

MODEL REFERENCE APPROACH FOR ROBOT CONTROL

Aldo Balestrino Giuseppe De Maria Bruno Siciliano

Istituto Elettrotecnico - University of Naples
via Claudio 21 - 80125 Naples - Italy

ABSTRACT.

In view of a hierarchically intelligent control system for robotic manipulators, the major problems arising at hardware control level and coordination level are analyzed. In particular, based on adaptive control theory, solutions are proposed both for effective control in the drive oriented space and for the inversion of coordinate transformation. Finally a robust control scheme is proposed directly in the task oriented space.

INTRODUCTION.

Since 1980 research in robotics has been undertaken at Istituto Elettrotecnico, University of Naples, by the control team.

Manipulation systems represent an appealing research field where intelligent control theory can be successfully applied. A hierarchically intelligent control approach has been proposed by Saridis [1] as unified theoretic approach of cognitive and control systems methodologies. The control intelligence is hierarchically distributed according to the principle of decreasing precision with increasing intelligence. One can recognize the following three basic levels of controls, even though each level may contain more than one layer of three-structured functions:

- 1) organization
- 2) coordination
- 3) hardware control.

As an example a hierarchically intelligent control system for a manipulator with visual feedback [1] is reported in Fig. 1.

This work was supported by Ministero della Pubblica Istruzione.

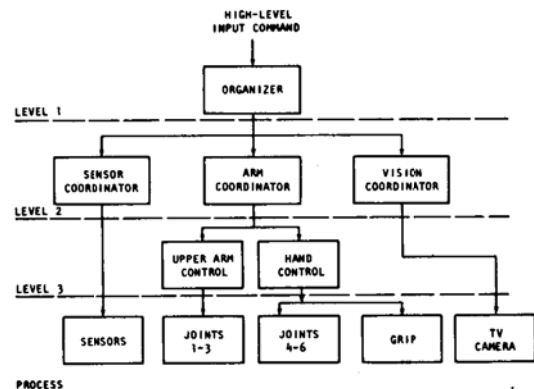


Fig.1 Hierarchically intelligent control system for a manipulator.

In the light of this reference scheme research in robotics has been carried out by the above control team following a bottom-up approach. Such a choice has arisen from the intent to seek for robust control algorithms suitable for highly nonlinear coupled systems, like robotic manipulators. This approach has been thought as lightening the upper levels, in particular the 'linguistic decision schemata' of the coordination level, after all the software burden.

Listed are below some problems arising at the lowest level

- i) modeling of the manipulator
- ii) control of the plant with uncertain dynamics
- iii) manipulator control in the drive oriented space
- iv) coordinate transformation from the task oriented space to the drive oriented space
- v) manipulator control in the task oriented space.

These topics are not definitely exhaustive,

but they are just as well indicative of the above research activities in robotics during latest years. By the way, various contributions are illustrated in the next sections.

MANIPULATOR MATHEMATICAL MODELS.

Modeling of manipulators is a well established topic of classical mechanics [2]. Robotic manipulators consist of a set of $n+1$ rigid bodies linked together by n actuated joints. It must be underlined, however, that system elasticities can play a significant role as far as control performance is concerned. In this paper such effects are neglected. Fig. 2 shows a commercially available Cincinnati Milacron Model T3; each joint of this industrial robot is electric-driven.

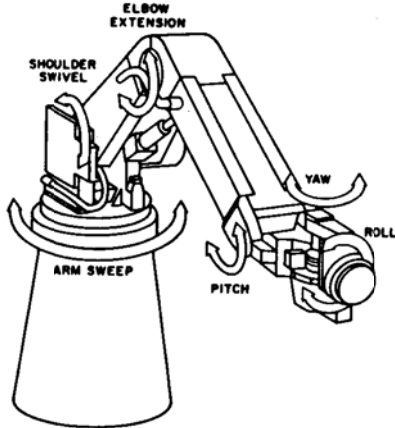


Fig. 2 Cincinnati Milacron T3.

Kinematics.

A robot task is naturally specified in terms of hand Cartesian coordinates. As indicated in Fig. 3 the position is described by a position vector $p(t)$, whereas the orientation is defined through a unit approach vector $a(t)$ and a unit sliding vector $s(t)$. All these vector are defined with reference to the base coordinates of the manipulator [3]. Moreover a unit normal vector, defined as the cross-product $n(t)=s(t) \times a(t)$, is introduced in order to define the reference orientation in terms of Euler angles with respect to base coordinates. Therefore the state of the hand at time t in Cartesian coordinates with reference to the base coordinates is represented by a nine-dimensional vector $[p^T(t); a^T(t); s^T(t)]^T = [p^T(t); h^T(t)]^T$.

Let n be the number of joints and q_i for

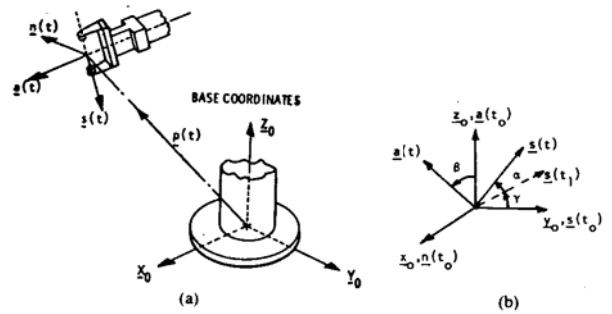


Fig. 3 (a) Position and orientation vectors of hand. (b) Euler angles of orientation.

$i=1,2,\dots,n$ the joint variables. Then the above vector can be expressed in terms of q_i as

$$[p^T(t); h^T(t)]^T = f(q_1, q_2, \dots, q_n) \quad (1)$$

where $f(\cdot)$ is a nonlinear nine-by-one vector-valued function.

Dynamics.

Using the above notation for joint variables the dynamical model of the manipulator can be written as

$$B(q)\ddot{q} = -c(q, \dot{q}) + g(q) + \tau \quad (2)$$

where $B(q)$ is the inertia matrix, $c(q, \dot{q})$ is the vector defining Coriolis and centrifugal terms, and τ is the vector of input generalized forces applied to the joints. The inertial terms and the gravity terms are in practice dominant in manipulator dynamics, whereas Coriolis and centrifugal terms count only when the manipulator is moving at high speed. It should be pointed out, however, that the inertia matrix is inclusive of the actuator inertias which mostly determine manipulator dynamics.

MANIPULATOR CONTROL IN THE DRIVE ORIENTED SPACE.

The control of the manipulator in the drive oriented space involves the computation of the input generalized forces, so that each joint will reach a desired position, eventually tracking a target trajectory. Nevertheless, (2) represent a set of highly nonlinear coupled second-order equations which introduce relevant difficulties in synthesizing a robust control algorithm. Various sophisticated dynamic con-

trol schemes have been proposed, like Resolved Rate Control [4], Inverse Problem Technique [5], Computed Torque Technique [6], Resolved Acceleration Control [3]; but all require accurate modeling of manipulator dynamics. Consequently, a great effort has been made by many researchers in this area to find efficient algorithms for automatic dynamics computation [7], [8]. Unfortunately a great amount of computation is always required during the motion, which limits the maximum sampling frequency to be used in the control of manipulator. Whatever control scheme is implemented, however, it must be kept in mind that the dynamic control is very sensitive to inaccuracies of the modeling, like errors in the lengths of the links, their masses and inertias, and above all variable payloads.

This kind of problems have been faced up resorting to adaptive control techniques [9], [10]; all these, however, assume a linear and time-invariant reference model and require the plant dynamics to be considered stationary when the adaptation mechanism operating. These assumptions are invalid for robotic manipulators with high dynamic performances; hence the necessity of finding out efficient adaptive control techniques for nonlinear time-varying plants with uncertain dynamics has led to establish peculiar control algorithms via hyperstability theory [11]. By the way, an adaptive model following control has been developed in [12] and applied in the case of a three-degree of freedom robotic manipulator.

Typically, industrial manipulators have six degrees of freedom, three of which are necessary to determine the wrist position, and all of them concur to define the orientation of the hand. As a matter of fact are the first three joints which are mostly sensitive to rapid and wide inertia variations; hence robust control algorithms must be used at wrist level, while for the control of the hand conventional control techniques may prove satisfactory.

As regards to the control of the wrist in the drive oriented space, reference is made to the scheme of Fig. 4. Consequently, denoting as $x_p = [q_p^T \dot{q}_p^T]^T$ the wrist state vector, manipulator dynamics (2) can be rewritten as

$$\dot{x}_p = A_p(x_p)x_p + \begin{bmatrix} 0 \\ -I_3 \end{bmatrix} B^{-1}(x_p)\tau \quad (3)$$

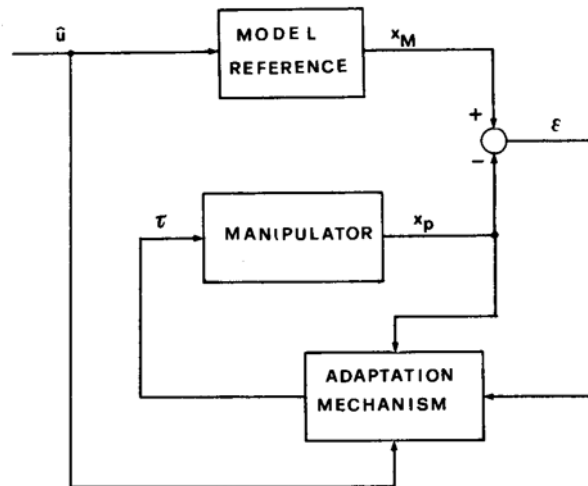


Fig. 4 Model reference adaptive control for robotic manipulator.

where the input generalized forces vector τ is given by:

$$\tau = M(x_p) [\phi(\epsilon, x_p) + \psi(\epsilon, \hat{u})]. \quad (4)$$

At this extent the design procedure set forth in [12] leads to the following choices

$$\begin{aligned} M(x_p) &= I_3; \\ \phi &= K_p v(\text{sgn } x_p)^T / \|v\|; \\ \psi &= K_u v(\text{sgn } \hat{u})^T / \|v\|, \end{aligned} \quad (5)$$

where $v = D\epsilon$ is the output of a linear compensator, K_p and K_u are design parameters and $\|v\|$ is any norm, usually the Euclidean one. This way, the generalized error ϵ is guaranteed to go asymptotically to zero, i.e. the controlled plant is forced to behave as the reference model.

Many other choices for $M(x_p)$, $\phi(\epsilon, x_p)$ and $\psi(\epsilon, \hat{u})$ are feasible [13]; in particular the dynamic structure of the manipulator generally ensures that a constant matrix $\hat{M}$ exists such that $B^{-1}\hat{M}$ is a diagonally dominant and positive definite matrix allowing an oversimplified adaptation mechanism like:

$$\tau = K\hat{M}\text{sgn}(v) \quad (6)$$

where K is a gain factor taking account of the maximum values of state variables, external inputs and disturbances.

Although the reference model in Fig. 4 pro

ves useful from the theoretical point of view, in robotics, usually, the state vector $x_M = [\dot{q}^T, \ddot{q}^T]^T$ is known because the target trajectory is wholly specified in advance at the upper level so that x_M can be assumed as the effective input vector, simply by reversing the arrows related to the model reference block.

The adaptation law (6) forces the system to operate in sliding mode [14] with the discontinuous control τ ideally switched at infinite frequency. In reality, imperfections such as switching hysteresis or delay, finite switching time or bandwidth and approximate modeling as well, i.e. neglecting electrical time constants of d.c. motors, all lead to a non-ideal sliding mode (chatter) with a finite and unpredictable frequency.

In order to avoid the above difficulties, a high frequency sawtooth signal $m(t)$ can be added to $v(t)$ so as to realize the modified adaptation mechanism

$$\tau = K_M \text{sgn}(v - m). \quad (7)$$

The auxiliary signal $m(t)$ locks the chatter frequency to a well defined value, far beyond the natural frequencies of the plant.

A very appealing feature of the modified adaptation mechanism (7) is that it can be easily implemented by means of a pulse width modulator (PWM) amplifier which is right the power amplifier usually employed in electrical drives [15]. Collecting together all previous remarks, the control scheme for a single joint, reported in Fig. 5, is achieved.

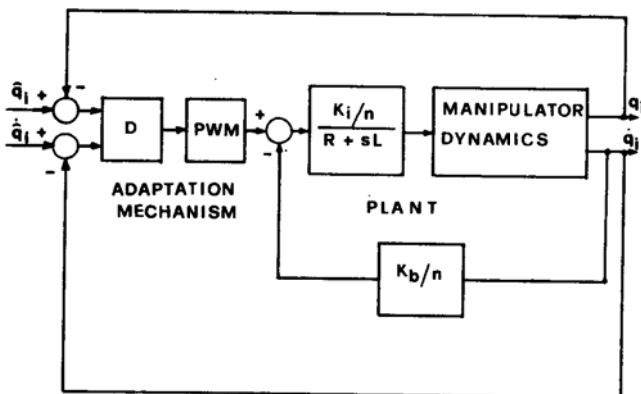


Fig. 5 Single joint adaptive control system.

It should be noted that frequently the matrix $\hat{M}$ in (7) can be chosen diagonal so that three independent control drive servos can be implemented. A single joint drive equipped with the above adaptation mechanism has been extensively tested in laboratory [15]. Results have shown the robustness of the proposed scheme with respect to wide unpredictable load inertia variations, achieving substantial improvements of the dynamic behaviour as compared to a conventional PI controlled joint drive. In Fig. 6 illustrated are some experimental drive responses; tracking characteristics are constrained only by the internal current limits.

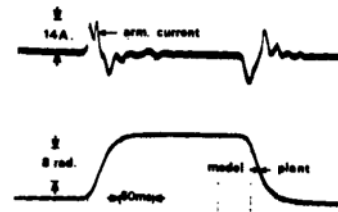


Fig. 6a Drive response with low moment of inertia.

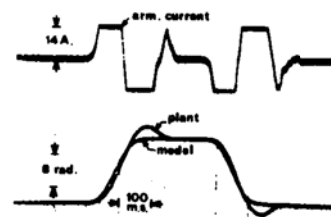


Fig. 6b Drive response with high moment of inertia when the current limit occurs.

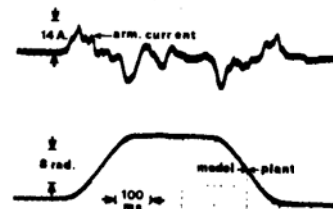


Fig. 6c Drive response with high moment of inertia.

COORDINATE TRANSFORMATION.

In order to provide the control led manipulator in the drive oriented space with the target trajectory $[\dot{q}_p^T, \dot{q}_h^T]^T$, the coordination level is required to perform a coordinate transformation from the task oriented space to the drive oriented space.

Whenever the goal is specified in terms of finite number of corner points or a repetitive trajectory in the task oriented space, the coordinate transformation can be performed either numerically off-line or recurring to the so-called 'teaching-by-doing' method [16]. On the contrary, if the target trajectory is not prespecified, the coordinate transformation must be evaluated on-line.

Referring to kinematics of robotic manipulator (1), because of the nonlinear character of the vector-valued function $f(\cdot)$, the computation of $f^{-1}(\cdot)$ is very time consuming [16]. In addition, further difficulties arise from the fact that $f^{-1}(\cdot)$ is a multi-valued function.

The algorithms which compute the coordinate transformation must be valued in the light of a compromise between computation time and precision requirements. In existing control schemes the determination of $\dot{q}$ is also needed; therefore, besides the inversion of $f(\cdot)$, the pseudo-inverse of the related jacobian matrix $J(\hat{q})$ must be evaluated in order to compute $\dot{\hat{q}} = [\dot{\hat{q}}_p^T, \dot{\hat{q}}_h^T]^T$ from

$$[\dot{\hat{p}}^T, \dot{\hat{h}}^T]^T = J(\hat{q}) [\dot{\hat{q}}_p^T, \dot{\hat{q}}_h^T]^T, \quad (8)$$

which is time consuming as well.

The on-line determination of $\hat{q}$ and $\dot{\hat{q}}$ directly from (1), (8) proves rather hard, then. In [17] an adaptive technique has been proposed in order to solve the coordinate transformation problem; the inversion of (1), (8) has been turned out into a dynamic problem whose asymptotic stability is ensured in advance.

At this extent, with the following partitions

$$f(\hat{q}) = [f_p^T(\hat{q}_p) | f_h^T(\hat{q})]^T \quad (9)$$

$$J(\hat{q}) = \begin{bmatrix} J_p(\hat{q}_p) & 0 \\ J_{hp}(\hat{q}) & J_h(\hat{q}) \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} \epsilon_p \\ \epsilon_h \end{bmatrix} = \begin{bmatrix} \hat{p} - p \\ \hat{h} - h \end{bmatrix} \quad (11)$$

and the choices

$$\gamma_p(\cdot) = 1 + \frac{\epsilon_p^T P_p \dot{p}}{\epsilon_p^T P_p J_p^T J_p P_p \epsilon_p} \quad (12)$$

$$\gamma_h(\cdot) = 1 + \frac{\epsilon_h^T P_h \dot{h}}{\epsilon_h^T P_h J_h^T J_h P_h \epsilon_h} + \frac{\epsilon_h^T P_h J_{hp} \dot{p}}{\epsilon_h^T P_h J_h^T J_h P_h \epsilon_h} \quad (13)$$

the scheme in Fig. 7 gives the required solution to the above problem.

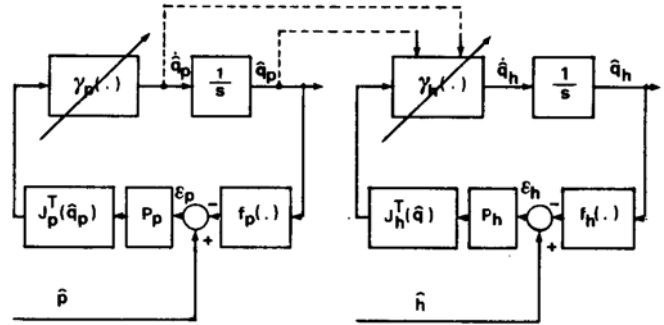


Fig. 7 Coordinate transformation scheme.

P_p and P_h are positive definite matrices at designer's disposal and their values affect convergence rate and precision attainable for a given settling time.

On the one hand the robustness of the proposed scheme derives from its closed-loop structure. On the other hand its simplicity leads to a digital implementation making use of a single dedicated microprocessor system, for instance NS16032 with NS16081 floating point unit. An appealing feature of this solution is that the hand orientation is automatically coordinated with the wrist motion, whatever kind of task is required to be performed. This way, one of the major problems [1] at coordination level, see Fig. 1, is overcome.

Simulation results for typical kinematical chains have shown that the maximum error ϵ can be kept below 1mm. during the motion, whereas it is practically zero at steady-state.

MANIPULATOR CONTROL IN THE TASK ORIENTED SPACE.

Target trajectories are usually planned in a coordinate frame characterizing the task-oriented space, that is the Carte

sian space. Consequently, it would be much more appealing to implement a controller which makes the end effector exhibit positions and forces according to the desired target trajectory, directly in the task oriented space. In this light, many attempts have been made like Resolved Motion Force Control [18], Dynamic Control in Operational Space [19]; but all require either accurate modeling or good load forecasting. In [20] an adaptive controller has been proposed, assuring insensitivity and decoupling in the task oriented space; but it suffers from the need of inverting, though approximately, the jacobian matrix (8).

At this extent, redrawing the scheme of Fig. 7 in the simpler form of Fig. 8, and even more considering the adapted manipulator in the drive oriented space and the coordinate transformation previously illustrated, lead, quite naturally, to the schemes of Fig. 9.

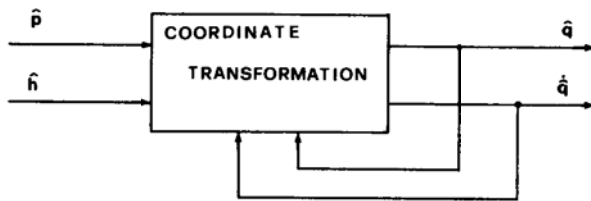


Fig. 8 Simplified coordinate transformation scheme.

It should be observed that the serial connection of Fig. 9a does not present any convergence problems from a theoretical point of view, but, in the worst case, errors accumulate, because of the open-loop structure.

On the contrary, the closed-loop structure of Fig. 9b looks like the scheme shown in Fig. 8, provided that the drive oriented space adapted manipulator outputs reproduce instantaneously the corresponding inputs. In reality the drive oriented space adapted manipulator exhibits a finite bandwidth, which could alter, even invalidate, the asymptotic convergence properties. Nevertheless the robustness of the scheme in Fig. 8 enables a reliable use of the solution proposed in Fig. 9b.

Simulation results with reference to Stanford manipulator [5] have shown, in fact, that both solutions prove adequate; in particular the closed-loop one yields limited errors in dependence of the opera-

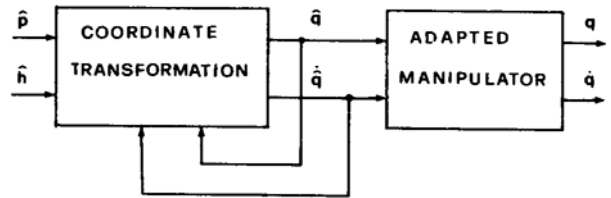


Fig. 9a Open-loop controlled manipulator in the task oriented space.

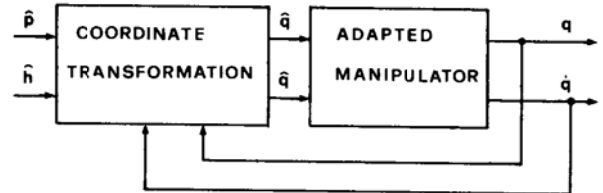


Fig. 9b Closed-loop controlled manipulator in the task oriented space.

ting speed. By the way, trajectories with typical trapezoidal velocity profiles are tracked in times 1/6 of those reported in [3], obtaining a maximum error less than 1 cm. for a 40 cm. straight-line path; on condition that the executing time is halved, the maximum error falls below 2 mm.. The steady-state errors remain, however, in the range of microns.

CONCLUSIONS.

This paper has dealt with the major problems existing at lower levels in a hierarchically intelligent control scheme for robotic manipulators.

Taking into account the highly nonlinear dynamics of a kinematical chain and the uncertainty, mainly due to variable payloads, robust control algorithms are needed. For this end, extensive use has been made of adaptive control theory for nonlinear and uncertain plants. In addition, this theory has proven useful in solving the inversion of coordinate transformation, which eases the coordinator at upper level of the computational burden.

Efficient control schemes for industrial robots have been proposed, both in the drive oriented space and directly in the task oriented space.

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