FACTA UNIVERSITATIS
Series: **Mechanics, Automatic Control and Robotics** Vol.3, N° 11, 2001, pp. 285 - 294

MATHEMATICAL MODELING AND CONTROL OF REDUNDANT ROBOTIC MANIPULATORS USING BIOLOGICAL ANALOG

UDC 517.93+519.713:007.52(045)

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Abstract. *In this paper it is considered problem of realization new mathematical models of redundant systems as well as control using suitable biological analog. The idea was to try to imitate human behavior and this is specially convenient for tasks which are similar to those characteristic for humans (e.g., assembling in industry, different jobs at home and in health service). If we consider speed, accuracy and stability of motion then the overall performance (taking into account all three of parameters) with machines is still far behind human reaching and grasping. Human arm movements are considered to be stable, fast and accurate due to properties of muscles, musculo-skeletal structures and hierarchical control. It was observed in the execution of functional motions that certain trajectories are preferred from the infinite number of options. Such behavior of organisms can be only explained by the existence of inherent optimization laws in self-organized systems governing the acquisition of motor skills. Existence of invariant features in the execution of functional motions points out that central nervous system (CNS) uses synergy [Bernstein,1967](i.e rule(s) that can be developed by the CNS based on some principles). The control of arm movement in humans relies very much on distributed usage of different joints, and inherent optimization of muscles which are active. Analysis of multijoint coordination in humans is an important source of information for synthesis of dynamic patterns in machines. In that way, model of redundant system is obtained using biomechanical principle - synergy i.e. introducing linear or nonlinear relations between independent parameters or their first derivatives which uniquely define redundant system. Moreover, one can introduced hypothetical control using joint actuator synergy approach as suggested [Bernstein, 1967] which imposes a specific constraint(s) on the control variables. Also, it can be applied biological concept called distributed positioning (DP) which is based on the inertial properties and actuation capabilities of joints of redundant system. The redundancy and DP concept [Potkonjak 1990] could be used for solving the trajectory that has problems with increased dynamic requirements.*

Received May 20, 2000
Presented at 5th YUSNM Niš 2000, Nonlinear Sciences at the Threshold of the Third Millenium, October 2-5, 2000, Faculty of Mechanical Engineering University of Niš

The concept of DP allows us to separate the smooth and accelerated components of required motions applying appropriate smoothing technique. The inverse kinematics of redundant robot has been solved at the coordination level via (DP) concept. Moreover, it is here proposed using other biological principles such as: principle of minimum interaction which takes a main role in hierarchical structure of control and self-adjusting principle, which allows efficiently realization of control based on iterative natural learning. Motor control is organized as a multilevel structure, is generally accepted. In assistive system involves man as the decision maker, a hierarchical control structure can be proposed with three levels from the left to right: -voluntary level, coordination level, actuator level. This imposes the system is decomposed into several sybsystems with strong coupling between subsystems. Explanation of previous can be understood using the principle of maximum autonomy or minimum information exchange [Tomović, Bellman, 1970]. According to this principle, the optimal solution is to delegate the execution of functional motions to the coordination level and local regulators once the task and the task parameters have been selected. Learning control for controlling dynamics systems, a class of tracking systems is applied where it is required to repeat a given task todesired precision. The common observation that human beings can learn perfect skills trough repeated trials motivations the idea of iterative learning control for systems performing repetitive tasks. Therefore, iterative learning control requires less a priori knowledge about the controlled system in the controller design phase and also less computational effort than many other kinds of control. For improving the properties of tracking is proposed appling biological analog - principle of self-adaptibility, [Grujuć,1989] which introduce local negative feedback on control with great amplifing.

1. INTRODUCTION

In this paper it is considered problem of realization new mathematical models of redundant systems as well as control using suitable biological analog. The idea was to try to imitate human behavior and this is specially convenient for tasks which are similar to those characteristic for humans (e.g., assembling in industry, different jobs at home and in health service). If we consider speed, accuracy and stability of motion then the overall performance (taking into account all three of parameters) with machines is still far behind human reaching and grasping. Human arm movements are considered to be stable, fast and accurate due to properties of muscles, musculo-skeletal structures and hierarchical control. Existence of invariant features in the execution of functional motions points out that central nervous system (CNS) uses *synergy* Bernstein,(1967)(i.e rule(s) that can be developed by the CNS based on some principles). In that way, model of redundant system is obtained using biomechanical principle - synergy i.e. introducing linear or nonlinear relations between independent parameters or their first derivatives which uniquely define redundant system. Moreover, one can introduced hypothetical control using joint actuator synergy approach as suggested Bernstein (1967) which imposes a specific constraint(s) on the control variables. Also, it can be applied biological concept called distributed positioning (DP) which is based on the inertial properties and actuation capabilities of joints of redundant system. The redundancy and DP concept Potkonjak (1990) could be used for solving the trajectory that has problems with increased dynamic requirements. The concept of DP allows us to separate the smooth and accelerated components of required motions applying appropriate smoothing technique. The inverse kinematics of redundant robot has been solved at the coordination level via (DP) concept.

Moreover, it is here proposed using other biological principles such as: *principle of minimum interaction* which takes a main role in hierarchical structure of control and *self-adjusting principle,* which allows efficiently realization of control based on *iterative natural learning,* Lazarevi}, (1999,d). In biological systems motor control is organized as a multilevel structure, is generally accepted. This imposes the system is decomposed into several subsystems with strong coupling between subsystems. Problem of coordinating segments of redundant robotic system can be stated as an optimization problem which is most likely to biological "principle of minimum interaction" which is formulated by Gelfan and Tseslin. Also, the common observation that human beings can learn perfect skills trough repeated trials motivations the idea of iterative learning control for systems performing repetitive tasks. For improving the properties of tracking is proposed applying biological analog - principle of self-adaptability, Gruju} (1991) which introduce local negative feedback on control with great amplifying.

2. PRELIMINARIES

The growing field of robot application requires very stable, fast, and accurate systems. Some complex industrial and nonindustrial tasks induced a new approach to robot configuration for a example precise industrial assembling, high speed manipulation, home robotics, robotized surgery, etc. Such demanding tasks could efficiently be solved if robot was configured as redundant. A robotic manipulator is called kinetically redundant if it has more degrees of freedom (DOF) then required for a realization of a prescribed task in a task space. The kinematic redundancy in a manipulator structure yields increased dexterity and versality and also allows to avoid collisions with obstacles by the choice of appropriate configurations. Recent researches offer a new approach to redundant robots. In many tasks, kinematics can be solved with nonredundant robot configuration but difficulties arise with dynamic effects and accuracy. Redundancy may help to solve these problems (Salisbary & Abramowitz, (1985); Egeland, 1987; Potkonjak et al., 1990, 1991). With such approach to redundant robots, one faces the problem of control, specially on the kinematic level. The task does not determine joint motions uniquely. As controlled plants, redundant robot manipulators are essentially nonlinear dynamic systems of high order with considerable interactions (cross couplings) between links. Hence, different kinematic or dynamic optimization criteria could be introduced to achieve the unique solution of the inverse kinematics. The other idea was to try to imitate human behavior. This is specially convenient for tasks which are similar to those characteristic for humans (e.g., assembling in industry, writing, different jobs at home and in health service). If we consider speed, accuracy and stability of motion then the overall performance (taking into account all three of parameters) with machines is still far behind human reaching and grasping. The control of arm movement in humans relies very much on distributed usage of different joints, and inherent optimization of muscles which are active. Analysis of multijoint coordination in humans is an important source of information for synthesis of dynamic patterns in machines. Thus, it is necessary to examine the way humans perform complex motions, find the biological analog, and apply it with robot.. But, redundant mechanisms also have a disadvantage of the difficulty in controlling them. Robots are substantially multipurpose systems and robot control system should be multipurpose (universal) one, i.e, its structure, parameters, and software must not change if control objective, mode, parameters are changed. The main question is how to choose a suitable mechanism configuration from the infinite number of possible configurations called "self-motions" which match each position of the manipulation object, for a prescribed point of the end-effector in a task space.

There are two major approaches to solve this problem. One is to impose certain mathematical constraints (equations) on changes in kinematic parameters. For example, Bailleul (1985) complemented the given set of equations by choosing additional set of constraints, and this method is refereed to as the "extended Jacobian method". The other approach is based on the possibility of optimizing manipulator motion, provided that the motion of the end-effector is prescribed. Now, optimization problem for redundant manipulators is stated as following: given a prescribed motion of the end-effector of the manipulation robot, find the motion of robot so as to minimize either a scalar function of the state variables at each time instant (the local optimization) Liegeois (1977), or a functional that depends on the motion as a whole (the global optimization) F. L. Chernousko (1994).

3. Applying Biological Analog in Robotics

3.1 Distributed positioning (DP)

The new approach in modeling redundant mechanism is based on biological analog i.e, the modeling is based on the separation of the prescribed movement into two motions: smooth global, and fast local motion, called distributed positioning (DP). Distributed positioning is an inherent property of biological systems. It is based on the inertial properties and actuation capabilities of joints. Humans, when writing, as shown in literature control their proximal joints, while the movement of distal joints follow them (synergy). Writing is a good representative of task that is characteristic for humans, but at the same time interesting for robots. It is fast and accordingly very demanding from the viewpoint of dynamics (high accelerations produce high inertial loads). In humans highly inertial arm joints (shoulder and elbow) provide smooth global motion, and low inertial hand joints (fingers) perform fast and precise local motions. The initial idea appeared in Salisbury & Abramowitz, (1985) and Egeland, (1987) and final version of DP concept was proposed for industrial robotic systems by Potkonjak (1990, 1991) and Potkonjak & Krstulović (1992 c).

3.1.1 DP concept for redundant mechanism in writing

The DP concept was originally developed for problems where massive robot was involved in fast manipulation (Potkonjak 1990, 1991; Potkonjak & Krstulović, 1992). Acceleration of massive segments leaded to drive overload and required redundancy. Let, the position of the arm is defined by the vector of joint (internal) coordinates of dimension $n = 8 : q = [q_1,\ q_1\ \dots q_8]^{\mathrm{T}}$. The position of the terminal device (pencil) is defined by the vector of external coordinates of dimension $n_e = 5 : X = [x\, y\, z\, \theta\, \varphi]^{\mathrm{T}}$, where x,y,z define the tip position and angles θ, φ define the pencil axis. The kinematic model of the arm-hand complex i.e. the transformation of coordinates (internal to external and vice versa) is highly nonlinear:

$$X = f(q) \tag{1}$$

where f is the function: $R^8 \to R^5$. The inverse kinematics (calculation of q for given X) has an infinite number of solutions since (1) represents a set of 5 equations with 8 unknowns. this is due to presence of redundancy. The dimension of redundancy is $n_r = n - n_e = 8 - 5 = 3$.The kinematic model can be written in the Jacobian form of the first or of the second order :

$$\dot{X}=J(q)\dot{q}\ ,\ \ddot{X}=J(q)\ddot{q}+A(q,\dot{q}) \tag{2}$$

where J is $n_e \times n$ (i.e. 5x8) Jacobian matrix and A is $n_e \times 1$ (i. e. 5×1) adjoint vector containing the derivative of the Jacobian. Let X_1 be the subvector containing the accelerated motions (dimension n_a), and X_2 be the subvector containing the smooth motions ($n_e - n_a$). Now

$$X = [X_1, X_2]^T.$$

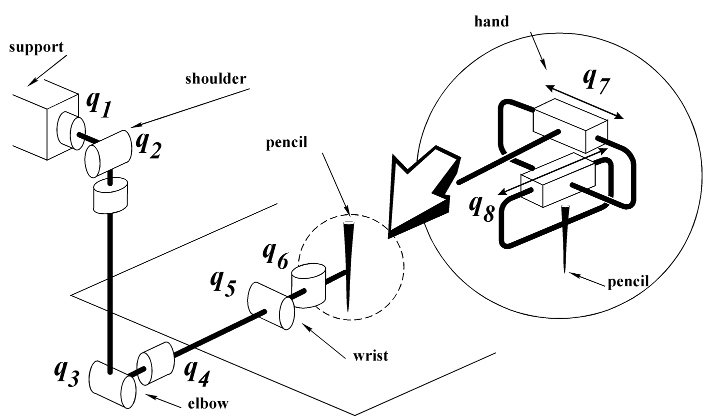

Fig. 1. Eight-DOF arm-hand complex

The redundant robot ($n_e = 8$ DOFs) is now separated into two subsystems. The subsystem with $n_e = 5$ DOFs with greatest inertia is called ***the basic configuration.*** The other subsystem is ***the redundancy*** having $n_r = 3$ DOFs. It holds that $n = n_e + n_r$. Analysing the plane writing task one finds that there are $n_a = 2$ accelerated external motions: $x(t)$ and $y(t)$.

The others (z,θ,φ) are constant or smooth. According to DP concept we introduce $X_1 = [x\ y]^T$ and $X_2 = [z\ \theta\ \varphi]^T$. It can be defined the basic configuration as a mechanism $q_b = [q_1\ q_2\ ...q_5]^T$. The resting joints, one wrist joint (q_6) and "fingers" (q_7,q_8), form the redundancy and $q_r = [q_6\ q_7\ q_8]^T$ defines the position of the redundancy. The DP concept solves the inverse kinematics of a redundant robot in two steps. At the first step the motion of basic configuration is calculated (q_b) using kinematic model and properties DP concept, and at the second step the motion of redundancy (q_r) is determined, Potkonjak, Lazarević, et. al. (1996,1998), Lazarević, (1999,b).

3.2 Synergy

Human arm movements are considered to be stable, fast and accurate due to properties of muscles, musculo-skeletal structures and hierarchical control. Analysis of multijoint coordination in humans is an important source of information for synthesis of dynamic patterns in machines. However, this the flexibility and the large number of degrees of freedom in the motor system are problem when same motor task is realized by movements. But, it was observed in the execution of functional motions that certain trajectories are preferred from the infinite number of options. Such behavior of organisms can be only explained by the existence of inherent optimization laws in self-organized systems governing the acquisition of motor skills. Existence of invariant features in the execution of functional motions points out that central nervous system (CNS) uses *synergy* Bernstein, (1967) (i.e rule(s) that can be developed by the CNS based on some principles). In fact, such behavior implies that it obeys the optimization at the coordination level where the goal is to minimize efforts in terms of synergy patterns. Speaking mathematically, the synergy imposes specific constraints on the control variables and on the state variables of joints which are related to the task dependent functions pertaining to classes of motor acts. Also, the control of arm movement in humans relies very much on distributed usage of different joints, and inherent optimization of muscles which are active. Arm muscles are found grouped in pairs about simple hinge joints where even in the simplest case of two antagonist muscles about a joint there are two distinct control variables. Moreover, muscles should be regarded as functional units with more than one control or activation parameter. The existence of motor-unit subpopulations in the muscle reflects a neural organization rather than differences in the mechanical effect of motor units. Understanding coordination of the muscle task-dependent activation patterns requires analysis of the activation of their patterns of motor unit-subpopulations. In papers Lazarevi}(1998,1999c) it is treated coordination control of a redundant anthropomorphic robot arm. It was presented that new robot control can be easily obtained using biological analog. It is suggested synergy approach which is established by optimization law at coordination level. In that way, model of redundant system is obtained using biomechanical principle - synergy i.e. introducing linear or nonlinear relations between independent parameters or their first derivatives which uniquely define redundant system. It allows unique solution for actuator redundancy and solution of the inverse kinematics of redundant mechanisms which is one of the necessary steps to robot manipulator control systems. In solving optimal control problem, a Pontryagin maximum principle is used. Also, it is introduced hypothetical control as suggested Bernstein (1967) which imposes a specific constraint(s) on the control variables. In that way, one can obtain a unique solution for kinematic redundant problem.

3.3 Principle of minimum interaction in hierarchical control

Also, motor control is organized as a multilevel structure, is generally accepted. In assistive system involves man as the decision maker, a hierarchical control structure can be proposed with three levels from the left to right: voluntary level, coordination level, actuator level. This imposes the robotic system is decomposed into several subsystems with strong coupling between subsystems. For an instance, the system dynamics of redundant robot are described by:

$$F_o = \{(U,Y,Z): F_1 = 0, F_2 = 0\} \quad (3)$$

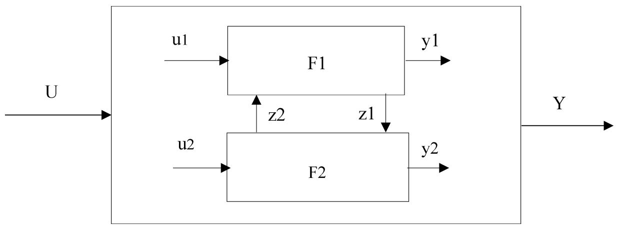

Fig. 2. Coordination of two subsystems

where $U \in R^m$ is the control input vector, $Y \in R^n$ the output vector, and $Z \in R^n$ the vector representing interactions between the two subsystems (segments). The cost function of a multiple-system is the sum of the cost functions of all subsystems:

$$J(U,Z,Y) = \sum_{i=1}^{N} J_i \quad (4)$$

The problem of coordinating multiple systems can be stated as an optimization problem: minimize the cost function J subject to the constraint F_0.

In paper Lazarevi}(1997) it is stated and solved the Bernstein problem which is related to kinematic redundancy of ARA. It is treated control of a anthropomorphic robot arm (ARA) with three degrees of freedom. The optimal control problem of continuous nonlinear dynamic systems - (redundant robotic manipulators), with quadratic performance index can be stated as follows. Determine $U \in L_2(t_0, t_k)$ such that under system constraints is minimized.

$$J = \frac{1}{2}\int_{t_o}^{t_f} [\| x(t) - x_d(t) \|_Q^2 + \| u(t) \|_R^2 + \| z(t) \|_S^2] dt \to \min \quad (5)$$

$$\dot{x}(t) = \frac{dx(t)}{dt} = F(x(t), u(t)) = g(x(t)) + h(x(t))u(t), x(t_o) = x_o \quad (6)$$

$$z(t) = x(t) \ \dim x = n, \dim u = m, \dim z = n \quad (7)$$

where x, u state and control vectors and z is interaction vector; weighting matrices Q, R, S are all block diagonal. So, problem of coordinating multiple systems can be state as an optimization problem which is most likely to biological "principle of minimum interaction" which is formulated by Gelfand and Tsetlin: "For complex controlling systems, the typical structure permits the separation of individual, relatively automatic subsystems. For each subsystem of that type all the remaining subsystems belong to the outside environment and the expediency of the subsystems appears in the minimization of interaction among them so that in stable conditions these subsystems function as if independently, autonomously." A major consequence of this principle is that the complexity of each subsystem does not depend on the complexity of the whole system. The application of the minimum interaction principle also leads to a structural form for the "self-organizing" controller. The solution of stated problem of control is generated in a sequence of steps involving a heuristic techniques of genetic algorithm that provides reliable initial guesses. Genetic algorithms are stochastic adaptive algorithms whose search method is based on simulation of natural genetic inheritance and striving for survival. To solve local problems, the minimum principle is used where the multi-level univariate hierarchical strategies is proposed. The problem is divided into two-level optimization problem which is solved iteratively until the desired performance is achieved, Lazarevi} (1999,p).

3.4 Learning control, self - adaptability

Recently, there have been extensive research activities in the topic of learning control for controlling dynamics non-linear systems in a iterative manner. The learning control concept differs from conventional control methodologies in that the control input can be appropriately adjusted to improve its future performance by learning from the past experimental information as the operation is repeated. The common observation that human beings can learn perfect skills trough repeated trials motivations the idea of iterative learning control for systems performing repetitive tasks. Therefore, iterative learning control requires less *a priori* knowledge about the controlled system in the controller design phase and also less computational effort than many other kinds of control. Learning control for controlling dynamics systems, a class of tracking systems is applied where it is required to repeat a given task to desired precision. Dynamic model of redundant robotic manipulator with uncertainties can be presented in the form of state space and output equations as a class of time-varying, non -linear system Lazarevi}, (1999,d)

$$\dot{x}_i = f(x_i, t) + B(x_i)u_i(t) \qquad y_i = g(x_i) \tag{8}$$

In these equations t denotes time, $t \in [0,T]$, $t \in \Re$, x_i the state vector, $x_i \in \Re^n$, u_i the control vector, v_i the vector uncertainties, $u_i \in \Re^m$, y_i the output vector of the system, $y_i \in R^r$ and i denotes the i-the repetitive operation of the system. The learning controller for generating the present control input is based on the previous control history and a learning mechanism. Motivated by human learning, the basic idea of iterative learning control is to use information from previous executions of the task in order to improve performance from trial to trial in the sense that the tracking error $e_i(t)$ is sequentially reduced. It is proposed applying biological analog - principle of self-adaptability which introduce local negative feedback on control with great amplifying. In the simplest case learning control law can be shown such as (Fig. 3):

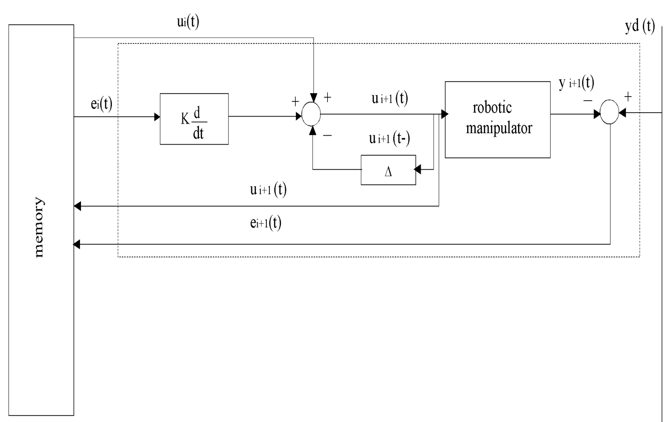

Fig. 3. Block diagram of iterative learning control

$$u_{i+1}(t) = -\Delta u_{i+1}(t^-) + u_i(t) + K(t)\dot{e}_i(t) + N(t)e_i(t) \tag{9}$$

4. CONCLUSION

In this paper it is suggested applying of suitable biological analog in realization new mathematical models of redundant systems as well as control. First, it can be applied biological concept called distributed positioning (DP) which is based on the inertial properties and actuation capabilities of joints of redundant system.Second, it is proposed using biological analog synergy due to existence of invariant features in the execution of functional motions points out that central nervous system (CNS). At last, it is proposed using other biological principles such as: *principle of minimum interaction* which takes a main role in hierarchical structure of control and *self-adjusting principle,* which allows efficiently realization of control based on *iterative natural learning*.

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MATEMATIČKO MODELIRANJE I UPRAVLJANJE REDUDOITNIM ROBOTIMA-MANIPULATORIMA KORIŠĆENJEM BIOLOŠKIH ANALOGA

Mihailo P. Lazarević

U ovom radu razmatran je problem realizacije novih matematičkih modela redudantnih sistema kao i upravljanja korišćenjem pogodnih bioloških analogona. Ideja je bila u tome da se imitira ljudsko ponašanje i to je posebno značajno za zadatke koji su slični onim zadacima karakterističnim za ljude. Prvo, može se primeniti biološki koncept distribuiranog pozicioniranja (DP) koji je zasnovan na inercijalnim osobinama i aktuatorskim mogućnostima zglobova redudantnih sistema. Drugo, predloženo je korišćenje biološkog analogona - sinergije koja je posledica postojanja invarijantnih osobina u izvršavanju funkcionalnih kretanja. Na kraju predloženo je korišćenje drugih bioloških principa kao što su: princip minimuma interakcije koji ima važnu ulogu u hijerarhijskoj strukturi upravljanja i principa samopodešavanja, koji dozvoljava efikasnu realizaciju upravljanja koje je zasnovano na iterativnom prirodnom učenju.