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Manipulator performance constraints in human-robot cooperation

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ABSTRACT

Physical human-robot cooperation is a rapidly emerging field that aims to support humans in industrial and everyday environments. In order to facilitate effective cooperation, the kinematic and dynamic capabilities of the robot must be taken into account, such as the ability of the end-effector to move and apply forces to all directions. An online approach is proposed in this paper to address the problem of providing feedback to the operator about the robot's performance under Cartesian Compliance control. The introduced performance constraints prevent the operator from guiding the robot to low performance configurations by effectively restricting the cooperative movement towards such configurations. The constraints are in the form of spring forces/torques expressed in the Cartesian tool frame that are applied by the robot to the operator. A numerical approximation algorithm is used to determine the gradient of configuration dependent performance indices and calculate the constraints online. Various performance indices are compared regarding their ability to indicate the distance from a singularity and render force constraints during cooperation. Experimental results conducted with a 7-DOF serial LWR manipulator and a number of subjects demonstrate significant improvement of the proposed method in low effort cooperation compared to others from the literature.

1. Introduction

A variety of manufacturing processes are executed by robots that are separated with fences from the operators or the workers. Cooperative task execution by means of physical human-robot interaction (pHRI) has significant advantages compared to guidance from the teaching pendant or simple robotic automation [1–3]. The synthesis of human skills with the robot abilities removes the gap between manual work and hard automation, contributing to the emergence of new applications in manufacturing and service domains. Humans present high levels of perception, decision making, adaptability and fast learning, while robots can apply high forces, and can move at high speeds with accuracy and repeatability. The complementary skills between humans and robots are currently exploited in industry by assistive robotic devices for co-manipulation of bulky and heavy objects. In assembly lines, pHRI is motivated by the requirements for higher levels of flexibility, adaptability and reusability of the assembly systems, and demonstrates promising results in complicated assembly tasks [2]. Other manufacturing tasks that can be performed by pHRI include deburring of complex surfaces and welding [4].

Manual robot guidance is an intuitive method for training manipulators with human skills, which is very important towards higher flexibility and versatility of manufacturing automation [5]. The applied forces between the operator and the robot during the physical interaction have to be regulated appropriately. Depending on the task, the interaction can involve contact to the body of the robot or to the end-effector. The latter case is preferred when a certain orientation of the end-effector is required for the task [4,6] and can present a serious limitation under Cartesian Compliance control, when the manipulator is near singular configurations. As a result, a compliant controller should be synthesized for successful co-manipulation that considers the manipulator's performance characteristics.

Active Compliance control methods, such as impedance and admittance control [7], are widely adopted from the research community and allow the imposition of a desired dynamic behavior between those external forces and the motion of the robot. The effects of singular configurations depend on the selected control scheme. When the Cartesian impedance control is used, the robot can remain stuck because the operator's forces that are applied to the end-effector are not mapped into joint torques [8]. Using the Cartesian admittance control, the inverse kinematic problem at a singularity is undetermined, while at the neighborhood of a singularity small operational space velocities require excessive joint velocities.

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The preconditions for efficient and safe physical interaction, raise the need to regulate the cooperation with respect to the performance of the manipulator. This performance can be quantified by using appropriate indices that characterize the robot. Two of the main challenges in human-robot cooperation are; the avoidance of low performance configurations, such as kinematic singularities of the manipulator, and the operation of the robot in a workspace with high performance. The first challenge aims to maintain the ability of the robot to move along/around all the directions of the end-effector, while the second targets at optimizing operation oriented criterion (e.g. minimize the motors' effort). Particularly at a singular configuration, the desired dynamic behavior of the end-effector (with impedance or admittance control) can no longer be achieved, deteriorating the effectiveness of the cooperation. Moreover, in the vicinity of a singularity, the effort of the motors must be increased to carry out the motion of the end-effector. To the authors' best knowledge, these limitations have not been fully addressed in terms of user comfort during human-robot cooperation.

The main idea of the paper is to facilitate efficient and comfortable interaction by providing force feedback to the operator about the kinematic and dynamic capabilities of the robot. In particular, we target at making a novice operator to become aware of a manipulator's limitations, such as workspace boundaries and singularities, by intuitively interacting with it. To achieve that, the following issues are addressed:

- Obtain the gradient of an appropriate measure with respect to the Cartesian position and orientation that represents the ability of the end-effector to move and apply forces/torques to the translational and rotational directions.
- Calculate online the force and torque feedback according to the performance measure, considering the task requirements, to constraint the approach to low performance configurations during cooperation.
- Facilitate comfortable and seamless cooperation.

1.1. Related work

Virtual constraints (also known as virtual fixtures or active constraints) in human-robot interaction, is a widely used technique to render virtual environments in impedance or admittance controlled robots and provide assisting feedback to the operator [9–11]. In the majority of the cases, the constraints were used to guide the operator into pre-configured virtual paths or configurations, by applying attractive or repulsive force feedback to improve the operator's performance. The constraints are in the form of geometric boundaries depending on the desired task and they are usually determined a priori. The force feedback can be rendered either by using a distance function from the constraints [12] or by using potential fields [13].

Apart from assisting the operator's performance, the framework of virtual constraints was used in joint limit avoidance [14,15] and to provide feedback to the operator about the performance of the manipulator itself. To obtain the constraint geometry for the latter, analytic solutions of singularities [16,17] can be incorporated, but it can be cumbersome to calculate them, particularly in redundant manipulators with multiple to infinite inverse kinematic solutions, where the determination of the singularity manifolds require significant computational work [18–20]. By monitoring online a performance index of the robot, a singularity avoidance technique was presented in [8], but without experimental demonstration. The authors proposed a secondary joint impedance controller to impose a repulsive potential field, calculated from the kinematic manipulability, to push the joints away from singular configurations. However, this approach requires the gradient of the manipulability index with respect to the joint variables and it does not consider the end-effector's orientation, so it is not appropriate for task space control, particularly in redundant manipulators where there is no unique mapping from joint torques to Cartesian forces/torques.

The operational space formulation [21] was used [22–24] to decompose and deactivate the task along the degenerate directions, based on the minimum singular value of the Jacobian matrix. The damped least square methods [25,26] can also deal with singularities by adding damping to reduce the increased joint velocities. These approaches do not avoid singularities but, instead, they cope with the problems that arise by removing the degenerate components of the motion. In human-robot cooperation this can be a substantial limitation because the desired dynamic behavior is distorted near singular configurations [8] and, as a result, the avoidance of these configurations should be preferred whenever it is possible.

Singularity avoidance techniques of position controlled manipulators have been proposed in the literature and focus on modifying the trajectory either at the joints level or at the task level [27,28]. The modification is based on the manipulability index, a commonly used performance measure for singularity avoidance, mainly because its gradient can be expressed analytically with respect to the joint variables [17]. The manipulability index being equal to zero is a necessary and sufficient condition for a singularity. However, it was argued in the literature that it is not a good measure of the distance from a singularity [29]. Improvements on the original definition of the manipulability index to overcome the scale, dimensional and order dependencies as well as to bound the index have been proposed [30]. Other performance measures such as the minimum singular value (MSV) or the condition number (CN) [31] are considered better indicators of the degree of ill-conditioning of the Jacobian, as to their closeness to singularities [32]. Numerical methods like Singular Value Decomposition are commonly used to obtain these indices. Reviewing the advantages and disadvantages of the aforementioned indices, the MSV and CN are considered to be better measures for the closeness to a singularity than the manipulability index [33]. Nonetheless, the gradient of the MSV and of the CN is difficult to be obtained in closed form, thus, they cannot be used in most of the aforementioned singularity avoidance techniques. Also, the effects of those indices have not been investigated in human-robot cooperation with singularity avoidance.

Typical human-robot cooperation involves both translation and rotation of the end-effector. Combining different physical units into a single performance index, particularly when a manipulator consists of different joint types, yields inconsistent results [34]. Therefore, it is preferred to use two different indices to represent the translational and rotational performance of a manipulator [35,36]. However, various methods have been proposed for homogeneous indices that can combine translational and rotational performance [37] or construct a normalized Jacobian [38] that does not suffer from unit dependency.

In a recent work [39], we introduced manipulator performance constraints for human-robot cooperation, that prevent the operator from guiding the end-effector towards low performance configuration. The performance constraints were calculated online by the gradient of the performance index with respect to the Cartesian frame attached to the end-effector. The initial results indicated promising and effective cooperation, even though only the manipulability index and the translation of the end-effector were considered.

1.2. Overview

In this paper, the preliminary work presented in [39] is extended towards the establishment of a framework for manipulator performance constraints during human-robot cooperation. An algorithm is developed to approximate the gradient of a performance index numerically and produce virtual Cartesian forces/torques that maintain efficient and safe human-robot cooperation, without the need of an analytical expression of the gradient of the index. The proposed method can be used for singularity avoidance in human-robot co-manipulation without prior calculation of the singularity loci and analytical inverse kinematic solutions.

A thorough experimental evaluation is conducted involving human-robot interaction with a 7-DOF serial manipulator in tasks with low kinematic performance, involving translational and rotational motion of the end-effector. By applying the performance constraints in a Carte-