M. Vukobratović
D. Stokić
Mihailo Pupin Institute
Beograd, Yugoslavia

Is Dynamic Control Needed in Robotic Systems, and, if So, to What Extent?

Abstract

The problem of dynamic control in robotic systems is considered in this paper. Robotic systems are essentially dynamic systems. The problem is whether is it necessary to take dynamics into account in controlling them, and, if so, to what extent. In cases of slow motion and mechanical configuration with weakly coupled subsystems (mechanical degrees of freedom) it is not necessary to solve the control task dynamically. In cases of faster motion and mechanical configuration with strongly coupled subsystems, however, the control task is essentially dynamic and we suggest some control strategies which include complete dynamics of the robot. Several examples of locomotion and manipulation robots' control synthesis are presented. We present postural stabilization of biped robot, as a representative of dynamically unstable locomotion robots. The control synthesis for three types of manipulation robots is described in order to show how the extent of inclusion of dynamics in the control depends on the mechanical configuration of a robot.

1. Introduction

The motion of robotic systems as active spatial mechanisms is described via essentially nonlinear, second-order, differential equations. Linearized or linear models of such motion make no technical sense in practical applications. On the other hand, to what extent are robotic systems dynamic from the control point of view? That is, how necessary is it to apply dynamic control to such dynamic systems—control synthesized on the basis of complete dynamic information about the whole system? In this short introduction, some characteristic examples will be discussed.

The International Journal of Robotics Research
Vol. 2, No. 2, Summer 1983,
0278-3649/83/020018-17 $05.00/0

Let us consider the most difficult type of legged locomotion system—a biped system. In a biped system, it is not possible to realize the conditions of dynamic equilibrium by the use of gravity only, because the system's inherent negligible stability margin is determined by a finite foot surface and acting inertial forces. The situation is different with multilegged systems, where several legs have contact with the ground and form a polygon with a significant stability margin. Multilegged locomotion systems can be treated quasi-statically.

With manipulation tasks and manipulation robots, the stability problem encountered with legged locomotion systems does not exist, so we can estimate to what extent manipulation tasks are dynamic exclusively by considering the control system, which can be either *kinematic* or *dynamic*. In cases of slow motion and mechanical configuration with weakly coupled subsystems (mechanical degrees of freedom or their groups), it is not necessary to solve the control task dynamically. In cases of faster motion and mechanical configurations with strongly coupled subsystems, however, the control task to be solved is essentially dynamic.

In addition to tasks whose solutions can be categorized as either kinematic or dynamic, there are several basically dynamic tasks whose solutions take into account (1) the dynamics of one part of the complete system or (2) the dynamics whose second-order effects are omitted from the complete system. Examples of the first case (dynamics of one system part) are massless legs within a biped system with inertial trunk, a multilegged system with inertial platform, and massless grippers within manipulation systems. An example of the second case (partial system dynamics in which second-order dynamic effects are omitted) is the omission of Coriolis and centrifugal forces from the complete dynamics of locomotion or manipulation systems.

In order to estimate the importance of dynamic models of robotic systems and the specificity of such systems' dynamic control algorithms, this paper will discuss the problems of mathematical modeling and the demands imposed on robotic control systems, especially manipulation systems.

2. Mathematical Models of Robotic Systems

The mathematical model of a robotic system with n degrees of freedom, on which external forces from the operating environment are acting, may be represented in a general form (Vukobratović and Stokić 1981; 1982*c*):

$$S^M: \mathbf{P} = \mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) + \sum_{l=1}^{L} \delta_l \mathbf{g}_l(\mathbf{q})\mathbf{F}_l, \qquad (1)$$

where $\mathbf{P}(t)$ is an $n \times 1$ vector of generalized forces in mechanism joints, $\mathbf{P} = P_1, P_2, \ldots, P_n)^T$; $q(t)$ is an $(n \times 1)$ vector of generalized coordinates, $\mathbf{q} = (q^1, q^2, \ldots, \mathbf{q}^n)$; $\mathbf{H}(\mathbf{q})$ is an $(n \times n)$ inertial matrix of mechanism; and $\mathbf{h}(\mathbf{q}, \dot{\mathbf{q}})$ is an $(n \times 1)$ vector of Coriolis, centrifugal, and gravitational moments;

$$\delta_l = \begin{cases} 1 \text{ if contact exists in the } l\text{th} \\ \text{point } 0 \text{ otherwise;} \end{cases}$$

$\mathbf{g}(\mathbf{q})$ is an $n \times 3$ matrix, determining the position of the lth contact point with respect to the centers of mechanism joints; $\mathbf{F}_l$ is the vector of the force acting in the lth contact point; and $l = 1, 2, \ldots, L$ (if $L \to \infty$, the sum in [Eq. 1] should be substituted by the resultant external force).

For a realistic presentation of the complete dynamics of robotic systems that takes into account their inertia and the possibility of direct dynamic control, the introduction of the dynamics of actuators is essential.

Actuators may be represented by a mathematical model of form

$$S^i: \dot{\mathbf{x}}^i = \mathbf{A}^i\mathbf{x}^i + \mathbf{b}^i N(u^i) + \mathbf{f}^i P^i, \qquad (2)$$

where $\mathbf{x}^i$ is, the state vector of the ith actuator of dimension n_i; $\mathbf{x}^i = [q_i, \dot{q}_i, x_r^i]$; $\mathbf{x}_r^i$ is the $(n_i - 2) \times 1$ vector of the remaining state coordinates of actuators; $\mathbf{A}^i$, $\mathbf{f}^i$, $\mathbf{b}^i$ are constant matrices of the model; $N(u^i)$ is a function of the saturation type of ith actuator input; and n_i is the order of subsystem S^i.

Models in the form of (Eqs. 1 and 2) form the complete dynamics of a robotic system. It is known that computation of the mathematical model S^M can be performed on the basis of elaborated algorithms for the automatic setting of mathematical models of dynamics of active spatial mechanisms (Vukobratović and Stokić 1981; 1982*c*; Vukobratović and Potkonjak 1982). The procedure is general and does not depend on which class of tasks is to be performed, although some specific features of the task should be taken into account. These features can be explained by the examples of biped locomotion and the assembly of mechanical parts by manipulators.

2.1. Biped Locomotion

The first feature of locomotion, particularly biped locomotion, is the existence of unpowered degrees of freedom that correspond to the displacements between foot and ground. In the subsystem modeled in (Eq. 2), $i = 1, 2, \ldots, m$, where m is the number of powered degrees of freedom and, therefore, control vector $u = (u^1, u^2, \ldots, u^m)^T$. Thus, the order of the complete system (mechanical part S^M and actuator part S^i) is $N = \sum_{i=1}^{m} n_i + 2(n - m)$, where n_i is the actuator order; $\mathbf{x} = (\mathbf{x}^1, \mathbf{x}^2, \ldots, \mathbf{x}^m, \mathbf{q}_N, \dot{\mathbf{q}}_N)^T$ is the state vector of the complete system; and $\mathbf{q}_N$ is the $(n - m)$ vector of angular displacements of unpowered degrees of freedom. So, at points of contact with the ground, or more precisely at points where the dynamic reaction forces act (centers of pressure exerted on the ground), the moments are zero ($P_j = 0, j = m + 1, \ldots, n$). Because of this, the mentioned points have been called the *zero-moment points* (ZMP) (Vukobratović 1976).

The second feature of biped locomotion is the presence of changes between open and closed mechanical configurations that alternate according to single and double support phases. The closed-mechanism configuration imposes some specific features on the formation of matrices **H** and **h** of the system modeled in (Eq. 1). By adopting the situation of equivalent, open-chain configuration, we introduce and satisfy the closing conditions of the equivalent chain by an iterative procedure (Vukobratović 1976). The coordinates have been classified as *basic* (known) and *supplementary* due to the closed configuration (the approximative values of which are known under the supposition that the deviations between the equivalent open chain and its exact closed configuration are small) (Vukobratović 1976). In the forming of differential equations of closed-chain dynamics, it is assumed that the last member of the equivalent chain is loaded by unknown force $\mathbf{R}^*$ and moment $\mathbf{M}^*$. These loads represent the ground reaction of closed-chain configuration. These two vectors have six unknown components, which can be represented by vector $\boldsymbol{\sigma}$:

$$\begin{aligned}\boldsymbol{\sigma} &= (\sigma_1, \sigma_2, \ldots, \sigma_6)^{\mathrm{T}} \\ &= (R_x^*, R_y^*, R_z^*, M_x^*, M_y^*, M_z^*)^{\mathrm{T}}.\end{aligned}$$

Differential equations for the closed mechanical configuration are

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{B}\sigma + \mathbf{h} = \mathbf{P}, \tag{3}$$

where matrices $\mathbf{H}$ and $\mathbf{h}$ are formed as for the open chain (Eq. 1) and, in matrix $\mathbf{B}$, all members are grouped depending on σ

2.2. Mechanical Assembly

When the problem to be solved is not locomotion but automatic assembly, the dynamics have to do with forces at the manipulator tip, more precisely at the point of contact between the part to be assembled (*peg*) and the opening (*hole wall*). According to (Eq. 1), the mathematical model of manipulator dynamics during assembly is

$$\begin{aligned}S^{\mathrm{M}}\colon \mathbf{P} = \mathbf{H}'(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}'(\mathbf{q}, \dot{\mathbf{q}}) + \delta_1 C_{\mathrm{k1}}\vec{\mathbf{R}}_{\mathrm{k1}} \\ + \delta_2 C_{\mathrm{k2}}\vec{\mathbf{R}}_{\mathrm{k2}}\end{aligned} \tag{4}$$

for the case when two contacts exist between the peg and hole wall.

Elements of matrices $\mathbf{H}'$ and $\mathbf{h}'$ are of the form

$$\begin{aligned}H'_{\mathrm{ik}} &= H_{\mathrm{ik}} + \vec{e}_{\mathrm{i}}(\vec{r}_{\mathrm{pi}} \times \vec{a}_{\mathrm{pk}} + \vec{b}_{\mathrm{pk}}) \\ h'_{\mathrm{i}} &= h_{\mathrm{i}} + \vec{e}_{\mathrm{i}}(\vec{r}_{\mathrm{pi}} \times \vec{a}_{\mathrm{p}}{}^{0} + \vec{b}_{\mathrm{p}}{}^{0} + \vec{r}_{\mathrm{pi}} \times \vec{G}_{\mathrm{p}}),\end{aligned} \tag{5}$$

where $\vec{\mathbf{e}}_{\mathrm{i}}$ are unit vectors of joint axes; $\vec{\mathbf{r}}_{\mathrm{pi}}$ are the position vectors between the peg's center of gravity and joint centers; and $\vec{\mathbf{G}}_{\mathrm{p}}$ is the vector of the force of gravity acting on the peg. H_{ik} and h_{i} are matrix elements of the manipulation system *without* the object; vector coefficients $\vec{a}_{\mathrm{pk}}$, $\vec{b}_{\mathrm{pk}}$ are functions of generalized coordinates; and $\vec{a}_{\mathrm{p}}{}^{0}$, $\vec{b}_{\mathrm{p}}{}^{0}$ are functions of generalized coordinates and velocities representing the contribution of object.

In accordance with (Eqs. 1 and 5), the equation of manipulator dynamics *with* the object can be written as

$$P_{\mathrm{i}} = \sum_{\mathrm{k=1}}^{\mathrm{n}} H_{\mathrm{ik}}\ddot{q}^{k} + h_{\mathrm{i}} + \vec{e}_{\mathrm{i}}[\vec{r}_{\mathrm{pi}} \times (\vec{F}_{\mathrm{p}} + \vec{G}_{\mathrm{p}}) + \vec{M}_{\mathrm{p}}], \tag{6}$$

where $\vec{F}_{\mathrm{p}}$ is the object's inertial force and $\vec{M}_{\mathrm{p}}$ the moment due to the inertial force.

In the case of one contact only between the object and the hole, the differential equations are of the form

$$P_{\mathrm{i}} = \sum_{\mathrm{k=1}}^{\mathrm{n}} H'_{\mathrm{ik}}\ddot{q}^{k} + h'_{\mathrm{i}} + \vec{e}_{\mathrm{i}}(\vec{r}_{\mathrm{k1}} \times \vec{R}_{\mathrm{k1}}), \tag{7}$$

where $\vec{r}_{\mathrm{k1}}$ denotes the vector from the ith joint's center of gravity to the contact point of the assembly object and the hole wall. Determining the reaction forces $\vec{R}_{\mathrm{k1}}$ is a separate problem, which will not be treated here (Vukobratović and Stokić 1982*c*).

The discussion above and in Section 2.1 illustrates insignificant deviations from the basic robotic system model in the form of open mechanical configuration for different tasks, here those of locomotion and "restricted" manipulation. However, the chief reason for presenting robotic systems in the form of two subsystems (the dynamics of mechanical configuration and of actuators) lies in adequate modeling of the complete system dynamics, which is necessary for so-called dynamic control. A second, no less important reason for this presentation is the possibility of decentralized control.

3. Dynamic Control of Robotic Systems

The task posed at the actuator level of robot control consists of the realization of its functional movements. In general, this task can be defined as the task of achieving practical system stability with a prescribed settling time. The most frequent task is to transfer the system from one bounded region of initial conditions into another bounded region of state space, with a predetermined settling time. The system state space should belong to some bounded region in the state space during the transfer of the system from one state to the other. Constraints on the regions are imposed by task conditions (notably, conditions relative to the region into which the system state should be transferred); by constraints on the system itself (e.g., kinematic constraints of the manipulator mechanism, constraints on the system inputs, constraints on the actuators; and by constraints imposed by the environment (e.g., obstacles). The control task is thus reduced to the task of achieving practical stability, under the assumption that the perturbations acting on the system can be reduced to perturbations of the initial-conditions type.

Systems theory offers various possibilities for the synthesis of robot control. Robotic systems are complex, mechanical, and essentially nonlinear, however, so some special features of robotic systems should be stressed. These features limit to some extent application of the usual control techniques. As stated previously, the special features of robotic systems originate from their mechanical, structural, dynamic, and control properties. Some special robot characteristics are (1) their variable structure; (2) degrees of freedom that cannot be controlled directly (e.g., in locomotion systems); and (3) redundancy of mechanisms, which necessitate multiple control systems for the realization of functional movements for locomotion and especially for manipulation. These characteristics require that care be taken in the application of general control synthesis methods to complex, nonlinear robotic systems.

3.1. Overview of Previous Research

What has, in fact, been done in the synthesis of manipulator control algorithms and, in general, in robotic systems? To date, most work on control synthesis at the level of trajectory realization has been based on the assumption that the desired trajectories can be realized via local servosystems, without analysis of the dynamic behavior of the complete system. However, there have been some attempts to synthesize control from the standpoint of complete robotic system dynamics.

3.1.1. Inverse Problem Techniques

Paul (1976) has considered several control versions that take into account dynamic system parameters, but he has not analyzed resultant system behavior. He applied *inverse problem* techniques, also called the techniques of *precalculated driving torques* (Bejczy 1974). According to the inverse problem techniques, the input driving torques, which are needed to drive the manipulator along the programmed trajectory, are calculated on-line as a function of the desired accelerations, velocities, and positions of the joints. A similar approach has been adopted by Timofeyev (Timofeyev and Ekalo 1976), in which the stabilization of the manipulator's trajectory is achieved by synthesized control, including on-line computation of the complete model of manipulator dynamics. This computation does not take into account practical application for complex, dynamic models of real manipulators. Compensation for manipulation system nonlinearity by on-line calculation of the complete manipulator dynamics model has also been proposed by Saridis and Lee (1979). They have proposed an algorithm that approximate the optimal choice of gains for the linear part of the system. A similar approach to the realization of trajectories in the supervisory control of manipulators has been proposed by Kulakov (1976, 1977). Based on the complete model of manipulator dynamics and on examination of Liapunov system stability, Kulakov has synthesized a nonlinear and complex control, the implementation of which demands the application of powerful processors for more complex manipulator configurations.

3.1.2. Linearized Models

The conventional procedure for the synthesis of control of complex nonlinear systems, a procedure that is based on linearized models, has also been used in the synthesis of manipulator control. By linearizing the complete dynamic manipulator model around trajectories, Popov and associates (1974) synthesized the linear, centralized regulator, minimizing the standard quadratic criterion. However, it should be kept in mind that the implementation of a linear regulator in a manipulation system leads to numerous problems, since the complex control has been synthesized based on the approximate linear model. The approach pursued by Popov and associates requires complex implementation at the lowest control level; hence, it has been less useful in practice than the conventional solution obtained via local servosystems.

3.1.3. Local Servosystems

Medvedov, Leskov, and Yushchenko (1978) have analyzed complete system behavior when trajectories, prescribed via the tactical level, are implemented by means of local servosystems only. They used a linearized model in centralized form. The synthesis of local servosystems led to the decoupled system model, so the authors analyzed the effect of coupling among subsystems and checked total system stability by analysis in the frequency range. As in the previous case (Popov et al. 1974), the validity of the analysis is restricted by the validity of the linearized system model. There remains the problem of introducing global feedback when decentralized control cannot produce satisfactory system performance. The synthesis of a servosystem for each actuator of the manipulator has also been considered, in which dynamic model of the manipulator takes into account dry friction, backlash and elastic deformations (Filaretov 1976).

3.1.4. Decoupling

It has been shown that the assumption that it is possible to stabilize manipulation system solely by means of local control is not applicable for (1) tasks requiring extremely fast movements or (2) manipulators with strong coupling among degrees of freedom (Vukobratović and Stokić 1980). In order to compensate for the *coupling effect* among subsystems, cross-feedback loops were introduced among subsystems based on the linear manipulator model (Yuan 1978). However, the proposed synthesis of a compensator for decoupling the system into subsystems is easily implemented only in simple manipulation systems, and its justification is restricted by the validity of the linearized system model in a broader zone of the state space.

A nonlinear control law and arbitrary placing of poles was proposed by Freund (1977). However, only simple manipulator configurations with three degrees of freedom were considered, and moments of inertia were neglected. Application of such nonlinear control to complex configurations leads to complex control laws. Roessler (1980) has decoupled the manipulation system by introducing global feedback implemented on the basis of on-line calculation of the complete nonlinear model of coupling among subsystems. The behavior of the complete system when local control is applied has not been analyzed, however, and the realistic requirements or possibilities for the introduction of the complex calculation of global control have not been considered. (This represents a serious problem in cases of complex manipulator configurations.)

An attractive idea for achieving the decoupling of manipulation systems via *global force-feedback* (feedback with respect to load, measured in each manipulator joint) has been published for the first time (Vukobratović and Stepanenko 1972; Vukobratović 1973) for the case of biped locomotion and further developed (Stokić and Vukobratović 1979; Vukobratović and Stokić 1982*c*; 1982*d*) for the case of manipulation robots. This idea has been studied further by Hewit and Burdess (1981), who introduced accelerometers that yield information about accelerations in manipulator joints. The inertial system matrix is calculated on-line in order to obtain information about gravitational, Coriolis, and frictional forces, making the control law unnecessarily complicated. Neither the stability of the nonlinear system nor the suboptimality of the chosen control have been considered. It should be mentioned that several attempts have been made to stabilize manipulation systems by nonlinear control laws, but these results are difficult to apply because they result in unsatisfactory system performance (Young 1978).

4. Decentralized, Completely Dynamic Control of Robotic Systems

From the short overview of the synthesis of robotic systems control in Section 3.1, it can be concluded that the problem of dynamic control of such systems has not been adequately solved. This problem can be reduced to the questions, Can we use the information about system dynamics for the synthesis and implementation of robotic systems control algorithms? and If so, to what extent can we use it? A partial answer to these questions is found in a two-stage approach to dynamic control of complex mechanical systems (Vukobratović and Stokić 1981; 1982*c*). The two-stage approach is a logical one because for the majority of robotic systems, especially industrial manipulators, the working conditions are known in advance.

4.1. First Stage of Control Synthesis

The first stage of control synthesis consists of synthesizing nominal programmed control and implementing the desired system motion for some chosen initial state. This is carried out with the assumption that the perturbations are not acting on the system and that the initial state matches the supposed nominal initial state ideally. Synthesis of nominal programmed control is performed by (1) defining in advance (and off-line) the robot's trajectory, so that it satisfies its functional requirements and by (2) calculating the corresponding programmed control for the complete system. It should be said here that calculating dynamics on-line is not necessary in industrial robotics today. In nonindustrial robotics, both trajectory planning and the synthesis of corresponding control must be done on-line. For that reason, it is useful to have procedures for on-line calculation of the nominal driving forces (nominal dynamics) (Luh, Walker, and Paul 1980; Cvetković and Vukobratović 1982). Surely it is possible to implement algorithms for on-line computation of dynamics that are oriented in their actuator parts primarily to some particular configurations and to the application of parallel processing using microcomputers (Vukobratović and Stokić 1982*b*). Otherwise, for the tasks of today's industrial robots, which are performed in conditions known in advance, a general-purpose computer could be used for off-line preparation and planning of trajectories for several manipulators, while the control algorithms could be implemented by microcomputers associated with each manipulator.

4.2. Second Stage of Control Synthesis

The second stage of control synthesis consists of synthesizing control for the tracking of nominal trajectories when the actual initial state deviates from the nominal initial state (but belongs within a bounded region of initial states). In the first stage, control synthesis (based on the complete centralized model) is performed; in the second stage, an approximate system model is used, in the form of a set of decoupled systems (decoupled meaning free from coupling in the perturbed working regime). Each subsystem corresponds to one mechanical degree of freedom, and its actuator (if the degree of freedom is powered). On the basis of such a decoupled system the stabilization of local subsystems is achieved. After that, the behavior of the complete system is analyzed to ascertain whether practical system stability is satisfied and to what extent the synthesized control is suboptimal (Vukobratović and Stokić 1982*c*).

As practical system stability in a bounded region of the state space is in question, the introduction of programmed control in the first stage of control synthesis diminishes the coupling effects among subsystems. Hence it is clear why it is possible to apply decentralized control in the second stage of synthesis, even in the case of dynamic tasks, which are most often unsatisfactorily performed if programmed control is not introduced. It is also clear why the decoupled system model is a better approximation of the complete system model when deviation from the nominal (programmed) regime is considered than when no nominal (programmed) control is adopted. The significance of sufficiently correct mathematical models of system dynamics is evident: on the basis of such models, open-loop control can be synthesized (i.e., such control signals can be determined that take into account the complete system dynamics in conditions of ideal, unperturbed regimes). In connection with this fact, a set of questions arises relating to the degree of model accuracy, the degree of the model's fidelity to complete system dynamics, and the degree to which an approximately accurate model can offer correct information about system dynamics. These questions are of special interest when, instead of off-line calculations of open-loop control on the centralized model, an implementation of mathematical models of various complexity is performed on microcomputers to produce control signals in an on-line regime.

4.3. Global-Feedback Loops

In spite of the reduced coupling effect among subsystems achieved by means of programmed (nominal) control synthesis, for some tasks or regimes the compensation for dynamic coupling achieved in the first stage of programmed control synthesis is not sufficient. In such cases, it is necessary to supplement the decentralized control structure by introducing the global-feedback loop with respect to load, that is, with respect to the dynamic coupling among subsystems. The problem was to introduce *load feedback*, which should ensure desired system behavior without making control too complex. This was achieved by taking advantage of a mechanism especially suited to robotic systems: the measurement of direct force and torque in the driving mechanism joints.

The introduction of global control in the form of force-feedback loops has two major advantages. First, it can minimize the destabilizing effect of coupling on the complete system (Vukobratović and Stokić 1982*a*; 1982*c*; in press), and, at the same time, minimize the suboptimality of applied decentralized control.

The second way of introducing global feedback consists of on-line calculation of force (load) acting on the individual degrees of freedom. This calculation of loads over the individual degrees of freedom can be performed on the basis of exact mathematical models. As a rule, such calculation requires computer backup, a requirement that can make justification of the second way of global-feedback introduction questionable. Dynamic coupling can, however, be presented adequately by approximate mathematical models of system dynamics. The "portion" of system dynamics that should be used in the calculation of dynamic coupling in order to establish a feedback loop with respect to load must be determined with respect to the robot's mechanism configuration and its working regime. Recent experience with the synthesis of global control indicates that effective compensation for dynamic coupling can be achieved based only on the gravity terms, which, in the model, are dominant in a broad range of robotic system velocities (Cvetković and Vukobratović 1982; Vukobratović and Stokić 1982*c*).

4.4. Summary

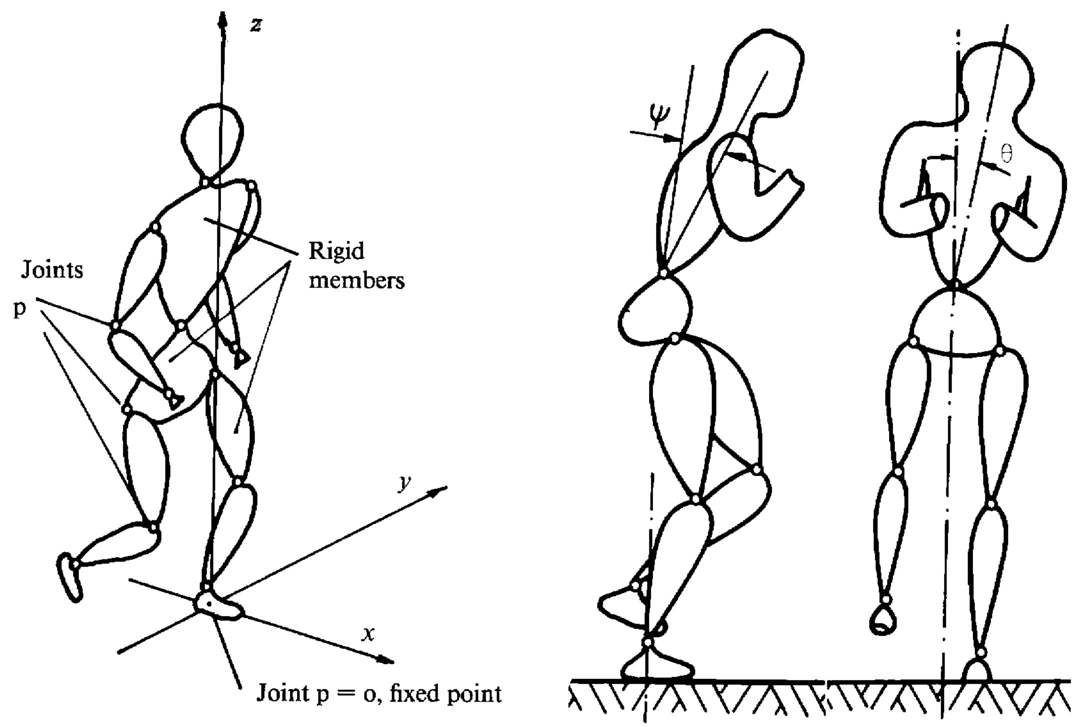
We have seen how the level of robotic system control can be implemented by executive local control at the level of individual subsystems and global control synthesized on the basis of complete system dynamics. Control synthesis at the executive level can be carried out whether or not programmed control based on the complete, centralized system model has been introduced at the tactical level. If programmed control has not been introduced, the need for global control becomes more evident because, in the absence of programmed control, control synthesis would be deprived of the effects of dynamic system parameters.

Two-stage control synthesis is suboptimal. Its chief advantages are that

1. Control synthesized does not minimize some criteria, but it satisfies practical requirements for stability.
2. Control of arbitrarily chosen, ititial nominal conditions is synthesized first.
3. Control that ensures the tracking of the nominal state (on the basis of the deviation model from the nominal state) is synthesized second.
4. The synthesis of nominal control is not an optimal synthesis.

Optimal control has not been synthesized at the level of deviation from the nominal regime either; rather, simple control synthesis has been carried out in a simple procedure. Engineering experience in system design has ensured satisfactory robotic performance. The proposed two-stage procedure, the synthesis of decentralized control using the decoupled system model, and the eventual reduction of suboptimality by the introduction of global control represent a compromise between the demands for "optimality" and those for a simple, suitable and reliable control system.

Fig. 1. Mechanical model of biped system.



5. Examples

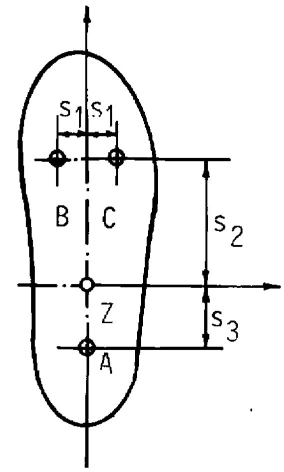
The examples that follow were designed to evaluate the significance of and the needs for dynamic control and the suitability of the two-stage control synthesis procedure for tasks of applied robotics.

5.1. Example 1: Biped Posture Control

One of the most difficult tasks in robotics in the broader sense is to maintain biped gait stability (dynamic equilibrium) (Vukobratović 1976). In the case of biped anthropomorphic systems (Fig. 1), contact with the environment is realized via forces F_l acting on the feet (Fig. 2). The control task imposed is to transfer the system S from one point in the state space to another in finite time τ. By means of one of the procedures, the system's nominal trajectories are determined (Vukobratović and Stepanenko 1972; Vukobratović 1976; Vukobratović and Stokić 1982*c*), and the task of equilibrium maintenance with respect to the absolute system is solved (i.e., the control that keeps the system in equilibrium is determined). As the biped gait system possesses unpowered degrees of freedom ($m < n$), the problem of how to stabilize these degrees of freedom with the other, powered (directly controlled) degrees of freedom arises. The dynamic connections between the powered and unpowered degrees of freedom must be determined. The forces F_l between the ground and feet (of the robot mechanism) are dynamic. Therefore, the need to stabilize the unpowered degrees of freedom via dynamic connections with other, powered degrees of freedom can be transformed into dynamic conditions in which the resultant forces (acting on the feet in contact with the support) are maintained in the desired position. As mentioned in Section 2, the point on which the resultant force of the support is acting is called the zero-moment point, or ZMP.

Hence the condition for maintaining the prescribed trajectory of ZMP can be reduced to maintaining

Fig. 2. *Measurement of reaction forces.*



dynamic equilibrium during gait[1], that is,

$$M_x = 0, M_y = 0, \tag{8}$$

where M_x, M_y are the projections of all moments of inertial and gravitational forces of the mechanism about ZMP onto coordinate axes. From the condition of (Eq. 8), which ensures dynamic equilibrium (for prescribed leg trajectories), the compensating body movements can be calculated.

$$\begin{aligned} M_x &= \tilde{M}_x{}^{11}(\mathbf{q})\ddot{\psi} + \tilde{M}_x{}^{12}(\mathbf{q})\ddot{\theta} + \tilde{M}_x{}^{1}(\mathbf{q})\ddot{\tilde{q}} + \bar{M}_x(\mathbf{q}, \dot{\mathbf{q}}) = 0 \\ M_y &= \tilde{M}_y{}^{21}(\ddot{\mathbf{q}})\ddot{\psi} + \tilde{M}_y{}^{22}(\mathbf{q})\ddot{\theta} + \tilde{M}_y{}^{2}(\mathbf{q})\ddot{\tilde{q}} + \bar{M}_y(\mathbf{q}, \dot{\mathbf{q}}) = 0, \end{aligned} \tag{9}$$

where ψ, θ are body angles (Fig. 1); $\tilde{q}$ are the angles of the legs; and $\mathbf{q} = (\tilde{q}, \psi, \theta)^T$. From (Eq. 8), when $\tilde{q}^0(t)$, $\ddot{\tilde{q}}^0(t)$ are prescribed, the compensating movements $\psi^0(t)$ and $\theta^0(t)$ can be calculated. In that way, the nominal trajectories $x^0(t)$ and the corresponding nominal (programmed) control $\mathbf{u}^0(t)$ can be calculated, which ensures system transfer from initial to terminal region of allowable system states. However, calculating $\psi^0(t)$ and $\theta^0(t)$ from (Eq. 9) requires considerable time or powerful computers, so it is performed off-line.

Local control $\Delta\mathbf{u}^i_{loc}$ and global control $\Delta\mathbf{u}_{G1}{}^i$ ensure the tracking of prescribed (calculated) trajectories in perturbed conditions, for the degrees of freedom with corresponding individual actuators. However, as there exist degrees of freedom between the feet and the ground, maintainenance of mechanism orientation in perturbed conditions with respect to the absolute system is not ensured. In this case it is necessary to introduce force feedback in the contact of the foot with the ground to maintain the ZMP in the desired instantaneous position; specifically, it is necessary to introduce global control $\Delta\mathbf{u}_{G2}{}^i(F_l)$. For this purpose, force transducers are introduced in the feet (Fig. 2), by means of which forces are measured and the deviation of the ZMP from the desired position is calculated, enabling the introduction of the correcting control

$$\begin{gathered} \Delta u_{G2}{}^{\psi} = K^{\psi}M_y = K^{\psi}[S_3F_3 - S_2(F_1 + F_2)] \\ \Delta u_{G2}{}^{\theta} = k^{\theta}M_x = k^{\theta}S_1(F_1 - F_2) \\ S_j = S_j(t); \qquad j = 1, 2, 3, \end{gathered} \tag{10}$$

1. The third condition of moment equilibrium ($M_z = 0$) has been omitted, because it is supposed that the friction moment between the biped feet and ground is sufficient to prevent yawing during gait.

where k^{ψ}, k^{θ} are global gains; S_j are distances (Fig. 2); and $\Delta u_{G2}{}^{\psi}$ and $\Delta u_{G2}{}^{\theta}$ are global control for the trunk's degrees of freedom when perturbations act on the system. Thus, by introducing global force feedback in the feet, it is possible to realize the tracking of prescribed nominal trajectories and provide the global dynamic equilibrium of the total system.

The example presented here demonstrates biped posture stabilization, which can be reduced to the previous case of biped gait, under the assumption that the positions of leg angles, instead of nominal leg trajectories, are prescribed. Thus, the task is reduced to maintaining the desired system posture by ensuring that the resultant of external (static) forces acting on the foot due to the support takes the position corresponding to the desired system posture.

A simplified biped model will be used to demonstrate the efficiency of force feedback in posture stabilization. The biped, which has two degrees of freedom, should be stabilized about its vertical position (Fig. 3). Biped parameters in the frontal plane are given in the figure. It is supposed that the biped model possesses two degrees of freedom: ξ(angular foot displacement relative to the ground) and θ(angular displacement of the trunk around the horizontal axis). Trunk motion is powered by actuator S^1, the model of which is given in (Eq. 2) and which represents a third-order electric servomotor ($n_1 = 3$). Evidently, $n = 2$ (the number of degrees of freedom), and $m = 1$ (one unpowered degree of freedom), so the total

Fig. 3. Biped model in frontal plane.

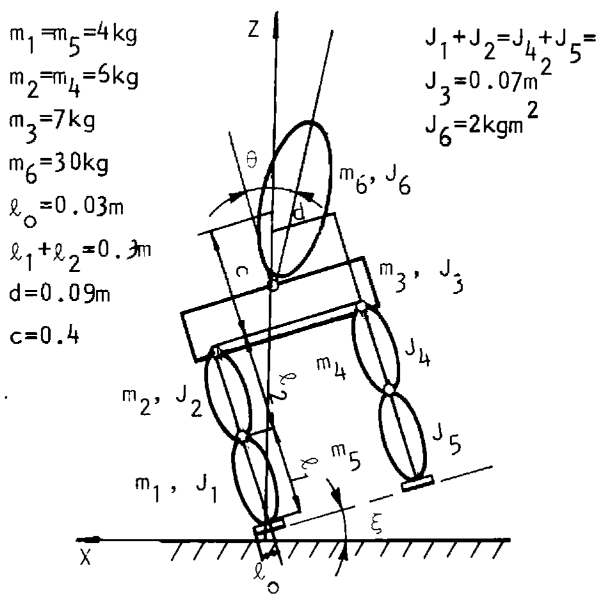
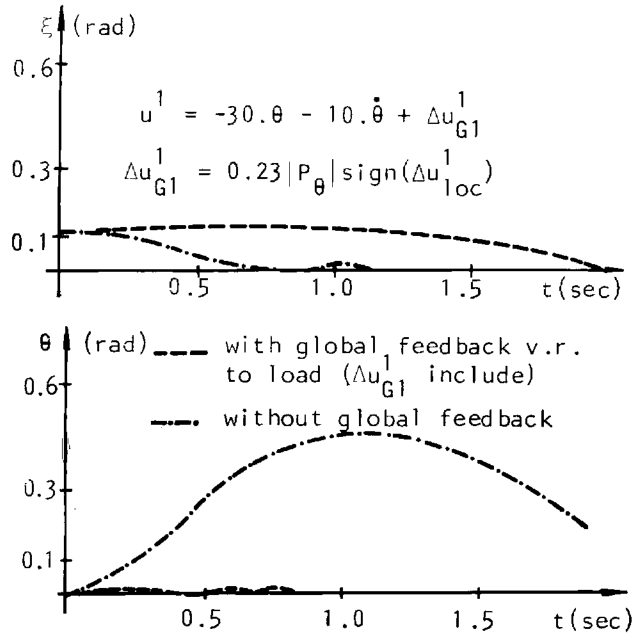


Fig. 4. Simulation results of posture control.



system order is $N = 5$, because two coordinates of vector $\mathbf{x}^1$ in (Eq. 2) coincide with θ and $\dot{\theta}$. It should be noted that for $\xi = 0$ the structure changes and that, with simultaneous support by two feet, the stability margin of the system is increased.

The level of nominal regime in this task is trivial: $\theta^0 = 0$, $\xi^0 = 0$, $\mathbf{u}^0 = \mathbf{u}_{static}$.

For the trunk degree of freedom θ, decentralized control $\Delta u^i = u^i_{loc}(\Delta x^i)$ in the form of linear feedback is applied in order to stabilize the free subsystem S^1:

$$\Delta u^1_{loc}(x^1) = -30\Delta\theta - 10\Delta\dot{\theta}. \tag{11}$$

Feedback gains correspond to the placing of the free subsystem's poles in the left half of complex plane with $|\sigma| > 2.5$. The unpowered degree of freedom is not stabilized by means of (Eq. 11). However, due to foot surface, there is a bounded region in the state space in which this degree of freedom returns to the point $\xi = 0$, $\dot{\xi} = 0$ (when $\theta = 0$ and $\dot{\theta} = 0$). Thus, the complete system is stable for the initial states belonging to the bounded region in the state space. This conclusion can be confirmed by simulation. Simulation results for initial conditions $\xi = 0.11$ rad, $\dot{\xi} = 0$, $\theta = 0$, $\dot{\theta} = 0$, and with control (Eq. 11) are shown in Fig. 4. However, the influence of coupling P_θ on subsystem S^1 is strong (see Fig. 4) and causes significant changes in θ. In order to diminish the influence of coupling S^1, global control $\Delta u_{G1}{}^i(P_i)$ with respect to moment P_θ can be introduced in the form:

$$u_{G1}{}^1(P_\theta) = 0.23|P_\theta| sgn(\Delta u^1_{loc}) = 0.23|P_\theta| \begin{cases} +1 & \text{for} \quad \Delta u^1_{loc} > 0 \\ -1 & \text{for} \quad \Delta u^1_{loc} < 0 \end{cases}. \tag{12}$$

Global control has been synthesized from the condition of minimizing the coupling influence on subsystem S^1 (Vukobratović and Stokić 1982*c*). Simulation results (Fig. 4) illustrate the efficiency of global feedback.

It can be shown, however, that for $\xi > 0.12$ rad and $\dot{\xi} \geqslant 0$, the system becomes unstable for control $\Delta u^i = \Delta u^i_{loc}(\Delta x^i)$, (Eq. 11), control $\Delta u^i = \Delta u^i_{loc}(\Delta x^i) + \Delta u_{G1}{}^i(P_i)$, and (Eq. 12). (See the simulation results of the system for $\xi(0) = 0.15$ rad, $\dot{\xi}(0) = 0$, $\theta(0) = 0$, and $\dot{\theta}(0) = 0$ with [Eq. 11] and for [Eq. 12] in Fig. 5.) In this case it is necessary to introduce control of type

$$\Delta u^i = \Delta u^i_{loc}(\Delta x^i) + \Delta u_{G1}{}^i(P_i) + \Delta u_{G2}{}^i(x, F_l),$$

Fig. 5. *Simulation results of posture control.*

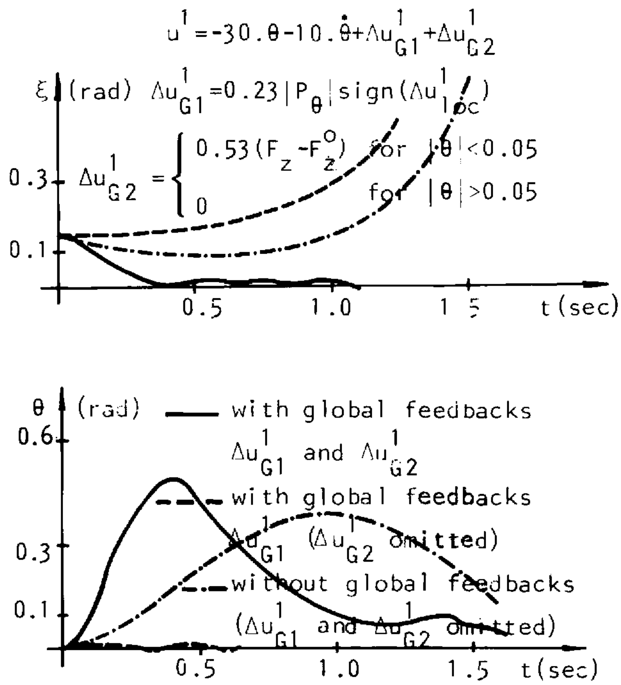
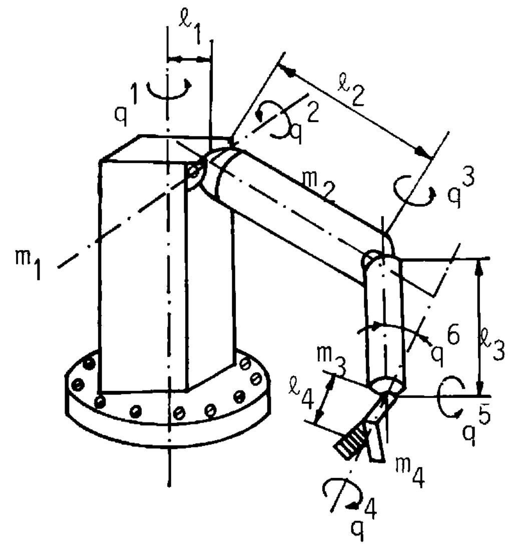


Fig. 6. *Anthropomorphic manipulator with six degrees of freedom.*



Manipulator data

Members	1	2	3	4
Mass (kg)m_i	0	4.7	6.	6.
Length (m)l_i	0.135	0.33	0.35	0.15
$J_{ix}(10^{-2}\text{kgm}^2)$	—	0.11	0.18	0.18
$J_{iy}(10^{-2}\text{kgm}^2)$	—	0.22	0.36	0.24
$J_{iz}(10^{-2}\text{kgm}^2)$	0.92	0.22	0.36	0.24

where F_l, $l = 1, \ldots, j$ is the reaction-force component, measured by transducers and arranged on the lower side of the mechanism feet. In this case, which is analogous to the case of feedback introduced with respect to reaction forces in (Eq. 10), feedback was introduced in the following form[2]:

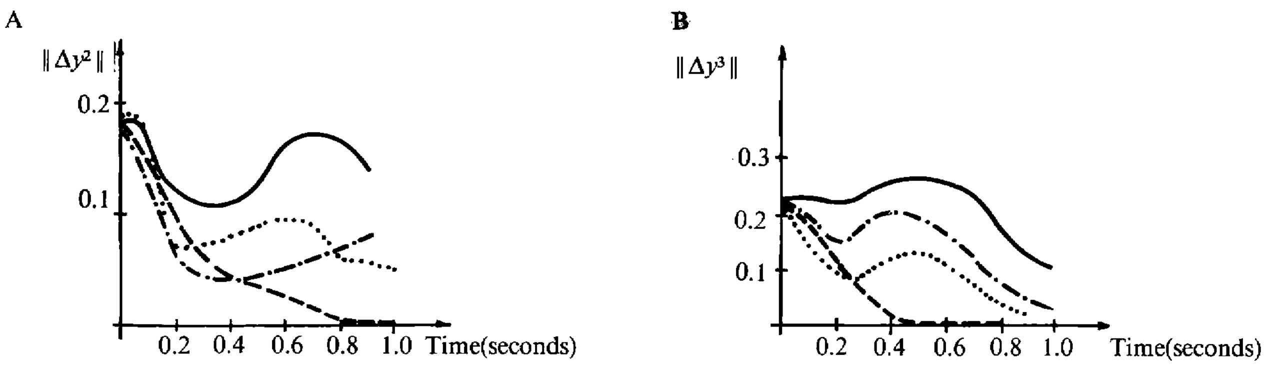
$$\Delta u_{G2}{}^1 = \begin{cases} 0.53(F_l - F_l^0) & \text{for } |\theta| < 0.05 \\ 0 & \text{for } |\theta| > 0.05 \end{cases}. \qquad (13)$$

This global control realizes the compensating motion of the trunk, which returns the ZMP to its position of static equilibrium. As the system is stable for initial conditions $\xi(0) = 0.15$ rad, $\dot{\xi}(0) = 0$, $\theta(0) = 0$, and $\dot{\theta}(0) = 0$, it is evident that it will be stable for all $\xi(0) < 0.15$ rad. This example demonstrates the efficiency of both forms of force feedback (Eqs. 12 and 13).

2. Global gains in (Eqs. 12 and 13) were chosen to be the minimal gains that guarantee practical stability of system S.

In the remaining examples, the authors will demonstrate the indispensability of complete dynamic control. In order to determine (1) whether it is necessary to introduce dynamic control for manipulation tasks and (2) how much of dynamic information should be used in dynamic control of manipulation robots, three different manipulator configurations will be presented. They include the anthropomorphic configuration, in which maximal dynamic coupling is inherent among the subsystems; the semianthropomorphic mechanism; and the so-called cylindrical scheme of the manipulation robot, in which, by definition, strong decoupling exists among subsystems (degrees of freedom) in the dynamic sense.

Fig. 7. Trajectory tracking for joints two and three different control laws. A. Joint two. B. Joint three.



—— $u^i = -50\Delta q^i - 2\Delta \dot{q}^i$, $i - 1, 2, \ldots, 6$
-·-·- $u^i = u^{0i}(t) - 50\Delta q^i - 2\Delta \dot{q}^i$, $i = 1, 2, \ldots, 6$
····· $u^i = -130\Delta q^i - 3\Delta \dot{q}^i$, $i = 1, 2, \ldots, 6$
----- $u^i = -50\Delta q^i - 2\Delta \dot{q}^i - 0.232|P_i|\mathrm{sgn}(\Delta u_i^L)$, for $i = 1, 2, 3$ $u^i = u^{0i}(t) - 50\Delta q^i - 2\Delta \dot{q}^i$, for $i = 4, 5, 6$

5.2. Example 2: Control of An Anthropomorphic Manipulator

In Fig. 6, a manipulation system with six degrees of freedom is shown. All six degrees of freedom are powered by dc servomotors with models S^i in the form of (Eq. 2) ($n_i = 3$, $x^i = (q^i, \dot{q}^i, i_R^i)$; for $i = 1, 2, \ldots, 6$, i_R^i is the rotor current $m = 6$, $N = 18$). Actuator models are linear and stationary. Decentralized control $\Delta u^i = \Delta u^i_{loc}(\Delta x^i)$, $i = 1, 2, \ldots, 6$ is adopted in the form of incomplete linear feedback, because subsystems S^i are linear and stationary. Actually,

$$\Delta u^i_{loc}(t) = -50(q^i(t) - q^{i0}(t)) - 2(\dot{q}^i(t) - \dot{q}^{i0}(t)). \quad (14)$$

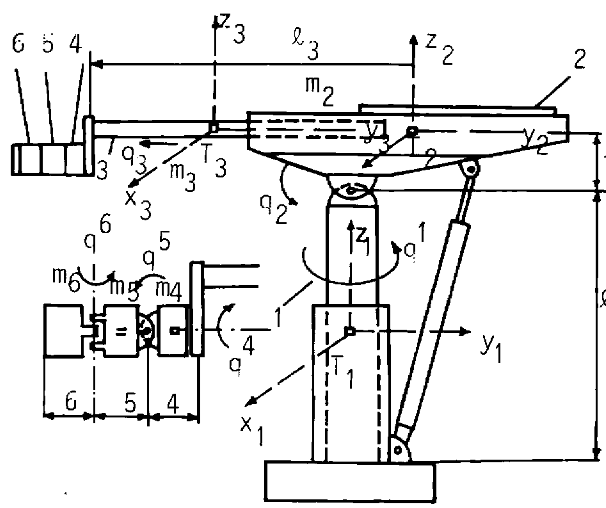
Gains were chosen from the conditions requiring subsystem poles to be in the left half of the complex plane for $|\sigma| \geqslant 7.7$. Digital simulation of nominal trajectory $x^0(t)$ tracking was performed for initial conditions: $\Delta \mathbf{g}(_0{}^0) = \mathbf{q}(_0{}^0) - \mathbf{q}^0(_0{}^0) = (-0, 26, 0, 18, -0, 22, 0, 26, -0, 26, 0, 26)^T$[rad], $\Delta\dot{\mathbf{q}}(_0{}^0) = 0$, $\Delta i_R{}^i(_0{}^0) = 0$, for $i = 1, 2, \ldots, 6$. Figure 7 shows the results of nominal trajectory tracking of the most heavily loaded manipulator joints (two and three). For the sake of estimating the "intensity" of dynamic control, tracking has been performed for three different control laws, whereby one control version has been shown with various feedback gains. In the figure, $\|\Delta y^i\| = [(\Delta q^i)^2 + 0.1(\Delta \dot{q}^i)^2]^{1/2}$. It can be seen that control (Eq. 14) is not adequate because of the strong influence among subsystems. Hence it is necessary to include global control $\Delta u_{G1}{}^i(t)$ in the form of load (torque) feedback P_i, acting in the form of coupling among subsystems S^i. In this case global control was introduced in the form $\Delta u_{G1}{}^i(t) = 0, 232\ \mathrm{sgn}\ (\Delta u^i_{loc}(t))|P_i|$ for the first three degrees of freedom $S^i(i = 1, 2, 3)$, while for subsystems corresponding to the gripper's degrees of freedom, this global feedback is unnecessary. Global gain was chosen from the condition that the influence of subsystem coupling (Vulcobratović and Stokić 1982*c*) be minimized. It is also evident that, by increasing the gains, decentralized control without global feedback also gives satisfactory results. However, it should be mentioned that, due to the increase in gains, the energy balance becomes worse, and more powerful actuators have to be implemented. The need for complete dynamic control becomes more serious in cases of "heavier" manipulators that perform with heavier loads and manipulator tip velocities higher than 1 m/5[3].

5.3 Example 3: Control of a Semianthropomorphic Manipulator

The mechanical configuration of a semianthropomorphic manipulator is presented in Fig. 8. The manipu-

3. In the considered example maximal velocity of manipulator tip was 0.7 m/s.

Fig. 8. Semianthropomorphic manipulator with six degrees of freedom.



Manipulator data

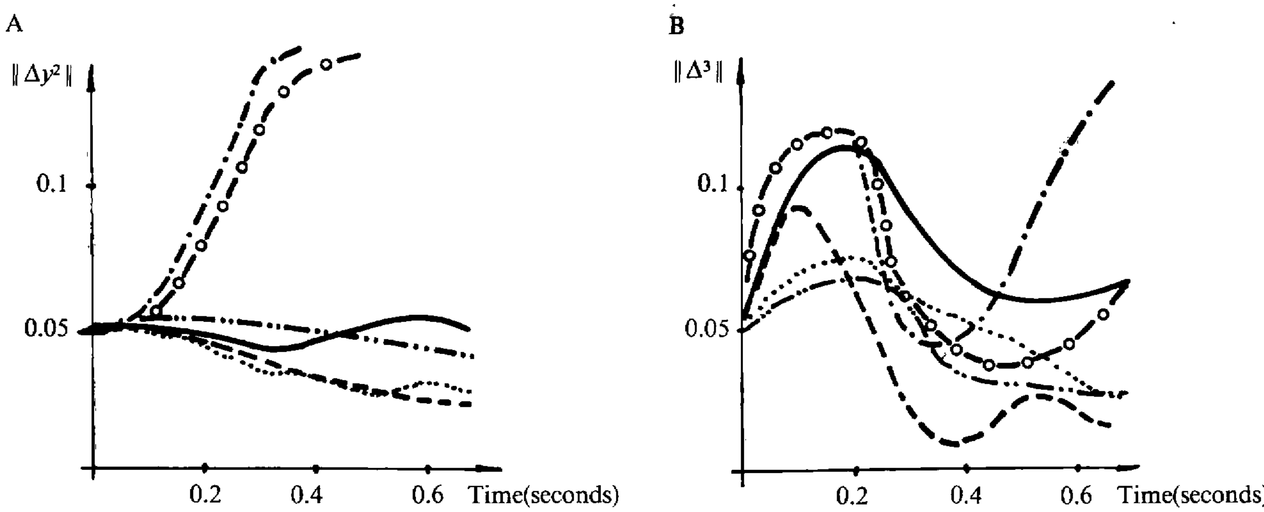
Members	1	2	3	4,5	6
Mass m_i (kg)	—	27.8	22.34	2.33	3.33
Length l_i (m)	1.2	0.142	1.14	0.14	0.26
J_{ix}(kgm^2)	0	2.98	1.21	0.004	.007
J_{iy}(kgm^2)	0	—	—	.004	.009
J_{iz}(kgm^2)	0.322	3.701	1.21	.004	.009

lator actuators are electrohydraulic. Servovalves (MOOG series 77-100) were used. Their frequency range is sufficiently broad so that, practically, their dynamics do not influence complete system behavior. Because of this, the hydraulic actuators were described by linear, third-order models ($n_i = 3$). The state vector of the hydraulic actuator model was taken as $x^i = (l^i, \dot{l}^i, p^i)$, where l^i is the piston stroke, $\dot{l}^i$ is the piston velocity; and p^i is the oil pressure in the cylinder (pressure difference). The stabilization of subsystems was performed in this case, as in example 2a by incomplete local-feedback loops. In contrast to example 2, only positional local feedbacks are introduced here (i.e., it is supposed that subsystem outputs are given by $y^i = l^i$ or $y^i = q^i$). First, for the subsystems S^i, the hydraulic actuators, local-feedback gains were chosen so as to achieve subsystem stability (i.e., with the poles of free subsystems as $\sigma < -5.0$). The gains were $k_1 = k_2 = k_3 = 90$[mA/m], $k_4 = k_5 = k_6 = 37$[mA/rad]. The degree of exponential stability was chosen so as to obtain certain zones of practical stability, which will not be discussed here. As earlier, when the deviation norm in the tracking of nominal trajectories was in question, it was assumed that the velocity deviation enters the norm with the coefficient 0.1. System stability analysis and simulation (Fig. 9) show that the system is not practically stable when only the nominal and local control with previously stated gains are applied (although the exponential degree of stability of local subsystems is 5). Hence it is necessary to introduce global control in the form of feedback loops with respect to coupling. By the analysis of complete system stability (Vukobratović and Stokić 1982*c*), global gains were chosen as $K_i^G = 0.12$[mA/N·m] for i = 1, 2, 4, 5, 6 and $K_3^G = 0.22$[mA/N]. By means of global control introduced in this way, system stabilization was achieved.

The second way to achieve system stabilization is, of course, to choose the local gains again, so that the required exponential degree of local subsystems stability is increased. If the degree of exponential stability is chosen to be 10, local gains are obtained as $k_1 = k_2 = k_3 = 179$, $k_4 = k_5 = k_6 = 73.5$, and it is proven that the system is practically stable only with nominal (programmed) and local control.

Tracking of nominal trajectories was simulated for all three mentioned control forms. Partial simulation results are presented in Fig. 9. In this case also, tracking was presented for the most heavily loaded degrees of freedom (two and three). Simulation was performed for the initial conditions: $\Delta l^1(0) = 0$; $\Delta l^2(0) = 0.05$; $\Delta l^3(0) = -0.05$[m]; $\Delta q^4(0) = \Delta q^5(0) = \Delta q^6(0) = 0.1$[rad]; $\Delta\dot{l}^i(0) = 0$; i = 1, 2, 3; $\Delta\dot{q}^i(0) = 0$; $i = 4, 5, 6$; $\Delta p^i(0) = 0$. In Fig. 9, the simulation results of tracking for three additional control forms are presented. In order to demonstrate the most usual situation (in which the desired trajectories are realized by only local control), the tracking of nominal trajectories with local control only was simulated, with the degree of exponential stability of subsystems 10. Simulation also included tracking with local and programmed control, synthesized at the subsystem level (inexact programmed control) u^{-i0}. Finally, control

Fig. 9. Trajectory tracking for joints two and three with different control laws. A. Joint two. B. Joint three.



—o—o— $u^i = \bar{u}^{i0} - 179\Delta l^i$, $i = 1, 2, 3$
$u^i = \bar{u}^{i0} - 73,5\Delta q^i$, $i = 4, 5, 6$

-·-·- $u^i = \bar{u}^{i0} + \Delta u_i^L + \Delta u_i^G$

····· = -·-·

—— $u^i = u^{i0}(t) - 90\Delta l^i$, $i = 1, 2, 3$
$u^i = u^{i0}(t) - 37\Delta q^i$, $i = 4, 5, 6$

----- $u^i = u^{i0}(t) - 90\Delta l^i + \Delta u_i^G$, $i = 1, 2, 3$
$u^i = u^{i0}(t) - 37\Delta q^i + \Delta u_i^G$, $i = 4, 5, 6$

····· $u^i = u^{i0}(t) - 179\Delta l^i$, $i = 1, 2, 3$
$u^i = u^{i0}(t) - 73.5\Delta q^i$, $i = 4, 5, 6$

-·-·- $u^i = -179\Delta l^i$ $i = 1, 2, 3$
$u^i = -73.5\Delta q^i$ $i = 4, 5, 6$

was simulated that differed from the last control case in that global control with the above-stated global gains was introduced. The simulation indicates to what extent the tracking of nominal trajectories can be improved by augmenting global control, which takes care of the complete dynamics of the mechanical part of the system. It should be noted that in such a semianthropomorphic manipulator configuration, the system can also be stabilized by means of decentralized control, along with centralized (programmed) control without global control. However, it is important to note the essential role of global control, which in practice compensates completely for "inexact" programmed control (programmed control synthesized on the decentralized model of the manipulation mechanism).

That in this case global control (or complete dynamic control) is not crucial is best illustrated by the simulation of tracking shown in Fig. 10, which demonstrates slight tracking improvement when global feedback is switched on. As can be seen, programmed control based on the centralized model of the dynamics model of mechanical robot configuration is hereby ensured. Finally, it should be noted that in this example the lower velocity of manipulator tip motion of about 0.4 m/s has been adopted.

5.4. Example 4: Control of Cylindrical Manipulation Robot Configuration

Cylindrical manipulator configuration is illustrated in Fig. 11. In this type of system, coupling among the degrees of freedom is less expressed, so the application of decentralized control is significantly facilitated and programmed, centralized control is mainly unnecessary. This holds particularly true for global control, which is practically useless. For this example, the following parameter values were selected:

$$\sigma_i < -5.5 \text{ and } k_1 = (53.4, 21.4)^T[\text{V/rad, V/rad/s}]$$
$$k_2 = (226, 7.59)^T[\text{V/rad, V/m/s}]$$
$$k_3 = (291, 9.77)^T[\text{V/m, V/m/s}]$$
$$\mathbf{k}_{4,5,6} = (34.3, 1)^T[\text{V/rad, V/rad/s}].$$

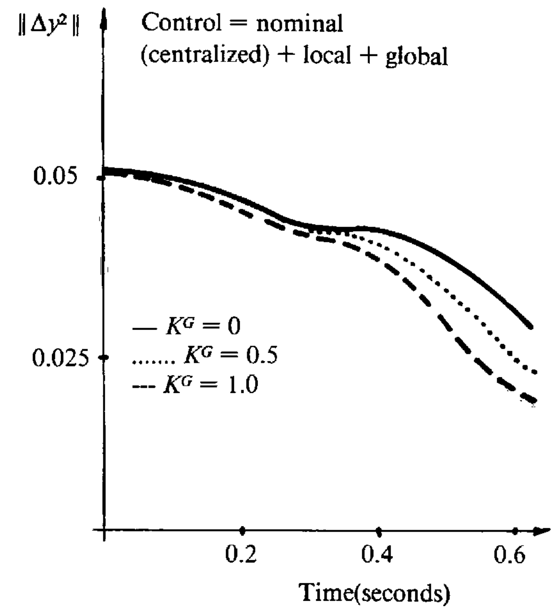


Fig. 10. Trajectory tracking for joint two with different gains of global feedback.

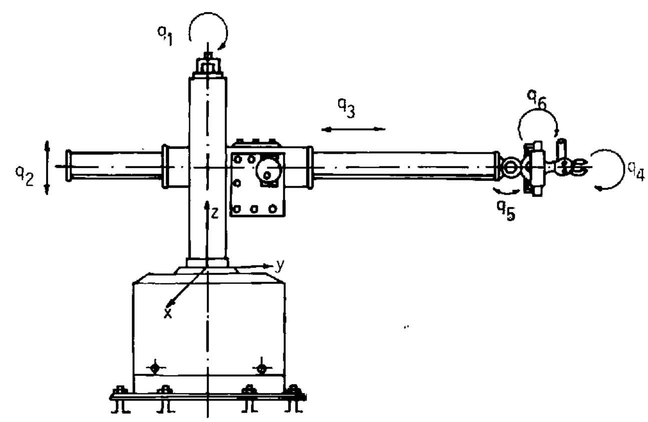


Fig. 11. Cylindrical manipulator with six degrees of freedom.

Manipulator data

Members	1	2	3	4.5.6
Mass (kg)	10.0	7.0	4.15	0.5
Length (m)	0.38	0.02	0.45	0.05
J_{xi}(kgm²)	—	—	—	0.001
J_{yi}(kgm²)	—	—	—	0.001
J_{zi}(kgm²)	0.029	0.055	0.318	0.0015

In order to examine the significance of global control for this manipulator type, global control Δu_i^G with respect to ΔP_i was introduced. The following global gains were chosen: $K_i^G = 0.906$[V/N·m], $k_2^G = 0.012$[V/N], $K_3^G = 0.054$[V/N], $k_{4,5,6}^G = 0.232$ [V/N·m]. Simulation of system behavior with different control forms was carried out for the following initial conditions:

$$\Delta\mathbf{q}(0) = (0.26, -0.01, 0.01, 0.26, 0.25, 0)^T,$$
$$\Delta\dot{\mathbf{q}}^i(0) = (0),\ \Delta i_R^i(0) = 0,\ i = 1, 2, \ldots, 6.$$

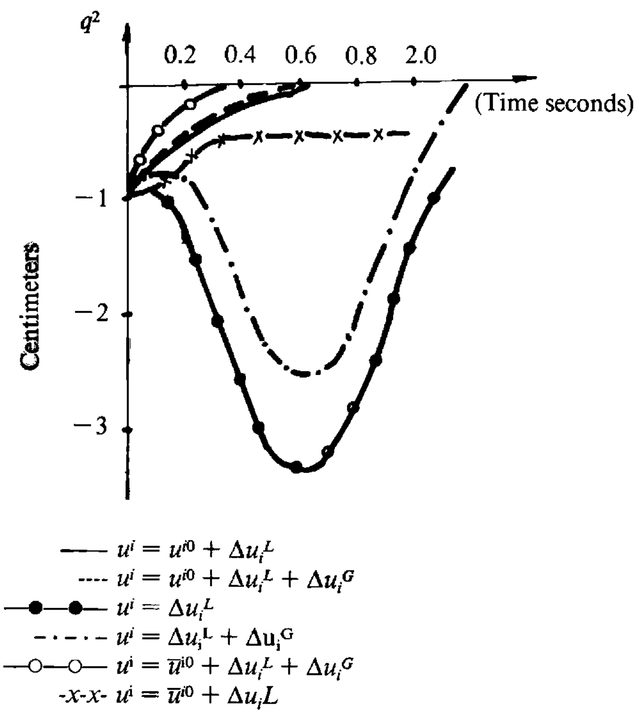
Figure 12 illustrates simulation of tracking for the most loaded degree of freedom, q_2. Manipulator tip velocity in this simulationm was approx. 0.7 m/s.

6. Conclusion

This paper was aimed at illustrating one class of dynamic tasks and dealing with the problem of dynamic control. Let us start with the postulate that robotic systems should not necessarily be controlled on the basis of complete dynamic models. From such a hypothetical statement we must exclude the tasks of locomotion system stabilization, particularly the tasks of locomotion systems in which the resultant force does not pass through the support polygon (case of biped gait) without adjustment, and in which directly uncontrollable (unpowered) degrees of freedom between the foot (feet) and the support (ground) can appear during motion.

The supposition that dynamic control is unnecessary with, for instance, manipulation robots, is incorrect; it is partly based on the fact that the industrial robots already in use do not possess dynamic control. This fact is not convincing, because the design of robotic systems, as well as that of some of the chronologically earlier complex technical systems (flying vehicles, road and track vehicles, etc.), was at the start approached without sufficient preparation. Designers were unprepared in the technological sense, and mini- and microcomputer systems were not sufficiently developed to solve even the slightly more complex dynamic

Fig. 12. Trajectory tracking for joint with two different control laws.



models that would have led to timely information about a system's future performance. The manipulator mechanisms and robotic control system designed during the seventies were based on static calculations, kinematic system models, and designers' experience. Today, there is no justification for such an approach to system design, for at least two reasons. First, the mathematical models of robotic system dynamics are now solved by digital computers, and this is already a routine job. Second, relatively long developmental phases of system design are no longer necessary or practical because new technologies and accompanying technical systems are being introduced all the time. (A good example of this is the development of robotic systems: it would be prohibitively time-consuming to collect and use designers' experiences as the sole basis for development of new designs.)

Some people might conclude that we should not talk about a priori needs for dynamic control of robotic systems because, as we have seen with characteristic types of manipulation robots, dynamic control has often proved unnecessary owing, for example, to the introduction of programmed control synthesized on the centralized model. It should be stressed, however, that this conclusion has a limited value in view of the fact that the examples in Sections 5.1–5.4, in which the tracking of nominal trajectories was simulated, were calculated for moderate manipulator velocities. Dynamic influence is strongly augmented, and the need for dynamic control is greater with higher manipulator velocities. Velocities attainable today are already 2 m/s, while angular velocities amount to 3 rad/s. It is true that the problem of higher dynamics can be resolved to a certain extent by a higher level of feedback gains, which, among other things, lead to higher demands for actuator power. But if manipulation with heavier loads is considered, the energy demands of such control laws are much greater. On the other hand, the introduction of complete or partial dynamic control requires, as we have seen, either force transducers or augmented computer capacity, depending on type of realization and degree of dynamic control.

Any decision regarding the introduction of partial or complete dynamic control should, in any case, follow a technological and economic analysis in which all the previously enumerated factors for a specific manipulation robot and a defined type of manipulation task must be considered. It can be concluded that the approach to the introduction of dynamic control must be selective and that, in the near future, augmented demands for dynamic control can be expected. Computer-aided design should resolve, for actual systems and in accordance with imposed criteria, all technological and economic dilemmas in the synthesis of mechanisms and control algorithms for robotic systems (Vukobratović and Stokić 1982*a*; 1982*b*).

References

Bejczy, A. K. 1974 (Feb.). Robot arm dynamics and control. NASA Tech. Memo. 33-669. Pasadena, Calif. Jet Propulsion Laboratory.

Cvetković V., and Vukobratović, M. 1982. Computer-oriented algorithm of variable complexity for mathematical modelling of active spatial mechanisms for application in robotics. *IEEE Trans. Syst. Man Cybern.* SMC-12(6):838–847.

Filaretov, V. F. 1976. Synthesis of nonlinear tracking systems for manipulator control with clearance, dry friction and elastic deformation. (In Russian.) *Teknicheskaya kibernetika* (6):87-95.

Freund, E. 1977. A nonlinear control concept for computer controlled manipulators. *Proc. 7th Int. Symp. Industrial Robots.* Tokyo, Japan: Japan Industrial Robot Association.

Hewit, R. J., and Burdess, J. S. 1981. Fast dynamic decoupled control for robotics, using active force control. *Mechanism Mach. Theory* 16(5):237-241.

Kulakov, F. M. 1976, 1977. Organization of supervisory control of robots manipulators. (In Russian.) *Teknitcheskaya kibernetika:* Part I, no. 5, pp. 37-46, 1976; Part II, no. 6, pp. 41-49, 1976; Part II, no. 1, pp. 51-66, 1977.

Luh, J. Y. S., Walker, M. W., and Paul, R. C. 1980. On-line computational scheme for mechanical manipulators. *Trans. ASME, J. Dyn. Syst. Measurement Contr.* 102(2):69-76.

Medvedov, V. S., Leskov, A. G., and Yuschenko, A. S. 1978. Systems of manipulation robots control. (In Russian.) *Scientific fundamentals of robotics* (series). Moscow: Nauka.

Paul, R. C. 1976. *Modelling trajectory calculation and servoing of a computer controlled arm.* (In Russian.) Moscow: Nauka.

Popov, E. P., et al. 1974. Synthesis of control system of robots using dynamic models of manipulation mechanisms. (In Russian.) *Proc. 6th IFAC Symp. Automatic Contr. in Space.* Moscow: Nauka.

Roessler, J. 1980. A decentralized hierarchical control concept for large-scale systems. *Preprint 2nd Symp. Large-Scale Syst. Theory Application,* ed. A. Titli and M. Singh. Oxford: Pergamon Press, pp. 171-180.

Saridis, N. G., and Lee, C. S. G. 1979. An approximation theory of optimal control for trainable manipulators. *IEEE Trans. Syst. Man Cybern.* SMC-9(3): 152-159.

Stokić, D., and Vukobratović, M. 1979. Simulation and control synthesis of manipulator in assembling mechanical elements. *Trans. ASME, J. Dyn. Syst. Measurement Contr.* 101(4):332-338.

Timofeyev, A. V., and Ekalo, J. V. 1976. Stability and stabilization of programmed motion of robots-manipulators. (In Russian.) *Automatika i Telemehanika* 10:148-156.

Vukobratović, M. 1973. How to control the artificial anthropomorphic systems. *IEEE Trans. Syst. Man Cybern.* SMC-3(5):497-507.

Vukobratović, M. 1976. Legged locomotion robots and anthropomorphic mechanisms. Monograph. Beograd, Yugoslavia: Mihailo Pupin Institute.

Vukobratović, M., and Potkonjak, V. 1982. Dynamics of manipulation robots: Theory and application. Monograph. Heidelberg: Springer-Verlag.

Vukobratović, M., and Stepanenko, Yu. A. 1972. On the stability of anthropomorphic systems. *Math. Biosci.* 15(3/4):223-234.

Vukobratović, M., and Stokić, D. 1981. One engineering concept of dynamic systems, manipulators. *J. Trans ASME, Dyn. Syst. Measurement Contr.* 103(2):108-118.

Vukobratović, M., and Stokić, D. 1982*a*. A procedure for interactive dynamic control synthesis of manipulators. *IEEE Trans. Syst. Man Cybern.* SMC-12(4):524-528.

Vukobratović, M., and Stokić, D. 1982*b*. (June 9-11, Paris) Computer-aided control synthesis of industrial manipulators. *Symp. Industrial Robots.* Kempston, Bedford, England: IFS.

Vukobratović, M., and Stokić, D. 1982*c*. Control of manipulation robots; theory and application. Monograph. Heidelberg: Springer-Verlag.

Vukobratović, M., and Stokić, D. 1982*d*. Dynamic control of manipulators using load-feedback. *J. Mech. Machine Theory* 17(2):107-118.

Vukobratović, M., and Stokić, D. 1980 (June 24-26, Toulouse, France). Choice of decoupled control law of large-scale mechanical systems Large-scale systems, theory and application. *Preprints of the IFAC Symp.,* ed. A. Titli and M. Singh. Oxford: Pergamon Press.

Vukobratović, M., and Stokić, D. In press. Contribution to suboptimal control of manipulation robots. Correspondence: *IEEE Trans. Automatic Contr.*

Young, K. D. 1978. Controller design for a manipulator using theory of variable structure systems *IEEE Trans. Syst. Man Cybern.* SMC-8(5):348-352.

Yuan, J. S. C. 1978. Dynamic decoupling of a remote manipulator system. *Trans. Automatic Contr.* AC-23(4):712-717.