

Dexterous Reconfiguration of a Two-Arm Robot System

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INTRODUCTION

The adoption of robot systems having multiple arms has lately been capturing the attention of an increasing number of robotics researchers. Several are the applications where cooperation may be requested, ranging from manipulation of large, heavy or non-rigid objects to space and underwater robotics.

The cooperation can be successfully performed only when an effective coordination of the arms is realized. This demands for accurate synchronization of relative motions, solution of collision avoidance problems, ease of robot programming, coordinated control, etc.

In the present work, we focus our attention on the mechanics and control aspects of cooperative robot systems. In particular, we are interested to investigating the problem of dexterous reconfiguration for such systems using proper manipulability indices. For the sake of exposition and interpretation of results, the study is focused on two-arm planar systems.

An effective description of the cooperative task space is derived in terms of suitable absolute and relative task variables. The former are naturally expressed in a common base frame for the system while the latter are conveniently referred to a reference frame attached to the object.

A closed-loop inverse kinematics scheme, previously developed for single arms, is here properly adopted to solve the non-trivial problem of finding the joint variables for the two-arm system when cooperative task space variables are assigned. In the case of kinematic redundancies, the scheme can also manage the introduction of additional constraint tasks.

Manipulability indices can be utilized to impose convenient constraints for redundant cooperative systems in order to determine optimal configurations to perform the task. In particular, we consider the force manipulability ellipsoid that gives a measure of the ratio between resulting object forces and applied joint torques; we choose to maximize this ratio along a given task space direction.

A number of case studies are included to analyze the performance of the solution. The unconstrained non-redundant system is solved first. Then, several types of redundancies are introduced by releasing one or more task space variables, and the system is reconfigured to more dexterous configurations to execute the given task.

TASK DESCRIPTION

In order to fully describe a cooperative task for a two-arm robot system, different choices for the absolute and relative variables are possible [1,2]. In the remainder, we restrict our analysis to three-degree-of-freedom planar arms; the cooperative task space is thus at most six-dimensional.

Consider the two-arm robot system carrying an object depicted in Fig. 1. The configuration of the task demands for *three* variables to describe the position and orientation of the object together with *three* variables to describe the relative posture of the two arms with respect to the object.

Our choice is to select first the absolute position of a suitable point on the object; without loss of generality, we have taken the (2×1) vector

$$\mathbf{p}_a = \frac{1}{2}(\mathbf{p}_1 + \mathbf{p}_2) \quad (1)$$

where $\mathbf{p}_1$ and $\mathbf{p}_2$ are the position vectors of the end-effectors of the two arms expressed in a common base frame (x_b, y_b) . Next, we assume that a reference frame (x_o, y_o) is fixed to the object with origin in $\mathbf{p}_a$ and x_o -axis aligned with the vector $\mathbf{w} = \mathbf{p}_2 - \mathbf{p}_1$. Then, the absolute orientation of the object is described as the angle formed by the x_o -axis with the x_b -axis

$$a_a = \text{atan2}(w_x, w_y) \quad (2)$$

Notice that, with the above choice, we implicitly exclude the possibility of end-effector sliding on the object, for which a moving object frame would result.

Next, the relative variables must be specified. First, we consider the relative position of the two end-effectors described by the vector $\mathbf{w}$. However, if $\mathbf{w}$ is conveniently expressed in the object frame, only the x_o component of $\mathbf{w}$ is significant; this is consistent with using one scalar variable to describe this portion of the task. Then

$$p_r = w_x \cos a_a + w_y \sin a_a \quad (3)$$

As for the remaining variables, we select the grasp angle of each arm relative to the x_o -axis, i.e.

$$a_{r1} = a_a - a_1 \quad (4)$$

$$a_{r2} = \pi + a_a - a_2 \quad (5)$$

where a_1 and a_2 represent the orientation angles of the two end-effectors with respect to the base frame; by the way, each angle is given by the sum of the three respective joint coordinates.

We complete our kinematic description of the task by deriving the Jacobian matrices which characterize the dependence of the above-defined variables on all six joint variables. To the purpose, let J_1 and J_2 indicate the (2×3) Jacobian matrices relative to p_1 and p_2 . Then, for the absolute variables of the task we get

$$J_{pa} = \frac{1}{2} [J_1 \quad J_2] \quad (6)$$

$$J_{aa} = [vJ_1 \quad -vJ_2] \quad (7)$$

where $v = (w_x^2 + w_y^2)^{-1/2} [w_y \quad -w_x]$.

On the other hand, for the relative variables of the task we get

$$J_{pr} = (-w_x \sin a_a + w_y \cos a_a) J_{aa} + [\cos a_a \quad \sin a_a] [-J_1 \quad J_2] \quad (8)$$

$$J_{ar1} = J_{aa} + [-1 \quad -1 \quad -1 \quad 0 \quad 0 \quad 0] \quad (9)$$

$$J_{ar2} = J_{aa} + [0 \quad 0 \quad 0 \quad -1 \quad -1 \quad -1] \quad (10)$$

INVERSE KINEMATICS SOLUTION

The inverse kinematics problem has been solved for a general single manipulator by adopting closed-loop algorithmic schemes that are based on the computation of either the transpose or the inverse of the manipulator Jacobian [3,4]. These schemes also allow to account for additional constraint tasks when kinematic redundancy is available [5,6,7].

To illustrate the method, let q denote the $(n \times 1)$ vector of joint variables, x the $(m \times 1)$ vector of end-effector task variables ($m \leq n$), $f(q)$ the direct kinematic function, $J(q)$ the associated Jacobian matrix; if x_d denotes the desired task space trajectory, the general joint velocity solution can be presented in the form

$$\dot{q} = J^\dagger(q) [\dot{x}_d + K(x_d - f(q))] - [I - J^\dagger(q)J(q)]\dot{q}_0 \quad (11)$$

where $J^\dagger$ denotes a pseudoinverse of J , K is a suitable positive diagonal feedback matrix and $\dot{q}_0$ is an arbitrary vector of joint velocities which, projected onto the null space of the Jacobian, can be used to satisfy a constraint task without affecting the end-effector task.

At this point, the task description introduced in the previous section can be effectively used to devise inverse kinematics solutions in the framework of solution (11). In fact, the kinematic mappings (1-5), together with the relative Jacobians (6-10), are functionally expressed in terms of the joint variables of the two arms. Then, depending on the cooperative

task to be performed, proper $f(q)$ and $J(q)$ can be set up for use in the scheme based on relations (1-10); see the case studies in the following section for specific examples.

In the case when the two-arm system is kinematically redundant with respect to the given task, an additional constraint task can be introduced. We have chosen to locally maximize the intersection of the force manipulability ellipsoid [8,9] along a given task space direction [10]; this corresponds to minimizing the scalar quantity

$$c(q) = u^T J_o(q) J_o^T(q) u \quad (12)$$

where u is the (2×1) unit vector identifying the chosen direction in the base frame and J_o^T is the (6×2) object Jacobian transpose representing the mapping between resulting forces on the object and applied joint torques [11]. It can be shown that in our case it is [12]

$$J_o J_o^T = \frac{1}{4} (J_1 J_1^T + J_2 J_2^T) \quad (13)$$

In order to embed the constraint (12) in solution (11), we select the gradient type law

$$\dot{q}_0 = -k_c \nabla_q c(q) \quad (14)$$

where k_c is a positive scalar.

CASE STUDIES

The considered cooperative system is constituted by two equal three-degrees-of-freedom planar arm whose links are 1 m long. The carried object is a disk of radius 0.5 m.

In order to test the effectiveness of the inverse kinematics solution (11) for the two-arm system, a non-redundant case is analysed first. A full six-dimensional task space is considered and all six joint variables are needed to ensure proper task execution; consequently, the joint velocity null space is empty and the second term of solution (11) is dropped. The initial configuration of the cooperative system is shown in Fig. 2; the corresponding values of the task variables are

$$p_a = \begin{bmatrix} 2.5 \\ 0 \end{bmatrix} \quad a_a = 0$$

$$p_r = 1 \quad a_{r1} = 0 \quad a_{r2} = 0$$

The task is to achieve the following values for the task variables (with given smooth trajectories)

$$p_a = \begin{bmatrix} 2 \\ 0 \end{bmatrix} \quad a_a = \frac{\pi}{6}$$

$$p_r = 0.8 \quad a_{r1} = -\frac{\pi}{6} \quad a_{r2} = \frac{\pi}{4}$$

Figure 2 shows the resulting final configuration; Figure 3 reports the obtained task-space trajectories which confirm the satisfactory performance of the scheme.

The inclusion of a constraint task is investigated in the following examples; to the purpose, a cooperative task space of reduced dimension has to be considered to provide a non-empty joint velocity null space. The initial configuration in all cases has been chosen so that an isotropic force ellipsoid is obtained; the values of the task variables are

$$\mathbf{p}_a = \begin{bmatrix} 1.5 \\ 1 \end{bmatrix} \quad a_a = 0$$

$$p_r = 1 \quad a_{r1} = 0 \quad a_{r2} = \frac{\pi}{2}$$

It is required that some task space variables remain constant while the degrees of freedom gained with the exclusion of the remaining variables are exploited to reconfigure the cooperative system minimizing the constraint (12) with

$$\mathbf{u} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

The assigned initial and obtained final configurations and respective force manipulability ellipsoids are illustrated for each example together with the time history of the constraint function.

In Figs. 4-5 the object orientation a_a is free: The constraint has been minimized within the limits of the available cooperative system workspace for the assigned task; notice that the left arm cannot further move without changing the grasp angle or losing the grasp.

In Figs. 6-7 the grasp angles a_{r1} and a_{r2} are both free, in Figs. 8-9 the absolute position $\mathbf{p}_a$ is free, in Figs. 10-11 all the orientation angles a_a , a_{r1} and a_{r2} are free: With respect to the previous example, the workspace limits are not reached and the reconfiguration is arrested as soon as a local minimum for the constraint is achieved.

In Figs. 12-13 the absolute position $\mathbf{p}_a$ and the grasp angles a_{r1} and a_{r2} are free: In this particular case, the system is allowed to reach the global minimum for the constraint which corresponds to a degenerate force ellipsoid; in fact, the final configuration of the arms is such that the system can sustain object forces of any magnitude along the given horizontal task space direction.

CONCLUSION

An inverse kinematics solution scheme has been devised for a two-arm redundant cooperative system with a force manipulability ellipsoid constraint. The

developed case studies have demonstrated that the solution is very flexible as it can handle different types of redundancies. Nonetheless, it should be remarked that the inverse kinematics of more complex multi-arm systems can be solved with the proposed scheme if an effective description of the cooperative task is provided. Moreover, other kinds of constraints can be considered in the same framework as long as they can be functionally characterized in terms of the joint variables of the overall system.

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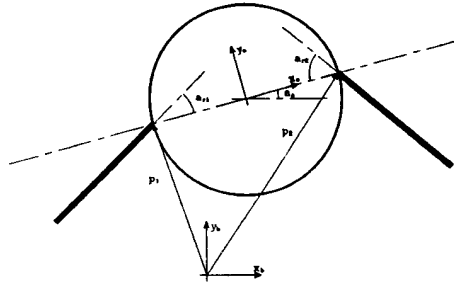


Figure 1. Schematic of two-arm cooperative system

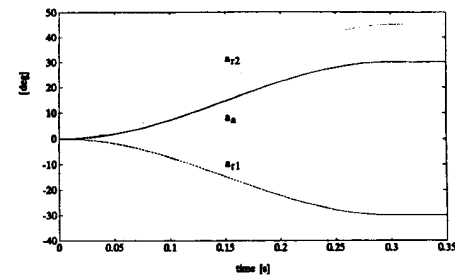
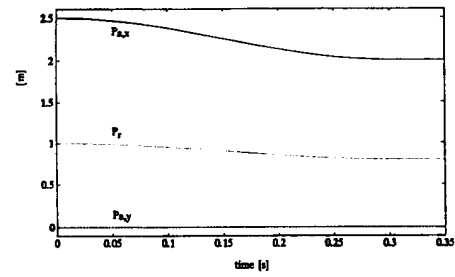


Figure 3. Obtained task space trajectories for the unconstrained case

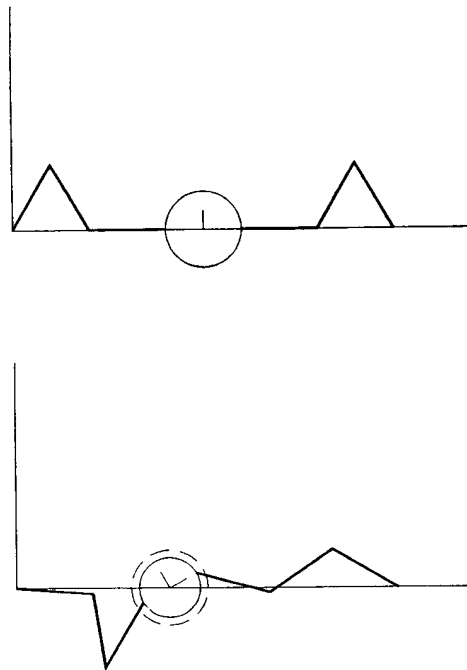


Figure 2. Initial and final configurations for the unconstrained case

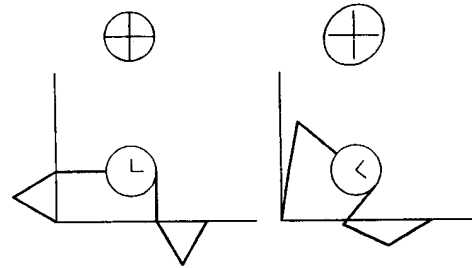


Figure 4. Initial and final configurations with force ellipsoids (a_a free)

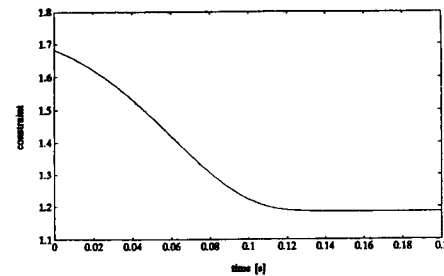


Figure 5. Time history of constraint value (a_a free)

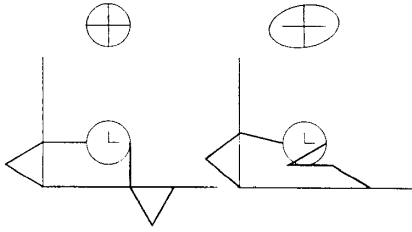


Figure 6. Initial and final configurations with force ellipsoids (a_{r1} and a_{r2} free)

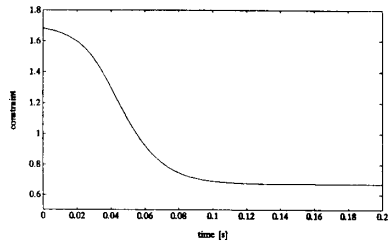


Figure 7. Time history of constraint value (a_{r1} and a_{r2} free)

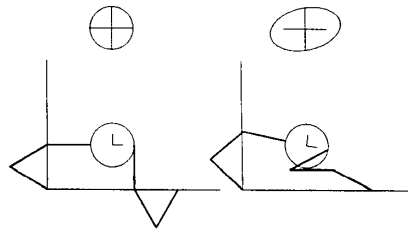


Figure 10. Initial and final configurations with force ellipsoids (a_a , a_{r1} and a_{r2} free)

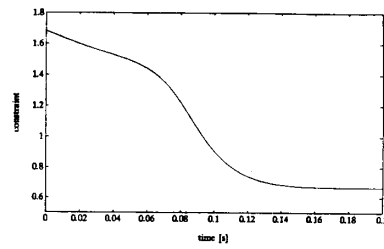


Figure 11. Time history of constraint value (a_a , a_{r1} and a_{r2} free)

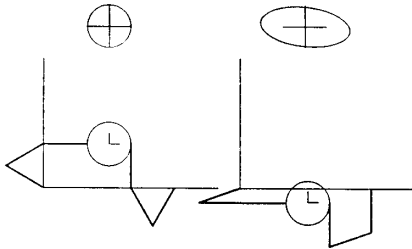


Figure 8. Initial and final configurations with force ellipsoids (p_a free)

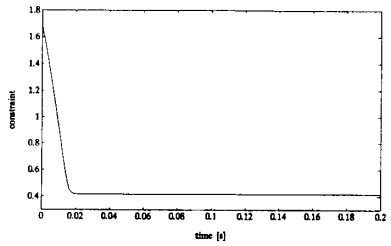


Figure 9. Time history of constraint value (p_a free)

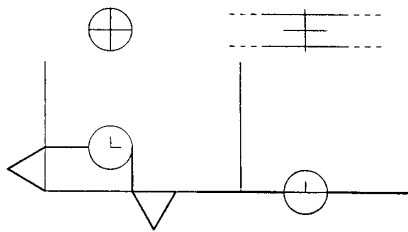


Figure 12. Initial and final configurations with force ellipsoids (p_a , a_{r1} and a_{r2} free)

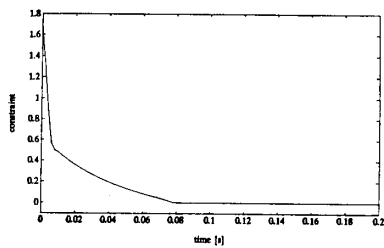


Figure 13. Time history of constraint value (p_a , a_{r1} and a_{r2} free)