Humanoid Robotics
– Past, Present State, Future –

Miomir Vukobratović

Director Robotics Center, Mihailo Pupin Institute
11000 Belgrade, P.O. Box 15, Serbia
E-mail: vuk@robot.imp.bg.ac.yu

Abstract: Humans are the most advanced creatures of the nature. I believe that humanoid robots will be the most advanced creatures of humans. Among the man-made creatures such as automobile, hand-phones and multimedia devices, robots of future will hopefully be the most ideal assistants to human beings. Robots can live up to this expectation because future intelligent and autonomous robots could free humans from, or ease them up of, repeatedly undertaking physically and mentally challenging routines. For instance, Robot Doctor could provide medical advices, pre-diagnostic, and even assist in surgical operation; Robot Nurse could assist patients in hospital or at home; Robot Soldier could participate in military intervention, and even fight terrorism; Robot Tutor could help our students to have a better learning experience; Robot Guard could make our society much safer; Robot Maid could keep our house clean and secure, and even help look after elderly people at home; Robot Rescuer could be deployed to places where human lives are in danger. The list of potential applications with intelligent and autonomous robots is growing.

Keywords: humanoid robot, ZMP, semi-inverse method, active exoskeleton, active suit, force-position control, artificial intelligent, dynamic control, decentralized control

1 Introduction

Rapid development of humanoid robots brings about new shifts of the boundaries of Robotics as a scientific and technological discipline. New technologies of components, sensors, microcomputers, as well as new materials, have recently removed the obstacles to real-time integrated control of some very complex dynamic systems such as humanoid robots, which already today possess about fifty degrees of freedom and are updated in microseconds of controller signals.

In view of the above statements, the work for the first time raises the essential question on the justifiability of increasing the number of degrees of freedom of humanoid robots, having in mind that for the overall skeletal activity man has at its disposal roughly about 650 muscles of human body which could be approximately expressed by more than three hundreds equivalent degrees of freedom, i.e. the same number of biological actuators.

In relation to this, the work raises also some new fundamental questions concerning the necessary anthropomorphism of humanoid robots, how to define the degree of anthropomorphism, and finally, how to achieve the highest degree of anthropomorphism with a lowest number of degrees of freedom. On the example of a humanoid robot, concrete measures are proposed how to achieve the desired degree of anthropomorphism of humanoids.

The above-mentioned obstacles being taken down, along with the humanoid robots playing mainly the role of communicators and entertainers, there have appeared humanoids of quite different aspirations in the domain of manipulation-locomotion activities of humans (case of sports-man on a trampoline, man on the mobile dynamic platform, running, balanced motion on the foot - a karate kick, playing tennis, soccer or volleyball, gymnastics on the floor or by using some gymnastic apparatus, skiing - balanced – motion with sliding, etc.).

The work is also promoting some new ideas concerning the already visible trends of expanding activities of humanoid robotics to cover the above new tasks. The novelty is related to generalized approach to the modeling of humanoid motion. Instead of a usual inductive approach that starts from the analysis of different real motion situations and tries to make a generalization, the work proposes a new deductive approach.

My opinion is that there are still limited results on human-like motion, while the field of human-like communication has produced several viable alternatives. On the other hand, human-like intelligence is the main obstacle to be overcome because of its complexity and multidimensionality; it is also responsible for coordination of the entire personal robot behavior.

And finally, bearing in mind the current progress in the constantly developing field of humanoid robotics, whose end products will certainly acquire with time more and more human-like characteristics, we can ask an ungrateful question:

Can we imagine that it may not be long before biologists construct a 'perfect personal robot' a real human cloned and genetically engineered with all attributes of a perfect servant (a worker, a soldier) despite of all the ethical, legal and sociological problems that may arise?

In my opinion, it will be possible to get closer to human characteristics only if such progress is made in technological innovations (artificial muscles, adaptive materials, self-learning) that will allow the performances of artificial systems become similar to those of man.

2 Beginnings of the Robotics

The word *robot* appeared first in 1920, in the play ‘Rossum's Universal Robots’, written by the Czech writer Karel Capek. The play depicts perfect workers – *robots*, endowed with emotions enabling to increase their productivity.

Concepts akin to today's robot can be found as long ago as 450 B.C. when the Greek mathematician Tarentum postulated a mechanical bird he called ‘The Pigeon’ which was pro-pelled by steam. Al-Jazari (1136-1206) a Turkish inventor designed and constructed automatic machines such as water clocks, kitchen appliances and musical automats powered by water.

One of the first recorded designs of a humanoid robot was made by Leonardo da Vinci in around 1495. Da Vinci's notebooks, rediscovered in the 1950s, contain detailed drawings of a mechanical knight able to sit up, wave its arms and move its head and jaw.

The first known functioning robot was created in 1738 by Jacques de Vaucanson, who made an android that played the flute, as well as a mechanical duck that reportedly ate and defecated. In 1893, George Moor created a steam man. He was powered by a 0.5 hp gas fired boiler and reached a speed of 9 mph (14 kph). Westinghouse made a humanoid robot known as Electro. It was exhibited at the 1939 and 1940 World’s Fairs, whereas the first electronic autonomous robots were created by Grey Walter at Bristol University, England, in 1948.

If, however, we want to look for the origin of robots as technical-tecnological category we ought to mention the Tesla's[*] patent and experiment in Madison Square Garden in New York in 1898 in which he demonstrated radio control of a ship. That was in fact the first remotely controlled object, i.e. robot in a wider sense of the term.

If we would like to relate the beginnings of robotics to the appearance of industrial robots we should point out that George Devol patented in the United States a first robotic device in 1954, whereas Joseph Engelberger, also an American, constructed first industrial robot in 1961. Therefore, the year 1961 was essential for the beginning of industrial robotics. Since 1970 we have witnessed an intensive development of industrial robotics. Robots have replaced men primarily in those jobs that were dangerous to humans and harmful to their health, and also introduced higher regularity and accuracy in machining of parts, assembly of blocks and systems, as well yielded increased productivity. For example, in the last 15-20 years car manufacturing has been automated and fully robotized, starting from the initial stage of forging, through engine manufacture, to assembly of parts into the final product – car, including its painting.

[*] Nikola Tesla (1856-1943), famous American scientist of Serbian origin

In addition to industrial robots whose number is presently estimated to 800,000, one third of them being made in Japan, in the last decade we have witnessed a rapid development of robots of special dedication.

These are, for example, robots for antiterroristic actions, for deactivating explosive devices, locating and destroying mines, mending damages in the electric power network without switching off, picking fruits, concrete works, digging underground chanals and their maintenance, cleaning tall buildings, replacement of damaged parts of tanks and pipelines, sheep shearing, robots-butchers for meat carving and deboning, micro-robots for inspection of intestinal tract, and even for examination of the quality of blood vessels, etc. There have been more frequent attmpts in which robots performed delicate surgical operations, either on the spot or at a distance.

Robotics, therefore, extends the frontiers of its application, whereby robots attain completely new functional structures and forms of construction.

Thus, for example, a pilotless aircraft is in fact a robot-aircraft, and automatically-guided tank (vehicle) with controlled fire action on the target, is again a robot of its kind; an automatically-guided torpedo is a submarine robot; a cruise missile is a pilotless aircraft that can not only track the target that should be destroyed, but, relying on artificial intelligence, detect it too.

3 Humanoid Robotics

The beginning of the development of humanoid robotics coincided with the beginning of the development of active exoskeletons, first in the world, in 1969 in the Mihajlo Pupin Institute under the guidance of Prof. Vukobratovic [1-5]. It should be noted that legged locomotion systems were developed first. Also, the first theory of these systems has been developed in the same institute, in the frame of active exoskeletons. Hence, it can be said that active exoskeletons were the predecessors of contemporary high-performance humanoid robots (Figures 1-6). Recently, there has been evident revived interest in active exoskeletons, first of all of military dedication [6]. The present-day active exoskeletons are developed as the systems for enhancing human natural skeletal system.

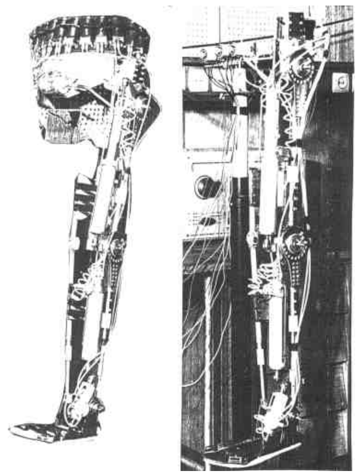

Figure 1
First Version of the Powered
Leg at Mihailo Pupin Institute (1971)

Figure 2
First in the world walking active exoskeleton, pneumatically powered and partly cinematically programmed, for producing near-anthropomorphic gait. Made in 1969 at the Mihailo Pupin Institute, predecessor of more complex exoskeletons devices for severely handicapped persons.

Figure 3
Most successful version of active exoskeleton for rehabilitation of paraplegics and similar disabled persons, pneumatically powered and electronically programmed, realized and tested at Belgrade Orthopedical Clinic in 1972. One example delivered to the Central Institute for Traumatology and Orthopedy, Moscow in the frame of the USSR-Yugoslav inter-state scientific collaboration. From 1991 the exoskeleton belongs to the basic fund of Polytechnic Museum (Moscow) and State Museum Fund of Russian Federation. It is displayed in the frame of the Museum's exposition dedicated to the development of automation and cybernetics.

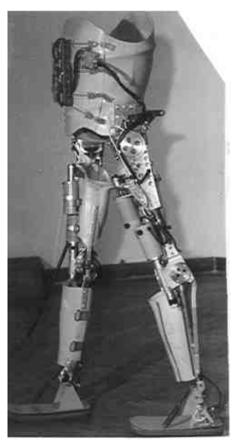

Figure 4
Active exoskeleton with electromechanical drives, electronically programmed, built and tested in 1974. Served mainly to evaluate and develop electro-mechanical drives for active orthotic devices, as the ‘active suit’ or active arm orthosis. This is the first example known in the world of active exoskeleton that used electric motors as actuators. As such, it can be considered as the predecessor of contemporary humanoid robots driven by electric motors.

Figure 5
'Active Suit', a modular semi-soft active orthotic device for dystrophics. Made in 1978. Electro-mechanically driven and microcomputer programmed and controlled. It was successfully used for the purpose of both rehabilitation tests and research purpose. As chance would have it, this was done within the project that was financed by the known US organizations, SRS (Social Rehab. Service) and NSF (National Science Foundation), in the frame of the intensive scientific cooperation USA-Yugoslavia. About this, there are official reports and documents, publications, movie tapes, etc. That was a real sensation and actually the first active exoskeleton in the world.
Delivered to the Texas Rehabilitation Center, Houston for evaluation purposes.

Figure 6
Successful developed active arm orthosis for rehabilitation of advanced cases of dystrophy and similar diseases. Controlled by means of a joystick. Made in Mihajlo Pupin institute, 1982.

3.1 Zero-Moment Point Concept and Semi-Inverse Method

In parallel with the states feedback including loads feedback at powered joints of legged locomotion robots and particularly of biped mechanisms, it is essential for dynamic stability of the overall system to control ground reaction forces arising at the contacts of the feet and the ground.

For instance, with the biped robot in the single support phase, shown in Figure 7, it is possible to replace all elementary vertical forces by their resultant. Let the point O_R (Fig. 7) represent the point at which the sum of moments is equal zero, so that this point where only force is acting is called Zero-Moment Point (ZMP) [7-10].

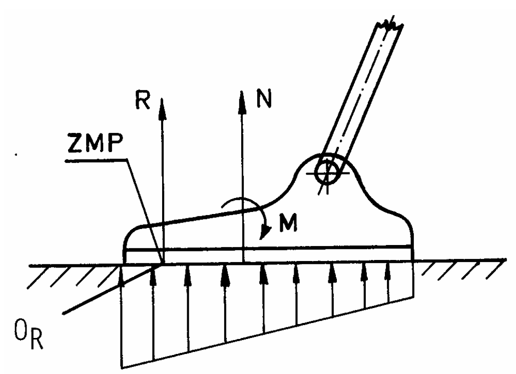

Figure 7
Load distribution along the foot

The equations of dynamic equilibrium of the biped mechanism can be derived for ZMP, so that the introduction of the ZMP notion made it possible solve this very specific problem of applied mechanics. Namely, for any other point except for ZMP, equations of dynamic equilibrium would contain unknown dynamic reaction forces, making thus the problem of dynamics modeling in the class of legged, particularly of biped locomotion robots, unsolvable. However, if we integrate the equations written for the ZMP, then it becomes possible to calculate the reaction forces, as they depend on all internal coordinates, velocities, and accelerations of the overall mechanism.

A next decisive step in modeling and control of legged, particularly biped locomotion robots, was the introduction of the semi-inverse method [8-11].

What is the essence of the semi-inverse method?

The conditions of dynamic equilibrium with respect to the coordinate frame attached to the Zero Moment Point give three relations between the generalized coordinates and their derivatives. As the whole system has n degrees of freedom (n>3), the trajectories of the (n-3) coordinates can be prescribed so as to ensure the dynamic equilibrium of the overall system (the trunk motion including the arms if the biped robot is in question). If there be some supplementary ZMPs (like passive joints of the biped arms), then for every additional ZMP another three equilibrium conditions are available.

Thus, when applied to the problem of investigating the dynamics of biped systems, the motion of the links is partly known, while the unknown moments are equal zero. Vanishing of the given moment results from the equilibrium conditions about the supporting point (ZMP) and about the joints of passive links.

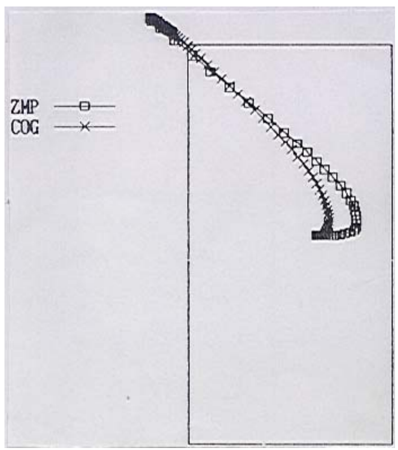

Figure 8
Walk Master: Trajectory of ZMP and projected center of gravity.

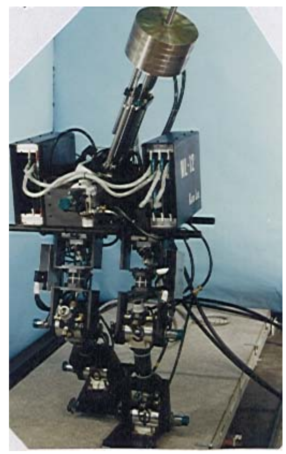

Figure 9
WL-12 (1986)

Using ZMP concept, the researchers in the Kato Laboratory elaborated three-dimensional graphics of a walking robot (Fig. 8) in 1984. This system enabled the analysis of ZMP in the course of biped robot's walking, and the composition of a walking pattern combined with the robot’s actuators' characteristics on three-dimensional graphics (Fig. 8).

The ZMP concept and semi-inverse method was elaborated in the further research [12-13] Ichiro Kato and his associates were the first who realized dynamic walking compensation with the body (Fig. 9, WL-12, 1986).

Figure 10
Honda Robot

A walking bipedal robot must be able to set its own gait so as to be capable of adapting to rough terrain, or avoiding obstacles. So these researchers developed the WL-12 with a body that stabilized its own gait. The WL-12 was capable of performing 30-cm steps in 2.6 s, using a newly proposed algorithm that automatically composed the time trajectory of the body while arbitrarily giving the trajectory of the lower limbs and ZMP.

Based on the same ZMP method, the authors from Honda R & D Co. Ltd. Wako Research Center have presented [14-15] the HONDA Humanoid Robot (Fig. 10) – the most successful result in biped locomotion to date.

Among many research activities in the domain of humanoid robots (modeling and control) I would like to emphasize the importance of a big and very promising project on Virtual Humanoid Robot Platform [16].

The ZMP method has recently attracted tremendous interest of researchers and has found very attractive applications in humanoid, biped and multi-legged robots. It was demonstrated that the ZMP method provides a quite useful dynamic criterion for the characterization and monitoring of the human/humanoid robot locomotion. The concept of ZMP is also very useful for the analysis and control of the human gait in rehabilitation robotics [17].

4 Some Pioniring Results of ‘Belgrade Scool of Robotics’ from Domain of Dynamics and Dynamic Control

4.1 Recursive Formulation of Robot Dynamics

Recursive formulation of robot dynamics was presented in 1973 by Vukobratovic and Stepanenko, while complete recursive Newton-Euler formulation in robot modeling was given by Vukobratovic [18], along with the application of this computation method onto open-link manipulator mechanisms [19]. To expand this, Vukobratovic and Potkonjak derived the first recursive Lagrangian formulation in robots modeling [20]. The method has been dedicated to the direct and inverse problems of dynamics. The method of Appel’s equations, conceived by E. P. Popov [21], was developed in its final form by Vukobratovic and Potkonjak [22], to solve both the inverse and direct dynamics problems.

4.2 Computer-Aided Generation of Robot Dynamics in Symbolic Form

Computer-aided generation of robot dynamics in symbolic form has been developed in the Mihajlo Pupin Institute under the guidance of Professor Vukobratovic. At the time of the beginnings of numerical procedures, their computational deficiencies were an obstacle to the application in on-line controllers. The same was true of the numeric-kinematic algorithm. However, symbolic approaches to deriving robotic models can be much more efficient than the numerical ones. A symbolic method exploits in full the particular kinematic and dynamic structures of the manipulator. These ‘customized’ algorithms eliminate the unnecessary arithmetic operations. The advantages of customized symbolic methods in robotics were recognized first in [23, 24] and an efficient method of modeling serial-link manipulators in numeric-symbolic form was elaborated in [23].

4.3 Dynamic Approach to Generation of Trajectories for Robotic Manipulators

Dynamic approach to generating robotic trajectories is the method for an optimal synthesis of manipulation robot trajectories. It was proposed first in 1982 [25], whereby the system was considered as a complete, nonlinear dynamic model of the mechanism and actuators [25]. Regarding the practical importance of the energy for optimal motion synthesis ensuring simultaneously a smooth, jerkless motion and minimal actuators’ strains, a particular attention was paid to the energy needed for an optimal motion of nonredundant manipulators. A procedure for the dynamic synthesis of redundant manipulator trajectories [26] was proposed for the first time in 1984. This procedure was not really dynamic for the reason that the system was presented by the kinematic model, but the optimality criterion was a dynamic one. This method exhibited considerable advantages over the kinematic approaches in the cases of manipulation of heavy objects by large, powerful robots, and high-speed manipulation with high-energy consumption.

4.4 Centralized Feed-Forward Control in Robotics

The centralized feed-forward control is one of the dynamic control laws which has been effectively used in practice. It includes the so-called nominal programmed control, which compensates for the dynamics of the overall mechanism along the nominal trajectory. The centralized feed-forward for the application in biped locomotion systems was proposed in the early papers [8, 9, 11]. With the biped walking machines, an accurate tracking of the pre-calculated nominal trajectories, achievable by the application of the centralized feed-forward control, was a prerequisite for ensuring dynamic equilibrium during the walk. The centralized feed-forward control to manipulation robots was introduced by Vukobratovic and Stokic [27-29]. As compared to other dynamic control laws (e.g. the so-called inverse dynamics or computed torque method) [30-32], the centralized feed-forward has exhibited considerable advantages such as higher robustness, simpler control scheme, requiring no changes in the basic structure of the classical servo-system schemes, etc. The application of centralized feed-forward in the commercial industrial robot controllers that showed full effectiveness of the proposed approach, has begun a number of years later. Optimal feed-forward control speeds up the motion of mechatronic systems near to the physical limits. In the recent applications, real-time optimal feed-forward control enhanced the international competitiveness of the leading robot manufacturers. Also, the robot-in-the-loop mathematical optimization reduced drastically the time needed for robot controller tuning.

4.5 Robot Dynamic Control

The first idea of applying dynamic control to robots originated from the goal to track a prescribed trajectory by the anthropomorphic active mechanisms, specifically biped locomotion systems. Vukobratovic and Juricic [7, 8] suggested a dynamic control scheme consisting of a feed-forward path (based on the complete dynamic model of the system) and feedback path, where the role of the feed-forward compensation is to cancel the nonlinearities of the nominal dynamics of the system. Several years later, such approach was proposed and elaborated for the joint space dynamic control of manipulation robots [27, 28, 33].

4.6 Decentralized Control and Observer Applied to Strongly Coupled Active Mechanisms

When a decentralized controller is applied to an active spatial mechanism, the system is considered as a set of subsystems. In order to compensate for the influence of dynamic coupling among the subsystems, a two-stage synthesis of control was introduced [8, 11, 27, 34]. This approach was applied first to biped locomotion systems, and was extended later to manipulation systems and other active mechanisms [35]. First, the so-called nominal programmed control is applied, realizing the desired motion of the system in an ideal case for some specific initial conditions. In the second stage of control synthesis, the control to stabilize the system around the nominal trajectory under the perturbations of the initial conditions, has to be synthesized. By introducing the programmed nominal control, the dynamic coupling among the subsystems is thus reduced, assuming that we consider the system state in the finite regions of state space. To further compensate for the influence of strong coupling, the following approach was proposed [27]: if each mechanical degree of freedom is considered as a subsystem, the coupling among such subsystems represents a force (torque) which could be either computed using the dynamic model of the mechanism, or directly measured. This enables the introduction of the so-called global control in the form of feedback via either computed torque/force or direct torque/force feedback. By applying such a global control, the destabilizing influence of the coupling upon the global system stability can be minimized [27, 35]. A similar approach can be applied if a decentralized observer is applied for a strongly coupled active mechanism [36].

4.7 Force Feedback in Dynamic Control of Robots

The application of the force feedback for the biped locomotion systems has been proposed for the first time by Vukobratovic and Stokic [11, 34, 35, 37]. The effects of joint force sensory feedback to compensate for the dynamic coupling among the joints of the articulated mechanisms, has been first recognized with the biped locomotion robots, since the coupling among the joints motion is very strong and has a major influence upon the overall system stability. Another advantage of this approach over the dynamic control laws based on the dynamic models of robots is that the force feedback compensation is not sensitive to the inaccuracy in the identification of the model nonlinearities and parameters.

4.8 Decentralized Control Stability Tests for Robotic Mechanisms

In the papers by Vukobratovic and Stokic [11, 27, 35, 38], the application of the decentralized control to large-scale mechanical systems in the domain of robotics has been considered for the first time from a theoretical point of view. Local control is synthesized for each subsystem, neglecting the interconnections among them. Since the influence of interconnections between the subsystems may be too strong, nominal programmed control calculated using a centralized model of the system has been introduced [27-29, 35]. However, this approach is acceptable when the desired motion is well known in advance and when the system parameters are precisely defined. If these assumptions are not met, then the synthesis and application of the nominal programmed control based upon the complete, centralized model is not appropriate. For these reasons a completely decentralized control law has been proposed [39-41]. This control law includes local servos around the joints and the local nominal feed-forward terms based on the decentralized model of the robot dynamics. This decentralized control approach has been used with industrial robots for a long time (normally without local feed-forward terms), but no theoretical analysis of such control scheme has been carried out.

4.9 Underactuated Robotc Systems

The appearance of unpowered degrees of freedom is most characteristic of legged, particularly bipedal, locomotion robots. Namely, during the real walking under perturbations, additional angles appear causing that the whole robot rotates around its feet edges. These passive (unpowered) degrees of freedom have a prevailing influence on the overall biped robot stability. Differing from the so-called underactuated systems that appear in the today's papers, in which the problems of control and stability are of academic character, the mentioned types of robotic mechanisms inevitably involve supplementary degrees of freedom which, by their nature, are really unpowered (passive). The presence of unpowered joints highly complicates the stability investigation of such robotic mechanisms [27-29, 38-41].

4.10 Application of Practical Stability Tests in Robotics

One of the main problems in the synthesis of control laws for robots represents the uncertainties in the robot dynamics models. The uncertainties in the dynamic model of the environment in different technological tasks may especially have high influence, because of the difficulties in the identification/prediction of the parameters of the environment and its behavior. Therefore, it is of major importance to test the robustness of the synthesized control laws with respect to these model uncertainties. The practical stability of a robot around the desired position trajectories (and force trajectories in the case of the so-called constrained motion tasks) are defined by specifying the finite regions around the desired position (and force trajectories) within which the actual robot's position coordinates and velocities (and forces) have to be during the task execution [27-29].

4.11 Unified Approach to Control Laws Synthesis for Robot Interacting with Dynamic Environment

The unified position-force control differs essentially from the above conventional hybrid control schemes. Vukobratovic and Ekalo [42-43] have established a dynamic approach to control simultaneously both the position and force in an environment with completely dynamic reactions. The approach of dynamic interaction control [42-43] defines two control subtasks responsible for the stabilization of robot position and interaction force. The both control subtasks utilize dynamic model of the robot and environment [44] in order to ensure tracking of both the nominal motion and force. Instead of the established traditional hybrid position/force control, a new approach was proposed, which for the first time involved dynamic environment in the dynamic control of the whole robot-environment system [42-43]. However, the model uncertainties, representing a crucial problem in control of robots interacting with a dynamic environment, have not been yet addressed appropriately. The inaccuracies of the robot and environment dynamic models, as well as the robustness of dynamic control have been considered in [45-47].

Conclusions

In view of the fact that, by force of circumstances, in the very beginning of our scientific and professional career I had to ask myself how to describe the human gait and then how to control the artificially synthesized gait on the basis of the mathematical models thus obtained, I feel it somehow my personal obligation to say something about the dilemma formulated in the title of the paper, which represents a constitutive part of my personal attitude as to the current position, and before all, the outlook for robotics, especially for humanoid robotics, which has undoubtedly attracted immense attention of researchers in the last several years.

For the sake of truth, I have to admit that in the first stage of our work on two-legged locomotion I deeply believed that the synthesis and control of anthropomorphic gait could have their practical application only in the domain of active exoskeletons for severely handicapped persons of paraplegic type. Because of that, already in the far 1968 we started with a very simplified exoskeleton, which was completed in the Mihajlo Pupin Institute during the next year. In 1972 we completed an intrinsically extended version of the pneumatically driven exoskeleton aimed at restoring the basic locomotory activities of the paraplegics, and this event, naturally, evoked favorable responses in the world.

In the beginning of our work on the theory and application of anthropomorphic mechanisms I could not envisage such an intensive development in the field of humanoid robotics. On the other hand, such a state of humanoid robotics, heralding its future advancements, represents to me and my associates and followers a real scientific and professional satisfaction as we can see that our theoretical results have become and, several decades since their appearance, have still remained a sound basis for the dynamic control of humanoid robots.

At the end of these professional reflections of mine I take the liberty of trying to resolve somehow the dilemma whether the present intensive development of humanoid robots is a temporary euphoria or real necessity. I myself am inclined to the latter option, having in mind the needs for personal, or more widely, service robots, although I am aware of the fact that on the way of their application, especially in the case of personal robots, there exist serious obstacles arising as a consequence of the unadjusted living and working environment in which humans and humanoids should co-operate. Given the present level of technology, the question is posed: Are we ready to move towards personal robotics, and what might be the first step? A possible answer to this question might be given through the analysis of the human-like characteristics a personal robot must possess: human-like motion, human-like intelligence, and human-like communication. Such a challenging goal requires coordinated and integrated research efforts that span over a wide range of disciplines such as system theory, control theory, artificial intelligence, material science, mechanics, and even biomechanics and neuroscience. Thus, the research is risky, but the target is challenging and promising.

My opinion is that the results achieved in the domain of human-like motion are still rather limited, while in the domain of human-like communication several viable alternatives have been produced. However, human-like intelligence is the main obstacle to be overcome because of its complexity and multidimensionality; it is also responsible for coordination of the entire personal robot behavior.

References

[1] Vukobratovic M., Hristic D., Stojiljkovic Z.: Development of Active Anthropomorphic Exoskeletons, Medical and Biological Engineering, Vol. 12, No. 1, 1974

[2] Vukobratovic M.: Legged Locomotion Robots and Anthropomorphic Mechanisms (in English), research monograph, Mihailo Pupin Institute, Belgrade, 1975, also published in Japanese, Nikkan Shumun Ltd. Tokyo, 1975, in Russian "MIR", Moscow, 1976, in Chinese, Beijing, 1983

[3] Hristic D., Vukobratovic M.: Active Exoskeletons Future Rehabilitation Aids for Severely Handicapped Persons, Orthopedie Technique, 12/1976, pp. 221-224, Stuttgart, Germany

[4] Vukobratovic M., Borovac B., Surla D., Stokic D.: Scientific Fundamentals of Robotics, Vol. 7, Biped Locomotion: Dynamics, Stability, Control and Application, Springer-Verlag 1989

[5] Vukobratovic M., Borovac B., Stokic D., Surdilovic D.: Active Exoskeleton, Ch. 27: Humanoid Robots, pp. 727-777, Mechanical Systems Design Handbook: Modeling, Measure and Control, CRC Press, 2001

[6] http://bleex.me.berkeley.edu/bleex.htm, Bleex hompage, active exoskeleton project under the guicance of prof. H. Kazerooni

[7] Vukobratovic M., Juricic D.: A Contribution to the Synthesis of Biped Gait, IFAC Symp. Technical and Biological Problem of Control, Yerevan, USSR, 1968

[8] Vukobratovic M., Juricic D.: Contribution to the Synthesis of Biped Gait, IEEE Trans. on Biomedical Engineering, Vol. 16, No. 1, 1969

[9] Vukobratovic M., Stepanenko Y.: On the Stability of Anthropomorphic Systems, Mathematical Biosciences, Vol. 15, pp. 1-37, 1972

[10] Juricic D., Vukobratovic M.: Mathematical Modeling of a Bipedal Walking System, ASME publication 72-WA/BHF-13, Winter Annual Meeting, New York, Nov. 26-30, 1972

[11] Vukobratovic M.: How to Control Artificial Anthropomorphic Systems, IEEE Trans. on Systems, Man and Cybernetics, Vol. SMC-3, Sept. 1973

[12] Vukobratovic, M., Hristic D., Stojiljkovic Z.: Development of Active Anthropomorphic Exoskeletons, Medical and Biological Engineering, Vol. 12, No. 1, 1975

[13] Vukobratovic M., Stokic D.: Dynamic Stability of Unstable Legged Locomotion Systems, Mathematical Biosciences, Vol. 24, No. 1/2, 1975

[14] Hirose M., Takenaka T., Gomi H., Ozawa N.: Honda Humanoid Robot (in Japanese), Journal of the Robotic Society of Japan, Vol. 15, No. 1, pp. 983-987, 1997

[15] Hirai K., Hirose M., Haikawa Y., Takenaka T.: The Development of Honda Humanoid Robot, Proc. of the IEEE Intern. Conference on Robotics and Automation, Leuven, Belgium, pp. 1321-1326, 1998

[16] Nakamura Y. et al.: Virtual Humanoid Robot Platform, Proceedings of Humanoids' 2000, Tokyo, 2000

[17] Vukobratovic M., Borovac B.: Zero - Moment Point - Thirty Five Years of Its Life Intern. Journal of Humanoid Robotics, Vol. 1, No. 1, pp. 157-173, 2004

[18] Vukobratovic M., Stepanenko Y.: Mathematical Models of General Anthropomorphic Systems, Mathematical Biosciences, Vol. 17, pp. 191-242, 1973

[19] Stepanenko Y., Vukobratovic M.: Dynamics of Articulated Open-Chain Active Mechanisms, Mathematical Biosciences, Vol. 28, pp. 137-170, 1976

[20] Vukobratovic M., Potkonjak V.: Contribution to Computer Forming of Active Chain Models via Lagrangian Form, ASME Journal of Applied Mechanics, No. 1, 1979

[21] Popov E. P.: Control of Robots - Manipulators (in Russian), Journal of Technical Cybernetics, No. 6, Moscow, 1974

[22] Vukobratovic M., Potkonjak V.: Two New Methods for Computer Forming of Dynamic Equations of Active Mechanisms, Journal of Mechanism and Machine Theory, Vol. 14, No. 3, 1979

[23] Vukobratovic M., Kircanski N.: Computer-Aided Procedure of Forming of Robot Motion Equations in Analytical Forms, Proc. VI IFTOMM Congress, New Delhi, pp. 965-973, 1983

[24] Aldon M. J., Liegeois A.: Computational Aspects in Robot Dynamics Modelling", Proc. of Advanced Software in Robotics, Elsevier Science Publishers B.V., Liege, Belgium, May 4-6, pp. 3-14, 1983

[25] Vukobratovic M., Kircanski M.: A Method for Optimal Synthesis of Manipulation Robot Trajectories, Trans. on ASME, Journal of Dynamic Systems, Measurement and Control, Vol. 104, No. 2, pp. 188-193, 1982

[26] Vukobratovic M., Kircanski M.: A Dynamic Approach to Nominal Trajectory Synthesis for Redundant Manipulators, IEEE Trans. on Systems, Man and Cybernetics, Vol. 14, No. 4, 1984

[27] Vukobratovic M., Stokic D.: Contribution to the Decoupled Control of Large-Scale Mechanical Systems, IFAC Automatica, Vol. 16, No. 1, 1980

[28] Vukobratovic M., Stokic D.: One Engineering Concept of Dynamic Control of Manipulators, Trans. ASME Journal of Dynamics Systems, Measurement and Control, Vol. 102, June 1981

[29] Vukobratovic M., Stokic D.: Control of Manipulation Robots: Theory and Application, Springer-Verlag, Berlin, 1982

[30] Paul C.: Modeling, Trajectory Calculation and Servoing of a Computer Controlled Arm, A. I. Memo 177, Stanford Artificial Intelligence Laboratory, Stanford University, September, 1972

[31] Bejczy A.: Robot Arm Dynamics and Control, Technical Memorandum 33-669, JPL, February, 1974

[32] Pavlov V., Timofeyev A.: Calculation and Stabilization of Programmed Motion of a Moving Robot-Manipulator, (in Russian) Tekhnicheskaya Kibernetika, No. 6., pp. 91-101, 1976

[33] Vukobratovic M., Stokic D., Hristic D.: Dynamic Control of Anthropomorphic Manipulators, Proc. 4th Int. Symp. Industrial Robots, pp. 229-238, Tokyo, Nov. 1974

[34] Vukobratovic M., Stokic D., Gluhajic N., Hristic D.: One Method of Control for Large-Scale Humanoid Systems, Mathematical Biosciences, Vol. 36, No. 3/4, pp. 175-198, 1977

[35] Vukobratovic M., Stokic D.: Simplified Control Procedure of Strongly Coupled Complex Non-linear Mechanical Systems, (in Russian), Avtomatika and Telemekhanica, also in English, Automatics and Remote Control, Vol. 39, No. 11, 1978

[36] Stokic D., Vukobratovic M.: Decentralized Regulator and Observer for a Class of Large Scale Non-linear Mechanical Systems, Large Scale Systems, Vol. 5, pp. 189-206, 1983

[37] Stokic D., Vukobratovic M.: Dynamic Stabilization of Biped Posture, Mathematical Biosciences, Vol. 44, No. 2, pp. 79-98, 1979

[38] Vukobratovic M., Stokic D.: Choice of Decoupled Control Law of Large-Scale Systems, 2nd IFAC Symp. on Large-Scale Systems, Toulouse, 1980

[39] Vukobratovic M., Stokic D., Kircanski N.: Non-adaptive and Adaptive Control of Manipulation Robots, Springer-Verlag, Berlin, 1985

[40] Stokic D., Vukobratovic M.: Practical Stabilization of Robotic Systems by Decentralized Control, Automatika, Vol. 20, No. 3. 1984

[41] Vukobratovic M., Stokic D.: Sub-optimal Synthesis of a Robust Decentralized Control of Large-Scale Mechanical Systems, IFAC Automatica, Vol. 20, No. 6, pp. 803-807, 1984

[42] Vukobratovic M., Ekalo Y.: Unified Approach to Control Laws Synthesis for Robotic Manipulators in Contact with Dynamic Environment, Tutorial S5: Force and Contact Control in Robotic Systems, IEEE Int. Conf. on Robotics and Automation, pp. 213-229, Atlanta, 1993

[43] Vukobratovic M., Ekalo Y.: New Approach to Control Manipulators Interacting with Dynamic Environment, Robotica, Vol. 14, pp.31-39, 1996

[44] De Luca A., Manes C.: Modeling of Robots in Contact with a Dynamic Environment, IEEE Trans. on Robotics and Automation, Vol. 10, No 4, 1994

[45] Ekalo Y., Vukobratovic M.: Robust and Adaptive Position/Force Stabilization Conditions of Robotic Manipulators in Contact Tasks, Robotica, Vol. 11, pp. 373-386, 1993

[46] Ekalo Y., Vukobratovic M.: Adaptive Stabilization of Motion and Forces in Contact Tasks for Robotic Manipulators with Non-Stationary Dynamics, International Journal of Robotics and Automation, Vol. 9, Issue 3, pp. 91-98, 1994

[47] Ekalo Y., Vukobratovic M.: Quality of Stabilization of Robot Interacting with Dynamic Environment, Journal of Intelligent and Robotic Systems, Vol. 14, pp. 155-179, 1995