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BELGRADE SCHOOL OF ROBOTICS

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Abstract. *In the paper the milestone scientific results of Belgrade school of robotics are shortly presented. By some chronological order they are: zero moment point concept and semi-inverse method, recursive formulation of robot dynamics, computer-aided generation of robot dynamics in symbolic form, dynamic approach to trajectories generation 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, new approach to modeling and control of multi-arm cooperating robots interacting with environment, connectionist algorithms for advanced learning control of robot interacting with dynamic environment, fuzzy logic robot control with model-based dynamic compensation, and internal redundancy - new way to improve robot dynamic performances.*

Key words: *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

In this unconventional paper I will try to show that the origins of fundamental results of Belgrade school of robotics to a large extent coincide with the world beginnings of robotics as a scientific field in technical sciences.

In the very condensed presentation of the results I was managed by the chronology of their appearances, trying to emphasize the basic novelties in sixteen different topics.

Before the survey of the most significant contributions, I would like to convey only partly the addresses of several worldwide very distinguished experts among numerous outstanding scientists and professionals with a worldwide reputation, who gave the

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evaluations of Belgrade school of robotics on the occasion of my thirty years' international scientific activity.

Professor Ichiro Kato, founder of Robotics in Japan: **"... Since 1975 we can speak about world recognized Yugoslav robotic school headed by professor M. Vukobratović. During the long period the investigations of the world recognized Robotics Laboratory in the Mihailo Pupin Institute gave numerous excellent results devoted to modeling, control and computer implementation of robotic manipulators.**

The robotic research in Japan is very influenced by the initial work of prof. Vukobratovic, whose several monographs were published in 1975, 1979 and 1985".

Professor Yoshihiko Nakamura from Japan: **"...** Vukobratović's first trip to Japan was made during 1970s and he made several seminars in universities.

I understand that academic research in robotics became active since then. Therefore, I could say that he sowed the seed of robotics research in Japan".

Academician E.P. Popov, founder of Robotics in Russia: **"...** Professor M. Vukobratovic **created a scientific school acknowledged over the world on the theory and practice of large scale systems, robotics, locomotion and active rehabilitation systems. He educated a prominent scientific team composed of talented young poeple, many of whom already have scientific degree and are also well known in robotics. For some extent our own works in such directions as robot dynamic automated simulation, real-time robot control systems, computer aided robot design were influenced by the ideas of this scientific school".**

Academician A.Yu. Ishlinski, Moscow, Russia: **"**Academician M. Vukobratović has headed the **Yugoslav school of robotics over a long period and is one among the world leaders in the science of robotics".**

Professor A. Morecki, founder of Robotics in Poland: **"...** I would like to say that professor Miomir Vukobratovic **created a world recognized school in robotics ..."**

Professor Alberto Rovetta, founder of robotics in Italy: **"... From the locomotion studies to the systems control analysis and advanced robotics developments, Vukobratovic's scientific school has given a world known contribution ..."**

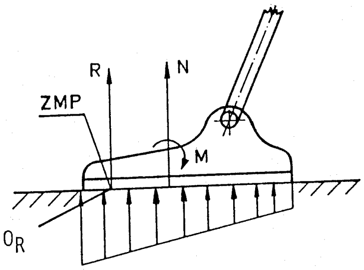
Professor Tzuh-Jong Tarn, President, IEEE Robotics and Automation Society, Washington Univ., St. Louis, USA, **..."**Pioneering work of Prof. Vukobratović in the past quarter of a century brought about many of the most important results in Robotics. **... Apart from being one of the forerunners of his field, he created a school, undoubtedly one of the most prominent in the world".**

Dr Suren Dwivedi, Prof. MAE Dept., West Virginia Univ., USA: "... M. Vukobratovic created a **school, which united scientific talents from different part of multinational Yugoslavia and other parts of our planet, for many of us consider ourselves to be his disciples and followers..."**

2. ZERO MOMENT POINT CONCEPT AND SEMI-INVERSE METHOD

Paralelly with load information at powered joints of legged locomotion robots and particularly of biped mechanisms, for dynamic stability of the whole system it is unvoidable to take into account ground reaction forces at the contacts of feet and environment.

In the Figure, for a biped robot in the single support phase it is possible to replace all elementary vertical forces by the resultant. **Let point O_R represent the point at which the sum of moments is equal to zero, so that this point where acts the force only is called Zero-Moment Point (ZMP) [Vuk68], [Vuk69], [Jur72].**



Load distribution along the foot

The equations of dynamic equilibrium for the legged vehicle 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 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.

As a next decisive step in modeling and control of legged, particularly biped locomotion robots, was the introduction of the semi-inverse method [Vuk69], [Vuk72], [Jur72].

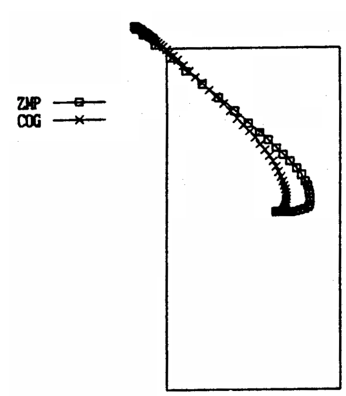
What is the essence of the semi-inverse method?

The conditions of dynamic equilibrium with respect to coordinate frame located at the Zero Moment Point give three relations between generalized coordinates and their derivatives. As the whole system has n degrees of freedom (n>3), the trajectories of the (n-3) coordinates should be prescribed as to ensure the dynamic equilibrium of the entire system (trunk motion including arms if the biped robot is in question).

If there are some supplementary zero-moment-points (like the passive joints of biped arms) then for every additional ZMP another three equilibrium conditions are available.

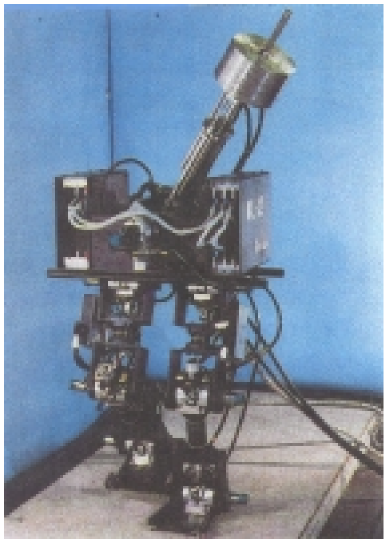
Thus, when applied to the problem of investigating the dynamics of biped systems, the motion of links is partly known, while the unknown moments are equal to zero. Vanishing of the given moment results from the equilibrium conditions about the supporting point (ZMP) and about the joints of passive links.

Using ZMP concept in the Kato Laboratory three dimensional graphics of a walking robot by WALK MASTER were elaborated (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 enables the analysis of the ZMP when the biped robot is walking, and the composition of a walking pattern combined with the robot's actuator's characteristics on three-dimensional graphics (see Figure).



WALK MASTER:
Trajectory of ZMP
and projected center of gravity

Using ZMP concept and semi-inverse method which were elaborated in further research [Vuk74], [Vuk75], Ichiro Kato with his associates was the first who realized DYNAMIC WALKING COMPENSATING WITH A



WL-12 (1986)

BODY (WL-12, 1986).

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

Among other results in biped locomotion based on the ZMP concept, I would like to emphasize the results given by Yamaguchi, Takanishi and Kato [Ya93]. The authors performed a walking experiment with the biped walking robot WL-12RV. As a result of the experiment, the authors realized dynamic biped walking at the walking speed 0.54 s/step with 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, too [Yo92].

[Vuk68] Vukobratovic M. and Juricic D., "A Contribution to the Synthesis of Biped Gait", IFAC Symp. Technical and Biological Problem of Control, Yerevan, Russia, 1968.

[Vuk69] Vukobratovic M. and Juricic D., "Contribution to the Synthesis of Biped Gait", IEEE Trans. on Biomedical Engineering, Vol. 16, No 1, 1969.

[Vuk72] Vukobratovic M. and Stepanenko Yu., "On the Stability of Anthropomorphic Systems", Mathematical Biosciences, Vol. 15, pp. 1-37, 1972.

[Jur72] Juricic D. and Vukobratovic M., "Mathematical Modeling of a Bipedal Walking System", an ASME publication 72-WA/BHF-13, Winter Annual Meeting, New York, Nov. 26-30, 1972.

[Vuk74] Vukobratovic M., Hristic D. and Stojiljkovic Z., "Development of Active Anthropomorphic Exoskeletons", Medical and Biological Engineering, Vol. 12, No. 1, 1975.

[Vuk75] Vukobratovic M., and Stokic D., "Dynamic Stability of Unstable Legged Locomotion Systems", Mathematical Biosciences, Vol. 24, No. 1/2, 1975.

[Ka85] Kato I., "Development of Waseda Robots - The Study of Biomechanisms at Kato Laboratory", Tokyo, Waseda University publication dedicated to I. Kato 60th anniversary jubilee, 1985.

[Yo92] Yoneda K. and Hirose S., "Dynamic and Static Fusion Gait of a Quadruped Walking Vehicle on a Winding Path", Proc. of IEEE Conf. on Robotics and Automation, pp. 143-148, Nice, France, May 1992.

[Ya93] Yamaguchi I., Takanishi A., Kato I., "Development of a Biped Walking Robot Compensation for Three-Axis Moment by Trunk Motion", Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Yokohama, Japan, 1993.

Also, in very recent time, a several interesting new applications of the ZMP concept were accomplished by the Japanese researchers, working on humanoid biped walking robots.

So, K. Nagasaka et all. [Naga 98], realized an experimental biped robot, using motion algorithms as input (Genetic Motion Acquisition Method) and the ZMP concept for dynamic stabilization.

J. Yamaguchi et all. [Yama 98], 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 A. Das Gupta and Y. Nakamura [Gup 98]; K. Yajima et all. [Yaji 98]; K. Inoue et all. [Ino 98]; S. Kajita and Saigo [Kaji 98]; Obata et all. [Oba 98]; T. Ikeda and T. Mita [Ike 98].

[Naga 98] Nagasaka K., Inaba M. and Inoue H, "Research on Human-based Genetic Motion Acquisition for Humanoid", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan, 1998, pp. 827-828.

[Yama98] Yamaguchi J., Aoyagi D., Gen S., Seitawan S.A., and Takanishi A., "Interaction Between Human and Humanoid through the Hand Contact", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan, 1998, pp. 951-952.

[Gup 98] Gupta A. Das and Nakamura Y, "On the Synthesis of Motion for a Humanoid Robot Using Human Motion Data", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan, 1998, pp. 1351-1352.

[Yaji 98] Yajima K., Mitobe K. and Nasu Y., "Control of a Biped Robot with Prismatic Joints", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan, 1998, pp. 1093-1094.

[Ino 98] Inoue K., Ishii A and Okawa Y., "Control of Biped Walking Robot with Arms-Moving While Working by Hands", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan, 1998. pp. 1095-1096.

[Kaji 98] Kajita S., and Saigo M., "Active Balance Control for a Mechanism with High Center of Gravity", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan, 1998. pp. 1113-1114.

[Oba 98] Obata S., Fujimoto Y. and Kawamura A., "Experiments of Biped Walking Attitude Control Based on Force Interaction Control", Proc. 16-th Ann.Conf. on the Robotics Soc. of Japan, 1998. pp. 1117-1118.

[Ike 98] Ikeda T. and Mita T., "Analysis and Design of Running Robots in Touchdown Phase", Proc. 16-th Ann. Conf. on the Robotics Soc. of Japan,1998, pp. 551-552.

Based on the same ZMP principle, group of the authors: M. Hirose, T. Takenaka, H. Gomi and N. Ozawa, from HONDA R & Co. LTD WAKO Research Center, have realized in 1997 HONDA HUMANOID ROBOT - the most successful result in biped locomotion to date (Journal of the Robotics Society of Japan, Vol. 15, No.7, pp. 983-987, 1997).

ZMP CONCEPT WAS BORN THIRTY YEARS AGO. BECAUSE OF ITS BIOLOGICAL JUSTIFICATION AND BIOMECHANICAL VALIDITY I STRONGLY BELIEVE IN ITS PERMANENCE AND FURTHER SUCCESSFUL APPLICATION IN LEGGED LOCOMOTION ROBOTICS GENERALLY.

3. ORIGIN OF RECURSIVE FORMULATION OF ROBOT DYNAMICS

Vukobratovic and Stepanenko presented in their journal paper [VUK73] for the first time in English the complete recursive Newton-Euler formulation in Robotics.

Their works were directed initailly toward the anthropomorphic robotic mechanisms.

In 1976 they published [STE76] and discussed the application of the recursive Newton-Euler computation to open-link manipulator mechanisms. Stepanenko published related material on dynamic modeling of linkages in Russian, too [STE70], [STE74].

McGhee, Ohio State University and Vukobratovic conducted a NSF-funded project in 1973-75. Working closely with McGhee, Orin and his student Hartoch were influenced by [VUK73] and [STE76] and made a further study in direction of computational improvement [OR79].

In the journal paper [VUK79] Vukobratovic and Potkonjak derived the first recursive Lagrangian formulation in robotics. The method has been dedicated to the direct and the inverse problems of dynamics. In [HOLL80] Hollerbach 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 Popov E.P. and associates [POP74], was developed in its final form in [VUK79a] by Vukobratovic and Potkonjak. It solves both inverse and direct dynamic problems. These equations were derived based on the Gibb's "acceleration energy" function.

[VUK73] Vukobratovic M. and Stepanenko Yu., "Mathematical Models of General Anthropomorphic Systems",Mathematical Biosciences,Vol.17, pp.191-242,1973.

[STE70] Stepanenko Y., "A Method of Analysis of Spatial Lever Mechanisms", (in Russian), Mechanics of Machines, Vol. 23, Moscow, 1970.

[STE74] Stepanenko Y., "Dynamics of Spatial Mechanisms", (in Russian), Mathematical Institute, Belgrade, Yugoslavia, 1974.

[STE76] Stepanenko Y. and Vukobratovic M., "Dynamics of Articulated Open-Chain Active Mechanisms", Mathematical Biosciences, Vol. 28, pp. 137-170, 1976.

[OR79] Orin E.D., Vukobratovic M., McGhee B.R., and Hartoch G.,"Kinematic and Kinetic Analysis of Open-Chain Linkages Utilizing Newton-Euler Methods", Mathematical Biosciences, Vol. 43, pp. 107-130, 1979.

[VUK79] Vukobratovic M., and Potkonjak V., "Contribution to Computer Forming of Active Chain Models via Lagrangian Form", ASME Journal of Applied Mechanics, No. 1, 1979.

[HOLL80] Hollerbach J.M., "A Recursive Formulation of Lagrangian Manipulator Dynamics, IEEE Trans. on SMC, Vol. 10, No. 11, pp. 730-736, 1980.

[POP74] Popov E.P., "Control of Robots-Manipulators", (in Russian), Journal Technical Cybernetics, No. 6, Moscow, 1974.

[VUK79a] Vukobratovic M. and Potkonjak V., "Two New Methods for Computer Forming of Dynamic Equations of Active Mechanisms", Journal of Mechanism and Machine Theory, Vol. 14, No. 3, 1979.

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

The computational deficiency of the numerical procedures prevented their application in on-line controllers. The same holds for numeric-kinematic algorithms. However, symbolic approaches to the generation of robot modeling can be much more efficient than numerical approaches. The symbolic method fully exploits 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 first recognized in [VUK83] and [ALD83]. In [VUK83] an efficient method of modeling serial-link manipulators in numeric-symbolic form was described.

First journal paper dedicated to the computer-aided generation of an analytical model for an arbitrary, given type of manipulator configuration was written by Vukobratovic and Kircanski [VUK85].

Kircanski N. defended his Ph.D. under the title: **Contribution to Dynamics and Control of Manipulation Robots,** (in Serbian), Electrical Eng. Faculty, Belgrade, 1984.

Practically in the same time, or very soon after [VUK83] and [VUK85], several significant papers devoted to the computer-aided symbolic modeling appeared [NEU85], [KHO85] and [KHA86].

[VUK83] Vukobratovic M. and Kircanski N., "Computer-Aided Procedure of Forming of Robot Motion Equations in Analytical Forms", Proc. VI IFTOMM Congress, New Delhi, pp. 965-973, 1983.

[ALD83] Aldon M.J. and Liegeois A., "Computational Aspects in Robot Dynamics Modelling", Proc. of Advanced Software in Robotics, Elsevier Science Publishers B. V., Liege, Belgium, May 4-6, pp. 3-14, 1983.

[VUK85] Vukobratovic M. and Kircanski N., "Computer-Assisted Generation of Robot Dynamic Models in an Analytical Form", Acta Applicandae Mathematicae, Vol. 3, pp. 49-70, 1985.

[NEU85] Neuman P. Ch. and Murray J. J., "Computational Robot Dynamics: Foundations and Applications", Journal of Robotic Systems, Vol. 2, No. 4, 425-452, 1985.

[KHO85] Khosla P. K. and Neuman P. Ch., "Computational Requirements of Customized Newton-Euler Algorithms", Journal of Robotic Systems, Vol. 2, No. 3, pp. 309-327, 1985.

[KHA86] Khalil W., Kleinfinger J.F. and Gautier M., "Reducing the Computational Burden of the Dynamic Models of Robots", Proc. IEEE Int. Conf. on Robotics and Automation, San Francisco, pp. 525-532, 1986.

Based on the paper: A New Program Package for the Generation of Efficient Manipulator Kinematic and Dynamic Equations in Symbolic Form, by Kircanski N., Vukobratovic M., Kircanski M., and Timcenko A., Robotica Vol. 6, pp. 311-318, 1988, **first robot symbolic model generator in user-oriented form appeared in 1988.**

5. ORIGIN OF DYNAMIC APPROACH TO TRAJECTORIES GENERATION OF ROBOTIC MANIPULATORS

A method for optimal synthesis of manipulation robot trajectories has been proposed for the first time in [VUK82], where the system is considered as a dynamic system modelled by the complete, nonlinear dynamic model of the mechanism and the actuators. Regarding the practical importance of the energy optimal motion synthesis which simultaneously provides for smooth, jerkless motion and minimal actuators' strains, a particular attention was paid to the energy optimal motion of nonredundant manipulators.

[VUK82] Vukobratović M., Kirćanski M. "A Method for Optimal Synthesis of Manipulation Robot Trajectories", Trans. on ASME, Journal of Dynamic Systems, Measurement and Control, Vol. 104, No 2, 1982. pp. 188-193.

A procedure for the dynamic synthesis of redundant manipulator trajectories has been proposed for the first time in [VUK84]. This procedure was not really dynamic for the reason that the system is modelled 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 the actuators. This method exhibited considerable advantages over kinematic approaches in the following cases: manipulation of heavy objects by large, powerful robots and high speed manipulation with high energy consumptions.

[VUK84] Vukobratović M., Kirćanski M., "A Dynamic Approach to Nominal Trajectory Synthesis for Redundant Manipulators", IEEE Trans. on System, Man and Cybernetics, Vol.14, No. 4, 1984.

Real-time implementable algorithm for redundant manipulator motion synthesis in an obstacle - cluttered environment has been presented for the first time in [KIR84, KIR86]. This procedure was based on the application of the performance indices which take the presence of the obstacles into account and thus prevent the manipulation mechanism from drawing too close to the obstacle

[KIR84] Kirćanski M., Vukobratović M., "Trajectory Planing for Redundant Manipulators in the Presence of Obstacles", V CISM-IFToMM Symp. on Theory and Practice of Robots and Manipulators, Udine, 1984.

[KIR86] Kirćanski M., Vukobratović M., "Contribution to Control of Redundant Robotics Manipulators in an Environment with Obstacles", Intern. Journal of Robotics Research, Vol. 5, No 4, 1986.

6. Origin of 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 the dynamic control of robots. The centralised feedforward control is one of the dynamic control laws which was effectively applied in practice. It includes so-called nominal programmed control which compensates for the dynamics of the complete mechanism along the nominal trajectory. The centralised feedforward control differs from the decentralised feedforward (so-called local nominal control), since the former includes computation the total nominal driving toques along the nominal trajectories (which represent the dynamic moment due to the movements of all joints of the robot), while the decentralised feedforward compensates just for the local actuator dynamics.

The centralised feedforward was first proposed to be applied in biped locomotion systems by Vukobratovic and Juricic in [VUK 69] and [VUK 73]. In the biped walking machines an accurate tracking of the pre-calculated nominal trajectories, which could be achieved by the application of the centralised feedforward, was prerequisite to ensure dynamic equilibrium during the walk.

The application of the centralised feedforward for the manipulation robot was firstly proposed and discussed by Vukobratovic and Stokic in [VUK 80], [VUK81], [VUK 82], [VUK 85]. They were first to define the needs and benefits of application of the dynamic control for manipulation robots, i.e. to define the robotic tasks for which an application of centralised feedforward control is beneficial. As compared to other dynamic control laws (e.g. so-calles inverse dynamic or computed torque method, [PAUL 72], [BEJ 74], [PAV 76], the centalised feedforward exhibits considerable advantages such as higher robustness, simpler control scheme which does not request change is basic structure of the classical servo-system schemes etc. Therefore, the centralised feedforward is relatively easy to integrate in the existing (industrial) robot controllers.

Vukobratovic and Stokic have analysed both asymptotic [VUK 80], [VUK 81], [VUK 82] and practical stability [VUK 85], [STO 84] of the control schemes which include the centralised feedforward terms. They were also the first to demonstrate the experimental application of such control schemes in [VUK 85]. The application of the centralised feedforward terms in the market available industrial robot controller started a number of years latter, showing full effectiveness of the proposed approach.

The reason for relatively late introduction of the centralised feedforward control in industrial practice may be attributed to the fact that the first robots were mainly oriented to relatively simpler applications (e.g. pick-and-place tasks etc.) where the benefits of the application dynamic control are not very high. Once the robot started to applied more complex tasks asking for an improved performance (e.g. higher speed and accuracy of trajectory tracking) a need for a dynamic compensation by appropriate control laws has become obvious, and a considerable attention has been given by the industry to the application of the centralised feedforward control.

One of the first implementations of centralized feedforward control has been presented in [OLO 90], ten years after the paper [VUK 80] in which the benefit from centralized feedforward control has been shown. The paper [OLO 90] contains the experiments with centralized feedforward, implemented in RCM-3 Siemens controller with KUKA 160-15 robot, resulting in significant tracking improvement of strongly dynamic trajectories.

The implementation of feedforward control has been also presented in [DOG 93] and [HIR 94]. The application of feedforward algorithms in industrial controlles, as well as the algorithms transfer implemented in DLR-light space robot have been presented in [HIR 94].

In [DOG 93] the dynamic control in COMAU C3G controller has been described.

Today 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 a resent application real-time optimal feedforward control enhanced the international competitiveness of leading robot manufacturers. Also robot-in-the-loop mathematical optimization reduces the time for robot controller tuning drastically.

[VUK 69] Vukobratovic M., Juricic D., "Contribution to the Synthesis of Biped Gait", IEEE Trans. Biomedical Engineering, Vol. 16, No. 1., 1969.

[VUK 73] Vukobratovic M., "How to Control Artificial Anthropomorphic Systems", IEEE Trans. on Systems, Man. and Cybernetics, SMC-3, No. 5., 1973.

[VUK 80] Vukobratovic M., Stokic D., "Contibution to the Decoupled Control of Large-Scale

Mechanical Systems", IFAC Automatica, Vol. 16., No. 1., 1980.
[VUK 81] 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.
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[DOG 93] Dogliani F., Magnani G., Sciavicco L., "An Open Architecture Industrial Controller", Newsletter of the IEEE Robotics and Automation Society, Vol. 7, No. 3, pp. 19-21, 1993.
[HIR 94] Hirzinger G., Gombert H., Dietrich J., Shi J., "Transfering Space Robot Technologies into Terrestrial Applications", Proceedings, 25 th ISIR, Hannover, 1994.

7. Origin of robot dynamic control

Dynamic control implies to control the motion and forces of a robot by explicitly taking care of the system dynamics.

The first ideas to apply dynamic control of a robot originates from the goal to follow a prescribed trajectory by the anthropomorphic active mechanisms, specifically biped locomotion systems. Vukobratovic and Juricic [VUK68], [VUK69] were first to discuss the control of a walking machine and suggested a dynamic control scheme consisting of a feedforward 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 latter, such an approach was proposed and elaborated for the joint space dynamic control of manipulation robots [VUK74], [VUK80a], [VUK81]. In these papers the dynamic control of manipulation robots was suggested as an effective mean to compensate for strong coupling among the joints of the robots and, by this, ensure the accurate tracking of the desired trajectories of robots.

In difference to the biped locomotion systems where application of the dynamic control is necessary to ensure a stability of the system at all, the benefits of the dynamic control for manipulation robots need a more sophisticated study. **In [VUK82], [VUK83] conditions under which the application of the dynamic control of robots is reasonable has been discussed in detail, showing that the dynamic control, although**

requiring more complex synthesis and implementation than simple decentralised servo approach, may bring considerable benefits for the robot performance. These benefits have been latter recognized by a number of researcher and different dynamic control schemes have been proposed.

On the occasion of the appearance of paper [VUK81] in the Forum: "Papers on control of robotic devices", **W. Book** in the same issue has written: **"The papers by**

Vukobratovic and Stokic [VUK81] and Takegaki and Arimoto [TAKE81] present overall frameworks in which the control of the robot manipulator can be approached".

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8. ORIGIN OF DECENTRALISED CONTROL AND OBSERVER APPLIED TO STRONGLY COUPLED ACTIVE MECHANISMS

When a decentralised 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 an inappropriate performance of the system in the case that just 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 in [VUK69], [VUK73], [VUK77], [VUK78], [VUK80]. This approach was first applied to biped locomotion systems, and latter extended to manipulation systems and other active mechanisms [VUK78].

First, the so-called nominal programmed control is applied, realising the desired motion of the system in an ideal case for some specific initial conditions. Such a programmed control is computed based a centralised, complete model of the system. Then, with the second stage (step) of the control synthesis, the control, to stabilise the system around the nominal trajectory when the perturbations of the initial conditions type are acting upon it, has to be synthesised. In this second step (the so-called stage of perturbed regimes) the decentralised control structure is applied. By the introduction of the programmed nominal control, the dynamic coupling among the subsystems is reduced at the stage of perturbed regimes, assuming that the system state in the finite regions in the state space is under consideration.

However, the coupling among the subsystems still could be too strong. To further compensate for the influence of such strong coupling, the following approach was proposed [VUK80]: if each mechanical degree of freedom is considered as a subsystem, the coupling among such subsystems represents force (torque) which could be either computed, using the dynamic model of the mechanism, or directly measured. This enables to introduce so-called global control in the form of feedback via either computed torque/force or direct torque/force feedback. **By application of such a global control, the destabilising influence of the coupling upon the global system stability can be minimised as recognised first in [VUK78], [VUK80].**

The similar approach can be applied if a decentralised observer is applied for a strongly coupled active mechanism [STO83]. A local observer is normally introduced for each subsystem (i.e. each degree of freedom). Using such an observer 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 in [VUK82], [STO83] that the subsystems can be stabilised by such a controller, which applies the estimate of the subsystem state instead of the actual state.** Next, the regions of the asymptotic stability of the whole ensemble (active mechanism + observer + regulator) were estimated when the coupling among the subsystems is taken into account. **The influence of coupling upon both decentralised controller and the decentralised observer is analysed, and it is shown that by the application of the global control, as explained above, these influences can be reduced in order to assure the over-all system stability [VUK82], [STO83].**

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9. Origin of force feedback in dynamic control of robots

The benefits which can be achieved by application of the direct force feedback in some specific servo systems applications have been recognised for a long time [GO52].

The application of the force feedback for the biped locomotion systems, has been proposed for the first time in the papers [VUK73], [VUK77], [VUK78], [STO79]. The effects of joint force sensory feedback to compensate for the dynamic coupling among the joints of the articulated mechanisms, have been first recognised for the biped locomotion robots, since the coupling among the joints motion is very strong and it has major effects upon the system overall stability.

The application of the direct force feedback in the robot joints or the manipulation robots has been first proposed by Vukobratovic, Stokic and Hristic [VUK75a], [VUK75b]. This approach has been latter elaborated in detail in [VUK77], [VUK80a], [VUK80b].

The application of the joint sensory feedback in manipulation robots enables to ensure improved accuracy of tracking of the desired trajectories without application of the complex dynamic laws. Another advantage of such an approach over the dynamic control laws based on the dynamic models of robots is that the force feedback compensation is not sensitive to inaccuracy in the identification of the model nonlinearities and parameters. On the other hand, the application of the direct force feedback is connected to certain technical problems which have been well analysed in [VUK82], [VUK83], [VUK85], [WHI87]. An overview of the joint force sensory feedback control in manipulation robots is provided in [STO93].

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10. ORIGIN OF DECENTRALIZED CONTROL STABILITY TESTS FOR ROBOTIC MECHANISMS

In papers [VUK73], [VUK78], [VUK80a], [VUK80b] etc. the application of the decentralised control to the large-scale mechanical systems has been considered for the first time in robotics from the theoretical point of view. Each degree of freedom (d.o.f.) of the mechanical system is considered as a subsystem. Local control is synthesised for each subsystem, neglecting the interconnections among the subsystems.

Since the influence of interconnections among sybsystems may be too strong, nominal programmed control calculated using a centralised model of the system has been introduced [VUK78], [VUK80a], [VUK81], [VUK82]. However, this approach is acceptable when the desired motion is well known in advance and when parameters of the system are precisely defined. If these assumptions are not met, then the synthesis and application of the nominal programmed control based upon the complete, centralised model is not appropriate. These were the reasons why the completely decentralised control law has been proposed in [VUK84], [STO84], [VUK85]. This control law includes local servos around the joints and the local nominal feedforward terms based on the decentralised model of the robot dynamics.

This decentralised control approach had been applied in industrial robots for a long time (normally without local feedforward terms), but no theoretical analysis of such control scheme was done.

The first analysis of the asymptotic stability of such controller was provided in [VUK80a] and [VUK80b], showing that the decentralised control scheme including the centralised feedforward can ensure the asymptotic stability of the system, provided that the feedback gains are appropriately selected. The stability of the robot in the case that the decentralised controller including centralised feedforward terms are applied, was analysed based on decomposition - aggregation approach.

In the case when only local controllers are applied (local servos + local feedforward terms) it is necessary to analyse the practical stability of the over-all system trajectory.

In [STO84], [VUK85] the practical stability of the large-scale mechanical systems with the decentralised control scheme was analyses for the first time, providing a mean to analyse the ability of such decentralised control to withstand nonlinearities of the model and parameters variations.

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11. ORIGIN OF UNDERACTUATED ROBOTIC SYSTEMS

The appearance of unpowered DOFs is most characteristic for legged, particularly biped locomotion robots. Namely, during the real walking under perturbations additional angles appear assuming that whole robot rotates around its edges of feet. These passive (unpowered) degrees of freedom have a prevailing influence on the overal biped robots stability.

Specifity of biped robots, in the functioning of which supplementary unpowered degrees of freedom can appear, has been noted already in journal papers [VUK72], [VUK73]. Differing from the, present in to-day's papers, so-called underactuated systems, with which the problems of control and stability are of academic (unnatural) character, with the mentioned types of robotic mechanisms inevitably appear supplementary degrees of freedom, which by their nature represent really the unpowered (passive) degrees of freedom.

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 [VUK80a], [VUK80b], [VUK81], [VUK82], [VUK84], [STO84], [VUK85]. The analysis is performed in the following way: 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 mechanisms which 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, might be stabilized. Further, the interconnections of the "composite" subsystem with the rest subsystems are taken into account, and criteria for stability tests of the overall mechanism are established.

The complete control synthesis as well as stability analysis of the robotic mechanisms having unpowered degrees of freedom (underactuated systems) has

been presented for the first time in the research monograph [VUK89] and journal papers [BORO89a], [BORO89b].

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12. Origin of Application of Practical Stability Tests in Robotics

One of the main problems in a synthesis of control laws for robots represent uncertainties in the dynamic models of robots. Especially the uncertainties in a dynamic model of environment in different technological tasks may have high influences, due to difficulties in identification/prediction of the environment parameters and behaviour of the environment. Therefore, it is of major importance to test robustness of the synthesised control laws against these model uncertainties. Taking into account it is of practical interest to require 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 (and force trajectories in the case of the socalled constrained motion tasks, i.e. the tasks in which manipulation robots are coming into contact to the environment) is defined by specifying the finite regions around the desired position (and force trajectories) within which the robot actual position co-ordinates and velocities (and forces) have to be during the task execution.

A need to study practical stability of robots was first recognised by Vukobratovic and Stokic already in the early eighties [VUK 80], [VUK 82]. However, in these early paper and monograph they applied a decomposition-aggregation method to study asymptotic stability of the manipulation robots in the finite regions, as an approximation of the practical stability analysis.

They were also the first to elaborate a procedure for direct testing of a practical stability of manipulation robotic systems moving in a free space when decentralised control law is applied [STO 84]. The procedure was extended to practical stability test for different control laws in [VUK85]. The elaborated conditions for the practical stability of a robot moving in a free space enable to study the model uncertainty issue in a control of robots without any approximations, i.e. to correctly examine 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 Michael [MI 70], for practical stability analysis of large-scale systems. A software package for practical stability analysis of robots moving in a free space was generated serving as an efficient tool for resting practical stability conditions [VUK 85].

The procedure for practical stability for manipulation robots was then extended to biped locomotion robots by Borovac, Vukobratovic and Stokic [BOR 89] and elaborated in detail in [VUK 90].

The so-called unpowered degrees of freedom represent a special problem in a stability analysis of the biped locomotion systems (i.e. the d.o.f. between the robot's feet and the ground). This problem was efficiently solved by appropriate modelling of these d.o.f. in combination to other powered joints.

The importance of practical stability study in the constrained motion tasks, due to uncertainties of the models of the environment a manipulation robot is interacting with, was also identified by Stokic and Vukobratovic [STO 95], [STO 98], [STO 99]. They derived a test enabling to examine which properties must be fulfilled by the environment, required nominal trajectories (position, force) and a control law in order to ensure practical stability of the manipulation robot. The practical stability appears to be more appropriate especially for this type of control tasks than the asymptotic stability test, since it enables to consider effects of uncertainties in the control laws which cannot guarantee asymptotic stability at all, but can fulfil practical stability conditions (e.g. the position control law which cannot asymptotically stabilise the robot when the environment parameters are nor perfectly known). The elaborated stability test may be used either to check stability of the specified control laws, or to establish procedures for synthesis of parameters of different control laws. By this, the control synthesis becomes much more accurate and effective, i.e. the robustness of control against the uncertainties in robot and environmental models can be better ensured, which is one of the most relevant aspects in potential industrial applications of robot in numerous important technological tasks where the robot is interacting with environment such as cutting, deburring, etc.

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13. Unified approach to control laws synthesis for robot interacting with dynamic environment (1993)

During the past decade, compliant motion control has emerged as one of the most attractive and fruitful research areas in robotics. The control of constrained motion of robots is a challenging research area, the successful solution of which will considerably affect further application of robots in industry and increase their efficiency and productivity. The increasing demand for advanced robot application has brought about an enormous growth of interest in the development of different concepts and schemes for the control of 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 to split the task into the motion control and interaction force control. This idea enabled Mason [MAS81], and later Raibert and Craig [RA81], to formulate an approach to manipulator control, called the hybrid possition/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.

The paper by Duffy [DUF90] pointed out the fallacy of 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. **Duffy claimed that the orthogonality is not invariant in the choice of coordinate frames and therefore that the conventional formulation lacks in the physical meaning.**

A weakness of this approach linked with the notion of "orthogonality" is caused not only by the fact that it is incorrect to use the therm "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 because in these directions they use, for the stabilization task, feedback loops with respect to motion or force only.

The approach proposed by Vukobratovic and Ekalo with other associates [VUK93], [EKA93], [VUK94], [EKA94a], [EKA94b], [EKA95], [VUK95a], [VUK95b], [VUK96a], [VUK96b], [VUK97a], [VUK97b], [VUK97c], [VUK98a], [VUK98b], [STO98], [STO99] is based on the general model of environment dynamics and solves simultaneously both stabilization tasks of position and interaction force with the environment. Based on closed-loop control system stability, the control laws use both position and force feedback.

Furthermore, it is shown that in the case of simultaneous stabilization of both position and contact force, the quality of position/force transient responses can be controlled.

Then, instead of established traditional hybrid position/force control a new approach was proposed, which for the first time involves environment as an active "participant" in dynamic control of the whole robot-environment system. Thus, the role of dynamic environment in solving this control task of robots was stressed out, and control laws which simultaneously stabilize both position and interaction force were applied.

The model of uncertainties represents the crucial problem in control of robots interacting with the dynamic environment. Especially the uncertainties in dynamic model of environment in different technological tasks may have high influences, due to difficulties in identification/prediction of the environment parameters and behaviour of the environment. Therefore, it is of major importance to test the robustness of the synthesised control laws against these model uncertainties and to establish a method for an accurate and effective analysis of influences of these uncertainties upon the system performance.

To enable such an analysis the conditions for practical stability of the robots around programmed motion and interaction forces with the environment were established for the first time [STO98, STO99].

Taking into account external perturbations, which do not expire with time (althoug being constrained), and model and parameter uncertainties, it may be dificult to achieve asymptotic (exponential) stability of the system (unless robust control laws including factor for compensating these perturbations and uncertainties are used). **Therefore, it may be of practical interest to require more relaxed stability condition, i.e. to concider 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 force have to be during the task execution. It is assumed that inaccuracy of the models parameters (robot and environment) is constrained. The conditions for practical stability are derived using the method of Michel, [MI70]. The inaccuracy in modelling, external perturbations, constraints upon motion, control and interaction forces are concidered in general form.

The practical stability tests are demonstrated upon 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 environment.

Note that such control law cannot ensure asymptotic stability of the robot unless the model of the environment is perfect, but practical stability can be achieved.

The second control law considered belongs tot he so-called hybrid position/force control schemes where the complete dynamic model of the robot is taken into account: in directions in which the desired position trajectories are specified the control law attempts to stabilise the position, while in the directions in which force trajectories are specified, the control law focusses on the force.

Contrary to the so-called classical control schemes, the control law considered takes into account complete dynamic models of the robot and environment as well as interaction among the directions in which position is controlled and directions in which force is controlled. Since this control does not require re-calculation of the desired position trajectories using inaccurate environment model as the first one, it exhibits better performance and higher robustness to parameter and model uncertainties. Based upon the derived practical stability test it is possible to make a 'fair' comparison of these two laws in the presence of model uncertainties.

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

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14. New approach to modeling and control of multi-arm cooperating robots interacting with environment

Unified approach to the control of robots interacting with dynamic environment [VUK96] gave a chance to solve in an adequate way the complex problem of multi-arm cooperating robots control.

The basic problems in solving the cooperative work lay in determining the forces at the contact point of the manipulator tip and the object (environment). Force undefinitness 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 deformations compatibility condition fulfilment. 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 manipulators are elastic. The assumption was adopted, that it is possible to approximate the elastic system by a spatial grid, in the nodes of which a system of external loads is acting, so that each node possesses six degrees of freedom and that the nodes coincide with the MC (mass centers) of the rigid objects, as representatives of the inertial properties of the elastic connections and the manipulated object [ZIV97].

Somewhat different approach to the forming of dynamic model based on the same fundamental idea about the contact of dynamic nature between multi-arm cooperating robot, object and environment, has been presented in [VUK98a]. The presented mathematical model of multi-arm cooperating robots takes into account complex effects, such as object dynamics, and environment dynamics.

The proposed modelling approach successfully solves the load distribution problem. The main idea used in the modelling of the motion of the dynamic object connected with 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, and in 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, the combined model of multiple robots/object/environment dynamics is presented.

Based on such developed model of cooperative manipulation dynamics the procedure for determining the nominal motion was given [ZIV98a]. It was required that the nominal motion of the cooperative system should be coordinated, i.e. that the manipulators at first perform the 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 objects and elastic contacts. The nominal trajectories of the elastic system for description of the dynamics 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.

Based on the obtained trajectories of the contact points and the nominal contact forces in them, the analysis of the cooperative system as a controlled object has been considered [ZIV98b]. It has been emphasized that there exist two typical contact tasks. The first is: tracking of the chosen points nominal trajectories only, while the second is: tracking of the nominal trajectory of the one point only, and of the nominal contact forces of the follower manipulator. For the tracking of the manipulated object mass center nominal trajectory and the nominal trajectories of the follower manipulators control laws were proposed. It was analytically proven that all magnitudes of the controlled cooperative system asymptotically tend towards their nominal values after the initial deviations from the same.

Based on the fundamental idea described in the unified approach to control robotic manipulator interacting with dynamic environment [VUK96] and the model derived in [VUK98a] the adaptive control have been synthesized [VUK98b], which simultaneously stabilizes both, the desired multiple robot and object position and interacting forces between the object and environment.

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

The common control problem for advanced robot applications based on constrained manipulation and robot contact tasks is to describe the robot-environment dynamics and to synthesize control laws which would stabilize both the desired position and the interactive force.

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

The first concern of this approach is an extension and generalization of approach developed for connectionist control in robot non-contact tasks in order to deal with problem of performing position and force control of robot manipulators. The connectionist architectures are applied for fast on-line learning of robot dynamic uncertainties used at the executive hierarchical control level in robot contact tasks. The main feature of proposed algorithms is integration of the connectionist structures integrated in robust non-learning control laws for contact tasks that enable stabilization and satisfactory tracking performance of position and force **[VUK96]**. The proposed neural network plays the role of robust controller to compensate for the uncertainties of the model of manipulation robots in contact with dynamic environment. The multi-layer perceptron being a part of hybrid learning control algorithm through the process of synchronous training, uses fast learning rules and available sensor information in order to improve robotic performance progressively in minimal possible number of learning. **This hybrid approach, based on model-based method and connectionist learning is chosen because 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 with fast on-line learning algorithm.**

The second important concern 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 **[KAT98]**. **This method classifies the type of robot environment using multi-layer perception through off-line training process and through process of on-line pattern association.** It is assumed that for classified dynamic environment, the control parameters and parameters of environment models (structure of environment model is known) are defined in advance, or that they can be obtained by the process of linear interpolation. Based on classification and generalized features of the proposed neural network, acquired in off-line training process, the control algorithm can select the appropriate control parameters which achieve the satisfying system performance. **In the proposed off-line training algorithm, convergence process is improved by using genetic algorithms in order to choose the optimal topology of the multi layer perception.**

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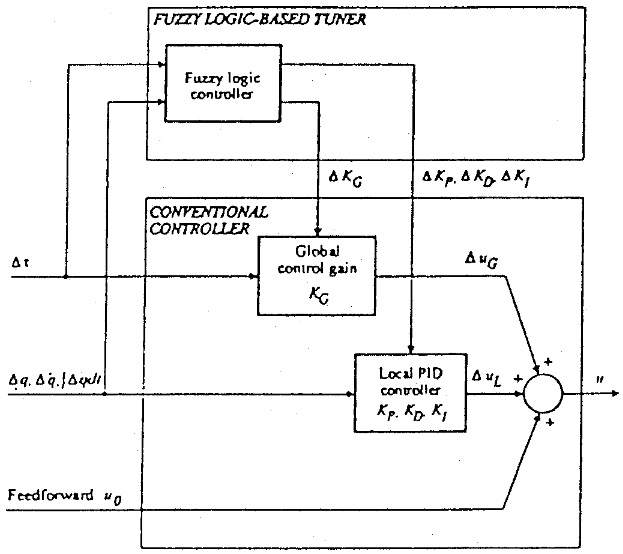
16. FUZZY LOGIC ROBOT CONTROL WITH MODEL-BASED DYNAMIC COMPENSATION

A tighter connection between fuzzy logic control (FLC) and standard control methods was proposed by Tzafestas and Papanikolopoulos [1], who suggested employing a two-level hierarchy in which an FLC-based expert system is used for fine - tuning of low-level PID control. However, the two-level hierarchy does not actually solve the problem of weak performance. **This shows that knowledge of a readily available mathematical model of robot dynamics should not be ignored.** Most importantly, it may be employed to decrease 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 yeld superior control schemes to both simple model-based or fuzzy-logic-based approaches.**

The genearal idea behind the hybrid approach [2] is to utilize a satisfactory approximation of the robot dynamics model to decrease 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 [3]. The hybrid design is an extension of decentralized control strategy. Each of the subsystems comprises two components: the traditional model - based controller and optional fuzzy-logic-based tuner (see the figure). The inputs to **i**th joint subsystem are nominal control signal u_{oi}, joint position error Δq_i, joint velocity error $\Delta\dot{q}_i$, and 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 robot dynamics, and the gains of **i**th local PID servo are synthesized to stabilize decoupled sub-system. In 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 computed or measured deviation of dy-



Hybrid control scheme.

namic 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 traditional controller. The tuner is designed as a fuzzy-logic-based controller that monitors joint response characteristics and modifies the gains to provide better responses. Starting from conditions of practical stability of motion with constant-gain control, sufficient conditions that warrant the practical stability of 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.

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17. INTERNAL REDUNDANCY - NEW WAY TO IMPROVE ROBOT DYNAMIC PERFORMANCES

The last decade is marked by a certain trend in the development of active technical systems and constructions. Many technical systems obtained a new property: their dynamic parameters (e.g. inertia or damping) became variable and controlled. The main reason for the tendency towards active systems lies in the real need for systems, constructions and structures that have to be compatible with various dynamic loads, variable external conditions and 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 different engineering fields, there is a necessity to maintain the desired system performance during variable working conditions, as well as during 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 and structures should be designed so as to feature variable geometry in appropriate limits - [VUK99a], [VUK99b], [VUK99c], [POT99].

Variable geometry means the variation of geometrical parameters that are relevant for 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. Then, there is an crucial difference from the traditional (kinematic) notion of redundancy. Here, the additional degrees of freedom do not influence the external motion and accordingly cannot improve end-effector ability for nameuvring. For this reason a new notion is introduced - the internal redundancy. One might say that internal redundancy improves the robot dynamic capabilities.**

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

q - joint (generalized) coordinates,

s - geometrical (fixed or variable) coordinates,

ξ - elastic (deformations) coordinates

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

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

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

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

And, finally, the general model of the system with 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

Application of variable structure does not solve only to a certain degree the conflicting requirements, for instance, between load capacity and speed of operation of robotic mechanisms, but the proposed principle can be implemented in constructions and structures of quite different types. Thus, e.g., with suspension bridges, particularly 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 vehicle global stability when driving along a winding road. In case of such system, including active suspension, too, lateral displacement, of, e.g., wheeels of about several centimeters, can prevent vehicle overturning.

Today these mentioned probably quite unusual solutions can become technical practice and adequate solutions in not too far future.

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18. Instead of Conclusion

Let us mention with special pleasure my most prominent Ph.D. students, and then also my closest coworkers in the field of robotics research, and most meritorious associates in my scientific team who helped me in founding Belgrade School of Robotics.

They are: **Dragan Stokić, Dragan Hristić, Vesna Cvetković-Živković, Veljko Potkonjak, Nenad Kirćanski, Manja Kirćanski and Branislav Borovac**.

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BEOGRADSKA ŠKOLA ROBOTIKE

Miomir Vukobratović

U radu se ukratko predstavljaju naučni rezultati beogradske škole robotike. Po nekom hronološkom redosledu oni bi se mogli svrstati na sledeći način: koncept tačke nultog momenta i semi-inverzna metoda, rekurzivna formulacija dinamike robota, generisanje dinamike robota uz podršku računara u simboličkoj formi, dinamički pristup generisanju trajektorija manipulatora robota, centralizovano feedforvard upravljanje u robotici, upravljanje dinamikom robota, decentralizovano upravljanje i primena rekonstruktora na strogo kuplovane aktivne mehanizme, povratna sprega po sili kod dinamičkog upravljanja robotima, testovi stabilnosti decentralizovanog upravljanja za mehanizme robota, neadekvatne performanse sistemi robota, testovi praktične stabilnosti u robotici, unificirani pristup sintezi upravljačkih zakona za robote koji su u interakciji sa dinamičkom okolinom, novi pristup modeliranju i upravljanju robota sa više ruku u interakciji sa okolinom,

algoritmi za napredno učenje upravljanja robota u interakciji sa dinamičim okruženjem, upravljanje robota fazi logikom sa dinamičkom kompenzacijom zasnovanom na modelu i unutrašnja redundantnost – novi način za poboljšanje performnansi dinamike robota.