DYNAMIC CONTROL OF MANIPULATORS
OPERATING IN A COMPLEX ENVIRONMENT*

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One of the main problems arising from the control of manipulators meant to act in a complex and evolving environment is the taking into account of objects and obstacles present in it.

Usually, th solution consists in calling for a high hierarchical level which permanently modifies the objectives of lower levels according to the constraints of the environment. This approach is of a great complexity at higher algorithms level and leads to serious problems in real time control.

The paper presents a synthesis method taking directly into account the obstacles by elaborating a force and torque control depending on an evolutive representation of the environment.

The results obtained by applying the control algorithm defined herewith to three examples of simulated manipulators, illustrate the efficiency of this method which, besides, ensures a good dynamic behaviour to the manipulator and allows it to move rapidly in presence of obstacles or in case of saturation of degrees of freedom.

Two main characteristics are required while designing a robot:

- its versatility, it is the ability to execute various tasks,
- its adaptability, it is the ability to perform a task in various conditions (saturation - evolving environment).

One of the main problems in the design of robots is developing the control algorithms. This can be done by a hierarchical approach in considering three levels of command:

- a decision level which provides a plan of operations for a given global objective
- a strategic level: which decodes each action generated by the former level, computes the following level's inputs and surveys the proper execution of these actions by solving difficulties which may occur during the execution.
- an execution level: which computes the input signals to be applied to each degree of freedom of the manipulator.

In order to be versatile and adaptative, a manipulator, like a biological system, has to be redundant, that is it has to have more degrees of freedom than necessary to execute a given action.

But the redundancy necessary for such a manipulator increases the complexity of the two problems arising at the third level's design, that is:

- the modelling of articulated mechanical systems
- the control synthesis

The main modelling methods for such systems are given in [10]. Several general programs of automatic generation of motion equations have been developed so far:

T.O.A.D. programs (Tele Operator Arm Design) [9], O.S.
S.A.M. (Ohio State Symbolic Algebraic Manipulator) [4] and
E.D.Y.L.M.A. (Equation Dynamique Litterale d'un Manipulateur
Articulé)[5], and all are very useful tools in articulated
systems design.

EDYLMA seems to provide a good compromise between the
TOAD and OSSAM programs' performances.

The control synthesis methods of redundant manipulators
can be separated into two large classes:
- methods considering the system kinematics only. The gen-
  eralized velocity is the controlled quantity (kinematic
  control) [3].
- methods leading to a generalized force control (dynamic
  control) [8], [10].

The kinematic control does not allow to obtain a fast
evolution of the manipulator and requires an arbitrary pre-
determination of the trajectory. This is why a dynamic con-
trol is preferable.

On the other hand, few synthesis methods consider the
environmental constraints [6]. Such constraints are gener-
ally included in the upper level algorithm which transmits
new data to the execution level, whenever the environment
makes the execution of the action impossible. The solution
of the problems arising from the environment leads to a rap-
idly increasing complexity of the upper level algorithm with
the required degree of adaptability, and presents a diffi-
cult problem for a real time control. The environmental
constraints are not considered at the execution level be-

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cause the control is deduced from the manipulator model only.

In this connection we propose for this level an adaptative control method derived from an evolutive representation of the environment. This method allows to reduce the load on the strategical level and provides a great adaptability for the execution level.

I. DYNAMIC CONTROL

The considered system has n degrees of freedom and is composed of rigid parts and joints of rotative and telescopic type. Let $Q = (q_1 q_2 \ldots q_n)^T$ be the vector representing the n generalized coordinates $Q \in E^n$ and $X = (x_1 x_2 \ldots x_m)^T$: the "objective" vector, the m components of which are independant variables; $X \in E^m$ and is represented by point M in this space.

The system's degree of redundancy is defined by (n-m).

This system has the kinetic energy T, and evolves in a potential U according to Lagrange equations

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = F_d^j, \qquad \text{where } L = T - U.$$

F_d^j is a non potential dissipative force.

The method exposed by M. Renaud [10] consists in considering the potential U as the sum of the gravity potential U_g and an imposed artificial potential U_{art}:

$$U_{art} = U_a + (-U_g),$$

where U_a is a potential allowing to reach the desired point.

Consequently, the generalized forces to be applied to the joint j are:

$$F_g^j = - \frac{\partial}{\partial q_j} \; [-U_g] \quad \text{and} \quad F_a^j = - \frac{\partial}{\partial q_j} \; [U_a]$$

and the Lagrange equations become:

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_j} \right) - \frac{\partial T}{\partial q_j} = F^j, \quad \text{where} \quad F^j = F_d^j + F_a^j + F_g^j \; .$$

The function U_a is obtained by fixing in the space E^m a concave and positive potential function V_a, the minimal null value of which is reached for $\underline{X} = \underline{X}^F$ ($\underline{X}^F$: vector corresponding to the imposed final point M^F)

$$V_a = V \; (x_1, x_2, \ldots, x_m) \geqq 0$$

and

$$V_a = 0 \iff \underline{X} = \underline{X}^F \; .$$

The relation between the components of vector $\underline{X}$ and the generalized coordinates $\underline{X} = G \; (\underline{Q})$ allows to compute the system's Jacobian matrix:

$$J \; (\underline{Q}) = \frac{\partial}{\partial \underline{Q}} \; (\; G \; (\underline{Q})).$$

The function G, usually nonlinear, is not injective in the case of a redundant manipulator.

The vector $\underline{F}_a$ is given by:

$$\underline{F}_a^j = -J^{j^T}(\underline{Q}) \quad \text{grad} \; V_a \; .$$

Computing the generalized forces to be applied to the manipulator does not affect its stability. Therefore the appli-

cation of the dissipative forces is necessary.

In the method mentioned above, these forces are of the form:

$$F_d^j = - 2 \xi_j q_j,$$

where ξ_j is the damping factor.

In the space of Cartesian coordinates, this stabilization method does not lead to a satisfying dynamic behaviour. For this reason, we introduced dampings operating directly on the Cartesian coordinates of the velocity, apart from the terms including $\dot{q}_j$.

The dissipative forces are therefore of the form:

$$\underline{F}_d = - (\xi_1 \dot{\underline{Q}} + \xi_2 J^T (\underline{Q}) \dot{\underline{X}}).$$

The generalized forces to be applied to the manipulator are:

$$\underline{F}_p = \underline{F}_a + \underline{F}_g + \underline{F}_d.$$

Figures 1 and 2 show the improvement resulting from the introduction of damping terms proportional to $\dot{\underline{X}}$, in case of two different manipulators (The Rancho Arm Modified) and a manipulator operating in the OXZ plane and possessing two rotations and one translation (Rotheta 2).

II. ADAPTATIVE CONTROL SYNTHESIS

The problem to be solved is to make a manipulator's terminal device, operating in a complex environment, move to a given position, eventually along a predefined path. The

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philosophy of our approach can be schematically described as follows:

"The manipulator moves in a field of forces. The final position to be reached is an attractive pole for the terminal device, and the obstacles are repulsive surfaces for all the manipulator parts."

Thus, the control vector will be composed of two terms; the first one is $\underline{F}_p$ (§ 1), and the second term is vector $\underline{F}_0$ which accounts for the environment.

The computing of vector $\underline{F}_0$ is explained in § II. 2. Now we shall be concerned about modelling of the environment.

II.1. $\underline{Environment\_modelling}$. This model is characteristic to the control execution level. The decision level world representation allows the strategic level to provide the elements concerning the environment which will be used by this model. We shall use the term "object" to designate anything that belongs to the manipulator's environment; for a given object, this modelling aims to obtain analytic equations describing an envelope approximating at the best the object's shape.

Objects description methods show that a large class of objects may be described by composition (union, subtraction, addition) of objects of simple shapes called "primitives" [1],[2].

As it will be shown later (§ II.2), the operation of subtraction can not be used for this modelling. However, we shall associate each object θ_i requiring the use of this operation, with the objects θ_i^p and θ_j^v described only by

union operations, so that the object θ_i can be described by:

$$\theta_i = \theta_i^P - \sum_{j=1}^{m_i} \theta_j^V \quad .$$

Let θ be the set of objects, envelopes of which are obtained by the union of a given number of elementary surfaces described by analytic equations. An object $\theta_i \in \theta$ is described by the set of equations E_i.

$$E_i \triangleq \left\{ f_i^j (x,y,z) = 0 \; ; \; j = 1, n_i \right\} \quad ,$$

where $f_i^j (x,y,z) = 0$ are the analytic equations associated with the primitives of different forms, for instance

$$\left(\frac{x-x_0}{a} \right)8 + \left(\frac{y-y_0}{b} \right)8 + \left(\frac{z-z_0}{c} \right)8 = 1 \quad \text{for a parallelepiped,}$$

$$\left(\frac{x-x_0}{a} \right)2 + \left(\frac{y-y_0}{a} \right)2 + \left[\frac{1}{2} \left(\left(\frac{z-z_0}{c} \right)8 + \left(\frac{z-z_0}{c} \right)7 - \left(\frac{z-z_0}{c} \right) + 1 \right) \right]2 = 1 \quad \text{for a cone,}$$

$$\left(\frac{x-x_0}{a} \right)2 + \left(\frac{y-y_0}{a} \right)2 + \left(\frac{z-z_0}{c} \right)8 = 1 \quad \text{for a cylinder.}$$

II.2. The control computing. To object $\theta_i \in \theta$ is associated with the set of equations E_i. Let F be the set of the mappings F_i from R^3 to R defined as follows:

$$F_i \triangleq \left\{ f_i^j \{x,y,z\} \; ; \quad j = 1, n_i \right\} \, .$$

For each element $f_i^j \in F_i$, we compute a potential function V_i^j having the following properties:

- $V_i^j (x,y,z)$ has a continuous gradient in $R^3 - \{x,y,z$; $f_i^j (x,y,z) = 0\}$.

- $V_i^j (x,y,z)$ is defined non negative.

- When $f_i^j (x,y,z)$ approaches zero, the potential $V_i^j (x,y,z)$ approaches infinity .

- For a given point $M (x^*, y^*, z^*)$ for which $f_i^j (x^*, y^*, z^*) \neq 0$, the potential $V_i^j (x,y,z)$ is identically null in the domain defined by

$$\left\{ x,y,z \; ; \quad | f_i^j (x,y,z)| > |f_i^j (x^*, y^*, z^*) | \right\} .$$

The last property enables us to define in the vicinity of the obstacle a surface inside or outside of which the potential V_i^j is null.

The potential $V_i^j (x,y,z)$ provided with these properties, defines at each point of the surface $f_i^j (x,y,z) = 0$, a potential barrier which becomes progressively negligeable beyond that surface. This allows the fast decreasing of the obstacle's influence, and the positioning of the manipulator near it regardless the obstacle shape and dimensions.

For a given $M (x^*, y^*, z^*)$ we may choose the potential:

$$V_i^j (x,y,z) = \begin{cases} (1/f_i^j (x,y,z) - 1/f_i^j (x^*, y^*, z^*))^2 \\ \qquad \qquad \text{for } | f_i^j (x,y,z)| \leq | f_i^j (x^*, y^*, z^*) | \; , \\ 0 \qquad \qquad \text{for } | f_i^j (x,y,z)| > | f_i^j (x^*, y^*, z^*) | \; . \end{cases}$$

The gradient continuity is ensured at the vicinity of the surface

$$f_i^j (x,y,z) = f_i^j (x^*, y^*, z^*)$$

since the function $V_i^j (x,y,z)$ partial derivatives are all null on both sides of the equation.

Considering the sum of potentials obtained from F_i, we have at each point of the surface enveloping the object θ_i an infinite potential barrier. Since for objects $\theta_i \in \theta (\theta_i = \theta_i^p - \sum_j \theta_j^v , \quad \theta_i^p \in \theta, \quad \theta_j^v \in \theta)$ the surfaces approaching θ_i^p and θ_j^v are not generally confounded, the subtraction of the associate potentials does not lead to an infinite potential barrier on such objects' envelope.

Let V_o^i be the sum:

$$V_o^i (x,y,z) = \sum_{j=1}^{n_i} V_i^j (x,y,z)$$

and let $N_K (x_K, y_K, z_K)$ be a given point of the manipulator, $N (x,y,z)$ its terminal point and $M_F (x_F, y_F, z_F)$ the final position to be reached in the environment devoid of the obstacles. Let θ_i be an imaginary object defined by E_i, supposed to be present in that environment, and consider the vector $F_o^{iK} = J_K^{jT} (Q)$ grad $(V_o^i (x_K, y_K, z_K))$. Applying the control $F = F_p + F_o^{iK}$ to the manipulator, its terminal device moves to the final position M_F.

The effect of V_o^i on point N_K (PSP: Potential Submit-

ted Point) forces this point's path to pass around the enve-
lope defined by E_i (see Figure 3). Defining an adequate num-
ber of PSPs enables to control all the manipulator parts, re-
garding a given object θ_i. The control vector then is:

$$F = F_p + F_o^i \text{ where } F_o^i = \sum_K F_o^{iK} \,.$$

In the same way, many objects can be easily taken into
account by PSPs after choosing the control vector: $F = F_p +$
$+ F_o$, where $F_o = \sum F_o^i$.

Hence, the manipulator will avoid all the obstacles in
its environment. Figure 4 shows the displacement of a manip-
ulator having four rotations (theta 4) in the OXZ plane, in-
side an enclosure.

Saturations. Generalized coordinates variations are usu-
ally limited

$$q_{i\ min} \leq q_1 \leq q_{i\ max}\,.$$

This defines a domain in the Euclidian space E^n to which
vector Q has to belong. Defining two infinite potential bar-
riers in the two hypersurfaces $q_i = q_{i\ min}$ and $q_i = q_{i\ max}$,
for each generalized coordinate q_i, and adding the forces
derived from these potentials to the corresponding control
vector components, makes possible to avoid the saturation
problems. An example is given in Figure 5.

II.3. Control organization and execution. The applica-
tion of the control, computed in the former section, to the
manipulator may lead under some specified conditions to sta-
ble states different from the imposed final state.

These states are related to the local minima of the potential function. Numerous mechanical locking cases may be resolved by introducing at the strategical level an unlocking procedure. This procedure could either be a suitable weigthing of the attractive potential gains in the directions Ox,Oy,Oz, or the definition of intermediate objective points. The major mechanical lockings that can not be resolved by such a procedure will be of the decision level competence.

Concerning objects $\theta_i \notin \theta$, defined by $(\theta_i = \theta_i^p - \sum_j \theta_j^v, \theta_i^p \in \theta, \theta_j^v \in \theta)$, two cases can be met:
- the required operation does not concern volumes θ_j^v, in this case, θ_i^p will be considered instead of θ_i.
- the displacement has to take place inside the volume θ_j^v; in this case, the operation will be carried out in a number of stages during which objects θ_i^p and θ_i^v will be successively considered or not.

Thus, this problem can be resolved at the strategic level by a specialized algorithm.

Data provided by the strategic level are of two kinds:
- data concerning the objective to be reached (final position, path, attitude).
- data related to environment (objects, PSPs).

An evolutive procedure taking into account the environment, permits to reduce largely computations by restricting them to the surrounding obstacles only.

Such a procedure consists in fixing, for a given operation, the objects that may collide with the manipulator, and defining the number and location of the corresponding PSPs.

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III. CONCLUSION

We believe that the synthesis method exposed above provides a quite interesting solution to some problems of adaptative manipulator control, especially those related to the environment; this last sort of problems is resolved quite simply by elaborating, at the execution level, a command depending on the environment representation.

This reduces the control total computing time and the load over higher levels, and thus increases the control system availability.

On the other hand, this method permits to force the manipulator to have a given attitude during its motion and to satisfy for the best some given constraints at its final state, each additional constraint being simply introduced by adding a corresponding potential function.

The introduced damping terms proportional to $\dot{X}$ and the adopted repulsive potentials shape, ensure a satisfying dynamic behaviour of the manipulator and permit it to move rapidly in the presence of obstacles and in case of saturation of degrees of freedom.

The development of unlocking procedures, operations of decomposition, objects and PSP definitions, at the strategic level, permit the adaptative and versatile control system to be designed, suiting the increasing demand of the advanced manipulators.

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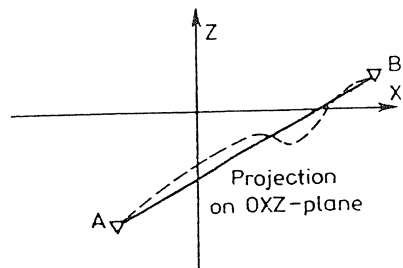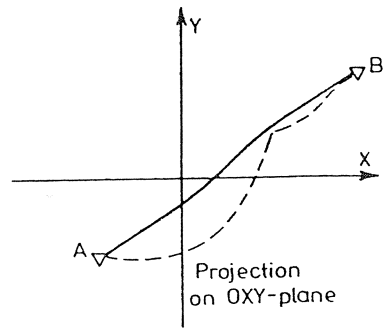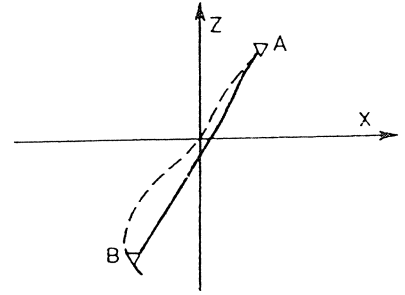
Fig. 1. Influence of damping
by $\underline{\dot{x}}$ (RAM) (full line).

Fig. 2. Influence of damping by
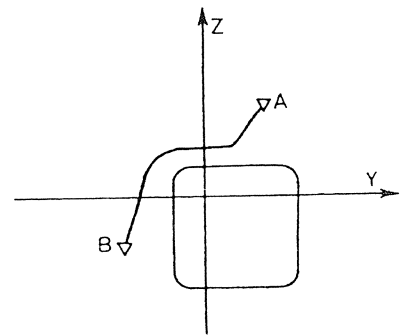$\underline{\dot{x}}$ (Rotheta 2) (full line).
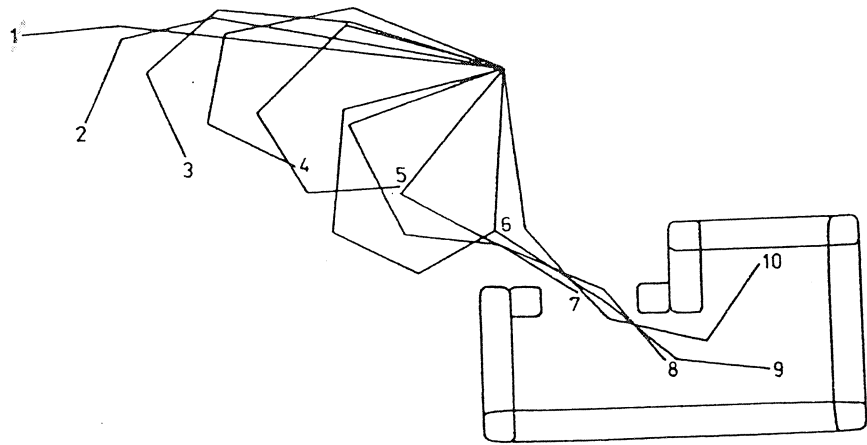

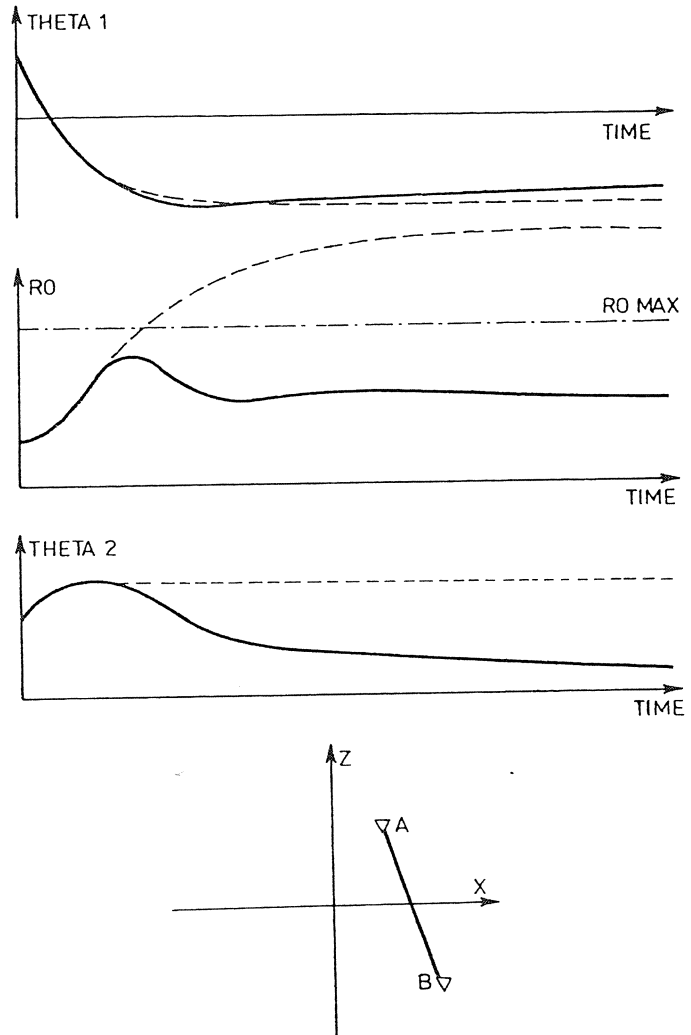Fig. 3. Avoiding an obstacle.

Fig. 4. Displacement of THETA 4 inside an enclosure.

Fig. 5. Taking saturation into account.