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Beginnings of robotics as a separate discipline of technical sciences and some fundamental results - a personal view

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SUMMARY

Based on the author's knowledge the paper gives a brief account of some of the scientific achievements of robotics that were of crucial importance to its development.

In a rough chronological order these are: zero-moment concept and semi-inverse method; recursive formulation of robot dynamics; computer-aided derivation of robot dynamics in symbolic form; dynamic approach to generation of trajectories of robotic manipulators; centralized feedforward control in robotics; robot dynamic control; decentralized control and observer applied to strongly coupled active mechanisms; force feedback in dynamic control of robots; decentralized control stability tests for robotic mechanisms; underactuated robotic systems; practical stability tests in robotics; unified approach to control laws synthesis for robot interacting with dynamic environment; modeling and control of multi-arm cooperating robots interacting with environment; connectionist algorithms for advanced learning control of robots interacting with dynamic environment; fuzzy logic robot control with model-based dynamic compensation, and internal redundancy – a new way to improve robot dynamic performance.

KEYWORDS: Zero-moment point; Semi-inverse method; Decentralized control; Feedforward control; Observer; Underactuated robotic systems; Practical stability; Dynamic environment; Connectionist algorithms: Fuzzy logic control; Internal redundancy.

1. INTRODUCTION

The aim of this work was to describe the emergence of some of the fundamental results of robotics that contributed to establishing it as a separate discipline of technical sciences.

In the presented selection of fundamental results of robotics I intentionally omitted those results that heavily rely upon, or more directly depend on, the level of technological development. Thus, for example, the first realizations of industrial robots, rehabilitation robots and the like have been left out. Hence, I chose sixteen topics, in the frame of which the results will be presented in a chronological order of their appearance.

Also, I would like to emphasize that though the selected results by their nature do not have a technological character, vigorous and rapid advancements in technology make them, with time, more attractive and more suitable for the application and implementation in practical realizations of a wide spectrum of robots and robotic systems.

2. 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 at the contacts of the feet and ground.

For instance, with the biped robot in the single support phase, shown in Figure 1, it is possible to replace all elementary vertical forces by their resultant. Let the point O_R (Figure 1) represent the point at which the sum of moments is equal to zero, so that this point, where only force is acting, is called ZeroMoment Point (ZMP).[1–4]

The equations of dynamic equilibrium for the biped mechanism can be derived for ZMP. Therefore, it has been made possible to 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, and thus it would be impossible to solve the problem of dynamics modeling in the class of legged, particularly biped locomotion robots. But, 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 whole mechanism.

A next decisive step in modeling and control of legged, particularly biped locomotion robots, was the introduction of the semi-inverse method.[2–5]

The conditions of dynamic equilibrium with respect to the coordinate frame located at the ZeroMoment 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 could be prescribed so as to ensure the dynamic equilibrium of the overall system (the trunk motion including the arms

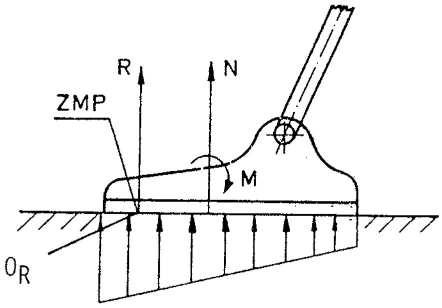

Fig. 1. Load distribution along the foot.

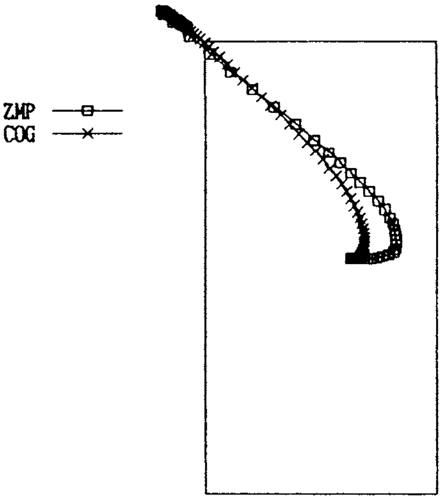

Fig. 2. WALK MASTER: Trajectory of ZMP and projected center of gravity.

if the biped robot is in question). If there be some supplementary ZMPs (like passive joints of 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 to zero. The vanishing of the given moment results from the equilibrium conditions about the supporting point (ZMP) and about the joints of passive links.

Using the ZMP concept, in the Kato Laboratory three dimensional graphics of a walking robot (Figure 2) were elaborated in 1984. The interactive software system WALK MASTER was written for a personal computer to analyze and compose the walking pattern of a biped walking robot. This system enabled the analysis of the ZMP when the biped robot is walking, and the composition of a walking pattern combined with the robot's actuators' characteristics on three-dimensional graphics (Figure 2).

Using the ZMP concept and the semi-inverse method elaborated in further research,[6,7] Ichiro Kato and his associates were the first to realize DYNAMIC WALKING COMPENSATING WITH A BODY (Figure 3, WL-12, 1986).

A biped walking robot must be able to set its own gait so as to be capable of adapting to rough terrain, or to avoid obstacles. So they developed the WL-12 with a body that stabilized its own gait. The WL-12 performed a step (in 2.6 seconds) using a newly proposed algorithm which automatically composed the time trajectory of the body while giving artibrarily the trajectory of the lower limbs and ZMP.

Among the other results in biped locomotion that were based on the ZMP concept, I would like to single out those by Yamaguchi, Takanishi and Kato.[8] They performed a walking experiment with the biped walking robot WL-12 RV. As a result of the experiment, the authors realized dynamic biped walking at the walking speed of 0.54 s/step with a 0.3 m step length.

Several years ago, based on the ZMP concept, a dynamic walk of the TITAN IV and TITAN VI quadruped walking vehicles was realized.[9]

Also, several new applications of the ZMP concept have been recently accomplished by the Japanese researchers working on humanoid biped walking robots.

Thus, K. Nagasaka et al.[10] realized an experimental biped robot, using the motion algorithms as input (Genetic Motion Acquisition Method) and the ZMP concept for dynamic stabilization.

J. Yamaguchi et al.[11] realized an experimental biped walking robot which follows human motion through hand contact by means of a complex sensor, attached to the left hand of the so-called WABIAN robot, and the ZMP concept for dynamic stabilization.

Several other researchers from other Japanese universities and R/D centers carried out theoretical investigations, applied and extensive simulation studies, concerning biped robot stabilization using the ZMP concept, as, for example, A. Das Gupta and Y. Nakamura.,[12] K. Yajima et al.,[13] K. Inoue et al.,[14] S. Kajita and M. Saigo.,[15] S. Obata et al.,[16] T. Ikeda and T. Mita.[17]

Based on the same ZMP method the authors from the Honda R&D Co. Ltd. WAKO RESEARCH CENTER, have presented[18,19] the HONDA HUMANOID ROBOT – the most successful result in biped locomotion to date.

Among many research activities in the domain of humanoid robots (modeling and control) I want to empha-

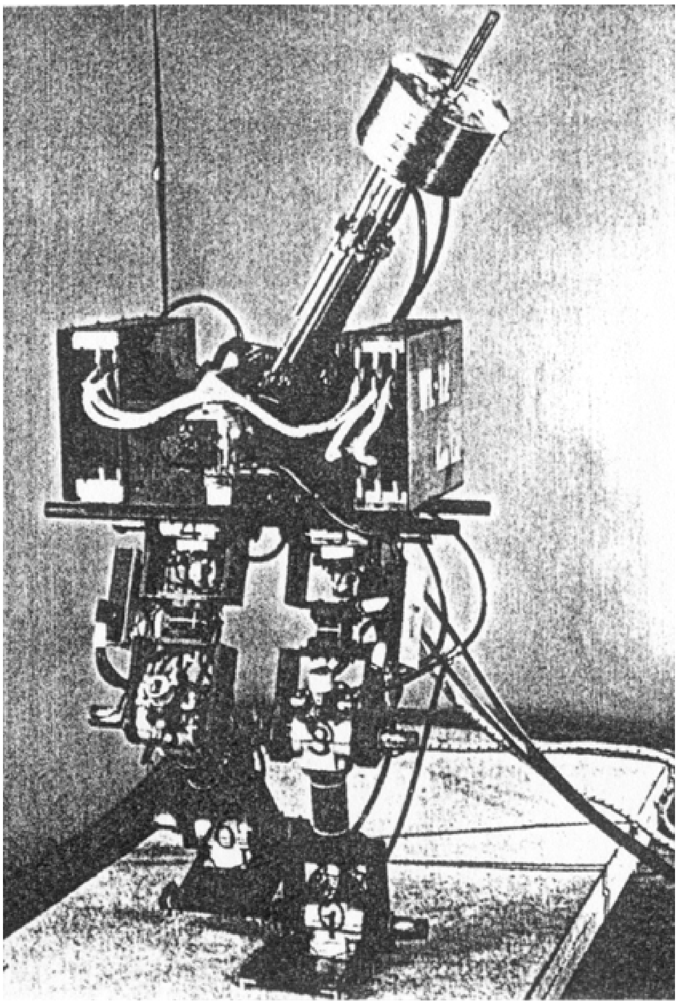

Fig. 3. WL-12 (1986).

size the importance of a big and very promising project[20] on a Virtual Humanoid Robot Platform.[20]

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 ZMP methods provide a quite useful dynamic criterion for the characterization and monitoring of the human/humanoid robot locomotion. The concept of ZMP is also quite useful for the analysis and control of the human gait in rehabilitation robotics.[21]

3. RECURSIVE FORMULATION OF ROBOT DYNAMICS

In 1973, Vukobratovic and Stepanenko presented for the first time in English the complete recursive Newton-Euler formulation in robots modeling.[22] Their work was initially directed toward the anthropomorphic robotic mechanisms. In 1976 they discussed the application of the recursive Newton-Euler computation to open-link manipulator mechanisms.[23] Stepanenko published the related material on dynamics modeling of linkages in Russian too.[24,25] Influenced by the previous results[22,23] McGhee et al.[26] made a further study in the direction of computational improvements.

Vukobratovic and Potkonjak derived the first recursive Lagrangian formulation in robots modeling.[27] The method has been based on the direct and inverse problems of dynamics. Hollerbach[28] developed the algorithm for solving the inverse problem of dynamics as a specific case of the Uicker-Kahn's method.

The method of Appel's equations, conceived by E.P. Popov and associates,[29] was developed in its final form by Vukobratovic and Potkonjak,[30] to solve both the inverse and direct dynamics problems. These equations were derived on the basis of the Gibbs "acceleration energy" function.

4. COMPUTER-AIDED GENERATION OF ROBOT DYNAMICS IN SYMBOLIC FORM

At the time of the beginnings of numerical procedures, their computational deficiences were an obstacle to their application in on-line controllers. The same was true of the numeric kinematic algorithm. However, symbolic approaches to deriving the robotic models can be much more efficient than the numerical ones. A symbolic method exploits in full the particular kinematic and dynamic structures of each manipulator. These "customized" algorithms eliminate, unnecessary arithmetic operations.

The advantages of customized symbolic methods in robotics were recognized first[31,32] and an efficient method of modeling serial-link manipulators in numeric-symbolic form was elaborated.[31]

In 1985 the first journal paper dedicated to the computer-aided generation of an analytical model for an arbitrary type of manipulator configuration had been published.[33]

Practically at the same time, or very soon after the above papers, several significant papers I devoted to the computer-aided symbolic modeling appeared.[34–36]

The first robot symbolic model generator in a user-oriented form[37] appeared in 1988 (SYM-Program Package for Computer-aided Generation of Optimal Symbolic Models of Robot Manipulators, Robotics Laboratory, Mihailo Pupin Institute, Belgrade, Yugoslavia).

5. DYNAMIC APPROACH TO TRAJECTORIES GENERATION FOR ROBOTIC MANIPULATORS

A method for optimal synthesis of manipulation robot trajectories has been proposed[38] for the first time in 1982, where the system is considered as a complete, nonlinear dynamic model of the mechanism and the actuators.[38] Regarding the practical importance of energy, optimal motion synthesis ensuring simultaneously a smooth, jerkless motion and minimal actuators' strains, particular attention was paid to the energy for optimal motion of non-redundant manipulators.

A procedure for the dynamic synthesis of redundant manipulator trajectories[39] has been proposed for the first time in 1984. This procedure was not really dynamic for the reason that the system is presented by the kinematic model, but the optimality criterion was a dynamic one. The performance index was the energy consumed by the actuators during the motion, evaluated from the dynamic model of the mechanism and actuators. This method exhibited considerable advantages over kinematic approaches in the cases of manipulation of heavy objects by large, powerful robots and high speed manipulation with high energy consumptions.

A real-time implementable algorithm for redundant manipulator motion synthesis in an obstacle-cluttered environment has been presented[40,41] in 1984 and 1986. This procedure was based on the application of performance indices which take into account the presence of obstacles and thus prevent the manipulation from drawing too close to an obstacle.

6. CENTRALISED FEEDFORWARD CONTROL IN ROBOTICS

The control laws which take into account and compensate for all (or some) dynamic effects in the robotic systems are called, dynamic control of robots. The centralized feedforward control is one of the dynamic control laws which has been effectively applied in practice. It includes the so-called nominal programmed control which compensates for the dynamics of the complete mechanism along the nominal trajectory. The centralized feedforward control differs from the decentralized feedforward (so-called local nominal control), because the former includes a computation of the total nominal driving torques (representing the dynamic moment due to the movements of all the robot joints) along the nominal trajectories, while the latter compensates just for the local actuator dynamics.

The centralized feedforward for the application in biped locomotion systems was proposed in the early papers.[2,3,5] With the biped walking machines, an accurate tracking of the pre-calculated nominal trajectories, achievable by the application of the centralized feedforward control, was a prerequisite for ensuring dynamic equilibrium during the walk.

The application of the centralized feedforward control to manipulation robots was introduced by Vukobratovic and

Stokic.[42–44] They were first to define the needs and benefits of the application of the dynamic control for manipulation robots, i.e. to define the robotic tasks for which the application of centralized feedforward control is beneficial.[45] As compared to other dynamic control laws (e.g. the so-called inverse dynamics or computed torque method)[46–48] the centralized feedforward has exhibited considerable advantages such as higher robustness, a simpler control scheme which did not require changes in basic structure of the classical servo-system schemes, etc. Therefore centralized feedforward is relatively easy to integrate in the existing (industrial) robot controllers.

Vukobratovic and Stokic have analyzed both asymptotic[42–44] and practical[45,49] stability of the control schemes that include the centralized feedforward terms. They were also the first to demonstrate the experimental application of such control schemes.[45] The application of centralized feedforward in the commercial industrial robot controllers, showing full effectiveness of the proposed approach, was begun a number of years later. The reason for a relatively late introduction of the centralized feedforward control in industrial practice may be attributed to the fact that the first robots were mainly oriented toward relatively simple applications (e.g. pick-and-place tasks, etc.), where the benefits of the application of dynamic control are not very high. Once the robots started to be employed in more complex tasks, requiring improved performance (e.g. higher speed and accuracy of trajectory tracking), the need for dynamic compensation by the appropriate control laws has become obvious, and considerable attention has been given by the industry to the application of the centralized feedforward control.

One of the first implementations of centralized feedforward control has been presented[50] ten years after the basic publication[42] in which the benefit from centralized feedforward control has been shown. The paper by Olomski[50] contains the experiments with centralized feedforward implemented in the RCM-3 Siemens controller with the KUKA 160-15 robot, resulting in a significant improvement of tracking of strongly dynamic trajectories.

The implementation of feedforward control has also been presented by Dogliani et al.[51] and Hirzinger et al.[52] The application of feedforward algorithms in industrial controllers, as well as the algorithms transfer implemented in DLR-light space robot, have been presented by Hirzinger et al.[52] In dynamic control involving the COMAU C3G controller it has also been described.[51]

In the last several years, it is evident that in all controllers of leading robot manufacturers feedforward control is implemented. So, the S4C robot controller uses powerful, configurable software and has a unique dynamic model-based feedforward control system which provides self-optimizing motion.

Optimal feedforward control speeds up the motion of mechatronic systems close to the physical limits. In recent applications, real-time optimal feedforward control enhanced the international competitiveness of leading robot manufacturers. Also, the robot-in-the-loop mathematical optimization reduces drastically the time for robot controller tuning.

7. ROBOT DYNAMIC CONTROL

By dynamic control we understand the procedure of managing the motion and forces of a robot by explicitly taking care of the system's dynamics.

The first idea of applying dynamic control to robots originates from the goal to track a prescribed trajectory by the anthropomorphic active mechanisms, specifically biped locomotion systems. Vukobratovic and Juricic[1,2] were first to discuss the control of a biped mechanism. They 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 feedforward compensation is to cancel the nonlinearities of the nominal dynamics of the system.

Several years later, such an approach was proposed[42,43,53] and elaborated for the joint space dynamic control of manipulation robots. In these papers, the dynamic control of manipulation robots was suggested as an effective means to compensate for strong coupling among the joints of the robots and thus ensure accurate tracking of the desired robot trajectory.

In contrast to the biped locomotion systems, where the application of dynamic control is necessary to ensure stability of the system at all, the benefits of the dynamic control for manipulation robots need a more sophisticated study. The conditions under which one can apply dynamic control of robots has been discussed in detail[44,54] showing that the dynamic control, although requiring more complex synthesis and implementation than simple decentralized servo approach, may bring considerable benefits for the robot performance. These benefits have been later recognized by a number of researchers, which resulted in various dynamic control schemes.

8. 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. It is common to consider each mechanical degree of freedom of the mechanism as a subsystem. However, with many active mechanisms the dynamic coupling among such subsystems could be very strong, leading to the inappropriate performance of the system in the case when only local controllers are applied. In order to compensate for the influence of dynamic coupling among the subsystems, a two-stage synthesis of control was introduced.[2,5,42,55] This approach was applied first to biped locomotion systems, and later was extended into manipulation systems and other active mechanisms.[56]

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. Such a programmed control is computed on the basis of the centralized, complete model of the system. 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. In this stage, stage of perturbed regimes, the decentralized control structure is applied. By introducing 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.

However, coupling among the subsystems may still be too strong. To further compensate for the influence of such strong coupling, the following approach was proposed:[42] 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.[42,56]

A similar approach can be applied if a decentralized observer is applied for a strongly coupled active mechanism.[57] A local observer is normally introduced for each subsystem (i.e. for each degree of freedom). In this way an estimate of the subsystem state vector is obtained, which is then used for local regulators instead of the actual (measured) state of the subsystem. Under the assumption that the subsystems are observable by the output, it has been shown[44,58] that the subsystems can be stabilized by such a controller which applies the estimate of the subsystem state instead of the actual state. Further, the regions of asymptotic stability of the whole ensemble (active mechanism + observer + regulator) are estimated when the coupling among the subsystems is taken into account. The analysis of the influence of coupling upon both the decentralized controller and decentralized observer shows that in the application of the global control these influences are reduced, yielding an overall system stability.[44,57]

9. FORCE FEEDBACK IN DYNAMIC CONTROL OF ROBOTS

The benefits that can be derived from the application of the direct force feedback in some specific servo systems have been recognised long ago.[58]

The application of the force feedback for the biped locomotion systems has been proposed for the first time by Vukobratovic and Stokic.[5,55,56,59] The effects of joint force sensory feedback to compensate for the dynamic coupling among the joints of the articulated mechanisms, has been first recognised with biped locomotion robots, since the coupling among the joints motion is very strong and has a major influence upon the overall system stability.

The application of the direct force feedback to the joints of manipulation robots has been first proposed[60,61] and later elaborated in detail.[42,55,62]

The application of the joint sensory feedback in manipulation robots ensures an improved accuracy of tracking of the desired trajectories without applying complex dynamic laws. 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. On the other hand, the application, the direct force feedback, is connected to certain technical problems which have been well analyzed.[44,45,54,63] An overview of the joint force sensory feedback, control in manipulation robots has been presented by Stokic and Vukobratovic.[64]

10. DECENTRALIZED CONTROL STABILITY TESTS FOR ROBOTIC MECHANISMS

In the papers by Vukobratovic and Stokic,[5,42,56,65] 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. Each degree of freedom of the mechanical system is considered as a subsystem. Local control is synthesized for each subsystem, neglecting the interconnections among them.

Since the influence of interconnections between the sybsystems may be too strong, nominal programmed control calculated using a centralized model of the system has been introduced.[42–44,56] 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.[45,49,66] This control law includes local servos around the joints and the local nominal feedforward 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 feedforward terms), but no theoretical analysis of such control scheme has been carried out.

The first analysis of asymptotic stability of such controller showed[42,65] that the decentralized control scheme including the centralized feedforward can ensure asymptotic stability of the system, provided that the feedback gains are appropriately selected. The stability of the robot in the case of applying the decentralized controller, including centralized feedforward terms, was analyzed on the basis of the decomposition-aggregation approach. In the case when only local controllers are applied (local servos + local feedforward terms) it is necessary to analyze the practical stability of the overall system trajectory.

Practical stability of large-scale mechanical systems with the decentralized control scheme was analyzed for the first time in the works of Vukobratovic et al.,[45,67] providing a means to estimate the ability of such decentralized control to withstand, model nonlinearities and parameters variations.

11. UNDERACTUATED ROBOTIC SYSTEMS

The appearance of unpowered degrees of freedom is most characteristic of legged, in particular of biped locomotion robots. Namely, during the real walking under perturbations, additional angles appear assuming 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.

The specificity of biped robots, whose functioning can result in the appearance of supplementary unpowered degrees of freedom, has been noted already in journal papers.[35] Differing from the so-called underactuated systems appearing in the today's papers, in which the problems of control and stability are of academic (unnatural) 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. The stability of the mechanisms having all joints powered has been investigated in several works of Vukobratovic and Stokic.[42–45,49,65,66] In the analysis performed the subsystem is associated with one powered joint.

First, the stability of each subsystem is checked (neglecting the coupling) and then, the dynamic coupling between the subsystems is analyzed. Criteria for stability of the overall system are established by taking into account all dynamic interconnections between the subsystems. However, these criteria require that all subsystems are stable.

In order to analyze the stability of the mechanisms that include unpowered joints we have introduced the so-called "composite" subsystems which consist of one powered and one unpowered joint. Thus we obtained a subsystem which, if considered as decoupled from the rest of the system, may be stabilized. Further, the interconnections of the "composite" subsystem with the rest of the subsystems are taken into account, and the criteria for stability tests of the overall mechanism are established.

The complete control synthesis and stability analysis of the robotic mechanisms having unpowered degrees of freedom (underactuated systems) have been presented for the first time in a research monograph[67] and journal papers.[68,69]

12. APPLICATION OF PRACTICAL STABILITY TESTS IN ROBOTICS

One of the main problems in the synthesis of control laws for robots represent the uncertainties in the robot dynamics models. The uncertainties in the dynamic model of the environment in different technological tasks may especially have great 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. Taking this into account, it is of practical interest to demand more relaxed stability conditions, i.e. to consider the so-called practical stability of the system. The practical stability of a robot around the desired position trajectories (and force trajectories in the case of the so-called constrained motion tasks, i.e. the tasks in which the manipulation robot comes in contact with the environment) 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.

The need to study practical stability of robots was first recognised in the early eighties.[42,44] However, in this early paper and monograph the authors applied a decomposition aggregation method to study the asymptotic stability of the manipulation robots in the finite regions, as an approximation to the practical stability analysis.

These authors were also the first to elaborate a procedure for direct testing of the practical stability of a manipulation robotic system moving in a free space when a decentralized control law is applied.[49] The procedure was extended to practical stability tests for different control laws.[45] The elaborated conditions for the practical stability of a robot moving in a free space enabled the study of the issue of model uncertainty in the robotic control without any approximation (i.e. to correctly examine the influence of different model uncertainties upon different control laws. The complete dynamic model of the robot was taken into account. The conditions were derived using the method of Michel[70] for the practical stability analysis of large-scale systems. A software package for the practical stability analysis of the robot moving in a free space, serving as an efficient tool for testing practical stability conditions, was generated.[45]

The procedure for practical stability of manipulation robots was afterwards extended to biped locomotion robots[69] and elaborated in detail.[67]

13. UNIFIED APPROACH TO CONTROL LAWS SYNTHESIS FOR ROBOTS INTERACTING WITH A DYNAMIC ENVIRONMENT

During the last fifteen years, compliant motion control has emerged as one of the most attractive and fruitful research areas in robotics. The control of the constrained motion of robots is a challenging research area, the successful solutions in which will considerably influence further applications of robots in industry and increase their efficiency and productivity. The increasing demands for advanced robot applications have brought about an enormous growth of interest in the development of different concepts and schemes to control compliant motion.

The difficulties encountered in solving the problem of simultaneous stabilization of programmed motion and programmed force of interaction of the robot in contact with the environment, have probably been the reason for introducing a simplifying idea of splitting the task into the motion control and interaction force control. This idea enabled Mason[71] and later Raibert and Craig,[72] to formulate an approach to manipulator control, called the hybrid position/force control.

The basic idea of this approach is that in a certain coordinate space the control task can be divided into two independent tasks. One task is the robot motion control along a predetermined part of the coordinates (directions). The other task is the control of the interaction force of the robot and the environment along the rest of the coordinates.

Duffy[73] pointed out the fallacy of a theoretical formulation of the hybrid position/force control. The orthogonality between the constraint force and the direction of unconstrained motion has been assumed and used in the majority of the works. The author claimed that the orthogonality is not invariant in the choice of coordinate frames and therefore the conventional formulation lacks physical meaning. The weakness of this approach related to the notion of "orthogonality" is caused not only by the fact that it is incorrect to use the term "orthogonality" itself, but also by the fact that, by finding the directions along which motion and force are "orthogonal", the authors (followers of hybrid control) commit a mistake. Namely, for the task of stabilization in these directions they use feedback loops with respect to motion or force only.

The criticism refers to the basic idea of the position/force stabilization based on traditional hybrid control concept, and not to the realization of this possibility itself by means of a certain procedure. However, there have been no attempts to realize the hybrid control concept by some other means, save the "orthogonal complements". The idea of splitting the task of the robot interacting with the environment into the task of position control in certain directions and the force control in other directions, represents by itself a more profound idea than the idea of hybrid control based on the "orthogonal complements".

The unified position-force control differs essentially from the above convential hybrid control schemes. Vukobratovic and Ekalo[74,75] I 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[74,75] defines two control subtasks responsible for stabilization of the robot position and interaction force. Both control subtasks utilize a dynamic model of the robot and the environment[76] in order to ensure tracking of both the nominal motion and force. In the numerous journal papers[77–90] further investigations in dynamic position-force control of robotic mechanisms interacting with a dynamic environment have been performed. Instead of the established, the traditional hybrid position/force control, a new approach was proposed, which for the first time involved the dynamic environment in the dynamic control of the whole robot-environment system.[74,75]

The stability issue, i.e. the establishment of the conditions under which a particular control law guarantees the stability of the robot in contact with the environment, is of particular importance. The control laws stabilizing simultaneously the motion of the robot and the force of interaction with a dynamic environment are synthesized, ensuring exponential stability of the closed-loop systems (based on the analysis of a complete dynamic model of the robot and the dynamic environment).[74,75,83] The conditions ensuring asymptotically stable position of the system in the first approximation (local stability) are formulated. In spite of sufficient conditions of the linearized system asymptotic stability being conservative, the fact is that the dynamic character of interaction of the environment with the robot can lead to positional instability. However, the model uncertainties representing a crucial problem in control of robots interacting with a dynamic environment, have not been appropriately addressed yet. Therefore, it can be difficult to achieve the asymptotic (exponential) stability of the system (unless robust control laws including factors that compensate for these perturbations and uncertainties are used).

Inaccuracies of the robot and environment dypamic models, as well as the robustness of dynamic control, have been considered.[77,78,80] The problem arising from uncertainties of parameters may also be resolved by applying the knowledge-based techniques.[91] Taking into account external perturbations, which do not expire with time, and model uncertainties, it may be difficult to achieve asymptotic (exponential) stability. Therefore it is of practical interest to require less restrictive stability conditions, i.e. to consider the so-called practical stability of the system. The practical stability of the robot around the desired position and force trajectories is defined by specifying the finite regions around the desired position and force trajectories within which the robot position and interaction force have to be during the task execution. The test conditions for practical stability of the robot interacting with dynamic environment were established recently for the first time.[92,93] The practical stability tests are demonstrated using two very representative control laws. The first one is the pure position dynamic control (based on the so-called inverse dynamic technique, or computed torque method), where the desired position trajectories are calculated based on the desired position and force trajectories, using the dynamic model of the environment. The second control law considered belongs to the so-called hybrid position-force control schemes, where the complete dynamic model of the system is taken into account: in the directions in which the desired position trajectories are specified the control law attempts to stabilize position, while in the directions in which force trajectories are specified, the control law focusses on the force. Different from the classical hybrid control approach, the control laws are based on complete dynamic models of the robot and the environment and take into account all dynamic interactions between the position and force controlled directions.

The elaborated stability test may be used either to check the stability of the specified control laws, or to establish procedures for the synthesis of parameters of different control laws. By this, the control synthesis becomes much more accurate and effective, i.e. higher robustness of the control to the uncertainties in robot and environmental models can be ensured,which is one of the most relevant aspects in the potential industrial applications of robot in numerous technological tasks where the robot is interacting with the environment (e.g. in cutting, deburring, etc).

14. MODELING AND CONTROL OF MULTI-ARM COOPERATING ROBOTS INTERACTING WITH THE ENVIRONMENT

The basic problems in solving a cooperative work lie in determining the forces at the contact point of the manipulator tip and the object (environment). Force undefiniteness can be overcome if the assumption of rigid manipulator and object is abandoned, or if that assumption is kept, but an elastic connection is established between the rigid manipulator and rigid object, along with the fulfilment of deformations compatibility condition. Based on the analysis of the function of the cooperative systems it has been adopted that the manipulators are rigid and the object (environment) connections of the manipulators are elastic. It is assumed that is possible to approximate an elastic system by a spatial grid, at the nodes on which is acting the system of external loads, so that each node possesses six degrees of freedom and the nodes coincide with the mass centers (MCs) of the rigid objects, as representatives of the inertial properties of the elastic connections and the manipulated object.[94]

A somewhat different approach to forming a dynamic model based on the same fundamental idea about the contact of dynamic nature between a multi-arm cooperating robot, object and environment, has been presented.[95] The proposed mathematical model of multi-arm cooperating robots takes into account the complex effects, such as object dynamics and environment dynamics.

The proposed modeling approach solves effectively the problem of load distribution. The main idea used in the modeling of motion of the dynamic object connected with the k-robot end effectors and the environment is that the manipulated object together with (k+1) connections can be presented by an elastic system of (k+1) rigid bodies; at the mass center of each local rigid body contact, gravitional, damping and elasticity forces act as external forces. Using the Lagrange equations of motion and taking into account the manipulator dynamics, the object dynamics and the environment dynamics, i.e. a combined model of multiple robots-object-environment dynamics, is presented.

Based on the developed model of cooperative manipulation dynamics, a procedure for determining the nominal motion was given.[96] It was requested that the nominal motion of the cooperative system should be coordinated, i.e. the manipulators perform first tightening of the object, and after that the general motion is to be continued without essentially violating the tightening conditions. Starting from this condition the elastic system was considered separately as consisting of the objects and elastic contacts. The nominal trajectories of the elastic system for the dynamics description were determined by solving the differential equations with the calculated contact forces as forced actions. Based on the obtained trajectories of the contact points and the nominal contact forces in it, the nominal driving torques were determined from the mathematical model of the manipulator dynamics. The obtained trajectories of the contact points and the nominal contact forces at these points served as a basis for the analysis of the cooperative system as a control object.[97] It has been emphasized that there exist two typical contact tasks. One is tracking of the nominal trajectories of chosen points, while the other is tracking of the nominal trajectory of one point only, along with the nominal contact forces of the follower manipulator. The appropriate control laws were proposed for tracking the manipulated object MC nominal trajectory and the nominal trajectories of the follower manipulators. It was analytically proven that all the quantities of the controlled cooperative system converge asymptotically to their nominal values after the initial deviations from the same. Based on the fundamental idea described in the unified approach to control of robotic manipulator interacting with dynamic environment[74,75] and the derived model,[95] the synthesized adaptive control is capable of simultaneously stabilizing both the desired multiple robot and object position and interacting forces between the object and the environment.[98]

15. APPLICATION OF CONNECTIONIST ALGORITHMS FOR ADVANCED LEARNING CONTROL OF THE ROBOT INTERACTING WITH A DYNAMIC ENVIRONMENT

A common control problem in advanced robotic applications based on constrained manipulation and robot contact tasks is how to describe the robot-environment dynamics and synthesize such control laws that would stabilize both the desired position and interactive force.

The newly proposed learning control algorithms for robotic contact tasks utilize the connectionist approach in cooperation with other intelligent techniques based on advanced learning concepts with the *a priori* low-level information and repetitive nature of the working task.

Of primary concern in this approach is the extension and generalization of the approach developed for connectionist control in robot non-contact tasks in order to deal with the problem of performing position and force control of the robot manipulators. The connectionist architectures, ensuring fast online learning of robot dynamic uncertainties, are applied at the executive hierarchical control level in robot contact tasks.

The main feature of the proposed algorithms is the integration of connectionist structures in the robust non-learning control laws for contact tasks that enable stabilization and satisfactory tracking performance of position and force.[91] The proposed neural network plays the role of a robust controller to compensate for the uncertainties of the model of the manipulation robot in contact with the dynamic environment. The multi-layer perceptron, being a part of hybrid learning control algorithm, in the process of synchronous training uses fast learning rules and available sensor information to improve progressively robotic performance in a minimal number of learning epochs. This hybrid approach, based on the model-based method and connectionist learning, is chosen because the information about the dynamic model is always available to some extent in the process of control synthesis. In this way, the tracking performance of position and force can be significantly improved using the multilayer perceptrons trained by applying a fast on-line learning algorithm.

Another important point of this approach is a new method for selecting the appropriate control parameters and parameters of dynamic robot environment for robot machining tasks, based on connectionist classification of unknown dynamic environments.[99]

This method classifies the type of robot environment using a multi-layer perceptron through off-line training process and through the process of on-line pattern association. It is assumed that for classified dynamic environment, the control parameters and parameters of the environment model (structure of the environment model is known) are defined in advance, or they can be obtained by the process of linear interpolation. Based on classification and generalized features of the proposed neural network acquired in the offline training process, the control algorithm can select the appropriate control parameters which yield satisfactory system performance. In the proposed off-line training algorithm, the convergence process is improved by using genetic algorithms to choose the optimal topology of the multilayer perception.

16. FUZZY LOGIC ROBOT CONTROL WITH MODEL-BASED DYNAMIC COMPENSATION

A tighter connection between fuzzy logic control (FLC) and standard control methods was proposed by Tzafestas and Papanikolopoulos,[100] who suggested the use of a two-level hierarchy in which an FLC-based expert system is used for fine tuning of the low-level PID control. However, the two-level hierarchy does not actually solve the problem of weak performance. This shows that the knowledge of a readily available mathematical model of robot dynamics should not be ignored. Most importantly, it may be employed to reduce the nonlinear dynamic coupling between its joint subsystems. Thus, fuzzy-logic-based control should not be viewed as a pure alternative to model-based robot control. Instead, a combined approach is preferred, and it may yield superior control schemes to both simple model-based or fuzzy-logic-based approaches. The general idea behind the hybrid approach[101] is to utilize a satisfactory approximation of the robot dynamics model to decrease the dynamic coupling between the joint subsystems, and then to engage the fuzzy logic-based heuristics as an effective tool for creating a nonlinear performance-driven PID control to handle the effects uncovered by the approximate model. A somewhat similar concept was formulated by De Silva and MacFarlane.[102] The hybrid design is an extension of the decentralized control strategy. Each of the subsystems comprises two components: the traditional model-based controller and the optional fuzzy-logic-based tuner (see Figure 4). The inputs to the i-th joint subsystem are the nominal control signal u_{oi}, joint position error Δq_i, joint velocit error $\Delta \dot{q}_i$, and the integral error $\int \Delta q_i dt$.

The nominal (feedforward) u_{oi} is calculated for a prescribed trajectory on the basis of the internal model of the robot dynamics, and the gains of the i-th local PID servo are synthesized to stabilize the decoupled subsystem. In the cases where a highly precise and fast trajectory tracking is demanded, the optional global feedback loop (full dynamic compensation) is added on the basis of the computed or measured deviation of the dynamic torque acting at the joint, and the global control is synthesized to ensure practical system stability. A further refinement is introduced by the upper control level, which is intended to tune the gains of the conventional controller. The tuner is designed as a fuzzy-logic-based controller that monitors the joint response characteristics and modifies the gains to provide better responses. Starting from the conditions of practical stability of motion with constant gain control, sufficient conditions that guarantee the practical stability of the variable-gain scheme with local gain tuners were derived. This work has demonstrated the improved accuracy which is not accompanied by degradation in other performance characteristics, such as energy consumption and maximum developed torques.

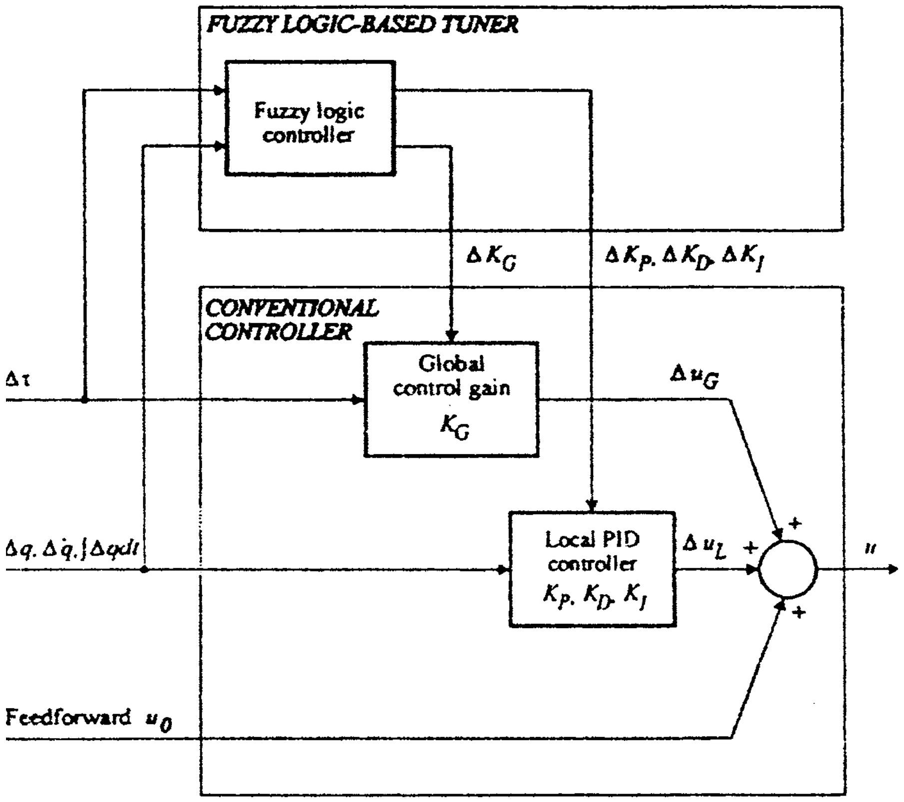

Fig. 4. Hybrid control scheme.

17. INTERNAL REDUNDANCY - A NEW WAY TO IMPROVE THE ROBOT DYNAMIC PERFORMANCE

The last decade has been marked by a notable trend in the development of active technical structures and constructions. Many technical systems obtained a new property: their dynamic parameters (e.g. inertia or damping) were made variable and controlled. The main reason for the tendency towards active systems lies in the real need for the systems and constructions that have to be compatible with various dynamic loads, variable external conditions and different working regimes.

Active responses of technical systems, objects and constructions (structures) are already becoming a real need in a broad range of engineering fields (mechanical, electrical, civil engineering, etc.). In each of these engineering fields, there is a necessity to maintain the desired system performance during variable working conditions, as well as in the case of different types of external perturbations that can lead to critical conditions of operation. The desired performance, however, depends on the relevant state coordinates of the system and its geometrical and dynamic parameters. For an active system, it is characteristic that by adjusting, e.g. the dynamic parameters, its dynamic performance is maintained in different working modes and under variable operating conditions. Differing from the approach to the synthesis and implementation of active systems where some dynamic parameters (inertial, stiffness, and most often damping characteristics) are changed, it is additionally proposed that the systems, constructions or structures should be designed so as to feature variable geometry within the appropriate limits.[103–106]

Variable geometry denotes the variation of geometrical parameters that are relevant to the change of system properties (stiffness and redistribution of static and dynamic load) that would adapt the system to the various tasks and different working conditions. Thus, new degrees of freedom are introduced. This leads to the redundancy – different internal motions are possible for a given external motion of the end-effector. Therefore there is a crucial difference from the traditional (kinematic) notion of redundancy. Here, the additional degrees of freedom do not influence the external motion and, accordingly, they cannot improve the end-effector ability for maneuvering. For this reason, a new notion is introduced – internal redundancy. One may say that internal redundancy improves the robot dynamic capabilities.

Then, each active system (construction or structure), in general, is described by the three types of coordinates:

q – joint (generalized) coordinates,
s – geometrical (fixed or variable) coordinates,
ξ – elastic coordinates

Instead of the dynamic system with fixed geometry (traditional case):

$$H(q)\ddot{q}+h(q,\dot{q})=\tau+D(q)w$$

the dynamic model of the system with variable geometry has the form:

$$H(q,s)\begin{bmatrix}\ddot{q}\\ \ddot{s}\end{bmatrix}+h(q,\dot{q},s,\dot{s})=\begin{bmatrix}\tau_q\\ \tau_s\end{bmatrix}+D(q,s)w$$

And, finally, the general model of the system with the variable geometry and elastic deformations becomes:

$$H(q,s,\xi)\begin{bmatrix}\ddot{q}\\ \ddot{s}\\ \ddot{\xi}\end{bmatrix}+h(q,\dot{q},s,\dot{s},\xi,\dot{\xi})=\begin{bmatrix}\tau_q\\ \tau_s\\ 0\end{bmatrix}+D(q,s,\xi)w$$

where,

τ – vector of driving forces or torques
D – matrix of action relative positions
w – external perturbation action
H – inertial matrix
h – vector of velocity and gravity terms

The application of a variable structure does not serve only to solve to a certain degree the conflicting requirements, for instance, between the load capacity and speed of operation of the robotic mechanism, but the proposed principle can be implemented in constructions or structures of quite different types. Thus, for example, with the suspension bridges, particularly with those of large spans, different moving dynamic loads can be analyzed from the aspect of adequate distribution of the bending moment, stress and deformation along the bridge structure, as well as the frequency and amplitude of deformation. With driverless road vehicles (full automatic control), or in their semi-automatic version, we are interested in the vehicle global stability when driving along a winding road. In the case of such a system, including active suspension too, a lateral displacement, of the wheels of e.g. several centimeters, can prevent the vehicle overturning.

The above, apparently quite unusual solutions, can become common technical practice in the near future.

18. CONCLUDING REMARKS

As said in the Introduction, the objective of this work was to present in a most succinct form the origination of some of the fundamental results of Robotics that contributed to its establishment as a new discipline of technical sciences.

At the end of this specific paper I would like to make a remark related to a conditional inconsistency that I made in the course of its writing.

Namely, in presenting sixteen topics that, in my opinion, had a decisive influence on forming the profile of robotics, I was aware of the fact that robotics had been established much before the appearance of some of the results described in the paper.

This is primarily related to the last five topics, concerned with the unified approaches to the dynamic model-based and learning control of single and multi-arm robots interacting with dynamic environment, as well as the internal redundancy as a new way to improve robot dynamic performance.

However, I considered it more purposeful to indicate a consequent line along which the research results in robotics have been generated, having their stronghold in system dynamics and the dynamic model-based control, that may not be substituted by the knowledge-based techniques, as the latter are to be used as complementary in a combined concept of hybrid control, whereby the model-based part is a pivot of dynamic control in all cases of the essentially dynamic systems in robotics.

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