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Kinematic control of redundant robots with guaranteed joint limit avoidance☆

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HIGHLIGHTS

- A novel kinematic control signal guaranteeing joint limit avoidance is proposed.
- In sensor driven tasks it generates feasible paths to the target.
- With planned task trajectories it can act as a null-space velocity.
- Smooth joint trajectories and accurate target reaching are achieved.
- Experimental results with a KUKA LWR4+ manipulator demonstrate its performance.

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ABSTRACT

A novel approach for addressing the inverse differential kinematics of redundant manipulators in the presence of hard joint position constraints is presented. A prescribed performance signal for joint limit avoidance guarantees is proposed that can be utilized with both planned and on-line generated trajectories. In the first case, it is a null space velocity for the primary task velocity mapping while in the second case, it modifies the generated reference by acting on the whole velocity space producing a feasible path to the target. Experimental results utilizing a 7DOF KUKA LWR4+ arm demonstrate the performance of the proposed kinematic controller.

1. Introduction

The new generation of robots that are intended for use in human centered environments are usually kinematically redundant in the sense that they possess more degrees of freedom than those required to perform a certain task. Motion coordination with redundant degrees of freedom requires a redundancy resolution scheme that can perform satisfactorily under constraints, disturbances and real-time control in dynamically changing environments. The problem of redundancy resolution is the focus of recent research activity and remains a challenging problem.

Respecting joint limits is often the main criterion when exploiting redundancies. In fact joint variables are limited by mechanical constraints and if the limits are violated in actual implementations, then physical damages may occur by commanded joints hitting their mechanical bounds. Thus, joint limit avoidance is a classical and crucial issue in robot control and one of the most important properties of the inverse kinematic solutions. The most common procedure to avoid joint limits is to treat joint limit avoidance as a secondary task and project into the kernel of the Jacobian matrix a signal that optimizes the joint avoidance criterion (e.g. minimizing the distance from the center value of the joint range) [1,2]. The use of the projection operator means that the joint limit avoidance process has no effect on the primary end-effector task. Unfortunately the success of this method relies on a parameter that has to be precisely tuned in order to ensure the joint limit avoidance. If badly chosen the task may fail [3]. In general, all methods that treat joint limit avoidance as a secondary task including Jacobian weighting [4,5] and task augmentation [6,7], cannot guarantee joint limit avoidance. Joint clamping that has also been used to block joints that reach their limits may result in permanent blocking some degrees of freedom [8]. Task priority strategies have also been utilized in handling joint limits. These methods resolve the

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priority problem among the tasks via the use of activation matrices which however introduce discontinuities in the inverse operator [9,10] even when the activation matrix is continuous with respect to joint activation [11]. Within the task priority framework, a general purpose optimization algorithm suggested in [12] solves the joint limit avoidance problem by formulating it as a constrained minimization of a quadratic function under equality and inequality constraints but with high computational cost. The QP solver was improved in [13] allowing satisfactory real time implementation of the method. However, the elementary form of the joint limit constraints is not exploited, resulting in computationally less efficient algorithms than those explicitly handling joint bounds such as the saturation in the null space algorithm (SNS). This algorithmic method handles joint bounds in position, velocity and accelerations, considering time scaling modifications on the planned task trajectory [14–16]. However, SNS relies on the existence of a planned trajectory which is typical of the traditional two stage approach of path/trajectory planning and motion execution and may not be applied in sensor driven tasks. Although many robotic applications like welding involve tasks in which the end-effector path and time trajectory is mandatory, there are other tasks like reaching a target, which are sensor driven. In sensor driven tasks a trajectory is generated on-line, typically by integrating a dynamical system representing the desired task, allowing reactivity to target perturbations that are captured by external sensors [17]. In general, the stability of most of these algorithms is either ignored or only partially investigated under some simplifying assumptions in [18,19] leading to strict gain conditions.

In this work, we propose a joint limit avoidance signal which guarantees the evolution of the joint positions within their respective bounds and can be utilized with both the traditional two stage planning/execution approach and the on-line trajectory generation characterizing sensor-driven tasks. With a planned trajectory, the proposed signal can be utilized as a null space velocity in the primary task's velocity mapping guaranteeing joint limit avoidance without interfering with the execution of the primary task. In on-line trajectory generation schemes, it modifies the generated reference by acting on the whole velocity space resulting in a feasible path to the target, which is accurately reached. Its design is based on the prescribed performance control methodology (PPC) introduced in [20] which allows the designer to impose certain bounds on the output signals of nonlinear systems, and in some cases, without even using approximators to acquire information regarding the considered system dynamics [21]. PPC has already been applied in controlling non-redundant robot motion and force exerted to the environment [22–24] and was further used in synthesizing kinematic and torque regulators for unconstrained reaching tasks of redundant arms without joint limit considerations [25–27].

The rest of the paper is organized as follows. Section 2 formulates the problem of solving the inverse kinematics of the first order task differential under hard joint constraints. The proposed joint limit avoidance control signal is presented in Section 3. Experimental results are provided in Section 4. Conclusions are drawn in Section 5 and preliminaries on the PPC methodology are given in the Appendix.

2. Problem formulation

Consider a robot manipulator with n joints and let $q \in \Re^n$ be the vector of the generalized joint variables. Let $p \in \Re^m$ be the generalized position of the robot end effector in the task space. Typically, kinematic redundancy occurs when the manipulator has more degrees of freedom than those strictly required to execute a given task, i.e. the task space dimension m is strictly less than the robot degrees-of-freedom (dof) ($m < n$). Let D be the continuous non-linear direct kinematics map associating each q to a unique p:

$$p = D(q) . \tag{1}$$

The first order differential kinematics is obtained by differentiating (1):

$$\dot{p} = J(q)\,\dot{q} \tag{2}$$

where $J(q) \in R^{m\times n}$ is the task Jacobian matrix. When the task space is the 6-dimensional space of rigid body motion ($m = 6$) and the manipulator possess more than 6 dof ($n > 6$), the manipulator's geometric Jacobian may be used to map joint velocities to end-effector spatial velocities consisting of the translational and angular velocity of the end effector. In general the task and geometric Jacobian may be related via a transformation matrix that depends on the minimal representation utilized for the orientation variables.

Let us further consider the following bounds on the joint values that should be respected at all times:

$$q_{min} < q < q_{max}. \tag{3}$$

In order to accomplish a task, kinematic control strategies require commanding of a proper joint motion that would accomplish the primary task and possibly secondary objectives. The required inverse kinematics is usually performed at the first order differential kinematics (2) as it represents linear equations with respect to the joint velocities. The general inverse kinematic solution of (2) is the least-square solution that is given by:

$$\dot{q} = J^{\dagger}\dot{p} + (I - J^{\dagger}J)\dot{q}_N \tag{4}$$

where $J^{\dagger}$ is the Moore–Penrose right pseudoinverse of J and in case it is full rank it can be computed as $J^{\dagger} = J^T\left(JJ^T\right)^{-1}$ while $\dot{q}_N$ is an arbitrary joint-space velocity that is utilized for redundancy resolution purposes. The second term of (4) is a null space velocity that does not affect task velocities and when it is set to zero ($\dot{q}_N = 0$) the minimum norm velocity solution is achieved. As inverse kinematics solutions (4) that result in joint limit violation are not feasible solutions, we are faced with the problem of resolving the differential kinematics (2) under the inequality constraints (3) which involve integrals of the problem variables. Within the SNS algorithm this problem is confronted by shaping the velocity constraints by joint range limits so that the latter are not exceeded in the next sampling interval [14]. Instead of an algorithmic solution, we synthesize a joint limit avoidance signal based on the prescribed performance control method, which guarantees the evolution of the joint positions within their respective bounds at all cases. The distance from the center of each joint's range modulated by its upper bound is utilized in a transformed form to achieve guaranteed satisfaction of joint limits as opposed to optimization approaches.

3. The proposed joint limit avoidance control signal

Define the distance of the joint position from its central value:

$$e_q = q - \bar{q} \tag{5}$$

where $\bar{q}$ is the vector of mid-range joint positions $\bar{q}_i = \frac{q_{imax}+q_{imin}}{2} > 0, i = 1, \ldots, n$ and associate to each joint distance component $e_{qi}(t)$ the following constant performance boundary:

$$b_i = \frac{q_{imax} - q_{imin}}{2} \quad i = 1, \ldots, n. \tag{6}$$