OPERATIONAL SPACE CONTROL OF COMPLEX MODULAR ROBOTIC STRUCTURES VIA DP BASED KINEMATIC INVERSION TECHNIQUES

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Abstract: The work deals with modular complex kinematic chains governed by an embedded distributed control system. More precisely, every joint of is assumed equipped with a simple local processing unit for properly driving its motion. As a consequence, each one of them plus the associated link is considered as a defective "1-dof only" separately controlled atomic manipulator, which is required to act in team with all the others, in order to accomplish to a common task specified in the operational space. In this framework the paper proposes a computationally distributed kinematic inversion technique that, via the on-line application of dynamic programming (based on a moderate data exchange among the processing units), allows the establishment of a global self-organizing behaviour; thus allowing the task execution by solely exploiting the control capabilities of each local processing unit, while also not requiring any acknowledge about the overall structure geometry and kinematics.

Keywords: Robot Control, Distributed Control, Dynamic Programming, Robotic manipulators, Kinematics.

1. INTRODUCTION

The paper considers manipulation structures of possibly high complex nature (see for instance fig. 2) characterized by the presence of a totally distributed embedded control system. More specifically, every joint within the structure is assumed to be equipped with a local "processing and communication unit" (PCU) (micro-controller or FPGA based) interfaced with both the joint sensory and actuation system, plus a communication system allowing data exchanges between adjacent joints. All the PCU's are assumed to be identical and devoted, each one, to properly drive the motion of its associated joint, thus allowing to consider each pair joint+link as a defective "1-dof-only" separately controlled atomic manipulator. As it will be better clarified within the work, the presence of additional PCU's, located in correspondence of the mechanical connection between two or more sub-chains (called "Y node") needs to be assumed for properly processing the information acquired from its connected sub-chains.
In this framework, the problem of controlling the operational space motion the of the overall kinematic structure, can be formulated in terms of decentralized control; requiring all the atomic manipulators to cooperate in order to guarantee the end-effectors of the overall structure to reach any assigned position and/or tracking any given trajectory.
In this perspective the paper proposes an effective distributed kinematic inversion control technique that, based on a set (one for each sub-chain) of finite step LQ dynamic programming algorithms that automatically induces a global self-organizing behaviour, which allows the task execution.
The distributed implementation of such dynamic programming algorithm is actually made feasible as the result of the moderate amount of information that every PCU needs to exchange with its adjacent ones, during each sampling interval.
The data exchanged during each transmission are always of the same constant dimensions and typology, thus resulting unrelated with both the structural complexity of the composing sub-chains and the number of their d.o.f.'s.
Moreover, since the set of information received by each PCU results sufficient to compute the control action in an optimal way, this consequently leads to a global optimal execution of the assigned task, without actually requiring any centralized a-priori

knowledge about the geometry and kinematics of the overall structure.

The paper is here intended as a new contribution to the whole field of modular robotic systems, in the sense that it allows to enlarge the original modularity concepts intensively dealt within the literature ([5-8]), till the operational space control level; being this last an issue that, at the best of authors knowledge, seems having been very little considered till recent years ([1]) and however, when seldom considered, always referred to centralized approaches. ([9-11]).

Meanwhile it also represents a breakthrough with respect to few very recent seminal works of the authors on the subject [2-4]. In [12] the problem of self-coordination within modular atomic units were for the first time approached, via the use of iterative techniques possibly exhibiting some limitations, for increasing complexities, as a consequence of the allowed communication bandwidths.

The more efficient dynamic programming based decentralized approach to inverse kinematic was instead introduced by the authors within the very recent work [13], even if with reference to open linear kinematic chains only.

The present paper, aims to extend the results of [13] to sub-chains connections of more complex nature.

2. LINEAR KINEMATIC CHAINS

Consider a generic open linear kinematic chain as in fig.1, where *<o>, <e>, <t>* denote the absolute-frame, the end-effector frame and the tool-frame (this last rigidly attached to *<e>*) respectively.

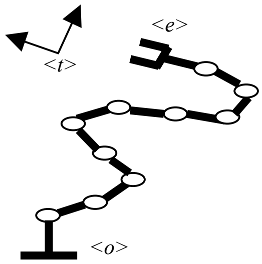

Figure 1.

Also assume that within the first part of each sampling interval a forward-backward pipelined exchange of geometric information is performed along the chain of serially connected PCU's, whose completion allow each *i*-th joint+link to know the current position of its base-frame *<b$_i$>* w.r.t. absolute frame *<o>*, as well as that of the end-effector *<e>* w.r.t. *<b$_i$>* (implementation details regarding such computations are reported in [13]). In the sequel of the section we shall instead concentrate on the successive problem of distributing, within the remaining part of the same sampling interval, all the computation required for then solving the kinematic inversion problem.

To this aim, by letting $\dot{x} \doteq [\omega^T, v^T]^T$ and $\dot{y} \doteq [\omega^T, u^T]^T$ be the end-effector and tool-frame generalized velocities (both referred and projected on *<o>*) respectively, first recall the linear relationship existing between the two; i.e.

$$\dot{y} \doteq S\,\dot{x} \quad ; \quad S \in \Re^{6x6} \tag{1}$$

Where non-singular matrix S represents the rigid body velocity transformation (projected on *<o>*) from frame *<e>* to *<t>*.

For sake of generality, also assume that a linear transformation of tool-frame velocity $\dot{y}$ is externally assigned of the form

$$\dot{\theta} \doteq H\,\dot{y} \quad ; \quad H \in \Re^{mx6} \tag{2}$$

for representing a possible partition of $\dot{y}$ (for instance solely the angular velocity vector ω, or the linear velocity u only) or in alternative any other needed linear transformation of $\dot{y}$, as it will be for instance for the cases that will be better clarified is sections 3 and 4.

Then, by letting $\dot{\bar{\theta}}$ be a desired value for $\dot{\theta}$, the problem of making $\dot{\theta}$ maximally close to the given reference can be formulated finding (generally one of) the solutions of the following quadratic optimization problem

$$\min_{\dot{q}} \left\| \dot{\bar{\theta}} - \dot{\theta} \right\|^2 = \min_{\dot{q}} \left\| \dot{\bar{\theta}} - HS\dot{x} \right\|^2 \tag{4}$$

Where $\dot{q}$ is the joint velocity vector producing the actual end-effector velocity $\dot{x}$, via the well known Jacobian relationship

$$\dot{x} = J\,\dot{q} \tag{5}$$

evaluated in correspondence of the current joint posture q.

By representing vector $\dot{\bar{\theta}}$ via the projected form

$$\dot{\bar{\theta}} = H\,\dot{\bar{y}} + d \doteq \dot{\hat{\theta}} + d \tag{6a}$$

where obviously

$$\dot{\bar{y}} \doteq H^{\#}\dot{\bar{\theta}} + (I - H^{\#}H)\,\dot{z} \tag{6b}$$

$$d = (I - HH^{\#})\,\dot{\bar{\theta}} \perp Span(H) \tag{6c}$$

with $H^{\#}$ the pseudo-inverse of matrix H and where $\dot{z}$ is any finite arbitrary vector; and moreover by also letting

$$\dot{\bar{x}} \doteq S^{-1}\dot{\bar{y}} \tag{6d}$$

we can successively substitute representations (6a), (6d) into (4); thus obtaining the following equivalent representation of the original problem (4)

$$\min_{\dot{q}} \left\| HS(\dot{\bar{x}} - \dot{x}) \right\|^2 + \left\| d \right\|^2 \tag{7}$$

Where the decomposition into the sum of two separate squares follows directly from the orthogonal property expressed by (6c); while the extraction of the second term from the minimum operation is instead a consequence of its independence from $\dot{x}$ and then from $\dot{q}$; thus implying that the solution of the original quadratic optimization