Physical and perceived safety in human-robot collaboration

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***Abstract*—This paper presents a complete motion control system for industrial manipulators, designed to maximize the robot productivity and meet the safety requirements of the human worker during human-robot collaboration. The real-time solution of a constrained optimization problem allows to control the robot's motion in accordance with a pre-programmed trajectory, satisfying both the kinematic contraints and those imposed by the adopted collision avoidance strategy. A human safety perception system is also introduced, which aims to increase the human worker's psychological safety and prevent potentially dangerous movements. A Mixed Reality software application, which provides the human worker with a digital visualization of the robot motion intention, and a real-time motion prediction algorithm, which computes the future poses of the robot, complete the system. Finally, a control stategy based on the human field of view is presented.**

***Index Terms*—Human-robot collaboration, physical safety, psychological safety, motion prediction, mixed reality**

I. Introduction

The transition from traditional to advanced manufacturing based on digitalization and on the paradigm of Industry 4.0 leads to the development and the implementation of smarter and sophisticated products with new capabilities, as well as complete control systems specifically designed to provide the coordination and the desired skills of a manufacturing process. Moreover, the growing demand of the human-robot collaboration (HRC) in the industrial framework requires the introduction of specific safety systems that guarantee and enhance the human worker physical safety. Preventing physical harm does not necessarily translate into stress-free and confortable HRC. In this context, one of the key issues is the so-called psychological safety; a lack of sense of safety affecting worker's feeling is associated with emotional response such as fear, stress and anxiety which negatively affect the productivity. Digital reality systems could be exploited not only to support the operator during human-robot cooperative operations or planning phases, but also to enhance the sense of safety perceived by the human worker including holographic forecast of the system's actions.

II. Safe Motion Control System

Nowadays, industrial robots are characterized not only by the ability to control their movements but also by the possiblity to react and interact to unpredictable external variations, e.g. the human workers moving inside the robot workspace. Clearly, suitable control strategies and external system integration, e.g. cameras or sensors, are necessary in order to obtain an overall system that is capable of perceiving the external environment of the robot and control its motion.

A. Background on safety constraints

One of the fundamental elements of the proposed motion control system is the concept of physical safety constraints, i.e. a set of mathematical constraints guaranteeing that, in presence of one or more detected obstacle, the robot is always able to deviate from its pre-programmed trajectory or stop if necessary. The geometry of a real manipulator is often complex. In the proposed work, the geometry of the robot is approximated with a set of 3D capsules representing each link. On the other hand, the volume occupancy of a 3D shape in the robot workspace is represented with the so-called convex hull [1], i.e. the smallest convex set in $\mathbb{R}^3$ that entirely contains a given shape. Referring to [2], is possibile to predict the human volume occupancy through the use of a motion sensing input device and a prediction algorithm based on linear Kalman filter. The collision avoidance requirement is represented by

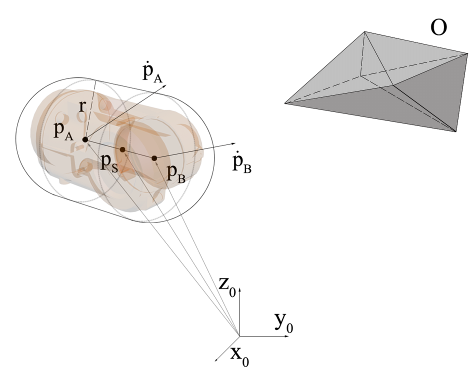

Fig. 1. Link approximation and convex-shaped obstacle O

the set of contraints reported in (1).

$$\mathbf{E}(\mathbf{p}_o)\dot{\mathbf{q}} \leq (d+\Delta)\begin{bmatrix}1\\1\end{bmatrix},\ \forall\, \mathbf{p}_o \in \mathbf{O} \qquad (1)$$

where $\mathbf{E}$ represents the matrix related to the minimum separation criterion [3], $\dot{\mathbf{q}}$ is the vector representing the joint velocities, Δ is a clearance parameter and d represents the minimum distance between the link of the robot and the convex polytope O.

B. Constrained Optimization Based Tracking control

The presented motion control system is characterized by a tracking control problem formulated in terms of a constrained Quadratic Programming optimization whose solutions represent the control variables. The main distinguishing feature of the considered strategy, compared to a traditional one, is the possibility to express each constraint to the robot motion in a mathematical form. The objective function to minimize is formulated in terms of a tracking error, i.e. the error among the joint positions and velocities reference values $\mathbf{q}_{k+1}^{ref}$, $\dot{\mathbf{q}}_{\mathbf{k+1}}^{ref}$ and the current ones $\mathbf{q}_k$, $\dot{\mathbf{q}}_{\mathbf{k}}$. Therefore, the presented optimization problem in addressed at the joint space level by solving the following objective function:

$$\underset{\ddot{\mathbf{q}}_k}{\text{minimize}} \quad \left(\|\mathbf{q}_{k+1} - \mathbf{q}_{k+1}^{ref}\|_{Qp}^2 + \|\dot{\mathbf{q}}_{k+1} - \dot{\mathbf{q}}_{k+1}^{ref}\|_{Qv}^2 \right) \tag{2}$$

with

$$\mathbf{q}_{k+1} = \mathbf{q}_k + \dot{\mathbf{q}}_k \Delta t + \frac{1}{2}\ddot{\mathbf{q}}_k \Delta t^2 \tag{3}$$

$$\dot{\mathbf{q}}_{k+1} = \dot{\mathbf{q}}_k + \ddot{\mathbf{q}}_k \Delta t \tag{4}$$

Δ t being the step size of time discretization.
The optimization problem is solved at each time step t_k in order to obtain the values of the decisional variable, i.e. the joint accelerations $\ddot{\mathbf{q}}_k$. In case of joint space trajectories, it is natural to consider the expression of the objective function reported in (2). On the other hand, in case of Cartesian space trajectories the objective function can be directly expressed as a function of the operational space quantities or can be obtained by computing the inverse kinematics solutions, e.g. CLIK algorithm. As already mentioned, the proposed optimization problem is subjected to several constraints representing the collision avoidance strategy (1) and all the kinematics contraints of the manipulator, e.g. joint limits and maximum speed.

III. Mixed Reality safety perception system

The proposed algorithm can be extended to account also for the perception of safety, other than the physical safety. The basic idea of the safety perception system startegy is to provide the human operator with a continuous and smooth visualization of the predicted robot motion. In other words, the proposed strategy was not conceived to provide a set of configurations that the operator visualized as stationary holograms, but instead it was designed in order to provide a continuous motion of the robot. The implemented algorithm consists in a recursive computation and simulation of the robot motion when updated data of both the current state of robot and the external environment are available. These operations are executed at each time step of the motion control system loop. In detail, at each time step t_k, the predicted robot configuration at time t_{k+n}, where n represents the fixed prediction horizon, is computed solving a set of constrained optimization problems according to both the current robot state of motion and the current data of the environment. It should be noticed that a fixed prediction horizon and an iterative future prediction strategy allow to provide the operator with a continuous visualization of the robot motion. In order to provide the operator with the hologram visualization of the future configuration of the robot, it is sufficient to transmit in real-time the computed joint position to the Mixed Reality device. Figure 2 shows a series of screenshots representing the visualization of the future motion of the considered robot. The actual robot motion is represented by the solid hologram, while the predicted one is represented by the slightly transparent hologram. This representation of the future motion of the robot through the holograms is then used within the optimization problem to keep the robot always in the field of view of the user, so as to improve the perception of safety. The overall controller in sketched in Figure 3.

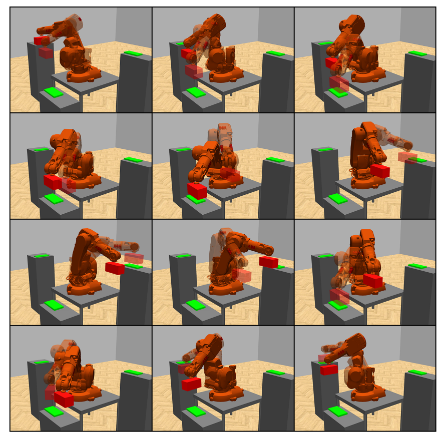

Fig. 2. Safety perception system: Future motion visualization

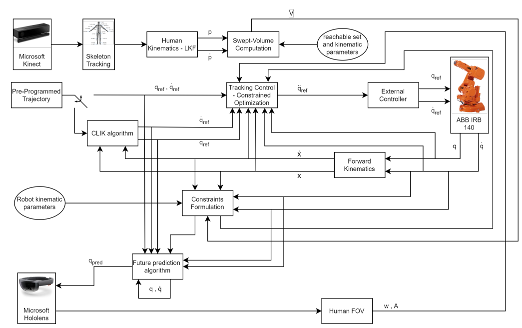

Fig. 3. Experimental setup - Safe motion control system

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