INTELLIGENT CONTROL TECHNIQUES FOR HUMANOID ROBOTS

Duško KATIĆ **Miomir VUKOBRATOVIĆ**
Robotics Laboratory, Mihailo Pupin Institute
P.O.Box 15, Volgina 15, 11000 Belgrade, Yugoslavia
fax: +381 - 11 - 775 - 870; e-mail:dusko,vuk@robot.imp.bg.ac.yu

Keywords: Humanoid Robots, Neural Networks, Fuzzy Logic, Genetic Algorithms

Abstract

This paper focuses on the application of the intelligent control techniques (neural networks, fuzzy logic and genetic algorithms) and their hybrid methods (neuro-fuzzy networks, neuro-genetic and fuzzy-genetic algorithms) in the area of humanoid robotic systems. This paper represents an attempt to give a report of the basic principles and concepts of intelligent control in humanoid robotics, with an outline of a number of recent algorithms used in advanced control of humanoid robots.

1 Introduction

Many aspects of modern life involve the use of intelligent machines capable of operating under dynamic interaction with its environment. The field of biped locomotion is representative of this interest concerning human-like robots [1], [2]. The main reasons for designing the humanoid robots as service and maintenance machines is to help us humans enjoy life and to relieve us of many of the mundane noncreative tasks which we all face every day. Recently, significant progress has been made in the design of a hardware platform of a humanoid robot and control of humanoid robots, particularly in the realization of dynamic walking in several full-body humanoids [3], [4] , [5]. It is as obvious as interesting that anthropomorphic biped robots are potentially capable to effectively move in all unstructured environments where humans do.

In order to accomplish high and complex demands, which they have as service machines, humanoid robots must incorporate the intelligent capabilities. Intelligent humanoid robots are functionally oriented devices built to perform sets of tasks instead of humans, as autonomous systems capable of extracting information from its environment and using knowledge about its world and intelligence of their duties and proper governing capabilities. Human operator can transfer to the robot his knowledge, experience and skill in advance, to make it capable of solving complex tasks.

Naturally, the first approach to making humanoid robots more intelligent was the integration of sophisticated sensor systems. However, today's sensor products are still very limited in interactivity and adaptability to changing environments. On the other hand, in to design robots and systems that best adapt to their environment, research includes investigations in the field of mechanical robot design, environment perception systems and embedded intelligent control. Also, in the case when the robot performs in an unknown environment, the previous knowledge may not be sufficient. Hence, the robot has to adapt to the environment and to be capable of acquiring new knowledge through the process of learning.

Connectionist theory (NN - neural networks), fuzzy logic (FL), and theory of evolutionary computation (GA - genetic algorithms), are of great importance in the development of intelligent humanoid robot control algorithms. Each of the proposed paradigms has their own merits and drawbacks. To overcome their drawbacks, certain integration and synthesis of hybrid techniques (symbiotic intelligence) are important for efficient application in humanoid robotics.

2 Control Problems in Humanoid Robotics

In spite of significant progress in the area of humanoid robots, a lot of work has still to be done in order to improve actuators, sensors, materials, energy accumulator, hardware and control software that can be utilized to realize user-friendly biped robots. We are still in a initial stage in understanding the motor control principles and the sensory integration subjacent to human walking. The major problems associated with the analysis and control of bipedal systems are the high-order highly coupled nonlinear dynamics and furthermore, the discrete changes in the dynamic phenomena due to the nature of the walking gait. At the same time, the degree of freedom formed between the foot and the ground is unilateral and underactuated, so it is necessary to synthesize control method for underactuated degrees of freedom. Also, the control algorithm must accomplish stable, fast and reliable performance considering different characteristics of walking and running.

Walking biped robots can be classified in three different categories. First category represents static walkers, whose motion is very slow so that system's stability is completely described by the normal projection of the Center of Gravity, which only depends on joint's position. Second category represents dynamic walkers, biped robots with feet and actuated ankles. These walkers are potentially able to move in a static way, provided that they have large enough feet and motion is slow. Third categpry represents purely dynamic walkers, robots without feet. In this case the support polygon during the single-support phase is reduced to a point so that static walking is not possible. With walking with dynamic balance, the projected center of mass is allowed outside of the area inscribed by the feet and the walker may essentially to fall during parts of the walking gait. The control problems for dynamic walking are more complicated than for walking with static balance, but dynamic walking patterns provide higher walking speed and great efficiency with more versatile walking structures. For all mentioned categories of walking robots, issue of stable and reliable biped walk is the most fundamental and yet unsolved with a high degree of reliability. The question has motivated the definition of several dynamic-based criteria for the evaluation and control of balance in biped locomotion. The most common criteria is a zero moment point (ZMP) [6].

A humanoid robot is however, a kind of integrated machines: two arm and two leg mechanism. Hence, we must not only focus locomotion function but also arm's function for this kind of machines. From this point of the view, it is necessary to develop advanced control methods for mobile manipulation of humanoid robots.

Biological investigations suggest that human's rhythmic walking is the consequence of combined inherent patterns and reflexive actions. The inherent dynamic pattern is rhythmic and periodic. It is considered as an optimal feedforward motion pattern acquired through development in the typical walk environments without disturbances. The reflexive action is a rapid response due to the feedback control using sensory information. The reflexive action determines stability against unexpected events such as external disturbances or ground irregularity. In this case, capabilities of adaptability and compensation of external disturbances must be included in advanced control algorithms.

3 Connectionist Control Algorithms in Humanoid Robotics

Recently, some researchers have begun considering the use of neural networks for control of humanoid walking [7], [8], [9], [10]. The various type of neural networks are used for gait synthesis and control design of humanoid robot as it is multilayer perceptrons, CMAC networks, fuzzy-neural network, RBF networks or Hopfield networks, that are trained by supervised or unsupervised (reinforcement) learning methods. The neural networks were used as efficient tool for solution of synthesis and off-line and on-line adaptation of biped gait as well as for solution the control problem of static and dynamic balance during process of walking and running on terrain with different environment characteristics.

Kitamura et all. [11] proposed a walking controller based on Hopfield neural network in combination with an inverted pendulum dynamic model.

Salatian et al. [12] studied off-line and on-line reinforcement technique for adapting a gait designed for horizontal surfaces in order to walk on sloping surfaces. They considered humanoid robot with 8 d.o.f and two force sensors on both foot. The control structure includes gait trajectory synthesizer and adaptive neural unit that are tuning by reinforcement signal from force sensors on the foot. The neuron unit includes more neurons with inhibitory/excitatory inputs from sensor unit. These control algorithms without considering kinematic and dynamic model of humanoid robot were evaluated only using a biped dynamic simulation.

More recently Miller [8],[9] has developed a hierarchical controller which combines simple gait oscillators, classical feedback control techniques and neural network learning and does not require detailed equations of the dynamics of walking. The emphasis is on the real-time control studies using an experimental ten axis biped robot with foot force sensors. There are 3 different CMAC neural networks for humanoid posture control. The Front/Back Balance CMAC neural network was used to provide for front/back balance during standing, swaying and walking. The training of this network is realized using data from foot sensors. The second CMAC neural network is used for Right/Left Balance in order to predict the correct knee extension required achieving sufficient lateral momentum for lifting the corresponding foot for the desired length of time. The training of this network is realized using temporal difference method based on error between desired and real time of foot rising. The third CMAC network is used to learn kinematically consistent robot postures. In this case, training is also realized by data from foot sensors.

The results indicate that experimental biped was able to learn the closed chain kinematics necessary to shift body weight from side-to-side while maintaining good foot contact. Also it was able to learn the quasistatic balance required to avoid falling forward or backward while shifting body weight from side-to-side at different speeds. It was able to learn the dynamic balance in order to lift a foot off the floor for a desired length of time and different initial conditions. There are many limitations (limited step length, slow walking, no adaptation for left-right balance, no possibility for walking at the sloping surface), hence in the paper [9], the upgrade and improvement of the proposed approach was realized. The new dynamically balance scheme for handling variable-speed gait was proposed that use preplanned but adaptive motion sequences in combination with closed-loop reactive control. There are new sensors (piezoresistive accelerometers and two solid-state rate gyroscope) which are mounted on the new UNH biped (Fig.1). The control structure on high-level control level include 7 components: gait generator, simple kinematics block and 5 CMAC controllers. The CMAC neural network are used for compensation of right and left lift lean angle correction, reactive front-back offset, right-left lean correction, right and left ankle - y correction and front-back lean correction. Training of neural network is realized through process of temporal difference learning using information about ZMP from robot foot sensors. The control structure on the lower control level include reactive lean angle control together with PID controller. The experimental results indicate that UNH biped robot can walk with forward velocities of the range (21cm/min - 72cm/min) with sideways leaning speed of the range (3.6 o/s - 12.5 o/s).

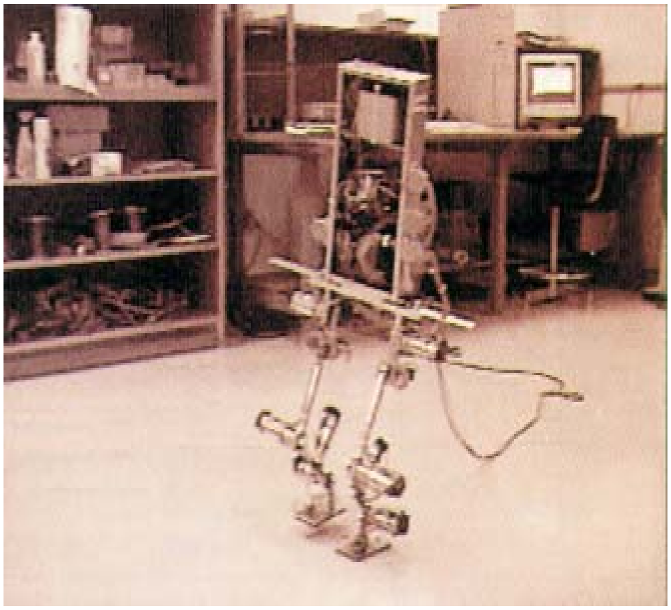

Figure 1: The UNH biped

The previously used CMAC controller is particularly good option for robotic motor control. It has quality of fast learning and simple computations in comparison with multilayer perceptrons and similar approximation capabilities as radial basis function networks. But there are problems with large memory requirements, function approximation and stability of dynamic walking. These problems are addressed in the paper [15] where self-organizing CMAC neural network structure is proposed for biped control based on a data clustering technique together with adaptation of basic control algorithm. In this case, memory requirements are drastically reduced and globally asymptotic stability is achieved in a Lyapunov sense. The structural adaptation of the network centers is realized to ensure adaptation to unexpected dynamics. Although robustness was enhanced in terms of height and pitch tracking as well as external disturbance rejection, the adaptive controller does not guarantee the long-term stability of the walking gait.

Wang et al.[10] has developed a hierarchical controller for a three-link two-legged robot. His approach uses the equations of motion, but only for the training of the neural networks, rather than to directly control the robot. Authors used very simplified model of biped with decoupled frontal and sagittal plane. There are 3 neural network (multilayer perceptrons) for control of leg on the ground, control of leg in the air and for body regulation. Training algorithm is standard back propagation algorithm based on error between decoupled supervising control law and output of all three neural networks. There are no feedback in real time control, hence it is great problem in the case when system uncertainties exist.

Beside considering the walking control problem, very little research has been done on the intelligent control of running control problem. Doerschuk et all [7] presented an adaptive controller to control the movement of simulated jointed leg during a running stride (uniped control). The main idea of this approach is using the modularity, i.e. using of separate controllers for each phase of the running stride (takeoff, ballistic, landing) thus allowing each to be optimized for the specific objective of its phase. In takeoff phase, objective of the controller to realize inverse feedforward control. The controller learns from experience to produce the control signals that will produce the desired height, distance and angular momentum. Three different types of neural networks are investigated (multi layer perceptrons, Cerebellar Model Articulation Controller (CMAC) and neuro-fuzzy nets). It was concluded that neuro-fuzzy nets achieve more accurate results that both others methods. The neuro-fuzzy takeoff controller very accurately controls the angular momentum of the stride after only two learning iterations. The ballistic controller controls the movement of the leg while the foot is in the air. The ballistic controller combines neural network learning with classic PD control. It is typical feedback error learnig schema. The controller learn the dynamic model of leg from experience generated by PD controller and improved upon its performance. CMAC controller is used for neural network learning part with possibility to very accurate control the movement of the leg along a target trajectory even during the first attempt. Ballistic learning is on-line method without the need for precomputed examples. This enables the great humanoid robot adaptability to various changes and new conditions.

The neural networks can be efficiently used for generation of trajectories (gait) of humanoid robots [14], [13]. For example, Juang and Lin [13] used back propagation through time algorithm for gait synthesis of a biped robot. The complex inverse dynamic computations were eliminated by using linearized inverse biped model.

4 Fuzzy control algorithms in humanoid robotics

As one of methodologies applied for biped gait synthesis and control of biped walking, some researchers used the fuzzy logic [16], [17]. Fuzzy logic were used dominantly as part of control systems on the executive control level, for generation and tuning PID gains, fuzzy control supervising, direct fuzzy control by supervised and reinforcement error signals. In paper [16], fuzzy logic is applied at the level of local control for tuning of gains of local PID controller, while the complete control structure includes nominal feedforward control (based on dynamic model of biped), also. It have showed that aggregation-decomposition method for stability analysis of complete biped system is applicable in the cases when local subsystems are stabilized with fuzzy regulators.

The problem of biped gait synthesis using the reinforcement learning with fuzzy evaluative feedback is considered in [17]. As first, initial gait from fuzzy rules is generated using human intuitive balancing scheme. Simulation studies showed that the fuzzy gait synthesizer can only roughly track the desired trajectory. A disadvantage of the proposed method is the lack of practical training data. In this case there are no numerical feedback teaching signal, only evaluative feedback signal exists (failure or success), exactly when the biped robot falls (or almost falls) down. Hence, it is a typical reinforcement learning problem. The dynamic balance knowledge is accumulated through reinforcement learning constantly improving the gait during walking. Exactly, it is fuzzy reinforcement learning that uses fuzzy critical signal. For human biped walk, it is typical to use linguistic critical signals such as ”near-fall-down”, ”almost-success”, ”slower”, ”faster”, etc. In this case, the gait synthesizer with reinforcement learning is based on a modified GARIC (Generalized Approximate Reasoning for Intelligent Control) method. This architecture of gait synthesizer consists of three components: action selection network (ASN), action evaluation network (AEN), and stochastic action modifier (SAM) (Figure 2). The ASM maps a state vector into a recommended action using fuzzy inference. The training of ASN is achieved as with standard neural networks using error signal of external reinforcement. The AEN maps a state vector and a failure signal into a scalar score which indicates the state goodness. It is also used to produce internal reinforcement. The SAM uses both recommended action and internal reinforcement to produce a desired gait for the biped. The reinforcement signal is generated based on the difference between desired ZMP and real ZMP in the x-y plane. In all cases, this control structure includes on-line adaptation of gait synthesizer and local PID regulators. The approach is verified using simulation experiments. In the simulation studies, only even terrain for biped walking is considered, hence the approach should be verified for irregular and sloped terrain. In the Figure 2 $Xzmp, Yzmp$ are the ZMP coordinates; $\theta^d_{zmp}, \theta^d_{zmp}$ are the desired joint angles of the biped gait.

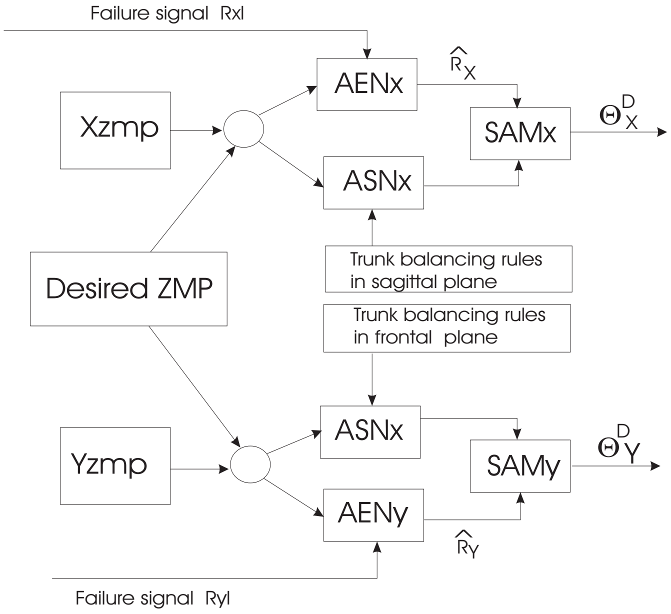

Figure 2: The architecture of the reinforcement learning based gat synthesizer

5 Genetic Approach in Humanoid Robotics

With locomotion robots, GA can be efficiently applied for hierarchical trajectory generation of natural motion of biped using energy optimization [18]. The hierarchical trajectory generation method consists of two layers, one is the GA level which minimizes the total energy of all actuators and the other is the evolutionary programming (EP) layer which optimizes the interpolated configuration of biped locomotion robots. The chromosome in the EP level represents the interpolated configuration expressed by 12 state variables (angles) of the biped. Also, a chromosome in a GA level consists of two parts, the first of them representing the set of interpolated configurations, while the second part includes a bit which represents the effectiveness of configuration (0 or 1). The process runs in cyclic procedure through the application of mutation and selection at the EP level, transfer of generated interpolated configuration into the GA level, and complete evolution process through crossover, mutation, evaluation and selection at the GA level. The fitness function at the GA level is connected to the optimization of total robot energy in order to ensure the natural movement of biped. The fitness function also contains some constraints related to the robot motion. The final result represents the optimized trajectory similar to natural human walking that was demonstrated by experiment.

Another example is the application of GA to PD local gain tuning and determination of nominal trajectory for dynamic biped walking [19]. The biped with 5 links is considered. In the proposed GA, 19 controller gains and 24 final points for determination of nominal trajectory are taken into account. Designs to attain different goals, such as the capability of walking on an inclined surface, walking at high speed, or walking with specified step size, have been evolved with the use of GA. The fitness functions are connected to total time of effective walking, average speed of biped body and the size of the walking step. Total number of generation for problem solving was between 10 and 60 generations. The research showed excellent results in the evaluation of control parameters as well as in optimization of mechanical design of biped.

6 Hybrid Intelligent Approaches in Humanoid Robotics

Hybrid soft-computing methods because their complementary capabilities find the place in the research of gait synthesis and control of humanoid robots, also. In paper [20], a learning scheme based on a neuro - fuzzy controller, for generation of walking gaits is presented. The learning scheme uses a neuro-fuzzy controller combined with a linearized inverse biped model. The training algorithm is *backpropagation through time*. The linearized inverse biped model provides the error signals for backpropagation through the controller at control time instants. For the given prespecified constraints such as the step length, crossing clearance, and walking speed, the control scheme can generate the gait that satisfies all mentioned constraints.

GA has been efficiently applied in robotic neuro approaches, as in the case of the neuro-GA controller for visually-guided swing motion of a biped with 16 DOFs [21]. The aim of this robot task is learning of swing motion by neural network using visual information from a virtual working environment. Instead of a real biped, virtual working environment is used for acceleration of the learning process. As we transfer the learning process from the virtual environment to the real robot, the difference existing between these two systems are neutralized by generalization capabilities of the neural network. The aim of learning for visually guided swing motion is increasing the swing amplitude by skillful change of the gravity center of the biped robot in the direction of swing radius, caused by dynamic change of the environment recognized by the vision sensor. The input to the network represents sensor information from the vision sensor, while the output of the neural network are the knee angles of the biped (Fig.3). GA optimizes the three sets of the weighting factors of this 4-layer neural network. At the output of the network, there are limiters of angular velocities in order to avoid extreme changes of joint angles. The genotype is represented by a sequence of weighting factors. The number of individuals in the initial population is 200. The fitness function is represented by the height of the center of gravity in the initial and final pose. The evolution simulation experiments are terminated when the number of alternations in generations reaches 50 alternations. The results show efficient learning of swing motion through successive generation that is verified through generalization experiments on the real robot biped.

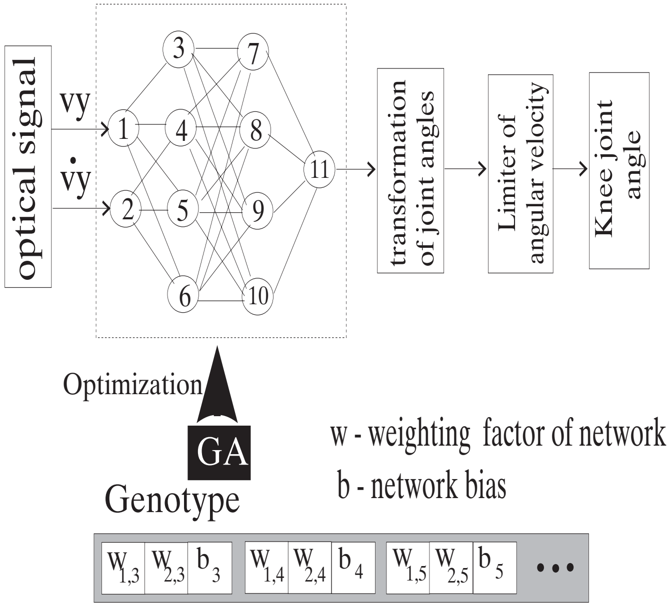

Figure 3: Neuro-GA approach for optimization

In the paper [22] the authors deal with a GA application for the determination of weighting factors of a recurrent neural network in order to generate a stable biped gait. The input to the network is the information about position of zero moment point (ZMP) taken from the force sensor, while the output of the network is the correction angles and correction velocities needed for a stable motion (Fig.4). Only self-mutation is used from the set of genetic operators based on addition of the Gauss noise with multiplication by the value of fitness function. The elite selection is chosen, while the fitness function is defined by the sum of squares of the deviations of the desired coordinates from the ZMP coordinates. The motion on the inclined surfaces is investigated, with initial population of 50 different individuals. It is shown that the use of this approach yields a stable biped gait.

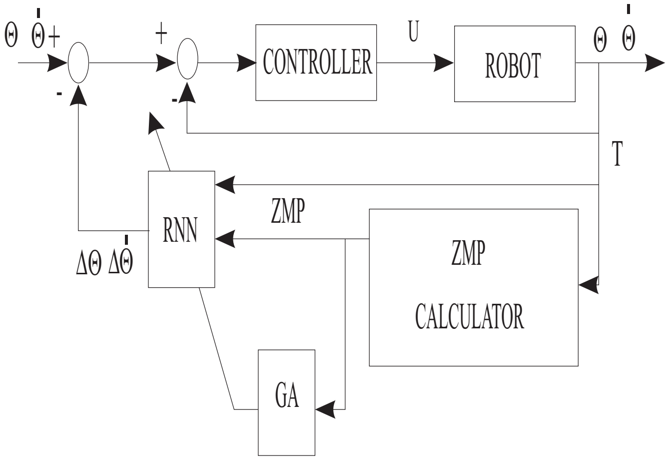

Figure 4: Stabilization Biped Control

7 Conclusions

In spite of the intensive development and experimental verification of various humanoid robots, it is important to further improve their capabilities using advanced hardware and control software solutions to make humanoid robots more autonomous, intelligent and adaptable to the environment and humans. The presented survey indicates that the intelligent techniques, if applied in an appropriate manner, can be very powerful tools for attaining these goals.

The neural networks were used for the synthesis and on-line adaptation of biped gait, as well as for the control of humanoid robots to ensure static and dynamic balance during the process of walking and running on the terrain with different environment characteristics. The main advantages are the compensation of system's uncertainties and the inclusion of learning capabilities. The majority of the proposed control algorithms were verified by simulation, while there were few experimental verification on real biped and humanoid robots. Besides, the inclusion of complex nonlinear models in real-time control, limited realized steps and slow walking are the problems in implementation of connectionist control algorithms. Fuzzy logic was used mainly as part of control systems on the executive control level, for generation and efficient tuning of PID gains and direct fuzzy control by supervised and reinforcement error signals. The main problem in using fuzzy control algorithms for biped robots remains the inclusion of a complex dynamic model and learning capabilities. The GA represents an efficient tool for searching the optimised solutions of gait synthesis and biped control, the main problem being how to cope with the reduction of GA optimisation process in real time and preserve stability of the motion. The hybrid methods using complementary characteristics of intelligent techniques have a great potential in the field of intelligent humanoid robots. An important idea from the area of artificial life is the use of simultaneous evolution of the robot design and control.

References

[1] K. Hirai, M.Hirose, Y.Haikawa, T.Takenaka, The Development of Honda Humanoid Robot, *Proceedings of the IEEE International Conference on Robotics and Automation*, Leuven, pp. 1321-1326, May 1998.

[2] P. Sardain, M.Rostami, G.Bessonnet, An Anthropomorphic Biped Robot: Dynamic Concepts and Technological Details, *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, vol.28, No.6, November 1998, pp.823-838.

[3] www.world.honda.com/robot

[4] F.Yamazaki, T.Matsui, T.Miyashita, H.Kitano, PINO The Humanoid That Walk,*Proceedings of the First IEEE-RAS International Conference on Humanoid Robotis*, 2000.

[5] www.symbio.jst.go.jp

[6] M.Vukobratović, How to control the Artificial Anthropomorphic Systems, *IEEE Transactions on Systems, Man and Cybernetics*, Vol.3, pp.497-507, 1973.

[7] P.I.Doerschuk, W.E.Simon, V.Nguyen, A.Li, A Modular Approach to Intelligent Control of a Simulated Jointed Leg, *IEEE Robotics and Automation Magazine*, Vol.5, No.2, June 1998, pp.12-21.

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

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

[10] H.Wang, T.T.Lee, W.A.Gruver, A Neuromorphic Controller for a Three Link Biped Robot, *IEEE Transactions on Systems, Man and Cybernetics*, vol.22, no.1, January/February 1992, pp.164-169.

[11] S.Kitamura, Y.Kurematsu, Y.Nakai, Application of the Neural Network for the Trajectory Planning of a Biped Locomotion Robot, *Neural Networks*, vol.1, pp.344-356, 1988.

[12] W.Salatan, K.Y.Yi, Y.F.Zheng, Reinforcement Learning for a Biped Robot to Climb Sloping Surfaces, *Journal of Robotic Systems*,Vol.14, No.4, April 1997, pp.283-296.

[13] J-G.Juang, C-S.Lin, Gait Synthesis of a Biped Robot Using Backpropagation Through Time Algorithm, *Proceedings of the IEEE International Joint Conference on Neural Networks*, Washington,D.C.pp.1710-1715,1996.

[14] Y.Kurematsu, O.Katayama, M.Iwata, S.Kitamura, Autonomous Trajectory Generation of a Biped Locomotive Robot, *Proceedings of the IEEE International Joint Conference on Neural Networks*, pp.1983-1988,1991.

[15] J.Hu, J.Pratt, G.Pratt, Stable Adaptive Control of a Bipedal Walking Robot with CMAC Neural Networks, Proceedings of the 1999 IEEE International Conference on Robotics and Automation, Detroit, May 1999, pp.1950-1956.

[16] M.Vukobratović, O.Timčenko, Stability Analysis of Certain Class of Bipedal Walking Robots with Hybridization of Classical and Fuzzy Control, *Proceedings of the 1st ECPD International Conference on Advanced Robotics and Intelligent Automation*, Athens, pp.290-295,1995.

[17] C.Zhou, Q.Meng, Reinforcement Learning with Fuzzy Evaluative Feedback for a Biped Robot,*Proceedings of the IEEE International Conference on Robotics and Automation*,San Francisko, pp.3829-3834, 2000.

[18] T.Arakawa, T.Fukuda, Natural Motion Generation of Biped Locomotion Robot Using Hierarchical Trajectory Generation Method Consisting of GA,EP Layers, *Proceedings of the IEEE International Conference on Robotics and Automation*, Albuquerque, pp.211-216, April 1997.

[19] M-Y.Cheng, C-S.Lin, Genetic Algorithm for Control Design of Biped Locomotion,*Journal of Robotic Systems*, Vol.14, No.5, pp.365-373, May 1997.

[20] J-G.Juang, Fuzzy Neural Network Approaches for Robotic Gait Synthesis,*IEEE Transactions on Systems,Man and Cybernetics,Part B: Cybernetics*, Vol.30, No.4, pp. 594-601, 2000.

[21] K.Nagasaka, A.Konno, M.Inaba, H.Inoue, Acquisition of Visually Guided Swing Motion Based on Genetic Algorithms and Neural Networks in Two-Armed Bipedal Robot, *Proceedings of the IEEE International Conference on Robotics and Automation* , Albuquerque , pp. 2944-2949, April 1997.

[22] T.Fukuda, Y.Komata, T.Arakawa, Stabilization Control of Biped Locomotion Robot Based Learning with GAs having Self-adaptive Mutation and Recurrent Neural Network, *Proceedings of the IEEE International Conference on Robotics and Automation*, Albuquerque, pp. 217-222, April 1997.