Automatic Supervisory Control of the Configuration and Behavior of Multibody Mechanisms

ALAIN LIÉGEOIS

Abstract—**A two-level adaptive control of the kinematics of multibody mechanisms, such as for robots or manipulators, is proposed. The mechanical systems under consideration are redundant with respect to the required functions. It is proved that the proposed control organization can be obtained by using a special form of the general solution of sets of linear equations. The adaptive qualities of a six degree-of-freedom manipulator illustrate these theoretical results.**

I. Statement of the Problem

The mechanical system under consideration consists of a linkage of rigid bodies with n revolute and/or prismatic joints. The vector $\bar{Y} = [\bar{y}_1, \cdots, \bar{y}_n]^T$ of generalized coordinates (where the superscript T denotes matrix transposition) is assumed to belong to the n-dimensional Euclidian space E^n. When the relative displacements of the actively controlled joints are chosen as coordinates $\bar{y}_i$ $(i = 1, 2, \cdots, n)$, the Lagrange equations of motion can be written as [1], [2]

$$\frac{d}{dt}\left(\frac{\partial \mathscr{L}}{\dot{\bar{y}}_i}\right) - \frac{\partial \mathscr{L}}{\bar{y}_i} = C_i + Q_i, \qquad i = 1, 2, \cdots, n, \tag{1}$$

where

- $\mathscr{L}$ Lagrange function,
- Q_i includes the effects of damping and disturbing forces,
- C_i active force or torque provided by the actuator about joint i,
- $(\dot{\ })$ (dot) denotes differentiation with respect to time t.

By means of an appropriate design of the regulators, it is possible to construct an automatic control system which forces the vector $\bar{Y}$ to track a desired trajectory $Y(t)$ in the E^n space. A possible solution is shown in Fig. 1; it uses a feedback-feedforward control based upon a simplified dynamic model of (1) [3], [4]. Such a tracking system will be considered in what follows as being perfect. Thus the next step in solving the control problem is to generate an input vector $Y(t)$ of the servomechanism as a function of a given task $X(t)$ defined in the m-dimensional Euclidian space E^m. When several solutions exist, it is desirable for the control system to select automatically that one which leads to the "best" behavior with respect to auxiliary constraints [5], [6] in the sense of avoiding external obstacles, of obtaining minimum displacements at the joints, and of avoiding internal locking situations due to mechanical stops or singularities.

In the general case, it is possible to write the constraints in terms of the y_i coordinates, so that the problem consists in solving at every instant of time the vector equation

$$X = F(Y), \tag{2}$$

where $X = X(t) \in E^m$ is given.

Equation (2) may have no solution, a single solution, or an infinite number of solutions. The latter case which requires $m < n$ is considered in this correspondence. The mechanism is redundant with respect to the tasks, and the problem is to obtain a coordination of the motions at the joints. Several schemes for obtaining

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The author is Maître de Conférences, Université des Sciences et Techniques du Languedoc, Laboratoire d'Automatique, Place Eugène Bataillon, 34060 Montpellier-Cédex, France.

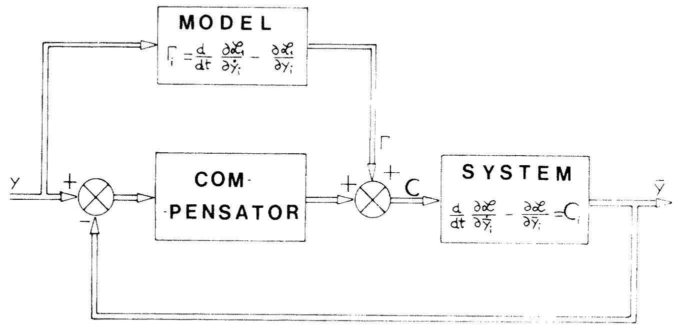

Fig. 1. Feedback-feedforward dynamic control.

artificial "synergy," i.e., coordinated motions, are found in the literature [5]–[9]; they make use of the linearized model of (2) by considering small displacements about the current configuration Y:

$$dX = J(Y)\, dY, \tag{3}$$

where $J(Y) = J$ is the $m \times n$ Jacobian matrix

$$J = \left(\frac{\partial F_i}{\partial y_j}\right), \qquad i = 1, 2, \cdots, m; \quad j = 1, 2, \cdots, n. \tag{4}$$

The various solutions proposed so far are equivalent in the sense that they use, more or less explicitly, a generalized inverse [10] G of J such that

$$JGJ = J \tag{5}$$

holds.

It can be assumed that J is of full rank; if the set (3) of linear equations is consistent, then a solution is given by

$$dY = G\, dX, \tag{6}$$

where $G = G(Y)$ is a generalized inverse matrix, of dimensions $n \times m$, of the matrix J.

Since rank $(J) = m < n$, there is an infinite number of solutions. This arbitrariness can be removed by selecting automatically the solution which minimizes a function of the type $\Omega = \Omega(dY)$ [6], [7], [11]. An alternative consists in selecting G in such a way that mechanical locks are avoided, while taking also into account the possible failures in the computing system [9], [12]. The mentioned strategies thus provide a first level of adaptation in the coordinated mechanism by finding a "short-range" optimal behavior as a function of dY and/or of the current properties of $J(Y)$. In the next section of this correspondence, a solution is proposed which allows a supervisory system (second level) to modify the behavior and the configuration of the mechanism in such a way that a higher-level criterion is satisfied which includes the vector Y instead of dY, for the sake of obstacle avoidance, of obtaining maximum availability, i.e., a state of the system when it is far from its limiting constraints, and so on.

II. Main Results

The main idea in developing the general solution derives intuitively from the fact that it is possible to add to the solution (6) any vector consistent with the constraints. This is asserted by the following theorem, the proof of which is adapted from [10] where the particular case $G_2 = G_1 = G$ is considered.

A. Theorem

The set of linear consistent equations

$$dX = J\, dY$$

admits as a solution

$$dY = G_1\,dX + (G_2 J - I_n)Z, \tag{7}$$

where

1) G_1 and G_2 are generalized inverse matrices of J, that is,

$$JG_1J = J \tag{8}$$

and

$$JG_2J = J, \tag{9}$$

2) I_n is the $n \times n$ unit matrix,
3) Z is an arbitrary vector in E^n.

Proof: One can write

$$J\,dY = JG_1\,dX + (JG_2J - J)Z,$$

based on the associative and distributive properties

$$= JG_1\,dX,$$

from equation (9)

$$= dX,$$

since (3) has $dY = G_1\,dX$ as a solution if and only if $JG_1J = J$, which is the case here by hypothesis (8).

B. Property

The vector $dY_2 = (I_n - G_2 J)Z$ represents the projection of Z on the null-space of J, along the range-space of $G_2 J$.

The proof can be found in [13, pp. 9 and 10].

C. Consequence

If one sets

$$Z = \alpha \cdot \nabla_y H, \tag{10}$$

where α is a real scalar and where $\nabla_y H$ is the gradient (n-dimensional column-vector) of a smooth function $H(Y)$ that a higher control level seeks to minimize, and if the projection operator $(I_n - G_2 J)$ is properly chosen, then the component dY_2 forces $H(Y)$ to decrease.

One can choose, for instance, the orthogonal projection. In that case, $G_2 J$ is hermitian:

$$J^T G_2^T = G_2 J \tag{11}$$

so that

$$G_2 = J^T(JJ^T)^{-1} \tag{12}$$

is the pseudo-inverse of J [13].

In the particular case where $dX = 0$, the proposed solution is identical to the gradient projection method [15]. $H(Y)$ is minimized, under the constraints $J\,dY = 0$ which are the equations of the hyperplanes tangent to the nonlinear constraints $F(Y) =$ constant at the point $Y \in E^n$. In the considered context, the electromechanical system therefore searches automatically for its best configuration, or attitude, in the sense of minimizing $H(Y)$.

The corresponding control-system's organization is presented in Fig. 2, where the box "plan generation" may be either a human supervisor-operator or some sort of "artificial intelligence," or both operating cooperatively [14]. In the latter case, such a distributed multilevel control relieves the operator of minor adaptations to changing constraints.

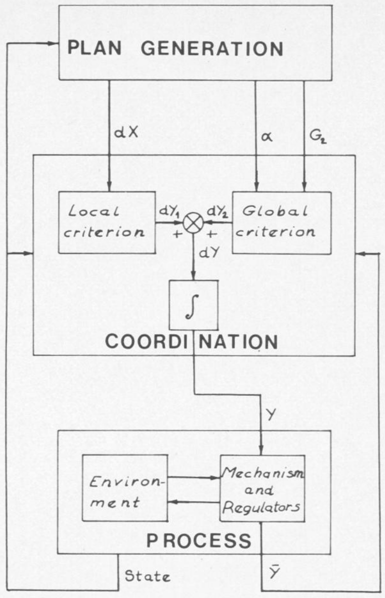

Fig. 2. System organization.

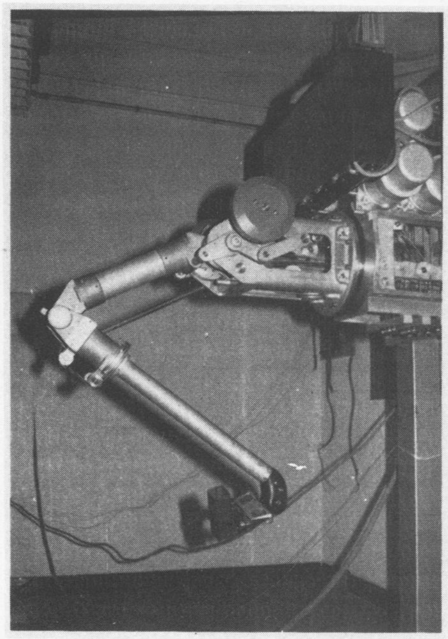

Fig. 3. Photograph of MA-23 slave manipulator.

III. Application

The proposed scheme of two-level coordination has been tested by using a model of the MA-23 slave manipulator [16] shown on the photograph in Fig. 3. Some results are shown in Figs. 5 and 6, which correspond to the task of drawing a circle of radius $R = 300$ mm in a vertical plane (Fig. 4) with a pencil rigidly gripped by the terminal device of the manipulator. The task's achievement thus requires $m = 3$ degrees of freedom, while the arm possesses $n = 6$ revolute joints with the following angular limitations[1]:

$$\begin{aligned}
y_{1m} &= -60^\circ \le \bar{y}_1 \le 60^\circ = y_{1M}\\
y_{2m} &= -70^\circ \le \bar{y}_2 \le 57^\circ = y_{2M}\\
y_{3m} &= -135^\circ \le \bar{y}_3 \le -30^\circ = y_{3M}\\
y_{4m} &= -179^\circ \le \bar{y}_4 \le 179^\circ = y_{4M}\\
y_{5m} &= -29^\circ \le \bar{y}_5 \le 109^\circ = y_{5M}\\
y_{6m} &= -180^\circ \le \bar{y}_6 \le 180^\circ = y_{6M}.
\end{aligned} \tag{13}$$

[1] This is a simplifying assumption for illustrative purposes. The actual limitations due to the driving mechanisms must also be taken into account in the exact model (see [3]).

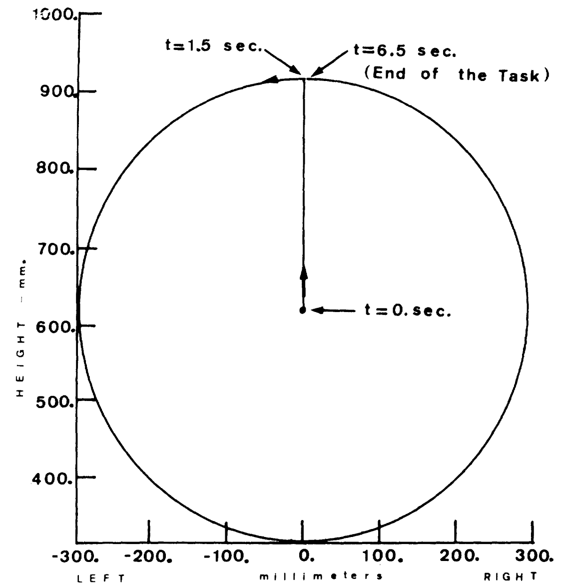

Fig. 4. Definition of task.

If the drawing point is situated along the sixth joint axis of rotation, this last movement is decouped from the other ones. In the task defined in Fig. 4, the increments in the E^m space are approximately equal to $\|dX\| = 2$ mm.

Fig. 5 shows the time-history of the joint angles when the lower level of coordination is used alone. In the case presented here, the simple decision scheme involved in this level consists in selecting, among the ten possible solutions (or fewer, if some joints hit their stops), the association G_1 of the three joint motions which avoids the singularities; the values of the ten 3×3 minors of J are scanned, and the maximum determinant is taken as the leading (principal) minor. The computer-simulated records reproduced in Fig. 5 show that the arm's final attitude is not "better," considering the inequality constraints (13), than the attitude which corresponds to the previous identical point on the circle in the E^3 space.

For the same arbitrarily chosen initial configuration, Fig. 6 exhibits the evolution of the joint angles when a second level of coordination is added, which forces the system to minimize (when there are no obstacles) the quadratic form:

$$H(Y) = \frac{1}{6} \sum_{i=1}^{i=6} \left(\frac{y_i - a_i}{a_i - y_{iM}} \right)^2$$

$$a_i = (y_{iM} + y_{im})/2. \qquad (14)$$

The different behaviors resulting from the two tactical-strategical algorithms can be easily compared. For instance, the records in Fig. 5 show that the three angles y_1, y_2, and y_3 are normally used; y_4 is zero, and y_5 is kept constant except in the interval $3.40 \text{ s} \leq t \leq 3.93$ s where it is used in place of y_3 which is saturated ($y_3 = y_{3M}$). On the contrary, Fig. 6 shows a better behavior of the five joint motions cooperating in order to avoid the mechanical constraints, and to force $H(Y)$ to decrease even when the circle is achieved ($t \geq 6.5$ s). In this way, the proposed control schema is able to drive the manipulator to reach its best availability (minimization of the deviations from the mean positions), during the phases when the intelligent supervisory control level is computing a new strategy of action (problem-solving) while maintaining the previously reached subgoal in the E^m space. Furthermore, the operator can change as it (he) wills the dynamical behavior by acting on-line upon G_2 and/or α in (7) and (10).

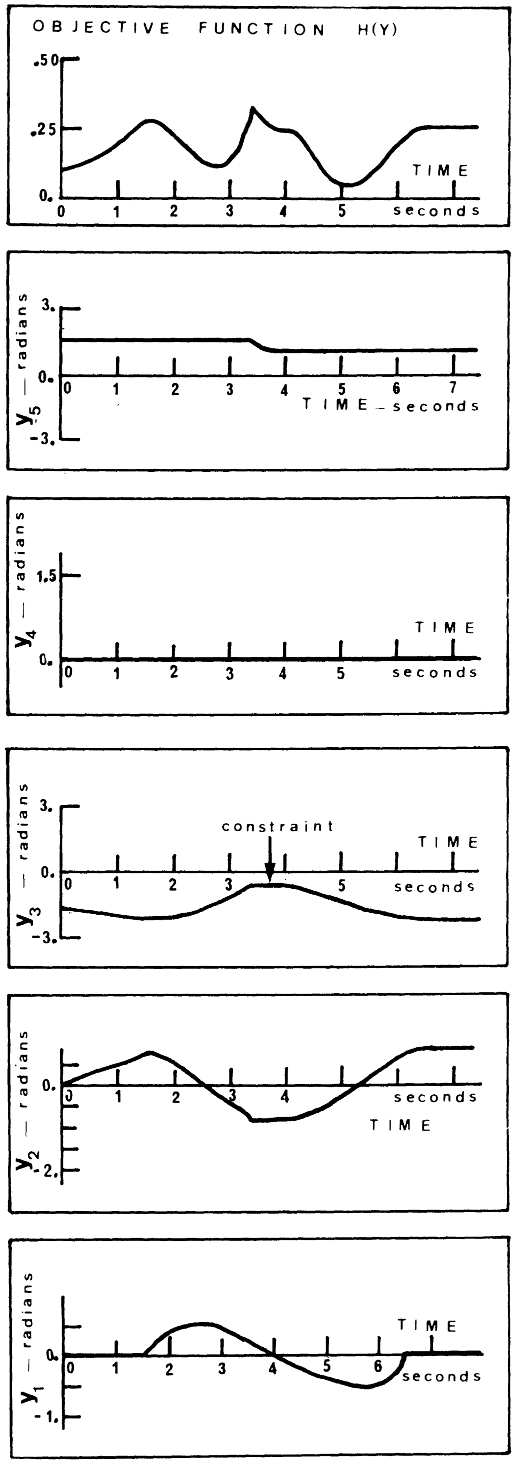

Fig. 5. Local coordination.

IV. Conclusions and Perspectives

A two-level coordinating control system has been proposed for designing highly adaptive actively controlled complex mechanical systems. The control system consists of the following.

1) An automatic coordination level which is able to select the best "synergy" of the various joint displacements, in the sense of a local criterion taking into account the internal constraints: mechanical stops, singularities, maximum velocities, etc.

2) A supervisory level which is able to modify the behavior of the mechanism when it is necessary to add more global criteria

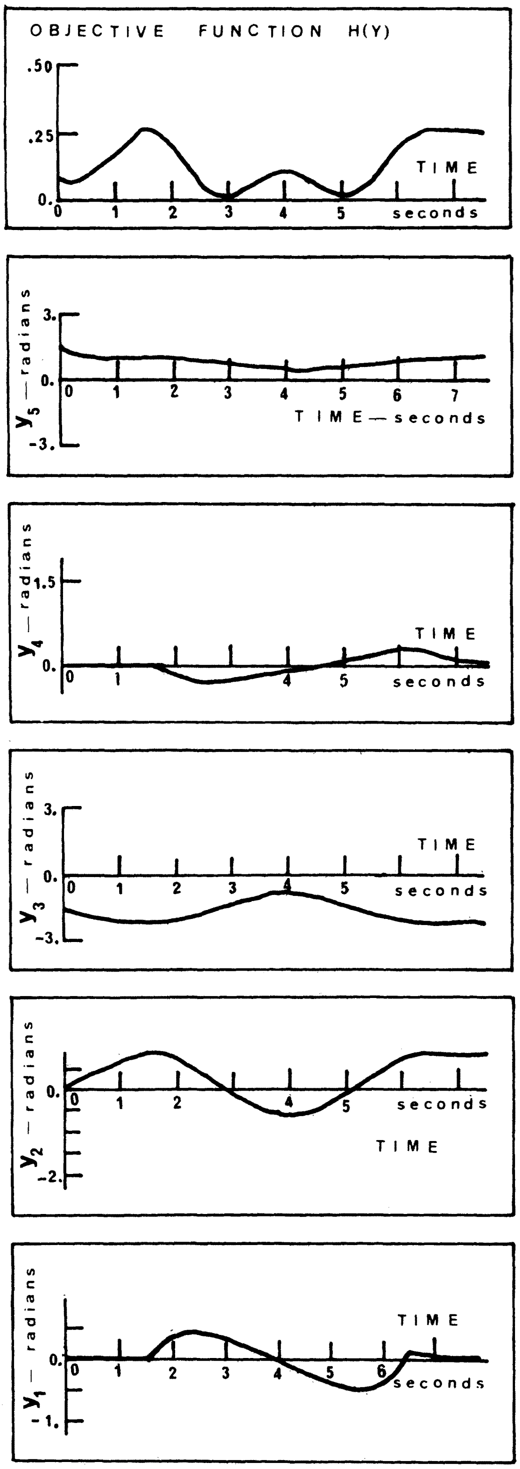

Fig. 6. Two-level coordination.

and constraints, such as obstacle avoidance or availability (in the sense of flexibility with respect to unforeseen changes of goals and actions which are planned by the human operator or by an artificial plan generator).

The question remains, however, of implementing the given algorithms in a practical manner, taking into account actual constraints on cost, reliability, and execution time of the coordinating processor. This problem is currently under investigation, and its solution will probably lead to a parallel/hierarchical computing structure.

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The Processing of Two Types of Command Statement: A Contribution to Cognitive Ergonomics

JULIAN NEWMAN

Abstract—**The lack of a cognitive psychology of command statements is identified as a major restriction on human factors studies in the design of computer software. Human command processing was investigated in an experiment in which ten subjects read and executed imperative statements of two logical types, designated "hypothetical standing commands" and "hypothetical one-shot commands," respectively. Analysis of encoding times, execution errors, and execution reaction times showed that the processing of one-shot commands is more complex than that of standing commands. Free recall of command sets revealed organizational processes analogous to those involved in "positive forgetting." Application of the results to the cognitive engineering of human-to-software interfaces is discussed, and directions for further investigation are briefly outlined.**

I. Introduction

A major hindrance to the development of a cognitive ergonomics [26] has been the dubious applicability of available psychological models to the design of human-software interfaces. The study of human factors in any technology must begin with an analysis of the task and its tools, and the elaboration of a suitable framework for the identification of ergonomically critical design

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The author is with the School of Psychology, Ulster College, The Northern Ireland Polytechnic, Newtownabbey BT37 0QB, Northern Ireland.