WHEN WERE ACITVE EXOSKELETONS ACTUALLY BORN?

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We are witnessing an unimaginably intensive development in the field of humanoid robotics. The field of active exoskeletons experiences also its renaissance and attracts an increasing attention of researchers worldwide. The objective of this article was to indicate the beginnings and review the history of the development of active exoskeletons, their original purpose and role in the systems for rehabilitation of severely handicapped persons. The present-day development of active exoskeletons has to a large extent determined their future and applications in both the military and some specific activities that come out of the frame of rehabilitation systems and go deeply into special systems for enhancing power and expanding physical and working capabilities of the man. However, the beginnings of robotics, and especially of humanoid robotics, did not foreshadow such a progress. We take a look back on the beginnings of the development of humanoid robots, especially bipedal locomotion systems and active exoskeletons, whose development marked the beginning of the research in the domain of humanoid robotics. Once more we point out some of our pioneering results in the domain of active exoskeletons that were originally dedicated to supporting locomotion of handicapped persons. We indicated the relationships between the initial research in the field of active rehabilitation techniques and contemporary humanoid systems and tried to predict the future directions of the development of humanoid robotics and active exoskeletal systems and their applications.

Keywords: Humanoid robot, biped locomotion, Zero-Moment Point (ZMP), semi-inverse method, active exoskeleton, power enhancement, active suit, force-position control, artificial intelligence, dynamic control, decentralized control.

1. Introduction

The rapid development of humanoid robots shifts anew 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 like the modern humanoid robots, which already today possess about sixty degrees of freedom and are updated in microseconds of the controller signals.

In view of the above statements, this article raises for the first time the essential question of the justification of increasing the number of degrees of freedom of humanoid robots, having in mind that for the overall skeletal activity the man has at the disposal roughly more than 600 muscles, which could be approximated by more than 300 equivalent degrees of freedom, i.e. the same number of biological actuators. The most recent knowledge from anatomy indicate that certain groups of muscles are responsible for dynamic movements of the particular body parts (shoulder, hip, backbone), encompassing complex translations and rotations at a joint. Hence, humanoid systems are presently modeled using the so-called synovial joints,[1] bearing in mind that a synovial joint has more than 3 degrees of freedom (rotational and translational). Human joints have dynamics which is qualitatively different from that of robotic joints, as human joints are more flexible than the robotic ones. Each human joint, in addition to dominant rotations (like with robots), possesses a small dose of concealed translations. The figure of the human knee shows that the femur and the tibia form a joint that is not fixed at a point, but the femur is supported on the tibia and connected by six cords (ligaments). From a point of view of mechanics, the link of the human hand or leg is not a rigid body fixed at a point – as is with contemporary robots, but a rigid body flexibly connected by short cords (ligaments). A realistic model for this is the SE(3) group of Euclidean motion of rigid body, with 6 coupled degrees of freedom. A natural physical model of the SE(3) group of motions is the helicopter "anchored" by short cords, and the corresponding problem of control, called "Contol on SE(3)-group", has been developed mainly for helicopters. Here we have the known 6-dimensional configurational manifold {roll, pitch, yaw, x, y, z}, with the additional structure of the Lee group, and the infinitesimal generators of coupled rotations and translations (control actions) are found in the accompanying Lee algebra.

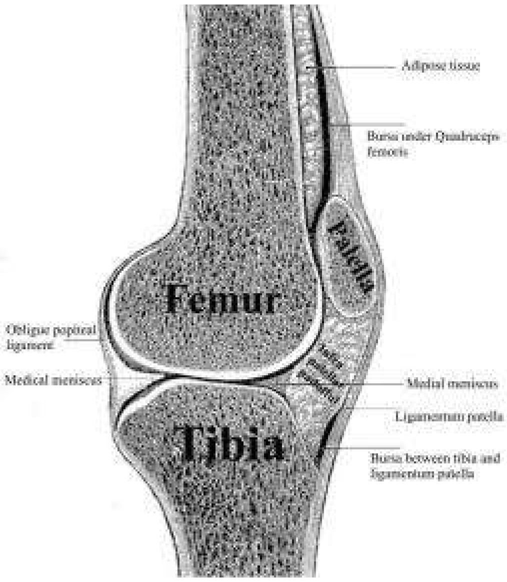

Figure 1. Anatomic picture of the human knee

The above obstacles being removed, along with the humanoid robots playing mainly the role of communicators and entertainers, there appear 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 using some gymnastic apparatus, skiing – balanced motion with sliding, etc.).

And finally, bearing in mind the current progress in the constantly developing field of humanoid robotics, whose end products will, for sure, gradually acquire more and more human-like characteristics, we can pose a thought-provoking question:

Can it happen that, not before long, biologists will be capable to 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 certain technological innovations (artificial muscles, adaptive materials, self-learning) that will allow the performances of artificial systems become similar to those of the 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 them 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 propelled by steam. Al-Jazari (1136-1206), a Turkish inventor, designed and constructed automatic machines such as water clocks, kitchen appliances and musical automata 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 [2 (p. 20)] able to sit up, wave its arms and move its head and jaw.

Figure 2. The wire diagram of the human's leg by da Vinci [2 (p. 14)]

Figure 3. The wire diagram of the human's shoulder by da Vinci [2 (p. 15)]

In Fig. 2 is presented anatomic drawing of the human leg by Leonardo da Vinci. (Notes were written in mirror handwriting, to prevent steal intellectual property.) This genius of the Renaissance and the most versatile mind of all times demonstrated an excellent knowledge of anatomy and understanding of the functions of tendons and muscles. Fig. 3 presents his anatomic study of the shoulder. He made models of muscles using copper wires, linen threads or cords, to represent the individual fascicles of muscle, numerous force and cord diagrams.[2(p.15)]

It is indicative that Leonardo da Vinci planned an automaton towards the end of the fifteenth century (Fig. 4), which was apparently a real robot. According to this sketch of mechanical joint for the automation a 'warrior in armor' was constructed by G. Torriano for King Charles V, which worked by a complex system of cables and pulleys.[2 (p. 20)]

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 (Fig. 5).[2 (p. 255)] The system 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.

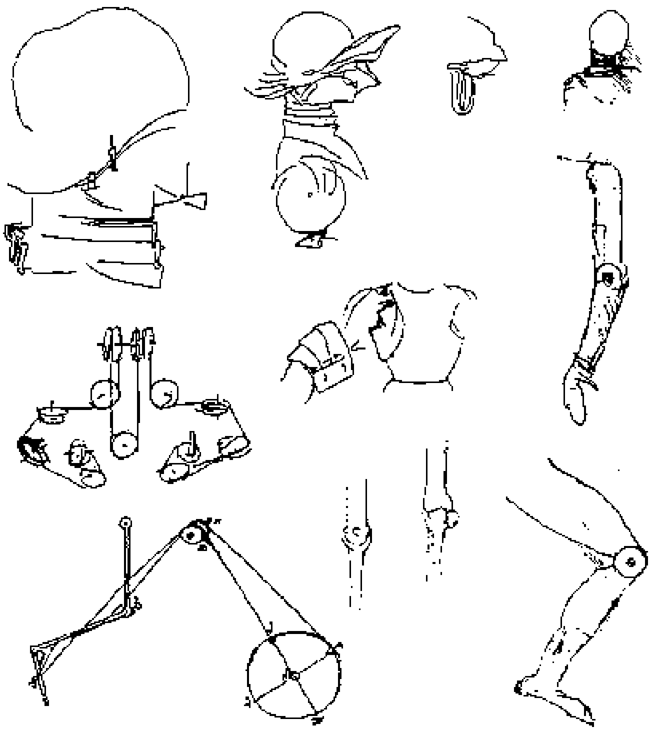

Figure 4. Sketch of a mechanism for robot by Leonardo da Vinci, c. 1497 [2 (p. 20)]

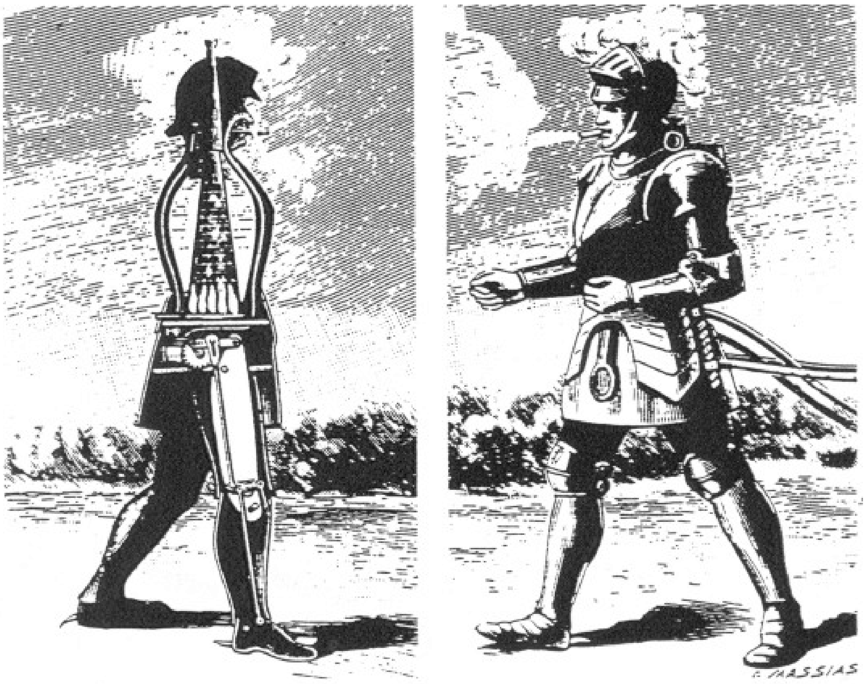

Figure 5. Steam man by George Moore [2 (p. 255)]

If, however, we want to look for the origin of robots as a technical-technological category we ought to mention the Tesla's [a] patent and experiment in Madison Square Garden in New York in 1898, in which he demonstrated a radio-controlled boat. 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 manufacturing, to assembly of parts into the final product – car, including its painting.

In addition to industrial robots, whose number is presently estimated to 900,000, 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 channels 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 the intestinal tract, and even for examination of the quality of blood vessels, etc. There have been more frequent attempts in which robots performed delicate surgical operations, either on the spot or at a distance.

It is interesting to notice that the very beginnigs of robotics in a historical sense are related to constructing articial doubles of man or of animals that exist in nature. Although the beginning of the development of robotics is usually related to the appearance of industrial robots, this can be considered only as a short break between historical attempts in making human's mechanical double and the present-day development of humanoid robotics and active exoskeletal systems. Presently, industrial robotics is apparently in stagnation, whereas humanoid robotics is experiencing its rapid development and, we can say, enters the phase of its renaisance.

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. However, this is not the end. If a building is capable of controlling its deviation from the vertical position, i.e. oscillations caused by strong wind blow, as well as in the circumstances of seismic soil acceleration, such a construction can be thought of as a specific, i.e. unconventional, robot or active system.

A special class of robots makes humanoid robots. There have already been numerous attempts, especially in Japan, to employ them as assistants in the human living and working environment. It is believed that in the decades to come they will find wide application in co-operation with man as service robots. Of course, a prerequisite would be some new norms of adapting appropriately the living environment, including furniture and various appliances. A

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

special characteristic of these robots is their anthropomorphic appearance and involvement of elements of artificial intelligence. By definition, rehabilitation exoskeletons should also be of anthropomorphic shape. Such robots, first in the world, were realized in the beginning of the eighth decade of the last century in the Mihailo Pupin Institute in Belgrade. It was the first example of an exoskeleton for anthropomorphic motion of handicapped persons of paraplegic type.

Figure 6. Complete model of the SANTOS digital Virtual Soldier project [3]

Presently we are witnessing a rapid development in the domain of humanoid robots and active exoskeletal systems. Their mechanical complexity and capabilities considerably converge to those of humans. Thus, the systems that are very close to humans are subject of active research. One such project is SANTOS Virtual Soldier,[3] carried out under the guidance of Dr Karim Abdel-Malek and under auspices of DARPA, is capable of modeling a humanoid system with even 103 degrees of freedom. On this project are engaged researchers from 10 renowned universities from the USA. SANTOS is a digital human model living in the computer. He is capable of accomplishing tasks on his own, unaided. The objectives are to develop a fifth-generation digital human that is intelligent, has realistic motion and postures, that evaluates prototypes of components and systems before they are built. In Fig. 6 is shown a complete mechanical structure of this simulation system.

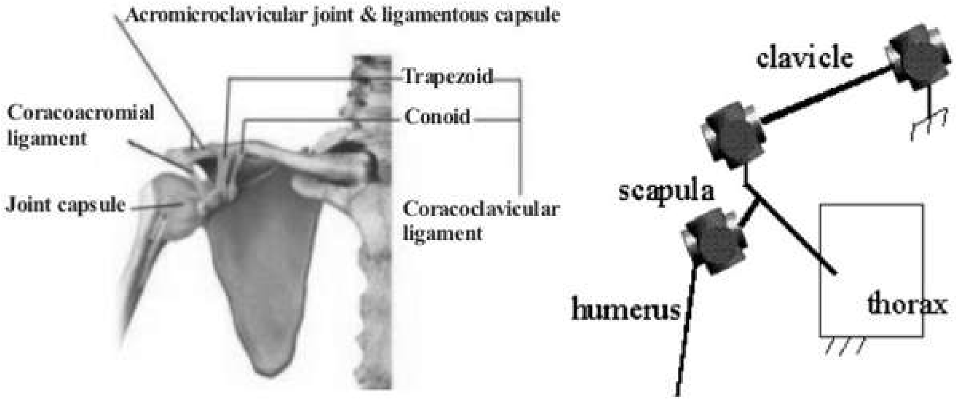

Figure 7. Anatomic analysis of the human shoulder and the equivalent mechanical model [3]

The main links of this system have been modeled with a special care to obtain as realistic as possible simulation of everyday human motions. Thus, for example, the shoulder has been modeled with 9 degrees of freedom (Fig. 7). Special attention was paid to the modeling of the human backbone (Fig. 8). While it has been accustomed to model the trunk (and the backbone itself) of contemporary humanoid robots at most with 4 degrees of freedom, with SANTOS the backbone is modeled with even 38 degrees of freedom.

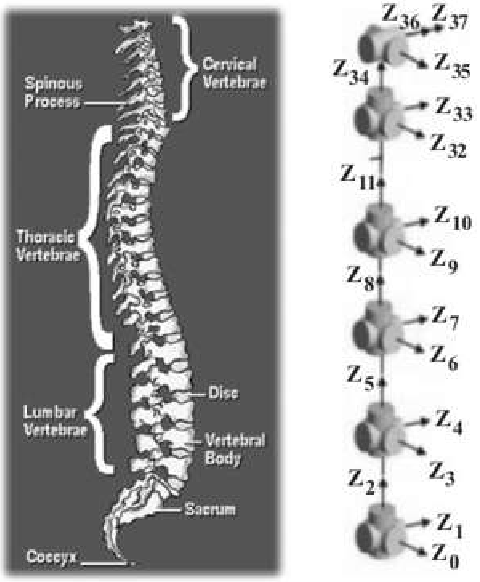

Figure 8. Anatomic analysis of the human backbone and the equivalent mechanical model[3]

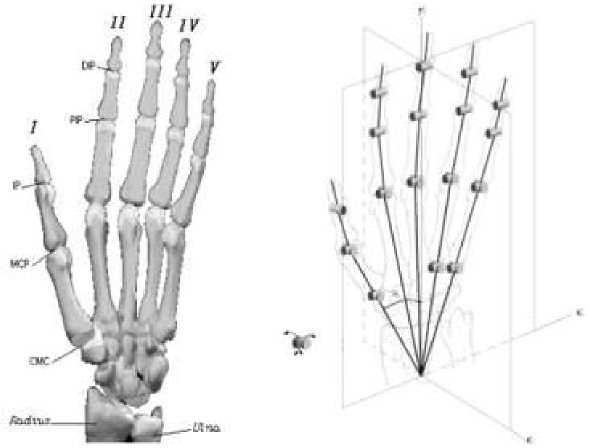

Figure 9. Anatomic analysis of the human hand and the equivalent mechanical model[3]

Still, the utmost attention has been paid to modeling the hand, as a supreme human system for performing most diverse tasks. In Fig. 9 is presented the anatomic analysis of the human hand and an equivalent mechanical model.

3. Humanoid Robotics

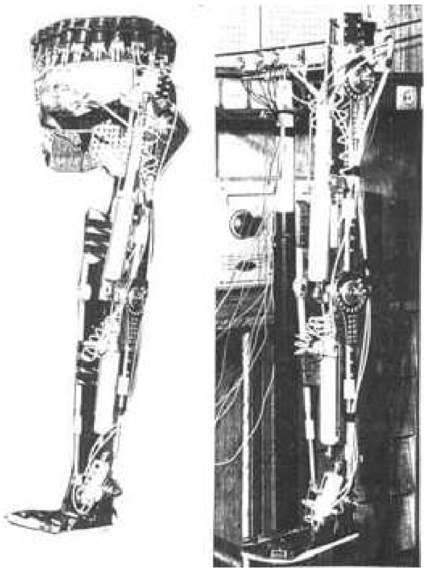

Figure 10. First Version of the Powered Leg at the Mihailo Pupin Institute (1971.)

The beginning of the development of humanoid robotics coincided with the beginning of the development of the world's first active exoskeletons at the Mihailo Pupin Institute in 1969, under the guidance of Prof. Vukobratovic.[4-8] It should be noted that legged locomotion systems were developed first. Also, the first theory of these systems was developed in the same institute, in the frame of active exoskeletons. Hence, it can be said that active exoskeletons (Figs. 10-11) were the predecessors of the modern high-performance humanoid robots. Recently, there has been evident a revived interest in active exoskeletons, first of all of military dedication.[9] The present-day active exoskeletons are developed as the systems for enhancing capabilities of the natural human skeletal system.

In the above articles,[4-8] published in several languages, we presented our first attempts to realize artificial gait with the potential application with handicapped persons. Thus, the world community has been informed about our initial results in the domain of so-called active rehabilitation with the aid of robots of exoskeleton type.

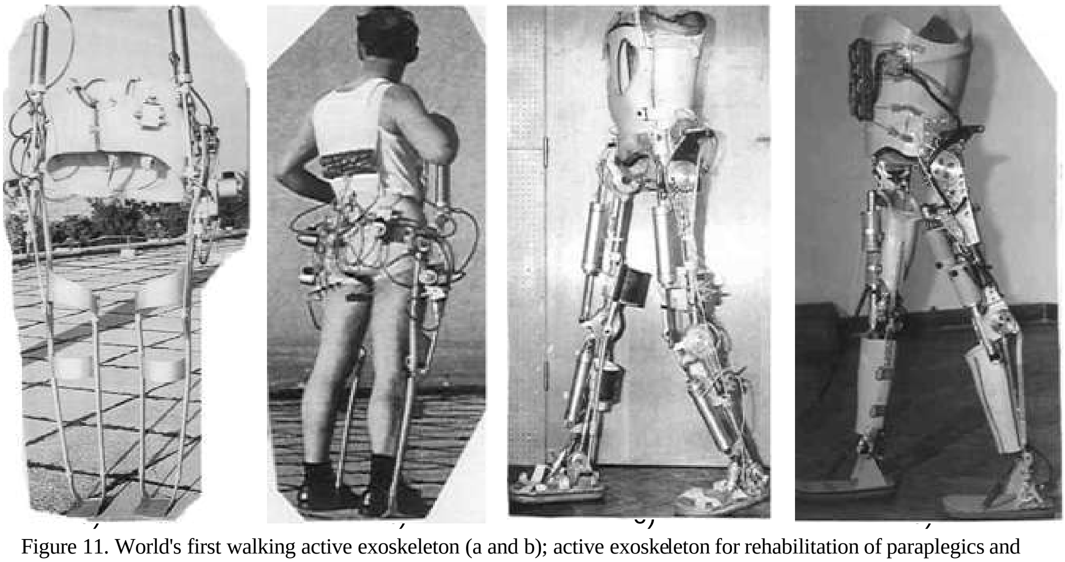

Figure 11. World's first walking active exoskeleton (a and b); active exoskeleton for rehabilitation of paraplegics and similar disabled persons (c); Active exoskeleton with electromechanical drives (d).

World's first walking active exoskeleton, pneumatically powered and partly kinematically programmed, for producing near-anthropomorphic gait is presented in Fig. 11 (a) and (b). Made in 1969 at the Mihailo Pupin Institute, it was a predecessor of more complex exoskeletal devices for severely handicapped persons.

Most successful version of an active exoskeleton for rehabilitation of paraplegics and similar disabled persons, pneumatically powered and electronically programmed, realized and tested at Belgrade Orthopedic Clinic in 1972 is presented in Fig. 11 (c). One specimen was delivered to the Central Institute for Traumatology and Orthopedy, Moscow in the frame of the USSR-Yugoslav inter-state scientific cooperation. From 1991 the exoskeleton belongs to the basic fund of Polytechnic Museum (Moscow) and State Museum Fund of Russian Federation (Fig. 14). It is displayed in the frame of the Museum's exposition dedicated to the development of automation and cybernetics.

Figure 12.

"Active Suit", a modular semi-soft active orthotic device for the dystrophic. 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 USA-Yugoslavia cooperation. 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.

Active exoskeleton with electromechanical drives, electronically programmed, built and tested in 1974 is presented in Fig. 11 (d). Served mainly to evaluate and develop electro-mechanical drives for active orthotic devices, as the "active suit" or active arm orthosis. This was the first example known in the world of active exoskeleton that used electric motors as actuators. As such, it can be considered as a predecessor of the contemporary humanoid robots driven by electric motors.

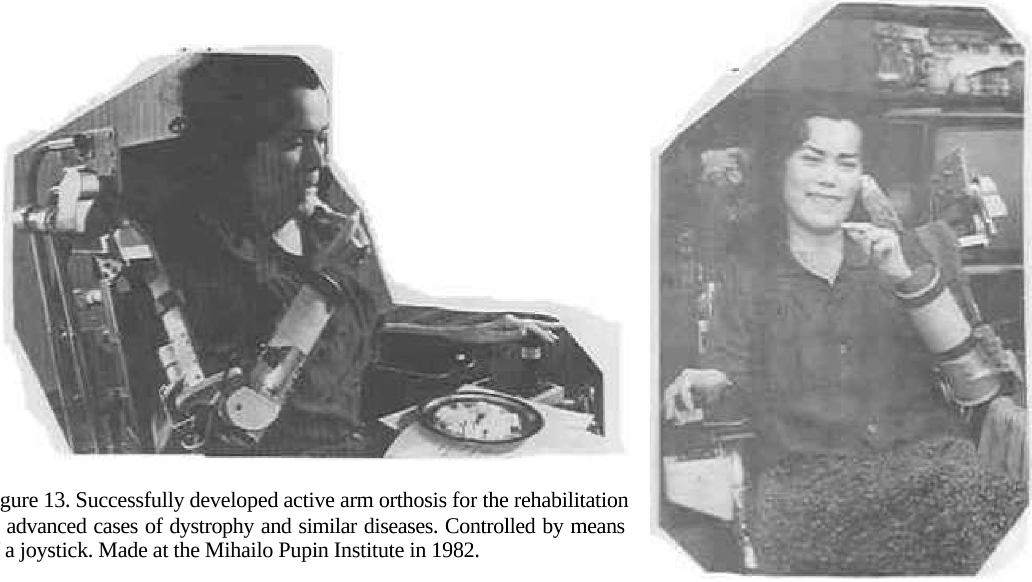

Figure 13. Successfully developed active arm orthosis for the rehabilitation of advanced cases of dystrophy and similar diseases. Controlled by means of a joystick. Made at the Mihailo Pupin Institute in 1982.

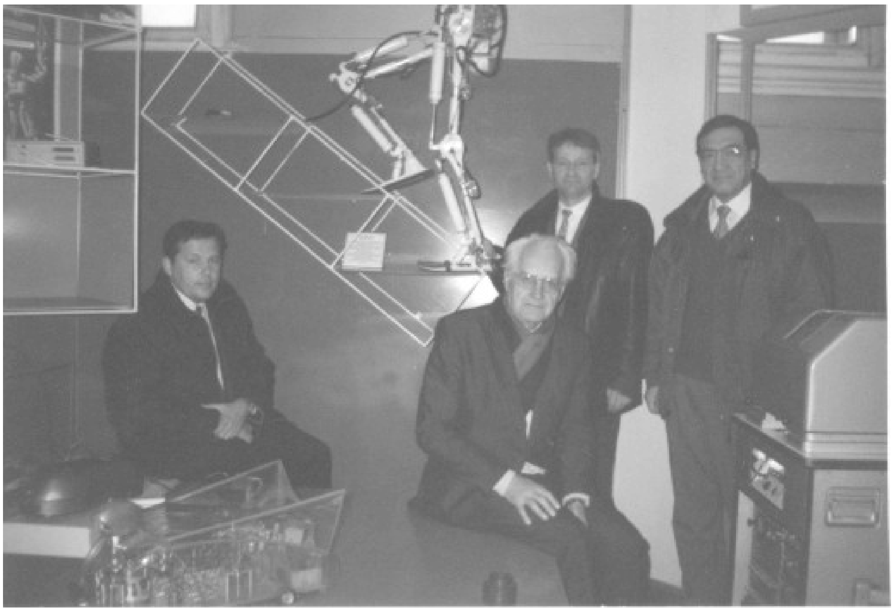

Figure 14. Belgrade active exoskeleton exhibited in the Polytechnical Museum in Moscow as an item of the basic fund of objects.

3.1. *Zero-Moment Point concept and Semi-inverse method*

In the course of the development of active exoskeletal systems and their application for the purpose of rehabilitation of handicapped persons, there naturally arose the problem of maintaining gait balance of such a hybrid system composed of the powered mechanical exoskeleton joined with the human organism. As a solution to this problem we introduced the method of Zero-Moment Point (ZMP method), which provides necessary and sufficient conditions for maintaining dynamic balance of the humanoid system during its gait, not only with active exoskeletal systems, but also with all legged locomotion systems.

In parallel with the state feedbacks, including load feedbacks, at the powered joints of legged locomotion robots and particularly of biped mechanisms, it is essential for dynamic balance of the overall system to control ground reaction forces arising at the contacts of the feet and the ground. For instance, with the foot of the biped robot in the single-support phase, shown in Fig. 8, it is possible to replace all elementary vertical forces by their resultant. Let the point depicted in Fig. 8 in the Cartesian frame be the point where the resultant ground reaction force is acting (the axes *x* and *y* being horizontal and the *z*-axis vertical), then a mathematical expression for achieving dynamic balance is: $\Sigma \boldsymbol{M}_x = 0$ and $\Sigma \boldsymbol{M}_y = 0$. It is not necessary for the moment about the *z*-axis be zero, provided it is compensated by the friction between the foot and the ground. Thus, $\Sigma \boldsymbol{M}_z \neq 0$ does not cause motion. Hence, this point (Fig. 15) inside the support area (excluding the edges) was termed Zero-Moment Point.[10-13]

The ZMP position in a dynamically balanced gait can be determined by measuring reaction forces acting on the supporting foot. If, because of the action of a large disturbance, the robot is overturning, its supporting foot (or foot's toes link in contact with the ground) is not immobile with respect to the ground and reference support area does not exist any more (degenerating to a line). Hence, at this moment, the robot is not dynamically balanced, the ZMP does not exist, and its position cannot be determined by measuring reaction forces acting on the supporting foot.

When humanoid robot control is concerned, no distinction is usually made between small and large disturbances; they are often confused, as well as the strategies of their compensation. A consequence of the disturbances, which unavoidably arise even in the realization of reference motion, is the deviations of joint trajectories, as well as of the ZMP position from the reference. Compensational movements can only be realized by the motions at the joints, which always influence the ZMP position. In other words, the control that has to minimize deviations at the joints should additionally take care of the preservation of the balance of the overall system, so that the cumulative effect of all the forces arising due to the correction of the deviations at the joints does not additionally increase the deviation of the ZMP from its reference position. If the applied control decreases simultaneously deviations at the humanoid's joints, and deviations of the ZMP from its reference position, the state of the system as a whole will approach the reference state. Then, it can be said that such disturbances belong to the class of small disturbances.

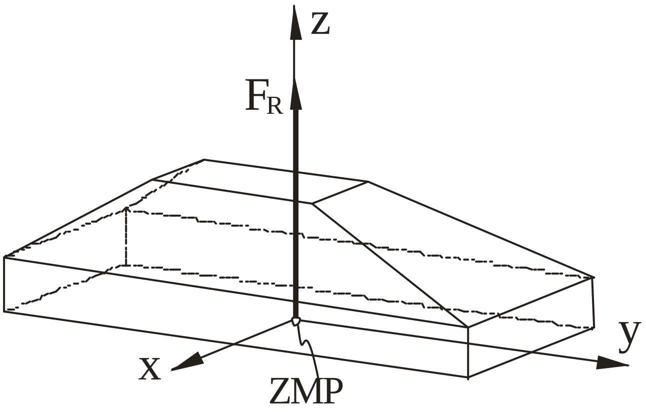

Figure 15. Foot of the supporting leg in single-support phase and the position of ZMP

However, the control synthesized with the aim of minimizing deviations at the joints can, as a side effect, produce an undesirable increase of the ZMP deviation and thus jeopardize dynamic balance of the mechanism. Hence, irrespective of the magnitude of deviations at the joints, the mechanism is in the zone of large disturbances. If the ZMP comes too close to the foot edge, which represents a threat of overturning, it is necessary to abandon temporarily the action of minimizing the errors in tracking of joint trajectories, impose the action of eliminating the danger of falling down (e.g. by stepping aside in a certain direction or by making energetic swing of the arms [5]) as the task of primary importance, reestablish dynamic balance and then, continue on tracking the reference motion.

The ZMP concept [b] has had a tremendous impact on the theory and realization of biped locomotion, and has been tested both theoretically and practically many times, as well as successfully applied. Because of that some researchers hold the conviction that the ZMP concept is clear by itself. Hence, one can find in the literature different definitions of ZMP [14-16] which, strictly speaking, have not been always precise, but it can be said that the ZMP concept has been used correctly. However, in the recent years, several papers have appeared [17-18] in which one can see the lack of understanding of the ZMP concept, inferring also some erroneous conclusions. All these cases were analyzed and explained in.[19-21]

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

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[b] Although a number of notions in the domain of biped locomotion have not been explicitely defined, no incorrect interpretations of the basic notions have been observed for a long time. Only recently, there appeared a need for a paper [23] in which some of the notions that have been in use a long time are formally defined.

dynamic balance would contain unknown dynamic reaction forces, making thus the problem of dynamics modeling in the class of legged, particularly bipedal, 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 mechanisms, particularly biped locomotion robots, was the introduction of the semi-inverse method.[11-13,22] What is the essence of the semi-inverse method?

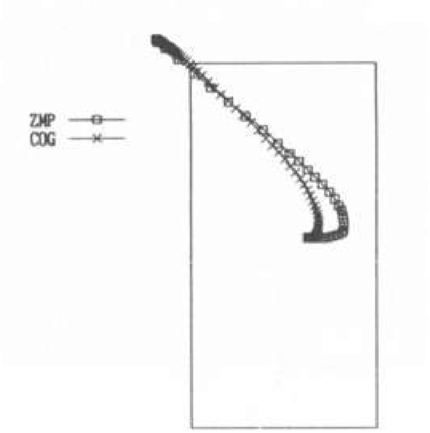


Figure 16. Walk Master: Trajectory of ZMP and projected center of gravity.

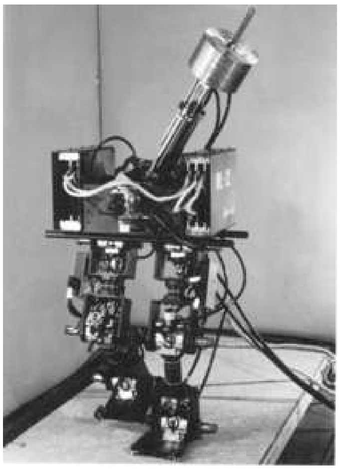


Figure 17. WL-12 (1986)

The conditions of dynamic balance 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 balance of the overall system (the trunk motion including the arms if the biped robot is in question). If there be some supplementary ZMP's (like passive joints of the biped arms), then for any additional ZMP another three equilibrium conditions should be 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 balance conditions about the supporting point (ZMP) and about the joints of passive links.

Using ZMP concept, the researchers in the Kato Laboratory elaborated three-dimensional graphics of a walking robot (Fig. 16) in 1984. This system enabled the analysis of ZMP behavior in the course of biped robot's walking and composition of a walking pattern combined with the robot's actuators' characteristics on three-dimensional graphics (Fig. 17).

The ZMP concept and semi-inverse method were elaborated in the further research.[24,25] Ichiro Kato and his associates were the first who realized dynamic walking compensation with the body (Fig. 17, WL-12, 1986).

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 new algorithm that automatically composed the time trajectory of the body while arbitrarily giving the trajectory of the lower limbs and ZMP.

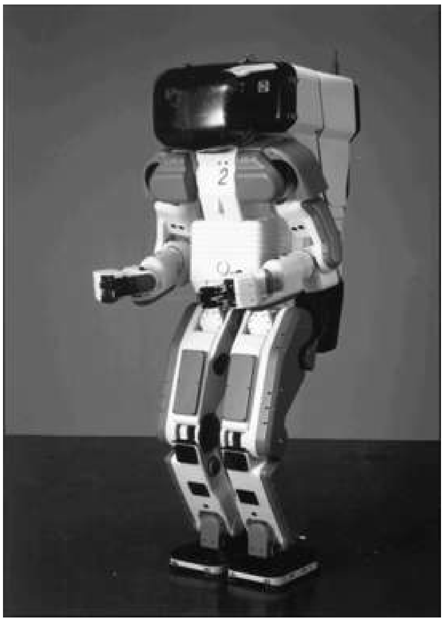


Figure 18. Honda Robot

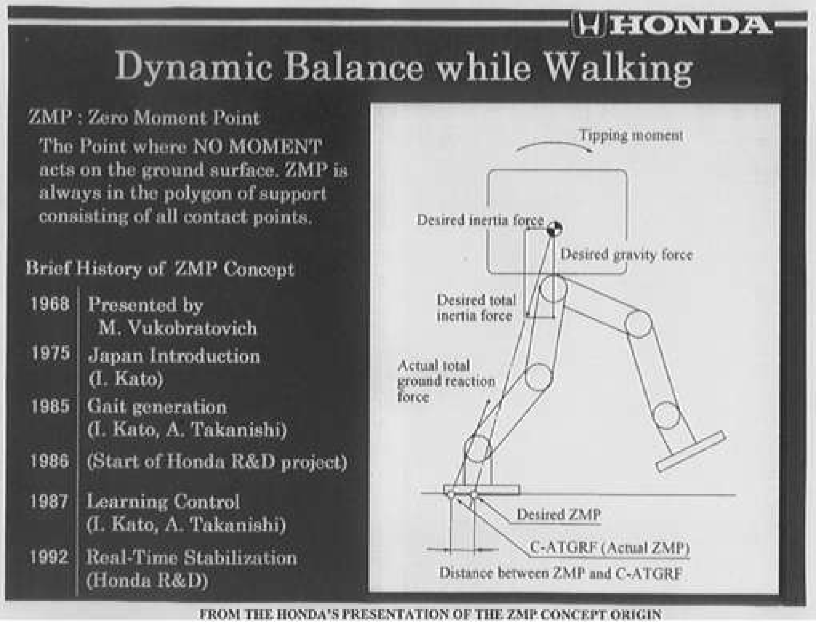
Based on the same ZMP method, the authors from Honda R & D Co. Ltd. Wako Research Center have presented [26, 27] the HONDA Humanoid Robot (Figs. 18 and 19), first in the world humanoid robot of high performances.

Among many research activities in the domain of humanoid robots (modeling and control) we would like to point out the importance of a big and very promising project of Virtual Humanoid Robot Platform.[27]

In Fig. 19 is given a short historical survey of the development of the ZMP method, its application and role in modern high-performance humanoid systems, from the very beginning to the recent time.

The ZMP method has recently attracted tremendous interest of researchers and has found very attractive applications in humanoid, bipedal and multi-legged robots.

It has been demonstrated that the ZMP method provides a very useful dynamic criterion for the characterization and monitoring of the human/humanoid locomotion. The concept of ZMP is also very effective in the analysis and control of the human gait in rehabilitation robotics.[20]



HONDA

Dynamic Balance while Walking

ZMP : Zero Moment Point

The Point where NO MOMENT acts on the ground surface. ZMP is always in the polygon of support consisting of all contact points.

Brief History of ZMP Concept

1968	Presented by M. Vukobratovich
1975	Japan Introduction (I. Kato)
1985	Gait generation (I. Kato, A. Takanishi)
1986	(Start of Honda R&D project)
1987	Learning Control (I. Kato, A. Takanishi)
1992	Real-Time Stabilization (Honda R&D)

FROM THE HONDA'S PRESENTATION OF THE ZMP CONCEPT ORIGIN

Figure 19. Based on the ZMP method, the authors from Honda R&D Co. LTD. WAKO Research Center, have presented the HONDA humanoid robot.

4. Fundamental scientist achievements in the domain of Robotics arising from the pioneering contribution to the development of active exoskeletons

The breakthroughs made in the domain of active exoskeletons have certainly influenced the further development of general robotics and especially humanoid robotics. In the preceding section we explained the ZMP method and gave examples of the application of the semi-inverse method onto humanoid systems. These two methods, which are unavoidable in the domain of humanoid robotics, enabled the solving of the complex problem of dynamic balance during the motion of active exoskeletons. Numerous results that appeared later, and which found their wide application in today's robotics, have been previously observed in the exoskeletal systems. Let us only mention: Recursive formulation of robot dynamics, initially concerned with the anthropomorphic robotic mechanisms; Dynamic approach to generation of trajectories for robotic manipulators, a method for optimal synthesis of manipulation robot trajectories where the system is considered as a complete, nonlinear dynamic model of the mechanism and of the actuators, first applied in active exoskeletal systems and then extended onto manipulation robotic systems; Centralized feed forward control in robotics, the control laws that take into account and compensate for all dynamic effects in the robotic systems and applied in bipedal locomotion system, proposed in the early papers;[11, 12, 22] Robot dynamic control, the procedure of managing the motion and forces of a robot with explicitly taking care of the system's dynamics and the first idea of applying dynamic control to robots, originating from the goal to track a prescribed trajectory by the anthropomorphic active mechanisms, specifically biped locomotion systems; Force feedback in dynamic control of robots, proposed by Vukobratovic and Stokic [22, 29-31] for the biped locomotion systems; Decentralized control stability tests for robotic mechanisms, considered for large-scale mechanical systems as humanoid systems are by their structure; Application of practical stability test in robotics, especially involved in humanoid locomotion systems, where it was studied first; Underactuated robotic systems, characterized by the appearance of unpowered degrees of freedom, which is a characteristic of legged, particularly bipedal, locomotion robots; Principle of the unified approach to control laws synthesis for robot interacting with dynamic environment, best observed during the gait of humanoid systems at the foot-ground contact; Modeling and control of multi-arm cooperating robots interacting with the environment, the problem of solving a cooperative work which lies in determining the forces at the contact points of the robot with its environment, and is especially present with humanoid locomotion systems, etc.

The above results, representing pioneering contributions to the theoretical analysis in robotics, have been valued by some of the most prominent world experts such as for example Prof. G. Hirzinger, Director of DLR Institute for Robotics and System Dynamics in Wessling, Germany, who says: "**Prof, Vukobratovic is for me one of the real pioneers in robotics. He was one of the first in the world to realize the importance of dynamics, even at a time where nobody working in robot industry could believe that robots might ever be something else than purely position-controlled machine on joint level. We are now indeed entering an area where industrial robots start to take into account the dynamics. Prof. Vukobratovic predicated this many years ago.**[32 (p. 60)]

We are going now to give a brief account of the most important results that came out from the research in the domain of active exoskeletons and rehabilitational legged locomotion systems.

4.1. *Dynamic approach to generation 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,[33] whereby the system was considered as an overall nonlinear dynamic model of the mechanism and actuators.[34] Regarding the practical importance of the energy for optimal motion synthesis that ensures 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 [34] 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.

4.2. *Centralized feed-forward control in robotics*

The centralized feed-forward control is one of the dynamic control laws that have 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 bipedal locomotion systems was proposed in the early papers [11, 12, 22]. 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 balance during the walk. The centralized feed-forward control for manipulation robots was introduced by Vukobratovic and Stokic.[35-38] As compared to the other dynamic control laws (e.g. the so-called inverse dynamics or computed torque method),[38-40] 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.

4.3. *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 [10, 11] 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.[35,36,41]

4.4. *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 between the subsystems, a two-stage synthesis of control was introduced.[11, 23, 29, 35] This approach was applied first to biped locomotion systems, and was extended later to manipulation systems and other active mechanisms.[30] Firstly, 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 between 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:[35] if each mechanical degree of freedom is considered as a subsystem, the coupling between such subsystems represents a force (torque) which could be either computed using the dynamic model of the mechanism or measured in a direct way. This enables the introduction of the so-called global control in the form of a feedback via either computed torque/force or direct torque/force feedback. By applying such global control, the destabilizing influence of the coupling upon the global system stability can be minimized.[30, 35] A similar approach can be used if a decentralized observer is applied onto a strongly coupled active mechanism[42]

4.5. *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.[23, 29-31] The effects of joint force sensory feedback to compensate for dynamic coupling between the joints of the articulated mechanisms, have been recognized first with the biped locomotion robots, since the coupling between 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 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.

4.6. *Underactuated robotic 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 the overall robot rotation 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.[35-37, 43-46]

5. Conclusions

In view of the fact that, by force of circumstances, in the very beginning of my scientific and professional career we have had to ask 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 question 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, particularly 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 at the Mihailo Pupin Institute during the next year. In 1972 we completed an intrinsically improved 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.

About the beginnings of the research in the domain of active exoskeletons their opinions gave at the time many world-known experts. Here we give only several of them concerning our pioneering achievements in the domain of active exoskeletons:

1. Academician, A. I. Lurie, Russian Academy of Sciences, St. Petersburg (1972)**: “Rational approach to the task solution of dynamics modeling and control of biped motion, clear and justified choice of approximations, high mathematical level of research, large scope of results conducted to practical application level, excellent presentation style - these characteristic points determine high features of the work. Professor Vukobratovic has been known since long ago as an outstanding scientist, widely known not only in his country”.** [32 (p.91)]

2. Academician I. I. Artobolevsky, Prof. A. E. Kobrinsky, Machine Theory Institute, Russian Academy of Sciences, Moscow (1975)**: “First of all we want to underline the great practical value and humane character of this area of scientific work, to which Professor Vukobratovic has devoted himself. In the course of several years he has been working successfully on creating the theoretical fundamentals and principles of the realization of the apparatus dedicated to restoring locomotion functions of human extremities, damaged as a result of severe diseases. Characteristic feature of Prof. Vukobratovic’s creative work is represented by a constant strive to conduct his theoretical results to practical verification and application.** The works of Prof. Vukobratovic are well known and highly evaluated by the Soviet specialists, which on several occasions listened to his presentations on symposia in the Soviet Union and other countries, and they got acquainted in detail with the results of Prof. Vukobratovic and profited of them in many ways in their research”. [32 (p.91)]

3. Academician D. E. Okhocimsky, Russian Academy of Sciences, Institute of Applied Mechanics, State University, Lomonosov, Moscow (1972)**:** "The work of M. Vukobratovic in the field of modeling, stabilization and realization of artificial anthropomorphic gait is of great interest. His approach to the problems and solution methods is completely original. **Let us underline the complex character of the research, the pioneering character of the work as a whole and its high scientific level”.** [32 (p.91)]

4. Academician V.O. Kononenko, Ukrainian Academy of Sciences, Director of the Institute of Mechanics, Kiev (1972)**: "Work of M. Vukobratovic represents an enormous scientific research oriented towards the elaboration of the scientific fundamentals of walking robots theory and the practical realization of the first in the world exoskeletal biped robot dedicated to the rehabilitation of severely handicapped persons.** The essential step in the development of robot theory in Vukobratovic's work represents the elaboration of system stabilization that ensures permanent dynamic balance of robot motion”. [32 (p.91)]

5. Prof. Ichiro Kato, Faculty of Science and Engineering, Waseda University, Tokyo, Japan, **Professor Vukobratovic is the founder of anthropomorphic mechanisms dynamics and stability and control of biped gait.** Under his leadership the first in the world rehabilitation exoskeleton was designed and applied in rehabilitation of severely disabled persons... [32 (p.14)]

6. George A. Bekey, Gordon Marshall Professor of Computer Science, University of Southern California, Los Angeles, USA, ... **During his scientific career (which I hope will continue for many years!) Dr. Vukoratovic and his team of researchers have made major contributions to robotics and rehabilitation. His work on the autonomous biped exoskeleton was remarkably courageous, given the technology of that time.....**[32 (p. 21)] Professor Bekey also wrote in his monograph [47 (p.446)] about our contribution in the domain of active exoskeletons: “**Two developments in Yugoslavia in the 1970s provided important**

background for later development of humanoid robots. A historically interesting robot, though not a full-body humanoid, was the walking lower body designed by Miomir Vukobratovic at the Pupin Institute. This machine consisted of a powered set of hollow legs that wrapped around the nonfunctional legs of a person with lower-body paralysis. The robot then provided walking mobility to the paraplegic, while he held on to horizontal bars for stability. [4, 10] "At the footnote of the same page it was also written: "**I saw this system demonstrated in Vukobratovic's laboratory in the 1970's. The exoskeleton did indeed walk, but the patient, captured within the moving frame, had no control over its movement. I have never seen a person with a more frightened expression than this patient!** "

7. From a letter of Professor R. McGhee to Mr. Gerson Sher, Responsible Officer at the Academy of Sciences, Washington D.C., dated March 21, 1975**.** Project: **THEORETICAL STUDY OF LEGGED LOCOMOTION WITH ANIMALS AND MACHINES** (1971-1976). Principal investigators of joint program between Ohio State University and Mihailo Pupin Institute, under NSF Grant GR – 25292 and GF – 31948, respectively: Professor R. McGhee, Electrical Engineering Department, Ohio State University, Columbus, Ohio, USA, Miomir Vukobratovic, Ph.D., Sc.D., Head of Biodynamics of Locomotion Unit, Automatic Control Laboratory, Mihailo Pupin Institute, Belgrade, Yugoslavia. Professor R. McGhee, one of the founders of world activity in legged locomotion robots says:…"In the late 1965, Prof. Tomovic [c] returned to Belgrade where he joined forces with the Mihailo Pupin Institute in an attempt to develop a light-weight lower extremity powered exoskeleton, to permit a further refinement of our control concepts. **Since the beginning, leader of this work at Mihailo Pupin has been Dr. Vukobratovic.** With the support of SRS from the United States, successful operation of a powered exoskeleton supporting a paraplegic subject was achieved in Belgrade by about 1971. Since that time, the exoskeleton has gone through a series of design improvements, including a change from pneumatic power to electric power. … We feel that the following joint activities will be severely curtailed or even terminated if no funds are made available to our Yugoslav collaborators: **Dr. Vukobratovic's group at Mihailo Pupin has developed the only electric biped exoskeleton in the world.** At present, his exoskeleton is controlled by a simple analog device permitting only constant speed locomotion in the straight line. While this hardware development has been going on, we have accepted responsibility at OSU for digital computer software development to achieve flexible voluntary control of the exoskeleton making use of a very small digital "microcomputer" of the type ....[32 (p. 92)]

8. Excerpt from an official letter of the Republic Council for International Scientific, Educational, Cultural and Technical Cooperation, Belgrade, dated February 9, 1976, to the Mihailo Pupin Institute, concerning the evaluation of the competed joint NSF project**: THEORETICAL STUDY OF LEGGED LOCOMOTION WITH ANIMALS AND MACHINES):** "We inform you that the representative of the National Science Foundation at the session of the Yugoslav-American Board for Scientific and Technological Cooperation held in **Washington, December 1975,** declared that the project: **"Theoretical Study of Legged Locomotion with Animals and Machines",** coordinator of which has been your Institute, and principal investigator **Dr. Miomir Vukobratovic, has been very positively evaluated by the American experts. They also pointed out, that they consider Dr. Vukobratovic as leading expert in the world in this area and they stated that for these investigations Japanese experts are interested, too".** ...[32 (p.93)]

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[c] Professor Rajko Tomovic, was the head of a team which developed the "Belgrade Hand", initiated in 1963 and practically terminated by 1968. The research was performed in, at that time, the Automatic Control Laboratory of the Mihailo Pupin Institute and the work in this specific area was one of the global incentives to begin with the robotics activities in the Institute, as well as in Yugoslavia.

In the beginning of our work on the theory and application of anthropomorphic mechanisms we could not envisage such an intensive development in the field of humanoid robotics, and especially in the domain of active exoskeletons. On the other hand, such a state of affairs in humanoid robotics, heralding its future advancements, represents to us 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.

Finally, it should be pointed out again that all the above pioneering activities represented advancements in the domain of conventional robotics, and that they were valued by renowned world experts in the field of robotics as valuable contributions. In the opinion of a number of world experts, the Belgrade School of Robotics has produced pioneering results in practically all the branches of conventional robotics, and especially in the domain of humanoid robots and active exoskleton systems, and contributed a great deal to establishing Robotics as a scientific discipline based on mechanics, applied mathematics, theory of automated control systems, information technologies, and computer techniques.

The expected future technological achievements in the field of special and composite materials, the development of new hybrid-type actuators or artificial muscles, then intensive development in the field of information technologies, new breakthroughs in the field of artificial intelligence and neural networks, and new and more efficient energy systems – all these advancements will certainly lead to a remarkable development of humanoid robotics as a whole, and hence, some new interesting results can also be expected in the domain of active exoskeletal systems. Manifold enhancement of human power and working capacities, as well as the increasing application of exoskeletal systems in rehabilitation, will lead to an essential increase in the overall quality of life of the modern man.

References

1 Ivancevic V., Ivancevic T., Human-Like Biomechanics – A Unified Mathematical Approach to Human Biomechanics and Humanoid Robotics" Springer, Netherlands, 2006

2 Mark E. Rosheim, Robot Evolution – The Development of Anthrobotics, John Wiley & Sons, Inc, 1994. USA.

3 http://santos.digital-humanos.org; home page of the web site of SANTOS Virtual Soldier at Iowa State University, USA.

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

5 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.

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

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

8 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.

9 http://bleex.me.berkeley.edu/bleex.htm, Bleex hompage, active exoskeleton project under the guidance of prof. H. Kazerooni.

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

11 Vukobratovic M., Juricic D., "Contribution to the Synthesis of Biped Gait", IEEE Trans. on Biomedical Engineering, Vol. 16, No 1, 1969.

12 Vukobratovic M., Stepanenko Y., "On the Stability of Anthropomorphic Systems", Mathematical Biosciences, Vol. 15, pp. 1-37, 1972.

13 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.

14 Dasgupta A., Nakamura Y., 1999, „Making Feasible Walking Motion of Humanoid Robots From Human Motion Capture Data”, Proc. of IEEE ICRA, Detroit, pp. 1044-1049.
15 Fukuda T., Komata Y., Arakawa T., 1997, „Stabilization Control of Biped Locomotion Robot based Learning with GAs having Self-adaptive Mutation and Recurrent Neural Networks”, Proceedings IEEE Conference on Automation and Robotics, Albuquerque, New-Mexico, pp. 217-222.
16 Hirai K., Hirose M., Haikawa and Takenaka T., *The Development of Honda Humanoid Robot*, Proc. of the IEEE Int. Conf. on Robotics and Automation, Leuven, Belgium, (1999) 1321-1326.
17 Goswami A, (1999), Postural Stability of Biped Robots and the Foot-Rotation Indicator (FRI) Point, The Int. Jour. of Rob. Res., Vol. 18, No. 6, pp. 523-533
18 Sardin P., Bessonnet G., (2004), Forces Acting on a Biped Robot. Center of Pressure – Zero Moment Point, IEEE Trans. on SMC – Part A, Vol. 34, No. 5, pp. 630-637
19 Vukobratovic M., Borovac B., Potkonjak V., ZMP: A Review of Some Basic Misunderstandings, Int. Jorunal of Humanoid Robotics Vol. 3, No 2, pp 152-175, 2006.
20 Vukobratovic M., Borovac B., Zero-Moment Point – Thirty five years of its Life”, Int. Journal of Humanoid Robotics, Vol 1, No 1, pp 157-173, 2004
21 Vukobratovic M., Borovac B., Note on the article Zero-Moment Point – Thirty five years of its Life”, Int. Journal of Humanoid Robotics, Vol 2, No 1, pp 225-227, 2005
22 Vukobratovic M. "How to Control Artificial Anthropomorphic Systems", IEEE Trans. on Systems, Man and Cybernetics, Vol. SMC-3, Sept. 1973.
23 Vukobratovic M., Borovac B., Potkonjak V., Towards a Unified Understandings of Basic Notions and Terms in Humanoid Robotics, accepted for publication in Robotica.
24 Vukobratovic, M., Hristic D., Stojiljkovic Z., “Development of Active Anthropomorphic Exoskeletons”, Medical and Biological Engineering, Vol. 12, No. 1, 1975.
25 Vukobratovic M., Stokic D., “Dynamic Stability of Unstable Legged Locomotion Systems”, Mathematical Biosciences, Vol. 24, No. 1/2, 1975.
26 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.
27 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.
28 Nakamura Y. et al., "Virtual Humanoid Robot Platform", Proceedings of Humanoids' 2000, Tokyo, 2000.
20 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.
30 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.
31 Stokic D., Vukobratovic M., “Dynamic Stabilization of Biped Posture”, Mathematical Biosciences, Vol. 44, No. 2, pp. 79-98, 1979.
32 “Belgrade School of Robotics”, Monograph, Publisher: Mihailo Pupin Institute, Belgrade, Editor M. Vukobratovic, Printed by “Kuca Knjige”, Belgrade 2001.
33 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.
34 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.
35 Vukobratovic M., Stokic D., “Contribution to the Decoupled Control of Large-Scale Mechanical Systems", IFAC Automatica, Vol. 16, No. 1, 1980.
36 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.
37 Vukobratovic M., Stokic D., Control of Manipulation Robots: Theory and Application, Springer-Verlag, Berlin, 1982.
38 Paul C., “Modeling, Trajectory Calculation and Servoing of a Computer Controlled Arm", A. I. Memo 177, Stanford Artificial Intelligence Laboratory, Stanford University, September, 1972.
39 Bejczy A., "Robot Arm Dynamics and Control", Technical Memorandum 33-669, JPL, February, 1974.
40 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.

41 Vukobratovic M., Stokic D., Hristic D., “Dynamic Control of Anthropomorphic Manipulators”, Proc. 4th Int. Symp. Industrial Robots, pp. 229-238, Tokyo, Nov. 1974.

42 Stokic D., Vukobratovic M., “Decentralized Regulator and Observer for a Class of Large Scale Nonlinear Mechanical Systems”, Large Scale Systems, Vol. 5, pp. 189-206, 1983.

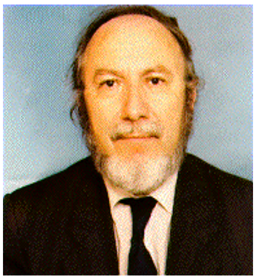
43 Vukobratovic M., Stokic D., “Choice of Decoupled Control Law of Large-Scale Systems”, 2nd IFAC Symp. on Large-Scale Systems, Toulouse, 1980.

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

45 Stokic D., Vukobratovic M., "Practical Stabilization of Robotic Systems by Decentralized Control", Automatika, Vol. 20, No 3. 1984.

46 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.

47 George Bekey, Autonomous Robots: From Biological Inspiration to Implementation and Control, Monograph, Publisher: The MIT Press Cambridge, Massachusetts, London, England, 2005.



Miomir K. Vukobratovic was born in Botoš, Serbia, 1931. He received his B.Sc. and Ph.D. degrees in Mechanical Engineering from the University of Belgrade in 1957 and 1964, respectively, and his D.Sc. degree from the Institute Mashinovedeniya, Soviet (now Russian) Academy of Science, Moscow, 1972. From 1968 he was head of the Bio-dynamics Department, then director of the Laboratory for Robotics and Flexible Automation and Director of the Robotics Center respectively at Mihailo Pupin Institute, Belgrade.

He has served as a visiting professor teaching graduate courses in robotics at several universities in the former Yugoslavia and abroad. He is the author/co-author of more than 220 scientific papers in the field of robotics and system theory, has published in leading international journals, and is also the author/co-author of about 380 papers in proceedings of international conferences and congresses. He has also authored/co-authored 15 research monographs published in English, Japanese, Russian, Chinese and Serbian, two advanced textbooks in robotics in English, and tell chapters in international monographs and handbooks. Among others, he is a holder of "Joseph Engelberger" award in robotics for his pioneering globally recognized results in applied research and education in robotics, awarded by the Robotic Industries Association in the USA in 1996.

Prof. Vukobratovic is a full member of the Serbian Academy for Sciences and Arts, a foreign member of the Russian (formerly Soviet) Academy of Sciences, a full member of the International Academy of Nonlinear Sciences, and several other foreign academies, president of Yugoslav Academy of Engineering, a foreign full member of the International Engineering Academy, Moscow, a foreign member of the Chinese Academy of Engineering, an honorary member of the Hungarian Academy of Engineering, and ether national academies. He is doctor honoris causa of Moscow State University named after M. V. Lomonosov and several ether universities in Europe. Based on the Citation Index, he has been cited more than 1,600 times.

Prof. Vukobratovic has presented thirty opening and plenary lectures at world conferences, symposia and congresses, and has lectured by invitation at more than 155 scientific seminars in the USA, Japan, Russia, China and Europe.

His major interest is in the development of efficient computer aided modeling of robotic systems dynamics, in particular dynamic non-adaptive and adaptive control of non-contact and contact tasks in manipulation robotics, as well as dynamics modeling, stability and control in legged locomotion, especially humanoid robots.