta_{a,p} + \theta_{k,p}) \quad (4)$$

$$\theta_{h,r} = -\theta_{a,r} \quad (5)$$

3 WALKING PATTERN GENERATION

The walking pattern generation approach adopted in this research is based on three fundamental movements (transfer, lift and extend), illustrated in Fig. 3, and does not have as an objective the robot stabilization during its entire motion. These fundamental movements are sequential and may overlap, depending on the walking speed desired. Despite the disadvantage of not considering the robot stability to generate its joint trajectories, this approach has an advantage: its simplicity, which provides low design and computation times.

The equations that describe the fundamental movements, presented in this section, are derived from geometrical relationships between their variables. These equations are shown in their final

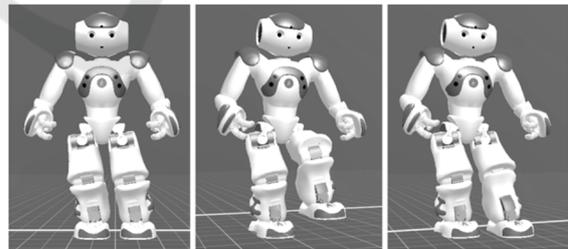


Figure 3: Fundamental movements: ‘transfer’, ‘lift’ and ‘extend’.

The second and third fundamental movements (lift and extend) are based on the same equations, (6)-(10). These movements change hip and knee pitch angles ($\theta_{h,p}$ and $\theta_{k,p}$) of the moving leg according to (6) and (7) to achieve the foot height desired (Δz). Whilst in the second fundamental movement (‘lift’), the foot height has a positive value, in the third fundamental movement (‘extend’)

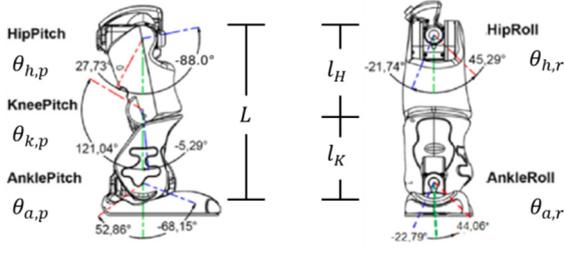


Figure 4: Leg parameters of NAO robot.

it is equal to 0, so that the foot touches the ground. Simultaneously, the ankle pitch angle $\theta_{a,p}$ of the moving leg is adjusted by (10) to maintain the moving foot parallel to the ground.

In (6), the hip pitch angle is adjusted by the torso pitch angle $\theta_{t,p}$, defined by (8) as the sum of the hip, knee and ankle pitch angles of the supporting leg, because the torso inclination directly affects the hip pitch angle of the moving leg. The current moving leg length is determined by (9) based on the current support leg length and on the desired foot height. The roll angles are used in the equation to account for the lateral inclination of both legs.

Free parameter α is used to simplify (6). α defines the relationship between hip and knee pitch angles, as shown in (7), and may have different values in ‘lift’ and ‘extend’, with a higher value in ‘extend’ to produce a more natural motion. The more negative α is, the straighter the moving leg is and the larger the step will be (until α is equal to $\theta_{h,p}$ and $\theta_{k,p}$ reaches 0).

$$\theta_{h,p} = -\arccos\left(\frac{L_{ml} - l_K \cos(\alpha - \theta_{t,p})}{l_H}\right) + \theta_{t,p} \quad (6)$$

$$\theta_{k,p} = \alpha - \theta_{hip,pitch} \quad (7)$$

$$\theta_{t,p} = \theta_{h,p,sl} + \theta_{k,p,sl} + \theta_{a,p,sl} \quad (8)$$

$$L_{ml} = \frac{L_{sl} \cos(\theta_{a,r}) - \Delta z}{\cos(\theta_{h,r})} \quad (9)$$

$$\theta_{a,p} = \theta_{t,p} - (\theta_{h,p} + \theta_{k,p}) \quad (10)$$

4 BIOLOGICALLY-INSPIRED NEURAL NETWORK

4.1 Fundamentals

A general neuron model, represented in the right-hand side of Fig. 5, may have different types of inputs, which determine the neuron activation and, consequently, its output. Whilst inhibitory inputs have only negative values and excitatory inputs have

only positive values, sensorial inputs can have either negative or positive values. Activation A_i of a neuron i is determined by the weighted sum of its n inputs Q_j , as shown in (11). Output O_i of a neuron i is a function of its activation A_i . In this research, a sigmoid function is adopted as the activation function, as represented in (12). Parameters s and m determine the activation function shift and slope, respectively, and the effects of their modification are shown in Fig. 6.

$$A_i^{t+1} = \sum_j^n w_j Q_j^t \quad (11)$$

$$O_i^{t+1} = 1 / [1 + e^{-m(A_i^t - s)}] \quad (12)$$

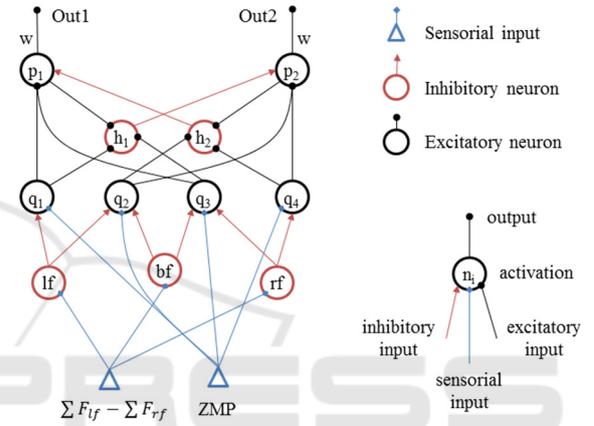


Figure 5: Biologically-inspired Neural Network.

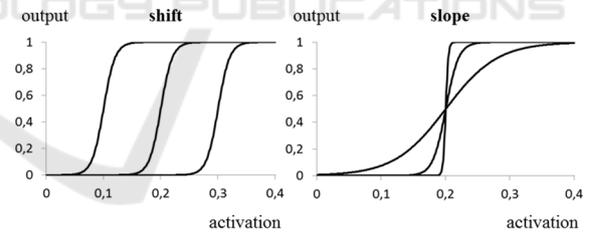


Figure 6: Activation functions of neurons.

4.2 Network Structure and Parameter Determination

The left-hand side of Fig. 5 illustrates the BiNN structure proposed to stabilize the humanoid robot walking motion. This research focuses on stabilizing the humanoid robot from lateral disturbances (y -direction). Hence, two BiNNs with this structure would be necessary in order to stabilize the robot in both x - and y -directions. The sensorial inputs of this network are: the difference between the sums of all FSR values of the left foot $\sum F_{Lf}$ and of all FSR values of the right foot $\sum F_{Rf}$; and the ZMP, calculated with the measurements and positions of

FSR sensors by the method detailed in (Tamura, Nozaki and Kawamura, 2015).

The former sensorial input is processed by the first layer of inhibitory interneurons (lf , bf and rf), which determine whether each foot is on the ground or not. Thereby, the slope coefficient modulus of their activation function (m) is high (500) to originate a steep threshold function. The slope coefficient of lf is positive and its shift coefficient is 0.1, causing an input higher than 0.1 to produce an output, which indicates that the left foot is on the ground. In contrast, the slope coefficient of rf is negative and its shift coefficient is -0.1, causing inputs lower than -0.1 to produce outputs. The activation function of bf is a combination of the activation functions of lf and rf , causing values between -0.1 and 0.1 to produce outputs.

The first layer of excitatory neurons (q_1 , q_2 , q_3 and q_4) has the ZMP as one of its inputs and represents the support polygon boundaries in the y-direction, producing outputs if these boundaries are violated. Therefore, their shift coefficients exactly match the values of the boundaries. However, only the neurons that represent the boundaries of the current support polygon do not have their outputs inhibited by the inhibitory interneurons.

Whilst q_1 represents the right boundary of the support polygon when either only the right foot or both feet are on the ground, q_2 represents the left boundary when only the right foot is on the ground, q_3 represents the right boundary when only the left foot is on the ground and q_4 represents the left boundary when either only the left foot or both feet are on the ground. The slope coefficient modulus of these neurons is 100 so that outputs are produced before the ZMP approaches the boundaries, creating a safety margin.

The second layer of inhibitory interneurons (h_1 and h_2) also have a steep activation function (m equal to 500) and a low threshold value (s equal to 0.1). Their purpose is to inhibit the activity of the opposite p neuron with lateral inhibition dynamics, which allows only one p neuron to become active at a time. These neurons receive inputs from p neurons, generating feedback inhibition, as well as from q neurons, generating feedforward inhibition. Whilst feedback inhibition reflects the current state of p neurons, feedforward inhibition anticipates variations in their inputs.

The second layer of excitatory neurons (p_1 and p_2) produces the neural network outputs (Out1 and Out2). Their activation functions have a low slope coefficient (10) and a shift coefficient of 0.5, providing a varying output in the input range of 0 to

1.0. These neurons receive inputs based on the distance of the ZMP to the support polygon boundaries and produce outputs with values from 0 to 1.0, which are transformed into angle increments by the synaptic weight w .

The synaptic weights of all connections between neurons are set to 1 in order to simplify the parameter determination. However, the synaptic weight w of the outputs (Out1 and Out2) is a free parameter. w determines the angle increment $\Delta\theta$ generated by the BiNN, which alters the ankle joint angles provided by the 'Walking pattern generation' block to stabilize the robot motion. Hence, w has a direct influence on the centre of mass position, generating a shift in the y-direction Δy_{CoM} with $\Delta\theta$.

From (2), and assuming that the centre of mass variation in the z-direction is negligible, as in [6], there are two possibilities to control the ZMP in the y-direction: by y_{CoM} or by \dot{y}_{CoM} . But, in the case of the NAO robot, the maximum value of the second part of (2) is 0.0014m, due to a low centre of mass height (0.27m) and a low stall torque (73.44mNm), which affects the maximum \dot{y}_{CoM} generated according to (13). In the equation, m is the robot mass (5.18kg) and F is the force generated by the torque T .

$$\dot{y}_{CoM} = F/m = T/(m z_{CoM}) \quad (13)$$

In contrast, the maximum value of y_{CoM} is 0.06m, due to an ankle angle limitation (22°). The first part of (2) influences the ZMP position 42 times more than the second part and, therefore, generating a Δy_{CoM} by choosing the appropriate value of w is the stabilization method proposed herein.

The ankle angle increment generated by the BiNN is represented by (14). As the maximum BiNN output is equal to 1, the maximum ankle increment is equal to w , as stated in (15). Hence, the synaptic weight w required to generate a centre of mass shift Δy_{CoM} is determined by (17), which is derived from (16) and (15).

$$\Delta\theta = w(Out1 - Out2) \quad (14)$$

$$\Delta\theta_{max} = w \quad (15)$$

$$\Delta y_{CoM} = \sin(\Delta\theta) z_{CoM} \quad (16)$$

$$w = \text{asin}(\Delta y_{CoM}/z_{CoM}) \quad (17)$$

To guarantee the compensation of an external disturbance with short duration (less than one second), the centre of mass variation generated by the ankle motors \dot{y}_{CoM} must be higher than the center of mass variation caused by the external force

\dot{y}_{ext} , as stated in (18). Thereby, a safety factor γ (e.g. 1.1) can be used to transform the inequality into an equality, as shown in (19). In the equation, the center of mass velocity caused by the external force is considered to be equal to the centre of mass acceleration caused by the external force \dot{y}_{ext} multiplied by its duration Δt . Subsequently, the center of mass acceleration caused by the external force is assumed to be equal to the external force F_{ext} divided by the robot mass.

$$\dot{y}_{CoM} > \dot{y}_{ext} \quad (18)$$

$$\dot{y}_{CoM} = \gamma \dot{y}_{ext} = \gamma \Delta t \ddot{y}_{ext} = \frac{\gamma \Delta t F_{ext}}{m} \quad (19)$$

Assuming the centre of mass variation to be equal to the centre of mass shift divided by the iteration step value, as in (20), the synaptic weight w required to compensate an external force F_{ext} is given by (21). This equation allows tuning w according to the maximum value of the expected external disturbance. Whilst a higher value of w compensates higher external forces and causes a more aggressive behaviour, a lower value of w causes a smoother behaviour, but cannot compensate higher external forces.

$$\dot{y}_{CoM} = \frac{\Delta y_{CoM}}{t_{step}} \quad (20)$$

$$w = \text{asin}\left(\frac{\gamma \Delta t F_{ext} t_{step}}{m z_{CoM}}\right) \quad (21)$$

Fig. 7 shows (21) for γ equal to 1.01, Δt equal to 0.2s, t_{step} equal to 0.01s and z_{CoM} equal to 0.27m, showing the stable and unstable regions that the equation originates. Force duration of 0.2s was chosen so that the force acts for a sufficient time so as not to be considered an impulse. In the figure, the maximum force that the robot is physically able to sustain is also shown. This value can be obtained by substituting the centre of mass acceleration \dot{y}_{CoM} by the external force F_{ext} divided by the robot mass m in (2), and rearranging the equation as shown in (22).

$$F_{ext} = \frac{mg(y_{CoM} - y_{ZMP})}{z_{CoM}} \quad (22)$$

Thereby, substituting the constants m , g and z_{CoM} in the equation and assigning to y_{ZMP} the value of the support polygon boundary (-0.06m) and to y_{CoM} its best feasible position (0.06m), the maximum external force of 22.48N is obtained. External forces higher than 22.48N cause a center of mass acceleration that drives the ZMP out of the support polygon regardless of the center of mass position

(among its feasible values). In this case, a stepping approach would be necessary to avoid falling.

5 SIMULATION RESULTS

In this section the BiNN performance for stabilizing the walking motion of the humanoid robot NAO is evaluated in two manners. The first regards the computation time of the BiNN for each iteration step, whereas the second evaluates the BiNN capacity of compensating external forces with different magnitudes and durations. Two software were used to conduct the simulations: Choregraphe (v. 2.1.4) and Webots (v. 8.4.0).

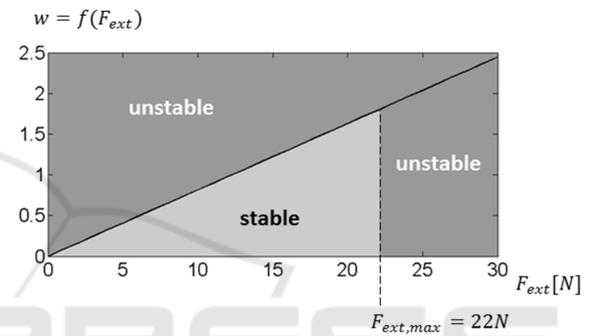


Figure 7: Synaptic weight w as a function of the external force F_{ext} .

5.1 Computation Time

The personal computer used to perform the simulations has an Intel Core i7-3517U processor with 1.9GHz and 8GB of random access memory (RAM). Twenty runs, with 106 iteration steps each, were conducted to obtain the results. The average computation time of the BiNN for each iteration step was 0.0027ms and its coefficient of variation was 0.62%. This computation time corresponds to the calculation of (11) and (12) for each neuron of the BiNN.

As an iteration step of 10ms was adopted for robot control, the BiNN computation time corresponds to less than 0.1% of the complete iteration step. Moreover, the low computation time obtained allows the combination of the BiNN with other control methods, which have average computation times of 20ms (Ishihara and Morimoto, 2015), 40ms (Carpentier *et al.*, 2016) and 300ms (Tedrake *et al.*, 2015) for each iteration step.

Figure 8 illustrates the computation times of these control methods, showing that the BiNN computation time is negligible in comparison to

them. This occurs because the BiNN only computes the current activation and output of its neurons, whilst predictive approaches are recurrent, i.e., they compute a sequence of iteration steps in the future in order to make a decision in the present.

5.2 Walking Stabilization

In order to evaluate the BiNN capacity of compensating external forces during a walking motion, the ‘Walking pattern generation’ block and the BiNN were programmed in Choregraphe platform. The walking pattern generated had an average duration of 0.05s for the double standing phase and of 0.5s for the single standing phase. The BiNN was evaluated in two simulation studies.

In the first simulation study, a force of 20N in the y-direction was applied to NAO for 0.2s during the single standing phase in Webots simulator with a physics plugin. This force is sufficient to knock the robot down in the cases in which it is being controlled either by the default Model Predictive Control (MPC) method of Choregraphe (Wieber, 2006) or by the open loop version of the control method proposed (i.e., without the BiNN feedback).

In this simulation, w was set to 1.63, according to (21). The centre of mass trajectory and the ZMP in the y-direction, illustrated in Fig. 9 and Fig. 10, respectively, show that the BiNN was able to compensate the applied force and that the robot was able to continue its walking motion. Moreover, the results also prove that the parameter determination method proposed is adequate.

Fig. 9 shows the centre of mass position in the y-direction y_{CoM} as well as its derivative \dot{y}_{CoM} , whose combined trajectory present a limit-cycle behaviour. This trajectory is highlighted in red from the moment in which the external force was applied.

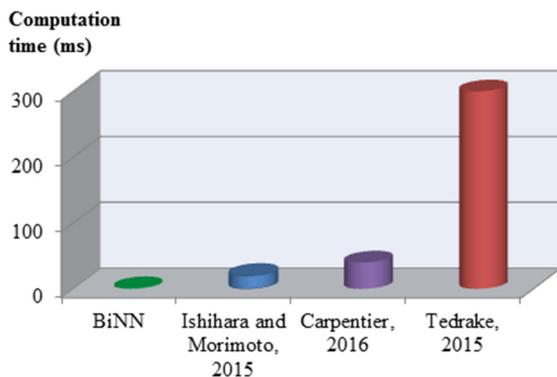


Figure 8: Computation time comparison.

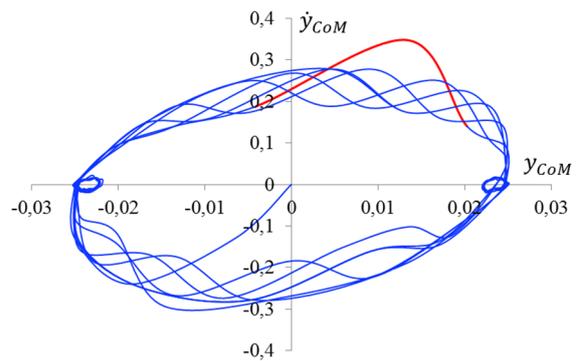


Figure 9: Centre of mass trajectory.

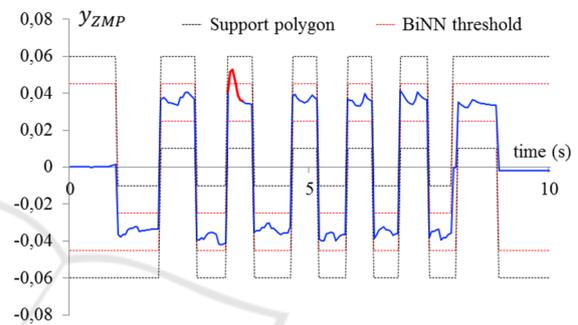


Figure 10: ZMP as a function of time.

The figure shows that the BiNN stabilizes the robot when the centre of mass trajectory deviates from its limit-cycle, bringing the trajectory back to it and allowing the robot to continue its walking motion without interruption.

The walking stabilization is also showed in Fig. 10, in which the ZMP, the support polygon boundaries and the BiNN threshold are plotted as functions of time. The BiNN threshold represents the ZMP values from which the q neurons start generating outputs, which originates a safety margin that prevents the ZMP from approaching the support polygon boundaries. In this figure, the ZMP is also highlighted in red from the moment the external force was applied. After crossing the BiNN threshold, the ZMP returned to the stable region in 0.084s, showing a fast response of the BiNN.

The second simulation study regards the evaluation of the BiNN capacity of compensating forces with different magnitudes and durations. In each simulation a force in the y-direction was applied to NAO in the exact same moment during the ‘lift’ movement of the single standing phase. The BiNN performance was compared to the performance of the default MPC used by Choregraphe (Wieber, 2006).

Fig. 11 illustrates the simulation results, showing that the BiNN was able to compensate a higher force magnitude for every force duration tested. Each combination of force magnitude and duration was evaluated 20 times for each control method. The lines plotted in the figure correspond to force magnitudes and durations which the robot was able to withstand in all 20 simulated experiments.

The BiNN was on average 52.55% better than the MPC, having higher improvements for shorter force durations. This occurs due to the BiNN fast response, which becomes less relevant for longer force durations. The maximum force compensated by the BiNN was 22N, applied for 0.1s, corroborating the theoretical result obtained with (22) by a margin of 2.14%.

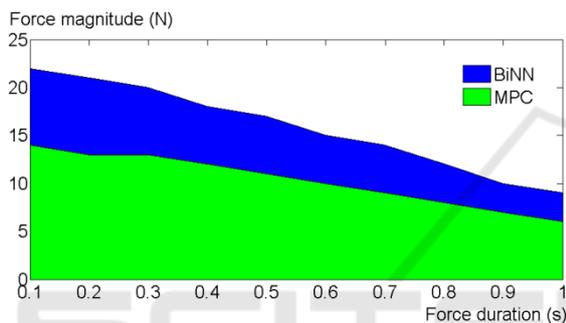


Figure 11: External force compensation.

These results reaffirm that the use of a simpler stabilization strategy, i.e. to control the ankle joint with the BiNN, is not only possible due to its low computation time, but also more effective than the standard stepping approach of NAO robot. Thereby, in the cases that the disturbance is moderate (10N-22N), the ankle joint control proposed would be active, whereas for stronger disturbances the robot could use a supplementary stepping approach, such as those proposed by Stephens and Atkeson (2010) and Luo *et al.* (2015).

6 CONCLUSION

This paper presented a Biologically-inspired Neural Network (BiNN) to stabilize the walking motion of humanoid robots. The approach proposed considers scenarios in which foot placement cannot be changed. Thus, the BiNN uses the Zero Moment Point (ZMP) as input and alters ankle joint angles to stabilize the robot.

Simulation studies evaluated the BiNN performance in compensating lateral forces with different

magnitudes and durations, which were applied during the walking motion. The BiNN presented a fast response to disturbances and had a performance, on average, 52.55% better than a MPC proposal. The simplicity and low computation time of the BiNN (0.0027ms) allows its combination with other control methods, such as reactive stepping approaches.

Future research directions encompass using two BiNNs with the proposed structure to compensate external forces contained in the x-y plane and three BiNNs to compensate omnidirectional external forces. Moreover, experiments will also be planned in order to evaluate the BiNN performance in compensating external forces with different magnitudes and durations applied to the actual NAO robot.

ACKNOWLEDGEMENTS

This work was supported by CNPq, *Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil / Brazilian National Council of Scientific and Technological Development.*

REFERENCES

- Cao, M. and Kawamura, A. (1998). A Design Method of Neural Oscillatory Networks for Generation of Humanoid Biped Walking Patterns. In *Proceedings of the International Conference on Robotics and Automation*, pp. 2357-2362.
- Carpentier, J., Tonneau, S., Naveau, M., Stasse, O. and Mansard, N. (2016). A Versatile and Efficient Pattern Generator for Generalized Legged Locomotion. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 3555–3561.
- Endo, G., Morimoto, J., Matsubara, T., Nakanishi, J. and Cheng, G. (2008). Learning CPG-based Biped Locomotion with a Policy Gradient Method: Application to a Humanoid Robot. *International Journal of Robotics Research*, 27(2), pp. 213-228.
- Helgadóttir, L. I., Haenicke, J., Landgraf, T., Rojas, R. and Nawrot, M. P. (2013). Conditioned behavior in a robot controlled by a spiking neural network. In *Proceedings of the International IEEE/EMBS Conference on Neural Engineering*, pp. 891–894.
- Ishihara, K. and Morimoto, J. (2015). Real-time Model Predictive Control with Two-step Optimization based on Singularly Perturbed System. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, pp. 173–180.
- Kajita, S., Kanehiro, F., Kaneko, K., Fujiwara, K., Harada, K., Yokoi, K. and Hirukawa, H. (2003). Biped

- Walking Pattern Generation by using Preview Control of Zero-Moment Point. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 1620–1626.
- Kandel, E. R., Schwartz, J. H., Jessell, T. M., Siegelbaum, S. A. and Hudspeth, A. J. (2012). *Principles of Neural Science*. McGraw-Hill Education.
- Lee, S. H. and Goswami, A. (2012). A momentum-based balance controller for humanoid robots on non-level and non-stationary ground. *Autonomous Robots*, 33(4), pp. 399–414.
- Liu, Z. and Li, C. (2003). Fuzzy neural network quadratic stabilization output feedback control for biped robots via H_∞ approach. *IEEE Transactions on Systems, Man, and Cybernetics, Part B*, 33(1), pp. 67–84.
- Lober, R., Padois, V. and Sigaud, O. (2014). Multiple task optimization using dynamical movement primitives for whole-body reactive control. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, pp. 193–198.
- Luo, D., Han, X., Ding, Y., Ma, Y., Liu, Z. and Wu, X. (2015). Learning push recovery for a bipedal humanoid robot with Dynamical Movement Primitives. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, pp. 1013–1019.
- Maalouf, N., Elhajj, I. H., Asmar, D. and Shamma, E. (2015). Model-Free Human-Like Humanoid Push Recovery. In *Proceedings of the IEEE International Conference on Robotics and Biomimetics*, pp. 1560–1565.
- Nichols, E., Mcdaid, L. J. and Siddique, N. (2013). Biologically inspired SNN for robot control. *IEEE Transactions on Cybernetics*, 43(1), pp. 115–128.
- Rai, J. K., Singh, V. P., Tewari, R. P. and Chandra, D. (2012). Artificial neural network controllers for biped robot. In *Proceedings of the International Conference on Power, Control and Embedded Systems*, pp. 625–630.
- Sano, A. and Furusho, J. (1990). Realization of natural dynamic walking using the angular momentum information. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 1476–1481.
- Saputra, A. A., Botzheim, J., Sulistijono, I. A. and Kubota, N. (2016). Biologically Inspired Control System for 3-D Locomotion of a Humanoid Biped Robot. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 46(7), pp. 898–911.
- Stephens, B. J. (2007). Humanoid push recovery. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, pp. 589–595.
- Stephens, B. J. and Atkeson, C. G. (2010). Push recovery by stepping for humanoid robots with force controlled joints. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, pp. 52–59.
- Sun, C., He, W., Ge, W. and Chang, C. (2016). Adaptive Neural Network Control of Biped Robots. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, PP(99), pp. 1–12.
- Taga, G., Yamaguchi, Y. and Shimizu, H. (1991). Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Biological Cybernetics*, 65(3), pp. 147–159.
- Tamura, K., Nozaki, T. and Kawamura, A. (2015). Visual Servo System for Ball Dribbling by Using Bipedal Robot Nao. In *Proc. Annual Conference of IEEE Industrial Electronics Society*, pp. 3461–3466.
- Tedrake, R., Kuindersma, S., Deits, R. and Miura, K. (2015). A closed-form solution for real-time ZMP gait generation and feedback stabilization. In *IEEE-RAS International Conference on Humanoid Robots*, pp. 936–940.
- Vukobratović, M. and Stepanenko, J. (1972). On the stability of anthropomorphic systems. *Mathematical Biosciences*, 15(1–2), pp. 1–37.
- Vukobratović, M., Borovac, B. and Potkonjak, V. (2006). ZMP: a review of some basic misunderstandings. *International Journal of Humanoid Robotics*, 3(2), pp. 153–175.
- Wieber, P. B. (2006). Trajectory Free Linear Model Predictive Control for Stable Walking in the Presence of Strong Perturbations. In *IEEE-RAS International Conference on Humanoid Robots*, pp. 137 – 142.
- Yu, J., Tan, M., Chen, J. and Zhang, J. (2014). A survey on CPG-inspired control models and system implementation. *IEEE Transactions on Neural Networks and Learning Systems*, 25(3), pp. 441–456.