Computing smooth human friendly motion with the variational formalism

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***Abstract*—Industrial collaborative robots distinguish from the traditional ones thanks to their built-in safety features that, if tuned correctly, make possible their physical interaction with humans. In addition to mechanical safety, ensuring that the operator does not suffer of psychological discomfort or stress is crucial for Human-Robot-Interaction (HRI). In this regard, the term psychological safety has been coined to identify the absence of such stressful effects during the HRI experience. In literature, several approaches propose to ensure mechanical and psychological safety by planning motion subject to safety constraints. Among these, minimum jerk trajectories have drawn the interest of robotic community thanks to the mechanical properties and their similarity to human motions. In this extended abstract, we comment the different approaches that have been developed to compute this kind of trajectories and compare them with the methods we developed based on the variational formalism.**

***Index Terms*—Motion and Path Planning, Optimization and Optimal Control, Physical Human-Robot Interaction**

I. Introduction

One of the most outstanding examples of Cyber Physical Systems (CPS) are the so-called collaborative robots. They are characterized by a design focused on Physical Robot-Human Interaction (pHRI), which facilitates the programming of tasks in compliance with the standard TS–15066 [4] and the four operative methods they propose: hand guiding, safety-rated monitored stop, speed and separation monitoring, and power and force limiting.

In the power and force limiting modality, physical contact between the robot and the operator is expected and guidelines for the risk reduction may be found in the technical specification TS-15066. This specification provides velocity limits for the robot's moving parts that ensure mechanically safe contacts.

The hand guiding modality provides an intuitive and simple way to teach to robots. It allows to construct a motion by manually bringing the robot into a sequence of desired positions called via-points, then a motion planner construct the geometrical path and the trajectory. This delegates the difficulties of path planning to the robot's operator. It follows that trajectory planning along via-points with velocity constraints can compute mechanically safe motions under the absence of quasi-static contacts. Commercially available robots implement such a method with trapezoidal velocity profile on the straight lines joining the given via-points (in either the operational or joint space). However, evidence whose that these motions are a source of psychological risk [1], [8].

In order to reduce the psychological risk authors in [5], [12], [14] propose the use trajectories that minimize the L^2 norm of the jerk, i.e. minimum-jerk trajectories. Because these trajectories has successfully modeled human hand motions [2], [9], it is also supposed that they are familiar to the operator. Moreover, the impact of such trajectories on the induced stress has been investigated in [6], showing that they significantly reduce heart rate in humans, thus suggesting an improvement of robot's acceptance and an increment of the psychological safety.

Studies on minimum jerk trajectories go back to [7] and [2], where the point-to-point and via-points problems have been addressed and solved as an optimal control problem (OCP). Another works like [3], [10], [15] use some kind of approximation to construct a Constrained Non Linear Program.

In this extended abstract we present the currently available methodologies to compute minimum jerk motions that have been recently presented in [11]–[13] In Section we present the problem of the minimization of the jerk and automatic methods that have been in collaborative robots. In Section we present a novel extension to this problem and examples.

II. Tools for computing minimum jerk trajectories

We identify the motion of the robot with a curve in $\mathbb{R}^n$ without considering the specific details of the task space. Suppose that the operator desires to execute a task through with via-points $VP = \{\mathbf{w}_0, \mathbf{w}_1, \ldots, \mathbf{w}_N\} \subset \psi(\mathcal{M})$.

The problem of trajectory planning along VP is that of finding a curve where via-point $\mathbf{w}_i$ is attained at the time t_i with $t_i < t_{i+1}$ during a given execution time interval $J = [0, t_f]$. Velocity and acceleration constraints can be added to the problem, deriving in the following constraints:

$$\begin{aligned} &\mathbf{q}(t_i) = \mathbf{w}_i \\ &\dot{\mathbf{q}}(t_0) = \dot{\mathbf{w}}_0 \quad \dot{\mathbf{q}}(t_N) = \dot{\mathbf{w}}_N \\ &\ddot{\mathbf{q}}(t_0) = \ddot{\mathbf{w}}_0 \quad \ddot{\mathbf{q}}(t_N) = \ddot{\mathbf{w}}_N. \end{aligned} \tag{1}$$

with $t_0 = 0$ and $t_N = t_f$.

The minimization of the jerk requires the minimization of the the integral

$$I(\mathbf{q}) = \int_0^{t_f} \|\dddot{\mathbf{q}}\|^2 \mathrm{d}t \tag{2}$$

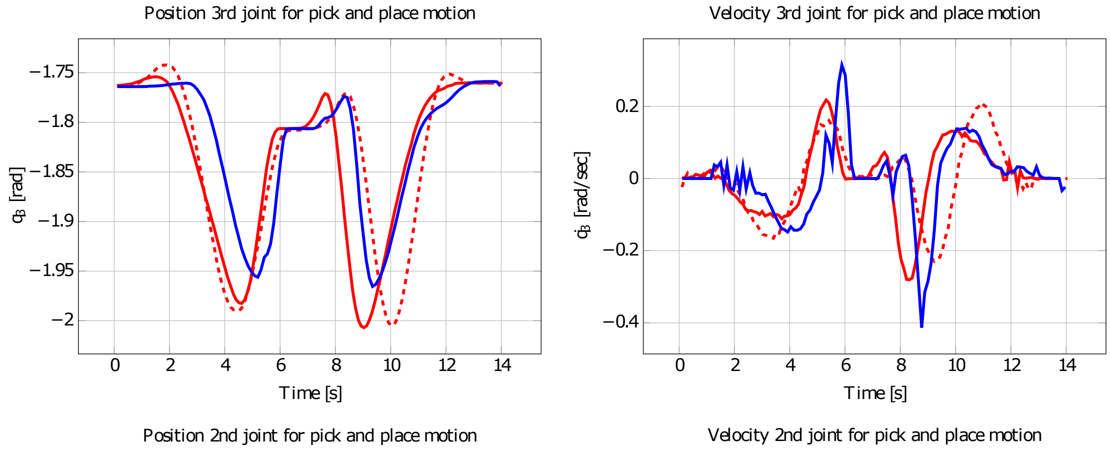

Fig. 1. Comparison between the different motions in the joint space. Only the first joint is depicted. The robot's native planner is depicted in blue, in red the proposed approach with $\alpha = 0.90$ and $\alpha = 0$ (minium jerk) with a solid and dashed line respectively.

A. *Automatic tootls for collaborative motion planning*

The complexity of the minimum-jerk motion algorithms and their implementation forbid unskilled users to implement less stressful motions in co-bots thus possibly preventing SMEs to exploit their benefits. Authors in [11] fix this gap by creating and integrating in a cobot controller and teaching pendant a new user-friendly toolbox and graphical user interface (GUI) for unskilled users in order to allow them to automatically plan minimum-jerk trajectories for the reduction of psychological stress while using common hand-guided methods. Such an interface is developed for Universal Robots as a URCAP plugin.

III. Further developments

Minimum jerk motions could have two potential drawbacks that degrade the robots behavior. Such motion may be much more slower than motions with trapezoidal velocity profiles and can show large deviation from the expected path. An approach to solve this issue has been presented by the authors in [13]. It consists in characterizing the extremals of the convex combination of the smoothness and a cost proportional to the arc-length given a parameter $\alpha \in (0, 1)$,

$$I(\mathbf{q}) = \int_0^{t_f} \alpha \|\dot{\mathbf{q}}\|^2 + (1-\alpha)\|\dddot{\mathbf{q}}\|^2 \mathrm{d}t. \tag{3}$$

In Figure 1 we can observe the difference between the native trajectories provided by an UR3 and the proposed approach.

IV. Conclusions

In this work we summarized our recent developed methods and tools for planning minimum jerk motions for collaborative applications. These allow to generate trajectories that fulfil the mechanical risk specifications and induce less stress in operators. As a proof of concept, we present an experimental result which shows the better performance of the proposed trajectories.

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