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Survey of Intelligent Control Techniques for Humanoid Robots

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Abstract. This paper focusses on the application of intelligent control techniques (neural networks, fuzzy logic and genetic algorithms) and their hybrid forms (neuro-fuzzy networks, neuro-genetic and fuzzy-genetic algorithms) in the area of humanoid robotic systems. It represents an attempt to cover 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. Overall, this survey covers a broad selection of examples that will serve to demonstrate the advantages and disadvantages of the application of intelligent control techniques.

Key words: humanoid robots, neural networks, fuzzy logic, genetic algorithms.

1. Introduction

Many aspects of modern life involve the use of intelligent machines capable of operating under dynamic interaction with their environment. In view of this, the field of biped locomotion is of special interest when human-like robots are concerned. Humanoid robots as anthropomorphic walking machines have been in operation for more than twenty years. Currently, research on humanoid robots and biped locomotion is one of the most exciting topics in the field of robotics. There are more than 50 major humanoid robot projects around the world, along with many other bipedal walking projects (an extensive list of projects is given at the site `www.androidworld.com`). The reason for increasing research interest in this domain is that major application areas have become self-evident. Humanoid robots are expected to be servants and maintenance machines with the main task to assist human activities in our daily life and to replace humans in hazardous operations. It is as obvious as interesting that anthropomorphic biped robots are potentially capable to effectively move in all unstructured environments where humans do. Hence, particularly, the fields of service robotics, medical applications, and operation in hazardous environments are of primary importance. Another important reason for the growth of humanoid robots research represents the development of advanced technologies in design and production of robot sensors, actuators and computing units.

Recently, significant progress has been made in the design of a hardware platform for humanoid robots and control of humanoid robots, particularly in the realization of dynamic walking in several full-body humanoids (`www.world.honda.com/robot`; Yamazaki et al., 2000; Hirai et al., 1998; Yamaguchi et al., 1998; Hirai, 1997; Sardain et al., 1998). The major class of humanoid robots use electric motors as actuators, while some types operate with fluidic (pneumatic) actuators (Schulz and Bretthauer, 2001; Klute et al., 1999). For example, still in 1986, HONDA (`www.world.honda.com/robot`) commenced the humanoid research and development program, which resulted in a series of robot prototypes (P1, P2, P3 and ASIMO). Key elements of the HONDA humanoid robot development included "intelligence and mobility" with intention to use humanoid robot in daily life, rather than a robot purpose-built for special operations. The design includes two-foot/leg mobility technology to make it compatible with most types of terrain, including very rough surfaces. Kitano's Symbiotic Systems Project team (`www.symbio.jst.go.jp`) has joined electronic component maker Murata Manufacturing in developing "Morph", Bluetooth-enabled humanoid robot. With full duplex data transmission at 720 kbps, Bluetooth could allow robots to be remotely controlled in real time while sending video images or sensor data to an operator, an advantage as mobile humanoid robots are envisioned for dangerous search and rescue operation. At the Institute of Applied Mechanics, Technical University of Munich, Germany, humanoid robot JOHNNIE (Pfeiffer et al., 2002) was designed that can already walk with intention to run.

Humanoid robot applications usually demand the robot be highly intelligent. Intelligent humanoid robots are functionally oriented devices, built to perform sets of tasks instead of humans. They are autonomous systems capable of extracting information from their environments and using knowledge about the world and intelligence of their duties and proper governing capabilities. Intelligent humanoid robots should be autonomous to move safely in a meaningful and purposive manner, i.e. to accept high-level descriptions of tasks (specifying what the user wants to be done, rather than how to do it) and would execute them without further human intervention. They have to be intelligent to determine all possible actions in an unpredictable dynamic environment using information from various sensors. Human operator can transfer to the robot his knowledge, experience and skill in advance, to make it capable of solving complex tasks. Future humanoid robots are likely to have greater sensory capabilities, more intelligence for valid reasoning and decision making, higher levels of manual dexterity and adequate mobility as compared to humans.

Naturally, the first approach to making humanoid robots more intelligent was the integration of sophisticated sensor systems as computer vision, tactile sensing, ultrasonic and sonar sensors, laser scanners and other smart sensors. However, today's sensor products are still very limited in interactivity and adaptability to changing environments. As the technology and algorithms for real-time 3D vision and tactile sensing improve, humanoid robots will be able to perform tasks that involve complex interaction with the environment (e.g., grasping and manipulating the objects). A major reason is that uncertainty and dynamic changes make the development of reliable artificial systems particularly challenging. On the other hand, to design robots and systems that best adapt to their environment, the necessary research includes investigations in the field of mechanical robot design (intelligent mechanics), environment perception systems and embedded intelligent control that ought to cope with the task complexity, multi-objective decision making, large volume of perception data and substantial amount of heuristic information. Also, in the case when the robot performs in an unknown environment, the 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. The robot learning is essentially concerned with equipping robots with the capacity of improving their behaviour over time, based on their incoming experiences.

There are several intelligent paradigms that are capable of solving intelligent control problems in humanoid robotics. 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. Due to their strong learning and cognitive abilities and good tolerance of uncertainty and imprecision, intelligent techniques have found wide applications in the area of advanced control of humanoid robots. Also, of great importance in the development of efficient algorithms are the hybrid techniques based on the integration of particular techniques such as neuro-fuzzy networks, neuro-genetic algorithms and fuzzy-genetic algorithms.

Intelligent control systems can benefit from the advances in artificial neural networks (Rumelhart and McClelland, 1986; Haykin, 1994) as a tool for on-line learning optimisation, and optimal policy making. The connectionist systems (neural networks) represent massively parallel distributed networks with the ability to serve in advanced robot control loops as learning and compensation elements using the abilities of nonlinear mapping, learning, parallel processing, self-organizing and generalization.

The fuzzy control systems (Zimmermann, 1990; Terano et al., 1992) based on mathematical formulation of fuzzy logic have the capability of representing human knowledge and experience as a set of fuzzy rules. Fuzzy robot controllers use human know-how or heuristic rules in the form of linguistic if-then rules, while fuzzy inference engine computes the efficient control action for a given purpose.

The technique of evolutionary computation with genetic algorithms (Goldberg, 1989; Haupt and Haupt, 1998) represents an approach to global optimization search which is based on the mechanics of natural selection and natural genetics. It combines survival of the fittest among string structures with a structured yet randomized information exchange to form a search algorithm with the expected ever-improving performance.

Each of the proposed paradigms has its own merits and drawbacks. To overcome the drawbacks, certain integration and synthesis of hybrid techniques (symbiotic intelligence) are needed for efficient application in humanoid robotics. Symbiotic Intelligence incorporates a new type of humanoid robotics system having many degrees of freedom (DOFs) and multi-modal sensory inputs. The underlying idea is that the richness of inputs to and outputs from the system, along with co-evoluting complexity of the environment mixed with various intelligent control paradigms, is the key to the emergence of intelligence. For example, neuro-fuzzy networks represent a combined tool where human operators are able to give their knowledge by means of membership functions. On the other hand, membership functions are modified through learning process as fine tuning by neural networks. After learning, the human operator can understand the acquired rules in the network. Neuro-fuzzy networks are faster than the conventional neural networks in terms of convergence of the learning. Also, fuzzy logic and neural networks can be evaluation functions for the genetic algorithms. At the same time, genetic algorithms can be structure optimizers for fuzzy and neural algorithms. The computational intelligence techniques map well onto nonlinear problems and are better at handling uncertainties like those that can be encountered in running over irregular terrain with obstacles.

All these techniques may be incorporated in advanced and sophisticated control systems of humanoid robots that were inspired in general by biological designs and neurobiological principles (Giszter et al., 2000; Garcia et al., 2000; Kiriazov, 2001). In the last two decades, many researchers explored the design of autonomous systems, swarms of intelligent agents, and biologically inspired control designs and actuators (Doya et al., 2001; Guihard and Gorce, 2001; Vijayakumar and Schaal, 2000; Billard and Mataric, 2000; Mataric et al., 1998; Kawato et al., 1987; Arkin, 1999; Brooks, 1997; Kawato, 1999). The research in this area is specially oriented toward the ideas of artificial life and adaptive behavour. An ultimate goal is the creation of a humanoid robot as autonomous agent which is capable of mimicking all aspects of human action, perception and cognition in everyday life and in remote and unfriendly environments.

The purpose of this survey is to present the main control problems in humanoid robotics and the background of some intelligent techniques as new paradigms and tools for solving control problems in humanoid robotics. An account of the basic principles and concepts is given, with the outlines of a number of relevant algorithms that have been shown to simulate or use the diversity of intelligent concepts for sophisticated humanoid robot control systems.

2. Control Problems in Humanoid Robotics

In spite of a significant progress and accomplishments achieved in the design of a hardware platform of humanoid robot and synthesis of advanced intelligent control of humanoid robots, a lot of work has still to be done in order to improve actuators, sensors, materials, energy accumulators, hardware, and control software that can be utilized to realize user-friendly humanoid robots. We are still in an initial stage when the understanding of the motor control principles and sensory integration subjacent to human walking is concerned.

There are various sources of control problems and various tasks and criteria that must be solved and fulfilled in order to create valid walking and other functions of humanoid robots. Previous studies of biological nature, theoretical and computer simulation, have focussed on the structure and selection of control algorithms according to different criteria such as energy efficiency, energy distribution along the time cycle, stability, velocity, comfort, mobility, and environment impact. Nevertheless, in addition to these aspects, it is also necessary to consider some other issues: capability of mechanical implementation due to the physical limitations of joint actuators, coping with complex highly-nonlinear dynamics and uncertainties in the model-based approach, complex nature of periodic and rhythmic gait, inclusion of learning and adaptation capabilities, computation issues, etc.

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 gait. Irrespective of the humanoid robot structure and complexity, the basic characteristic of all bipedal systems are: (a) the DOF formed between the foot and the ground is unilateral and underactuated (Goswami, 1999); (b) the gait repeatability (symmetry) and regular interchangeability of the number of legs that are simultaneously in contact with the ground. During the walk, two different situations arise in sequence: the statically stable double-support phase in which the mechanism is supported on both feet simultaneously, and statically unstable single-support phase when only one foot of the mechanism is in contact with the ground. Thus, the locomotion mechanism changes its structure during a single walking cycle from an open to a closed kinematic chain. Also, it is well known that through the process of running the robot can be most of the time in no-support phase. In this case, the control schemes that are successful for walking problem are not necessarily successful for the running problem. All the mentioned characteristics have to be taken into account in the synthesis of advanced control algorithms that accomplish stable, fast and reliable performance of humanoid robots.

The stability issues of humanoid robot walking are the crucial point in the process of control synthesis. In view of this humanoid walking robots can be classified in three different categories (Marchese et al., 2001). First category represents static walkers, whose motion is very slow so that the system's stability is completely described by the normal projection of the centre of gravity, which only depends on the joint's position. Second category represents dynamic walkers, biped robots with feet and actuated ankles. Postural stability of dynamic walkers depends on joint's velocities and acceleration too. These walkers are potentially able to move in a static way provided they have large enough feet and the motion is slow. The third category 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. In the walk with dynamic balance, the projected centre of mass is allowed outside of the area inscribed by the feet, and the walker may essentially fall during parts of the walking gait. The control problems of dynamic walking are more complicated than in walking with static balance, but dynamic walking patterns provide higher walking speed and greater efficiency, along with more versatile walking structures.

For all the mentioned categories of walking robots, the issue of stable and reliable bipedal walk is the most fundamental and yet unsolved with a high degree of reliability. This subject has been studied mainly through the following two classes of walking pattern generators and robot controllers. The first approach is to generate a dynamically consistent periodic walking pattern off-line. It is done assuming that the models of robot and environment are available, and the kinematic and dynamic parameters of the robot model are precisely defined (Hirai et al., 1998; Yamaguchi et al., 1998). On the other hand, the second approach uses limited or simplified knowledge of the system's dynamics (Raibert, 1986; Zheng and Shen, 1990). However, in this case, the control relies much on the feedback control, and it is necessary to develop methods without high computation resources for real-time implementation.

The rotational equilibrium of the foot is the major factor of postural instability with legged robots. 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 are the centre of pressure (CoP), the zero-moment point (ZMP) and the foot-rotation indicator (FRI) (Sardain and Bessonet, 2001; Vukobratović et al., 2002; Goswami, 1999). Of these criteria, the ZMP concept has gained widest acceptance and played a crucial role in solving the biped robot stability and periodic walking pattern synthesis (Vukobratović et al., 2002). The ZMP is defined as the point on the ground about which the sum of all the moments of the active forces equals zero. If the ZMP is within the convex hull of all contact points between the foot and the ground, the biped robot can walk.

For a legged robot walking on complex terrain, such as a ground consisting of soft and hard uneven parts, a statically stable walking manner is recommended. However, in the cases of soft terrain, up and down slopes or unknown environment, the walking machine may lose its stability because of the position planning errors and unbalanced foot forces. Hence, position control alone is not sufficient for practical walking, position/force control being thus necessary. Foot force control (Zhou and Low, 2001) can overcome these problems, so that foot force control is one of the ways to improve the terrain adaptability of walking robots. For example, in the direction normal to the ground, foot force has to be controlled to ensure firm foot support and uniform foot force distribution among all supporting legs; foot force in the tangential direction has to be monitored to avoid slippage.

On the other hand, biological investigations suggest that human's rhythmic walking is a 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 the 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 (Huang et al., 2001). A biped humanoid should not only perform rhythmic walk in a known environment but also adapt itself to real world uncertainties. In this case, the adaptability and ability of compensating external disturbances must be included in advanced control algorithms.

A practical biped needs to be more like a human – capable of switching between different known gaits on familiar terrain and learning new gaits when presented with unknown terrain. In this sense, it seems essential to combine force control techniques with more advanced algorithms such as adaptive and learning strategies. Inherent walking patterns must be acquired through the development and refinement by repeated learning and practice as one of important properties of intelligent control of humanoid robots. Learning enables the robot to adapt to the changing conditions and is critical to achieving autonomous behaviour of the robot.

Many studies have given weight to biped walking which is based only on stability of the robot: steady-state walking, high-speed dynamic walking, jumping, and so on. A humanoid robot is however, a kind of integrated machine: a two-arm and two-leg mechanism. Hence, we must not only focus on the locomotion function but also on arm's function with this kind of machines; manipulation and handling being major functions of robot's arms. The concept of mobile manipulation (Yoshikawa et al., 2001) considers that the leg motion is capable of increasing manipulation ability by changing stand position or adjusting posture of the body with bending and stretching of the legs. From this point of view, it is necessary to develop advanced control methods of mobile manipulation of humanoid robots.

When the ground conditions and stability constraint are satisfied, it is desirable to select a walking pattern that requires small torque and velocity of the joint actuators. Humanoid robots are inevitably restricted to a limited amount of energy supply. It would therefore be advantageous to consider the minimum energy consumption, when cyclic movements like walking are involved. With this in mind, an important approach in research is to optimise simultaneously both the humanoid robot morphology and control, so that the walking behaviour is optimised instead of optimising walking behaviour for the given structure of humanoid robot. Optimum structures can be designed when the suitable components and locomotion for the robot are selected appropriately through evolution.

It is well known that real-time generation of control algorithms based on highly-complex nonlinear model of humanoid robot commonly suffers from a large amount of computation. Hence, new time-efficient control methods need to be discovered to control humanoid robots in real time, to overcome the mentioned difficulty.

In summary, conventional control algorithms for humanoid robots can run into some problems related to mathematical tractability, optimisation, limited extendability and limited biological plausibility. The presented intelligent control techniques have a potential to overcome the mentioned constraints.

3. Connectionist Control Algorithms in Humanoid Robotics

Recently, some researchers have begun considering the use of neural networks for control of humanoid walking (Doerschuk et al., 1998; Miller, 1994; Miller et al., 1987; Kun and Miller, 1999; Wang et al., 1992). This approach makes possible the learning of new gaits which are not weighted combinations of predefined biped gaits. Various types of neural networks are used for gait synthesis and control design of humanoid robots such as multilayer perceptrons, CMAC (Cerebellar Model Arithmetic Controller) networks, recurrent neural network, RBF (Radial Basis Function) networks or Hopfield networks, which are trained by supervised or unsupervised (reinforced) learning methods. The majority of the proposed control algorithms have been verified by simulation, while there were few experimental verifications on real biped and humanoid robots. Neural networks have been used as efficient tools for the synthesis and off-line and on-line adaptation of biped gait. Another important role of connectionist systems in control of humanoid robots has been the solving of static and dynamic balance during the process of walking and running on terrain with different environment characteristics.

Kitamura et al. (1988) proposed a walking controller based on Hopfield neural network in combination with an inverted pendulum dynamic model. The optimization function of the Hopfield network was based on complete dynamic model of biped.

Salatian et al. (Salatian and Zheng, 1992a, 1992b; Salatian et al., 1997) studied off-line and on-line reinforcement techniques for adapting the gait designed for horizontal surfaces to be executed on sloping surfaces. They considered humanoid robot SD-2 with 8 DOFs and two force sensors on both feet. These control algorithms without considering kinematic and dynamic models of humanoid robot were evaluated using a biped dynamic simulation (Salatian and Zheng, 1992a, 1992b), as well as on real biped SD-2 (Salatian et al., 1997). The control structure includes gait trajectory synthesizer (with the memory of previously stored and learned gaits) and neural networks that are tuned by reinforcement signal from force sensors at the feet. The joint positions of the robot are adjusted until the force sensors indicate that the robot has a stable gait. The neural network has the task to map the relation between foot forces and adjustment of the joint positions. The reinforcement learning is used because the neural network receives no direct instruction on which joint position needs to be modified. The neural network is not a conventional type of network (perceptrons) and includes a net of more neurons with inhibitory/excitory inputs from the sensor unit. Every joint of the robot is associated with a neuron called *joint neuron*. Every joint neuron is further attached to two pairs of neurons, called *direction neurons*. Each neuron possesses a value of activation function called *neuron value*. During the learning process, a joint neuron with the maximum neuron value is selected to modify the position of the corresponding joint, while direction neuron is selected to determine the direction of modification. If the selected joint and direction neuron result in a correct motion (the robot becomes more stable), the selection is reinforced by increasing the neuron value. Otherwise, the neuron value is reduced. Using previously mentioned "regard-and-punish" strategy, the neural network converges quickly and generates a stable gait for the sloping surface. In this way, reinforcement learning is very attractive because the algorithm does not require an explicit feedback signal. The computation issues for reinforcement learning are simple, while the noise from the feet sensors is taken in the process of learning. During one step of the biped, there are 8 static configurations, which are called the primitive points. The neural network is only responsible for the motion in the sagittal plane. Hence, including the redundancy at the hip joint. there are $3 \cdot 8 = 24$ joint neurons. Because of the nature of reinforcement learning, each time only one joint neuron is active. Static and pseudo-dynamic learning are demonstrated to prove that the proposed mechanism is valid for robot walking on the sloping surface. In this approach, kinematic and dynamic models were not used, hence it would be a problem for real dynamic walking with a high speed. Also, the real terrain is more complex than the environments used in test experiments, so that more studies need to be conducted to make the robot walk robustly on different sorts of terrain.

More recently, Miller (Miller, 1994; Miller et al., 1987; Kun and Miller, 1999) has developed a hierarchical controller that 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. The neural network learning is achieved using CMAC controller, where CMAC neural networks were used essentially as context sensitive integral errors in the controller, the control context being defined by the CMAC input vector. There are 3 different CMAC neural networks for humanoid posture control. The front/back balance CMAC neural network was used to provide 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, to predict the correct knee extension required to achieve 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 the difference between the 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 indicated that the experimental biped was able to learn the closed-chain kinematics necessary to shift body weight side-to-side while maintaining good foot contact. Also, it was able to learn the quasi-static balance required to avoid falling forward or backward while shifting body weight side-to-side at different speeds. It was able to learn the dynamic balance in order to lift a foot off

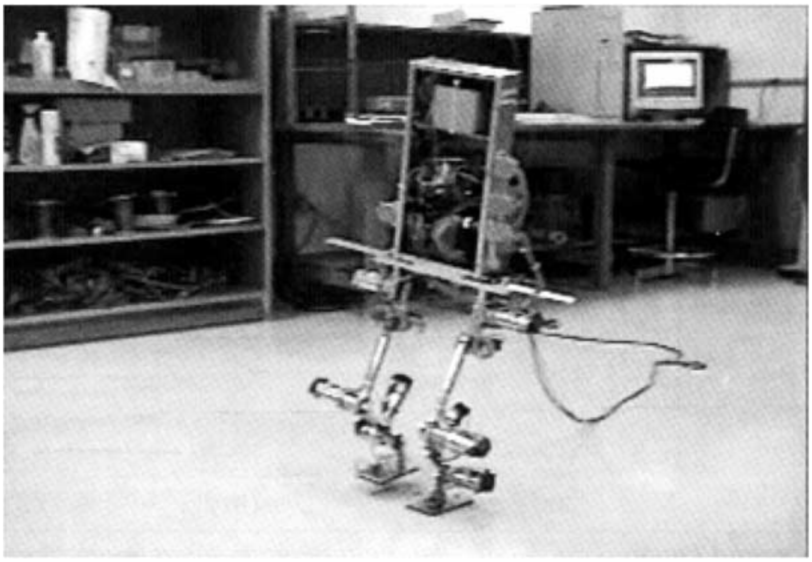

Figure 1. The UNH biped walking.

the floor for a desired length of time and different initial conditions. There were, however, many limitations (limited step length, slow walking, no adaptation for left–right balance, no possibility of walking on sloping surfaces). Hence upgrading and improvement of this approach were proposed in (Kun and Miller, 1999). The new dynamically balanced scheme for handling variable-speed gait was proposed based on the preplanned but adaptive motion sequences in combination with closed-loop reactive control. This allows the algorithm to improve the walking performance over consecutive steps using adaptation, and to react to small errors and disturbances using reactive control. New sensors (piezoresistive accelerometers and two solid-state rate gyroscopes) are mounted on the new UNH biped (Figure 1). The complete control structure consists of high-level and low-level controllers (Figure 2) The control structure on high-level control includes 7 components (Figure 3): gait generator, simple kinematics block and 5 CMAC controllers. The operation of the gait generator is based on simple heuristics and an appropriate biped model. The CMAC neural networks 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 networks is realized through the process of temporal difference learning using information about ZMP from robot foot sensors. The five CMAC neural networks were first trained during repetitive foot-lift motion similar to marching in place. Then, training was carried out during the attempts at walking for increased step length and gait speeds. The control structure on the lower control level includes reactive lean angle control, together with a PID controller.

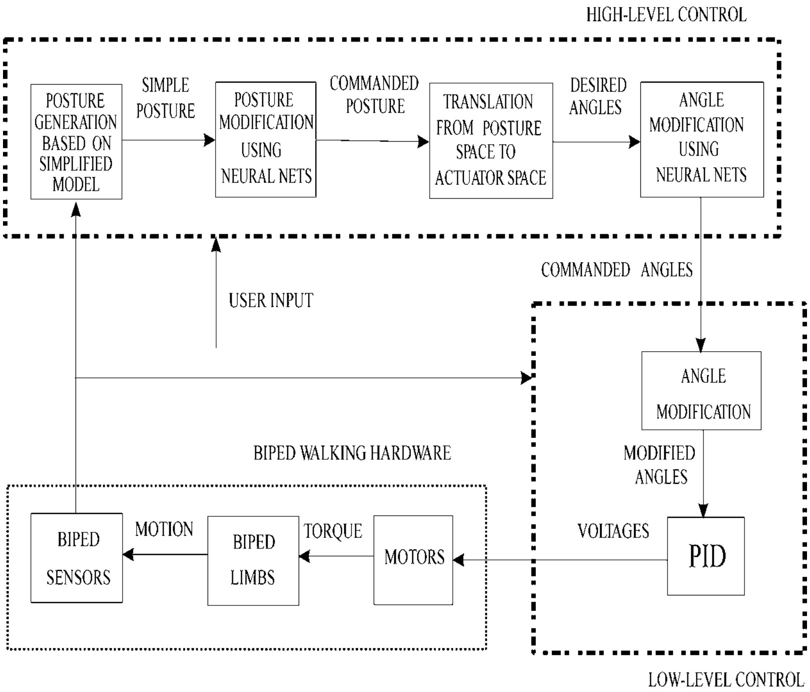

Figure 2. Block diagram of overall biped control system.

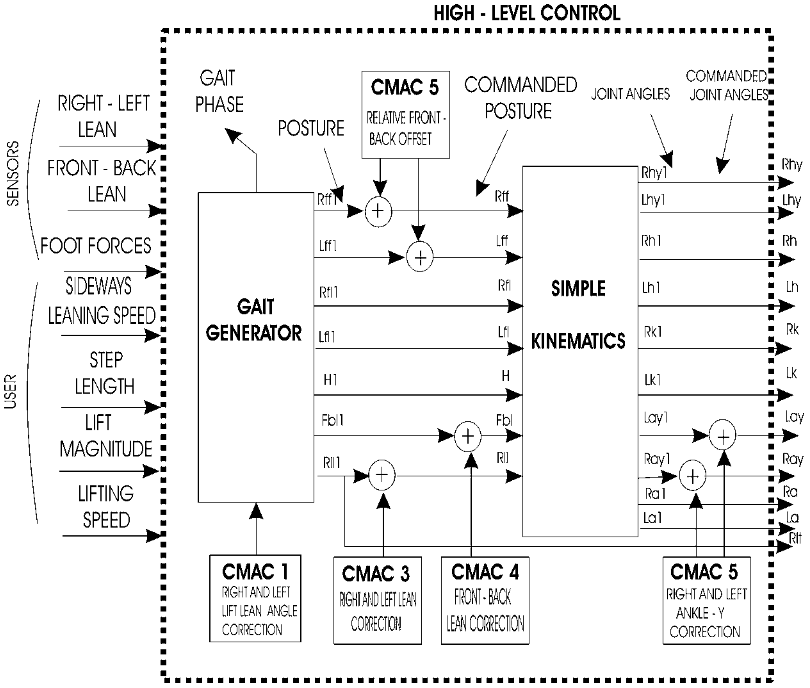

Figure 3. High-level control architecture.

The experimental results indicate that the UNH biped robot can walk with forward velocities in the range of 21–72 cm/min, with sideways leaning speed in the range of 3.6–12.5 deg./s. The main characteristic of this controller is the synthesis of the control signal without dynamic model of biped. The proposed controller could be used as a basis for similar controllers of more complex humanoid robots in the future research. However, this controller is not of a general nature, because it is suitable only for the proposed structure of biped robot and must be adapted for the bipeds with different structures. More research efforts are needed to simplify the controller structure, to increase the gait speed, and to ensure stability of dynamic walking.

The previously used CMAC controller is a particularly good option for robotic motor control. It has the quality of fast learning and simple computation in comparison with multilayer perceptrons and similar approximation capabilities such as radial basis function networks. However, there are problems with large memory requirements, function approximation and stability of dynamic walking. These problems have been addressed in (Hu et al., 1999), where self-organizing CMAC neural network structure was proposed for biped control based on a data clustering technique together with adaptation of the 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 centres is realized to ensure adaptation to unexpected dynamics. Unsupervised learning using CMAC can be implemented with a Lyapunov trajectory index. The distance between the input vector and the centre vectors of the CMAC is calculated, then the memory cells corresponding to the centres (hit by the input) are found, and finally, computation of the CMAC output by a linear combination of CMAC basis functions and weights of the memory cell is achieved. The weights in the fired memory cells are updated by unsupervised learning. The approach is verified through simulation experiments on a biped with 7 DOFs. An important characteristic of this approach is the inclusion of adaptation for CMAC and PID controllers with a moderate increase of controller complexity to handle disturbances and environmental changes. Although the robustness was enhanced in terms of height and pitch tracking along with external disturbance rejection, the proposed adaptive controller does not guarantee the long-term stability of the walking gait, where the following posture parameters are presented in Figure 3: H – height; *Rff* and *Lff* are right and left foot forward; *Rfl* and *Lfl* are right and left foot lift; *Fbl* is front–back lean and *Rll* is right–left lean.

Wang et al. (1992) have developed a hierarchical controller for a three-link two-legged robot. The approach uses the equations of motion, but only for the training of the neural networks, rather than to directly control the robot. The authors used a very simplified model of biped with decoupled frontal and sagittal planes. There are 3 neural networks (multilayer perceptrons) for control of leg on the ground, control of leg in the air, and for body regulation. This approach uses off-line training and on-line adaptation. Training algorithm is a standard back-propagation algorithm based on the difference between the decoupled supervising control law and output of all three neural networks. There are no feedback in real-time control, and this is a great problem in the case when the system uncertainties exist.

Apart from considering the walking control problem, very little research has been done on the problem of intelligent control of running. Doerschuk et al. (1998) 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 the application of modularity, i.e. the use of separate controllers for each phase of the running stride (take-off, ballistic, landing), thus allowing each to be optimized for the specific objective of its phase. In the take-off phase, the controller's objective is to realize inverse feedforward control (for desired height, distance and angular momentum it is necessary to produce control signals that achieve these objectives). The controller learns from experience to produce the control signals which will produce the desired height, distance and angular momentum. Three different types of neural networks are investigated (multilayer perceptrons, CMAC, and neuro-fuzzy nets). It was concluded that neuro-fuzzy nets achieve more accurate results than the other two methods. It is not needed for off-line global training because of using local learning. The neuro-fuzzy take-off controller controls very accurately the value of 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. In this case, ballistic controller combines neural network learning with the conventional PD control. It is a typical feedback error learning scheme where a PD controller generates the torques that are applied to the joints, producing movement of the leg. The controller learns the dynamic model of leg from experience generated by the PD controller and improved upon its performance. The CMAC controller is used for neural network learning part with the possibility to very accurately control the movement of the leg along a target trajectory even during the first attempt. Ballistic learning is accomplished on-line without the need for precomputed examples. This enables effective adaptability of humanoid robot to various changes and new conditions.

The neural networks can be effectively used to generate trajectories (gait) of humanoid robots (Kurematsu et al., 1991; Juang and Lin, 1996). Kurematsu (1991) proposed a multi-layered network by using the centre of gravity concept in trajectory generation. For example, Juang and Lin (1996) used the back propagation through time algorithm for gait synthesis of a biped robot. Due to a high number of DOFs of the biped, it is difficult to get a high nonlinear model of the biped. Hence, the complex inverse dynamic computations were eliminated by using linearised inverse biped model. The neural controller is a three-layer feedforward network. The simulation results show that the neural network as open-loop controller can generate control sequences to drive the biped along a prespecified trajectory. This algorithm can also be used for the slope surface training.

4. Fuzzy Control Algorithms in Humanoid Robotics

Some researchers used the fuzzy logic (Vukobratovic and Timčenko, 1995; Zhou and Meng, 2000; Yang and Low, 2002; Ivanescu et al., 2001) as the methodology for biped gait synthesis and control of biped walking. Fuzzy logic was used mainly as part of control systems on the executive control level, for generating and tuning PID gains, fuzzy control supervising, direct fuzzy control by supervised and reinforcement error signals.

In (Vukobratovic and Timčenko, 1995), fuzzy logic is applied at the level of local control for tuning of local PID gains, while the complete control structure includes nominal feedforward control (based on the biped's dynamics model), too. It has been shown that the aggregation-decomposition method for stability analysis of the overall biped system is applicable in the cases when local subsystems are stabilized with fuzzy regulators. For the synthesis of fuzzy regulators a method of parallel distributed compensation was utilized.

The problem of biped gait synthesis using the reinforcement learning with fuzzy evaluative feedback is considered in (Zhou and Meng, 2000). 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 4). 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. where $Xzmp$, $Yzmp$ are the ZMP coordinates; θ^d_{zmp}, θ^d_{zmp} are the desired joint angles of the biped gait.

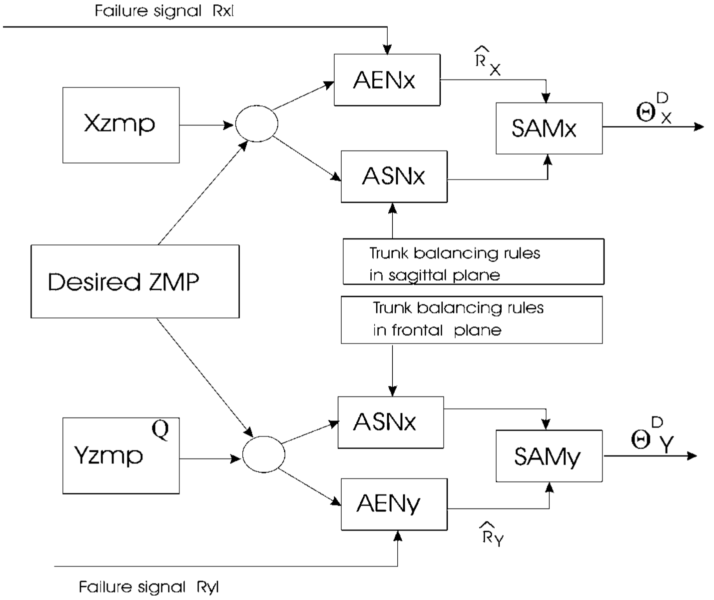

Figure 4. The architecture of the reinforcement learning-based gait synthesizer.

In (Yang and Low, 2002), conventional fuzzy controller for position/force control of robot leg is proposed and experimentally verified. This intelligent walking strategy is specially intended for walking on rough terrain.

A main problem in the synthesis of fuzzy control algorithms for biped robots remains the inclusion of dynamic model and learning capabilities in order to obtain exact tracking of biped trajectories as well as the steps with greater speed, preserving dynamic stability of the biped gait.

5. Genetic Approach in Humanoid Robotics

It is considered that GA can be efficiently applied for trajectory generation of the biped natural motion on the basis of energy optimisation (Arakawa and Fukuda, 1997; Capi et al., 2001), as well as for walking control of biped robots (Cheng and Lin, 1997) and for generation of behaviour-based control of these systems (Pettersson et al., 2001).

The hierarchical trajectory generation (Arakawa and Fukuda, 1997) method consists of two layers, one is the GA level which minimises the total energy of all actuators and the other is the evolutionary programming (EP) layer which optimises the interpolated configuration of biped locomotion robots. The trajectory of biped is generated using ZMP stability conditions. The chromosome on 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 the configuration (0 or 1). The process runs in a 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 optimisation of total robot energy in order to ensure the natural movement of the biped. The fitness function also contains some constraints related to the robot motion. The final result represents an optimised trajectory similar to natural human walking, which was demonstrated by the simulation experiment.

A typical example of the application of GA in humanoid robotics was presented in (Capi et al., 2001), where the main intention was the optimal gait synthesis for biped robots. The proposed method can easily be applied onto other tasks like overcoming obstacles, going down stairs, etc. In solving these optimization tasks, the most important constraint included is the stability, which is verified through the ZMP concept. To ensure a stable motion, the jumping of the ZMP is realized by accelerating the body link. GA makes easy handling of the constraints by using the penalty function vector, which transforms a constrained problem into an unconstrained one. The optimisation process is based on considering two different cost functions: minimisation of consumed energy (CE) and minimisation of torque change (TC). In this optimisation process, some constraints are included such as the stability conditions defined by ZMP to be within the sole length. The block diagram of the GA optimisation method is presented in Figure 5.

Based on the initial conditions, the initial population, represented by the angle trajectory in the form of a polynomial of time, is created. Its range is determined on the basis of the number of angle trajectory constraints and the coefficients are calculated to satisfy these constraints. In the simulation experiments, the parameters of real humanoid robot “Bonten-Maru I” are used. For the optimisation of the cost function, a real-value GA was employed in conjunction with the selection, mutation and crossover operators. GA converges within 40 generations, while the maximum number of generations is used as the termination function. Based on simulation, the biped robot posture is straighter, like the human walking when the CE is used as cost function. The torques change more smoothly when minimum TC is used as a cost function.

However, for the real-time applications, some process of GA optimisation is time-consuming (in this case, optimisation process needs 10 min). Hence, the author considered teaching a RBFNN (Radial Basis Function Neural Networks) based on GA data. When the biped robot was to walk with a determined velocity and step length, the RBFNN input variable would be step length and step time, while the output variables of the RBFNN were the same as the variables generated by GA. Simulations showed good results generated by RBFNN in a very short time (only 50 ms).

Another example is the application of GA to PD local gain tuning and determination of nominal trajectory for dynamic biped walking (Cheng and Lin, 1997).

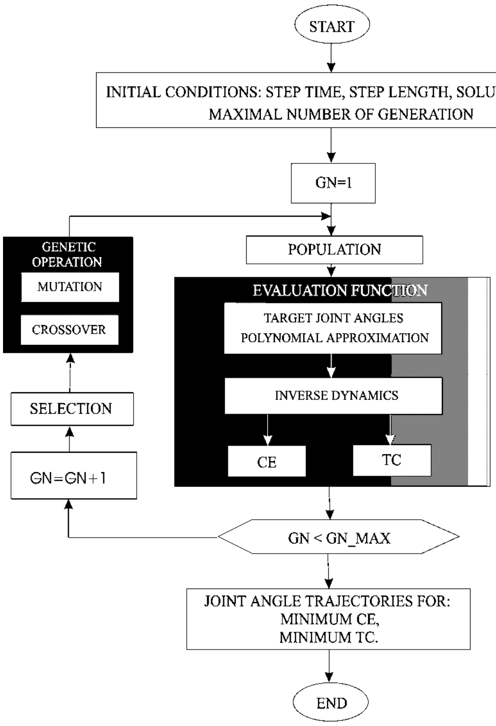

Figure 5. Block diagram of the GA optimization process.

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. In order the biped body be in the vertical plane during walking, some constraints related to the fixation of joint angles are realised. Hence, it is possible to reduce the number of parameters of nominal trajectory for optimisation by 6 parameters. 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 related to total time of effective walking, average speed of the biped body, and the size of the walking step. The total number of generations for problem solving was between 10 and 60. The research showed excellent simulation results in the evaluation of control parameters, as well as in optimisation of the mechanical design of biped.

The main problem of GA application in humanoid robotics represents the coping with the reduction of GA optimisation process in real time.

6. Hybrid Intelligent Approaches in Humanoid Robotics

Because their complementary capabilities hybrid intelligent methods have also found their place in the research of gait synthesis and control of humanoid robots.

In (Juang, 2000), a learning scheme based on a neuro-fuzzy controller to generate walking gaits, is presented. The learning scheme uses a neuro-fuzzy controller combined with a linearised inverse biped model. The training algorithm is *back propagation through time*. The linearised inverse biped model provides the error signals for back propagation 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 the mentioned constraints. Simulation results are verified for a simple structure of five-link biped robot.

The GA has been efficiently applied in robotic neural approaches, as in the case of the neuro-GA controller for visually-guided swing motion of a biped with 16 DOFs (Nagasaka et al., 1997). The aim of this robot task is learning of swing motion by neural network using visual information from a virtual working environment. As is known, GA requires a lot of computing time in order to evaluate the fitness function for each individual in a population. Hence, it is not desirable to use direct execution of the working task on a real biped because of task complexity and inaccuracies of the sensors. Instead of a real biped, virtual working environment is used for acceleration of the learning process. As the learning process is transferred from the virtual environment to the real robot, the difference existing between these two systems is neutralized by generalisation 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 centre of the biped robot in the direction of swing radius, caused by dynamic change of the environment recognised by the vision sensor. The input to the network represents sensor information from the vision sensor, while the output of the neural network is the knee angles of the biped

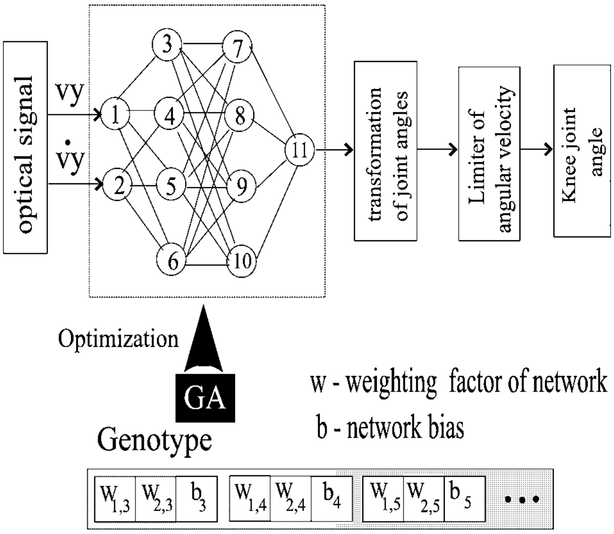

Figure 6. Neuro-GA approach for optimization of robot swing motion.

(Figure 6). GA optimises the three sets of weighting factors of this 4-layer neural network. At the output of the network, the data are transformed into joint angles and then using limiters of angular velocities (to avoid extreme changes of joint angles), the knee joint angle is calculated. 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 centre of gravity in the initial and final pose. The evolution simulation experiment is terminated when the number of alternations in generations reaches 50. The results show the efficient learning of swing motion through successive generation that is verified through generalisation experiments on the real robot biped.

In (Fukuda et al., 1997) 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. When the biped robot walks on the ground which has some gradients, the optimal trajectory is not known, hence the optimal trajectory of ZMP is not realised. Because of that, the reinforcement learning is used by applying a recurrent neural network. Recurrent neural network is chosen in order to select best biped configuration (desired joint position and velocity) using ZMP as stabilisation index. This type of neural network was chosen because the output of the network generates the dynamic output data for static inputs and can describe time records easily. The input to the network is the information about position of ZMP taken from the force sensor, while the output of the network is the correction angles and correction velocities needed for a stable motion. The ZMP is calculated using the values from force sensors at each sole and values of joint angles. 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. In both single-support and double-support phases of walking the algorithm calculates the ZMP by using values from four force sensors at each sole, while correction to actuation angles and velocities is determined by recurrent neural networks with the ZMP being within the supporting area of the sole of the robot. The block diagram of the stabilisation biped control is shown in Figure 7, where θ, $\dot{\theta}$ are the joint angles and velocities; θ_{D}, $\dot{\theta}_{\mathrm{D}}$ are the desired joint angles and velocities; U is the control signal; F is the foot force. The motion on inclined surfaces is investigated with initial population of 50 different individuals. It has been shown that the use of this approach yields a stable biped gait.

Reil and Husbands (2002) proposed an evolutionary approach for the biped controller based on dynamic recurrent neural network. Each neural network consists of 10 fully interconnected neurons. The first 6 neurons represent motor neurons because that control biped actuators (the biped has 6 DOFs). Their outputs are scaled to map to the angle limits. The GA has a task to optimize the weighting factors, time constant, and bias of activation functions for the chosen neurons. Parameter values are coded using real numbers with different ranges for each type.

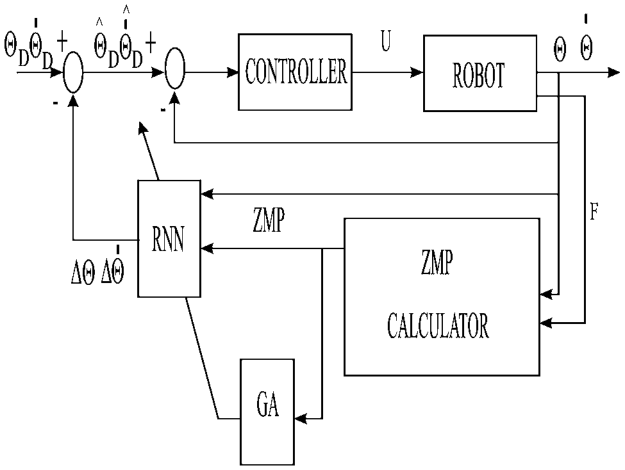

Figure 7. Block diagram of stabilization biped control.

Each population consists of 50 individuals. The rank-based selection is used for generating new generations with a fittest fraction. From the genetic operators, only mutation with small rate is applied. The fitness function considers two components: (1) the minimisation of travelling distance from the origin; (2) the gravity centre can not be below a certain height. The fraction of evolutionary runs leading to stable walkers was 10%, of which the average walking distance was 20.577 m. All controllers in the simulation experiments walked in a straight line without the use of proprioceptive inputs and without active balance control. because of the application of the mentioned fitness function. The authors proposed an additional criterion for fitness function in order to reward cycling activity. In this way, the proportion of successful runs is increased to 80% but without improvement of the overall time efficiency. In order to achieve walking on a rough terrain, some set of simulation experiments with inclusion of sensor signals as input to neurons of the neural network, are realized. These preliminary experiments on the integration indicate that cyclic walking activity can indeed be modified by external stimuli in a meaningful way. The quality of simulation results indicates a further improvement by a refined fitness function, together with inclusion of coupled neural oscillators instead of a single neural network. Also, it is desirable to incorporate biomechanical knowledge about human walking. However, because of the existence of only simulation results, a real problem is the implementation of the proposed theory on the embodied humanoid robots.

A very interesting approach was proposed in (Endo et al., 2002), using the ideas of artificial life. The main idea is to optimise both the morphology and control of biped walking at the same time, instead of optimising the walking behaviour for the given hardware. It was shown that the generated robots have diverse morphologies and control systems, while their walking is fast and efficient. Both the morphology and neural systems are represented as simple large tree structures that are optimised simultaneously. From the morphology side, the lengths of the lower and upper limbs are optimised. Two types of control systems are analysed: the one based on neural network and the other based on neural oscillator. The input to the neural network represents the velocity, acceleration and ZMP position, while the output of the network represents the joint angles. It is a layered neural network with a pair of hidden layers. The chromosome includes the following parameters for optimization: information on initial angle and velocity, length of each link and weights of each neuron in the neural network. The simulation experiments with population size of 200 individuals and 600 generations were realized using standard genetic operators. In the first phase of GA, the fitness function was the distance between the centre of mass of the robot and the initial point. In the second phase, two fitness functions were evaluated based on the efficiency and stability of walking. The preferred solution has appropriate locomotion and morphology. As the other solution for control algorithm, neural oscillator was used, because the biped walking is a periodical and symmetrical solution. Neural oscillator generates the rhythm for the biped walking. In this case, it is not necessary to use a large-size GA chromosome, as was the case with neural networks. The structure of the neural oscillator represents some kind of recurrent neural network dynamic state, while the other parameters of GA optimisation process are the same as in the previous case. The walking patterns for the neural network and neural oscillator are similar, even though the sizes of chromosomes are much different (the neural network chromosome has 1000 bits size, while the size of the neural oscillator is 300 bits). Therefore, a larger dynamic model of biped can be applied to the model with a neural oscillator. It has been shown that there is a close relation between the morphology and locomotion. The proposed co-evolution of the morphology and control systems may be a potentially powerful method for designing the real humanoid robots.

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.

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