2nd International Conference on Autonomous Robots and Agents
December 13-15, 2004 Palmerston North, New Zealand

Hybrid Controller for Biped Gait Generation

Tee Wei In and Prahlad Vadakkepat
Department of Electrical and Computer Engineering,
National University of Singapore, 4 Engineering Drive 3, Singapore, 117576
{eng00428, elepv}@nus.edu.sg

Abstract

This paper deals with the gait generation of a small robot RoboSapien. The proposed controller is a hybrid one, merging the central pattern generator with the dynamics-based approach. This controller succeeded in enabling walking initiation, walking continuation, speed variance, and robustness to body mass changes. All this was achieved using a single hybrid controller without parameter changes, and a single control input. This is a departure from past controllers where “walking” and “starting to walk” were treated separately.

Keywords: Biped robot, central pattern generator, gait generation, neural oscillator

1 Introduction

The fascination for human-like machines will never end until the advent of such machines that can independently survive in the human environment. The debut of the Honda robot [1] and the recent introduction of Sony’s QRIO have further increased the allure of creating humanoid robots that can operate autonomously in our world. The foremost concern for any robot to successfully manage in our environment is mobility. Legged motion is the choice in this aspect, given the uneven terrain typical of our surroundings.

Bipedal walking has been variously compared to “bicycling”, “pendulum action” and “controlled falling” [2]. These connote two main characteristics of walking – a cyclic pattern of body movements, and the controlled translation of a mass. The generation of biped gaits is basically about devising controllers to achieve such characteristics. Controllers in literature can be roughly divided into three major types, namely, trajectory-based (kinematics control), dynamics-based, and central pattern generators.

The most common approach to making biped robots walk is to control the joint angles to mimic those of humans. This can be by playback of pre-recorded joint trajectories or generating these joint angles in real-time using mathematical models of human walking patterns. Many current methods build on such a trajectory-based control approach, using additional control units to augment the reference joint trajectory ([1], [3], [4] – [11]). A common form of this augmentation is by way of the “Zero Moment Point” (ZMP), to calculate a desired foot placement location for maintaining stability ([1], [4], [5]). An extension of this idea is the “Foot Rotation Indicator” (FRI), which gives more information than the ZMP, including the degree and direction of postural instability [6]. These trajectory-based bipeds have been pretty successful in moving across a variety of terrains, including staircases.

Trajectory control approaches however, may produce unnatural looking motions due to limitations of actuators and are energy-inefficient. Tad McGeer has studied passive-dynamic robots, which function purely on natural dynamics. The passive-dynamic approach has been tested successfully on a three-dimensional walker [12], but can only walk down slopes since no actuators are used. Extending the passive-dynamic idea, several dynamics-based methods have been formulated that exploit the natural dynamics of bipeds ([13] – [17]). These robots walk more naturally and use less energy. Moreover, unlike trajectory-based approaches where walking models are required, intuitive ways can be used to derive the controls. Some examples are, allowing the swing leg to swing passively, and having a kneecap to prevent the leg from inverting [14]. Such simple heuristic control laws reduce the computation required.

The third type of control looks to nature for inspiration. Neurophysiological experiments suggest the existence of neural circuits in vertebrates that produce rhythmic patterns. These rhythmic neural outputs couple with the body dynamics to produce locomotion [18]. Many researchers have modeled these neural oscillators, called Central Pattern Generators, or CPGs ([19] – [21]). The Matsuoka oscillator formulated in [19] has been used successfully to realize walking in both biped and quadruped robots ([22] – [29]).

In this paper, the Matsuoka oscillator will be used for rhythm generation in the hips and knees. However, the dynamics-based approach is used for joints where, intuitively, there is little evidence of rhythmic motion in human walking e.g. in the ankles. It is seen that even though such joints are not entrained to the CPG frequency, stable limit cycles are attained. This hybrid controller worked well enough to give a relatively fast gait. Even without any changes in the parameters, the controller could still function with different body masses. Moreover, a single control input can be used to start the walking, vary the speed, and stop the walking.

2 Simulation parameters

2.1 Robot model specifications

The humanoid robot RoboSapien was built by a Master's student [30]. This robot is meant to be a test-bed for different walking algorithms. It was also built to participate in the Humanoid Robot Soccer Tournament (HUROSOT) in September 2003. RoboSapien won this competition using a simple obstacle algorithm. It used a trajectory-based approach for the walking control.

Table 1 lists the specifications of RoboSapien that will be used in the simulation model.

Table 1: RoboSapien specifications

	Length (m)	Mass (kg)
Body (trunk)	0.14	1.1
Thigh	0.08	0.4
Shank	0.08	0.2
Foot	0.043	0.1

2.2 Joint variables

In this paper, the Cartesian coordinate reference frame is used. The x-axis (roll) is pointing to the right, y-axis (pitch) pointing into the paper, and z-axis (yaw) pointing upwards. The joint angle, joint velocity and joint torque are referred to with a leading "q_", "qd_" and "tau_" respectively. This is then followed by the respective names of joint. RoboSapien is a 12 DOF robot, but the hip yaw joint will not be actively controlled. The rest of the joints have names h_pitch, h_roll, k, a_pitch, and a_roll, to represent the hip, knee and ankle joints with their respective axis of rotation. Thus, the right ankle roll joint angle is "q_ra_roll", while the left knee torque is "tau_lk". Other joint references are made similarly. The body pitch and roll angles are referred to by q_pitch and q_roll, while the body angular velocities are q_wy and q_wx for the respective axes of rotation.

2.3 Feedback variables

The human motor system receives two different types of sensory information: proprioceptive and exteroceptive information [22]. These provide the sense of position and movement of the different parts of the body, and the relationship between the body and the environment.

Two main sensory signals are used: inertial angles and foot somatic sense. The inertial angle measures the angle of the robot link (thigh, shank or foot) with respect to the normal to the ground. Figure 1 shows the inertial angles in the right leg.

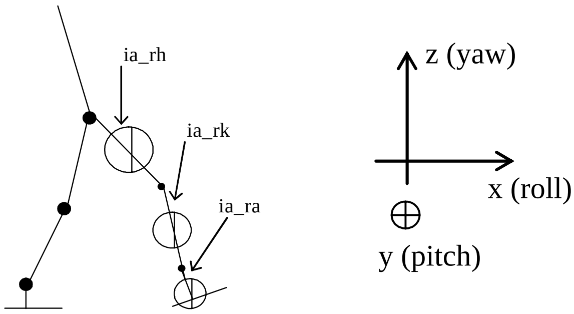

Figure 1: Inertial angles in the right leg. These are named after the respective joints with the leading "ia_" qualifier.

Each foot of the robot has 4 force sensors. These are placed at the 4 corners of the rectangular foot. In a normal walking cycle, each foot can be in one of the four states: 1.FOOT_STRIKE; 2.SUPPORT; 3.TOE_OFF and 4.SWING [2]. The foot somatic sense fed back to the controller is referred to as fs_rheel, fs_rfoot, fs_rtoe and fs_rswing respectively for the right leg. The "fs_" leading qualifier stands for "foot switch". These sense variables can have a value of 0 or 1.

2.4 Neuron model

The neuron model adopted in this paper is a discretized version of the continuous-time, continuous-variable neuron model by Matsuoka [19]. Discretization reduces the computational complexity. The following equations are used to calculate the neuron state at each integration time step:

$$u[n+1] = (1 - \frac{t_s}{T_r}) \cdot u[n] + \frac{t_s}{T_r} \cdot (s - b \cdot v[n] + wtSum) \quad (1)$$

$$v[n+1] = (1 - \frac{t_s}{T_a}) \cdot v[n] + \frac{t_s}{T_a} \cdot y[n] \quad (2)$$

$$y[n+1] = \max(u[n+1], 0) \quad (3)$$

where u is the inner state of the neuron, s is an external input, v is a variable representing the degree of adaptation or self-inhibition effect of the neuron, b= 2.5 is the fatigue constant, and y is the output of the neuron. T_r = 0.2 and T_a = 0.2 are the rise time constant and adaptation time constant respectively, n is the time index and t_s = 0.0005s is the integration time step. The input "wtSum" represents the weighted sum of feedback signals to the neuron from the robot sensors, and possibly output from other neurons as well.

2.5 Oscillator schematics

Simplified block diagrams are used to represent basic oscillator units. The concept of reciprocal connections [22] is used to simplify the diagrams. Figure 2 shows the simplified diagram for the two-neuron mutually-inhibiting oscillator.

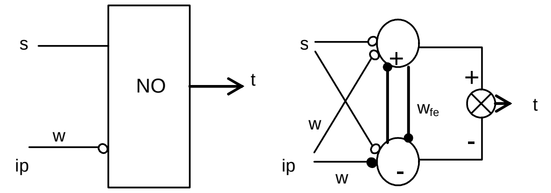

Figure 2: Simplified diagram (left) of a basic oscillator network (right). Excitatory connections increase the neuron inner state value, inhibitory connections decrease. Output of neural oscillator is the difference between outputs of the '+' and '-' neurons (extensor/flexor neurons). $w_{fe} = 2$.

The left and right hip pitch angles are 180° out of phase during walking. To produce this alternation between the movements of the two legs, the neurons from the left and right sides are made mutually inhibiting. Figure 3 shows the simplified block diagram for this network.

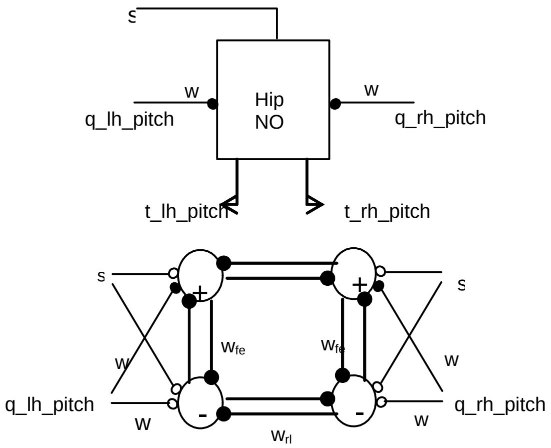

Figure 3: Simplified diagram (top) of the hip pitch neural network (bottom). Outputs "t_rh_pitch" and "t_lh_pitch" are the outputs of the right hip pitch oscillator and left hip pitch oscillator respectively. w_{rl} =2.

3 Hybrid controller

3.1 Single input oscillator network

An intuitive approach is used to build the oscillator network. It is postulated that the knee joints are reactive in nature and do not receive any direct control from the central nervous system. The knee joint movements are effected by the movement of the hips instead. The hip pitch joints on the other hand are controlled directly with the single control input, s. This input signals the system to start rhythm generation and also controls the amplitude of oscillation. Additional inputs to the hip oscillators shape how the rhythm generators oscillate. The final oscillator network obtained is shown in Figure 4. Note that the control input, s, is variable.

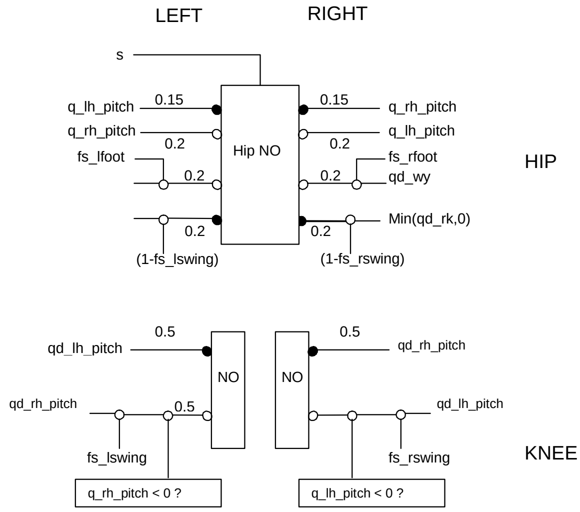

Figure 4: Oscillator network in hybrid control.

3.2 State-specific control

The ankle pitch, ankle roll and hip roll are not part of the oscillator network. This is a heuristic that is based on personal observations. Their control is mainly reactive, affected by the specific state that the leg is in. This means a completely intuitive way of formulating the controller can be used. In the following, the torque calculations for the right leg joints are shown. The left leg joints torque can be formulated by simply replacing the "r" with "l" (and vice versa) in the joints names.

Note the use of inequalities (in programming language style) as an abbreviation. The inequalities give a 1 if true, and 0 if false.

3.2.1 Ankle pitch

tau_ra_pitch =

20 (0 - ia_ra - 0.2 q_ra_pitch) - qd_ra_pitch

+ (qd_rh_pitch>0?)(1 - fs_rswing)[-5(0 - q_pitch)+qd_wy]

+ (ia_lk<0?) (fs_lswing) [8 (-0.3 - q_ra_pitch)]

The first line expresses the concept that the ankle tries to keep the foot parallel to the ground (by keeping foot inertial angle zero), together with the spring-damper system to maintain the ankle joint angle and velocity at zero.

The second line deals with the problem of the body pitching that seemed inherent when using the oscillator network. The ankle controls the body pitching only when the leg is moving backwards ("qd_rh_pitch>0?") and when the leg is not swinging. The need for such conditions was experimentally obtained. The ideal case is to express it as "when the leg is in support" ("fs_rfoot"), but this did not work satisfactorily.

The last line conveys the idea that the ankle will flex (to the desired angle of -0.3 radians) when the contralateral leg is extended ("ia_lk<0?") and in front of the body, but has not touched ground ("fs_lswing"). This is especially desired when moving down slopes.

3.2.2 Ankle roll

tau_ra_roll =

20 (0 - q_ra_roll) - 0.5 qd_ra_roll

+ (fs_rfoot) (1 - fs_lfoot) qd_wx

+ (q_lh_pitch>0?) (fs_lswing) [-5 (+0.1 - q_roll)]

The first line is the spring-damper system to maintain ankle roll at zero. The second line is for maintaining the body roll velocity (qd_wx) at zero (i.e. damping the body roll). This prevents the robot from falling sideways too quickly. The ankle exerts this control only when the foot is in support and the other foot is not. This rules out the state when the robot is standing.

The last line is characteristic of walking. The ankle controls the body to roll (q_roll) in order to give the other leg enough clearance to swing forward. Due to the reference frames convention, the right ankle rolls to make the body roll achieve +0.1 radians. For the left ankle, this will be -0.1 radians.

3.2.3 Hip roll

tau_rh_roll =

20 (0 - q_rh_roll) - qd_rh_roll

+ (fz_r>0.5robot_wt?) (fs_rfoot) (12 q_roll + 10 qd_wx)

The hip roll can simply be kept at zero for the robot to walk relatively well. The additional control, where the amount of force on the foot (fz_r) is used as a feedback signal, helps the robot deal with different loads.

The first line is the usual spring-damper system to maintain zero hip roll. The second line controls the body rolling when the foot is in support. The force on the foot must also be more than half the robot's weight for this control to kick in. This inherently means shifting the robot's weight over the supporting foot.

4 Results

With this hybrid controller, the robot achieved walking from standing and can continue walking indefinitely. By changing the control input, s, the walking speed of the robot can also be varied. It is capable of reaching a maximum average speed of 18cm/s. The robot legs are also able to carry loads of up to 1.5kg.

Using control input s = 0.8, the following walking gait is obtained. Figure 5 shows the initiation phase where the robot starts to walk from a standing position. Figure 6 shows the walking gait at "steady state".

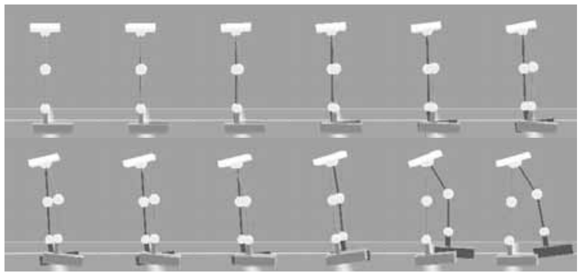

Figure 5: Walking initiation using hybrid controller.

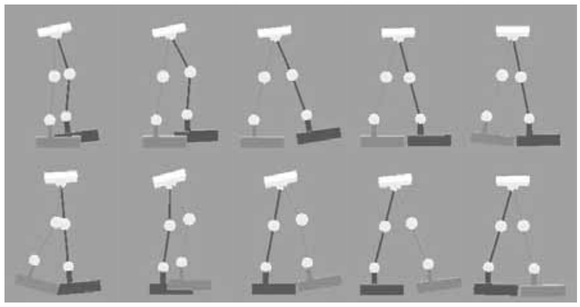

Figure 6: Walking gait with hybrid controller, s = 0.8.

The following phase plots for the pitch joints (Figure 7) show that stable limit cycle is obtained.

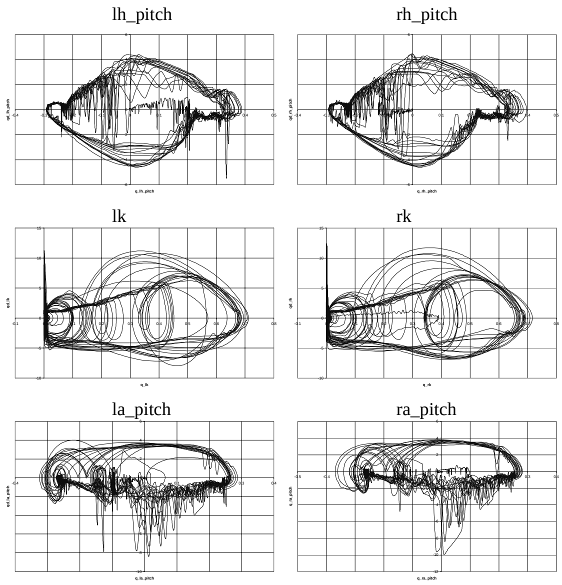

Figure 7: Phase plots of pitch joints for hybrid controller, s = 0.8.

Varying the value of control input s over time, we can see how the walking speed changes. Figure 8 shows the velocity in the x-direction plotted against time.

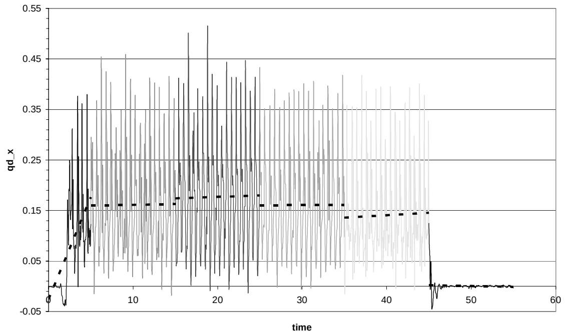

Figure 8: Graph of horizontal velocity (qd_x) against time. The walking cycle is split into 6 intervals. In the first 5 seconds, s = 0.75. This is for the robot to start walking and build up speed. The next 4 intervals are 10s each and the control input values are 1, 1.25, 1 and 0.75 respectively. In the final interval, the control input is set back to 0. The average speed for each interval is given by the dotted lines.

It can be seen that the maximum average speed is about 0.18m/s. This is actually quite fast, considering that the actual robot RoboSapien took 25s to complete the 1.2m "Dash" in one trial during the HUROSOT competition.

5 Conclusion

A hybrid controller was proposed in this paper. It is able to control walking from standing. It remains to be seen if it is completely robust to uneven terrain. Implementation on the actual RoboSapien is the next step to be done. It would be interesting to know if a combination of oscillator network and heuristic dynamics-based controller would give better results than current methods of biped walking control.

6 References

[1] K. Hirai, M. Hirose, Y. Haikawa and T. Takenaka, "The development of Honda humanoid robot.", *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp 1321–1326 (1998).

[2] J. Rose and J. G. Gamble, *Human walking*, Williams and Wilkins. (1994).

[3] E. Nicholls, "Bipedal dynamic walking in robotics", *Honours Thesis, The University of Western Australia* (1998).

[4] R. Zhang and V. Prahlad, "An evolutionary algorithm for trajectory based gait generation of biped robot", *Proceedings of the International Conference on Computational Intelligence, Robotics and Autonomous Systems* (2003)

[5] R. Zhang, V. Prahlad and C. M. Chew, "Development and walking control of a biped robot", *submitted to IEEE Transactions on Mechatronics*

[6] M. Hardt, O. von Stryk, D. Wollherr and M. Buss, "Development and Control of Autonomous, Biped Locomotion using Efficient Modeling, Simulation, and Optimization Techniques", *Proceedings of the IEEE/ASME International Conference on Robotics and Automation*, pp 1356–1361 (2003)

[7] A. L. Kun and W. T. Miller, "Control of Variable Speed Gaits for a Biped Robot.", *IEEE Robotics and Automation Magazine 6, No. 3*, pp 19-29 (1999).

[8] W. T. Miller, "Real-Time Neural Network Control of a Biped Walking Robot.", *IEEE Control Systems Magazine*, pp 41-48 (1994).

[9] A. W. Salatian, K. Y. Yi and Y. F. Zheng, "Reinforcement Learning for a Biped Robot to Climb Sloping Surfaces.", *Journal of Robotic Systems 14, No. 4*, pp 283-296 (1997).

[10] J. G. Juang, "Fuzzy neural network approaches for robotic gait synthesis.", *IEEE Transactions on Systems, Man and Cybernetics – Part B: Cybernetics 30, No. 4,* pp 594-601 (2000).

[11] K. Wolff and P. Nordin, "Evolution of efficient gait with an autonomous biped robot using visual feedback", *Proceedings of the 8th Mechatronics Forum International Conference 2002*, pp 504-513 (2002)

[12] S. H. Collins, M. Wisse and A. Ruina, "A three-dimensional passive-dynamic walking robot with two legs and knees.", *International Journal of Robotics Research 20, No. 7,* pp 607-615 (2001).

[13] J. E. Pratt, "Exploiting inherent robustness and natural dynamics in the control of bipedal walking robots", *PhD Thesis, Massachusetts Institute of Technology*, (2000).

[14] J. E. Pratt and G. A. Pratt, "Exploiting natural dynamics in the control of a 3D bipedal walking simulation", *International Conference on Climbing and Walking Robots (CLAWAR99)*, (1999)

[15] S. P. Allen, "Control of a simulated, three-dimensional bipedal robot to initiate walking, continue walking, rock side-to-side, and balance", *Master's Thesis, Massachusetts Institute of Technology,* (2000).

[16] F. Asano, M. Yamakita, N. Kamamichi and Z. W. Luo, "A Novel Gait Generation for Biped Walking Robots Based on Mechanical Energy Constraint" , *Proceedings of the IEEE/RSJ Intl. Conference on Intelligent Robots and Systems 3*, pp 2637-2644. (2002)

[17] F. Asano, Z. W. Luo and M. Yamakita, "A unified formulation and solutions to gait generation problems based on passive dynamic walking", *International Conference on Climbing and Walking Robots (CLAWAR03),* (2003)

[18] J. Duysens and H. W. A. A. Van de Crommert , "Neural control of locomotion Part 1: The central pattern generator from cats to humans.", *Gait and Posture 7*, pp 131-141 (1998).

[19] K. Matsuoka, "Sustained oscillations generated by mutually inhibiting neurons with adaptation.", *Biological Cybernetics 52*, pp 367-376 (1985).

[20] T. Iwasaki and M. Zheng, "The Lur'e model for neuronal dynamics.", *Proceedings of IFAC World Congress*, (2002).

[21] B. J. West and N. Scafetta, "Nonlinear dynamical model of human gait.", *Physical Review 67*, pp 1-10 (2003).

[22] G. Taga, Y. Yamaguchi and H. Shimizu, "Self-organized control of biped locomotion by neural oscillators in unpredictable environment.", *Biological Cybernetics 65*, pp 147-159 (1991).

[23] G. Taga, "A model of the neuro-musculo-skeletal system for human locomotion. I. Emergence of basic gait.", *Biological Cybernetics 73*, pp 97-111 (1995a).

[24] G. Taga, "A model of the neuro-musculo-skeletal system for human locomotion. II. Real-time adaptability under various constraints.", *Biological Cybernetics 73*, pp 113-121 (1995).

[25] S. Miyakoshi, G. Taga, Y. Kuniyoshi and A. Nagakubo, "Three dimensional bipedal stepping motion using neural oscillators – towards humanoid motion in the real world.", *Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp 84-89.

[26] Y. Fukuoka, H. Kimura and A. H. Cohen, "Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts.", *International Journal of Robotics Research 22, No. 3-4*, pp 187-202 (2003).

[27] H. Kimura, S. Akiyama and K. Sakurama, "Realization of dynamic walking and running of the quadruped using neural oscillator.", *Autonomous Robots ??*, pp 1-9 (??).

[28] M. Asada, Y. Katoh, M. Ogino and K. Hosoda, "A humanoid approaches to the goal – reinforcement learning based on rhythmic walking parameters.", *Proceedings of the International Symposium of RoboCup2003*, (2003).

[29] S. Ok, "Evolution of neural system with sensory feedback for bipedal locomotion", *Proceedings of the International Conference on Computational Intelligence, Robotics and Autonomous Systems*, (2003)

[30] R. Zhang, V. Prahlad and K. W. Chan, "Mechanical design and control system configuration of RoboSapien humanoid robot", *Proceedings of the International Conference on Computational Intelligence, Robotics and Autonomous Systems*, (2003)