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Online Planning of Path-Consistent Stop Trajectories for Collaborative Robotics

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Online planning of path-consistent stop trajectories for collaborative robotics

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Abstract This paper presents a method for the online planning of path-consistent stop trajectories for collaborative robotics. The proposed approach considers the manipulator to be enclosed in bounding volumes, whose sizes account for a protecting separation distance and are minimized online considering the robot dynamics and its torque constraints. In case a collision danger between bounding volumes enclosing human and robot is detected, the robot is guided to stop along a safe trajectory that preserves the geometrical path. Simulation results on a validated model of a 7-degree-of-freedom manipulator show the feasibility of the method and provide a more effective human-robot collaboration with respect to a similar approach that does not preserve path consistency during safety stops.

1 Introduction

Collaborative robotics is one of the enabling technologies of Industry 4.0. In this context, industrial robots can work and interact with human operators in a common workspace to carry out shared tasks. In this way, productivity and flexibility of industrial systems can be improved, and advantages can be achieved in terms of working conditions and ergonomics of the operators. Ensuring safety in collaborative robotics becomes essential, as it is attested by a multitude of works on the topic [6].

Safety in human-robot collaboration can be achieved in multiple ways. Injury minimization approaches rely on strategies to guarantee safety in case of non-functional

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or unwanted contacts between robot and human. Examples are the control of contact motion and force in physical human-robot interaction [11], the sense of contact force by means of film-type sensors [9], or the mitigation of impact shocks with compliant structures [15].

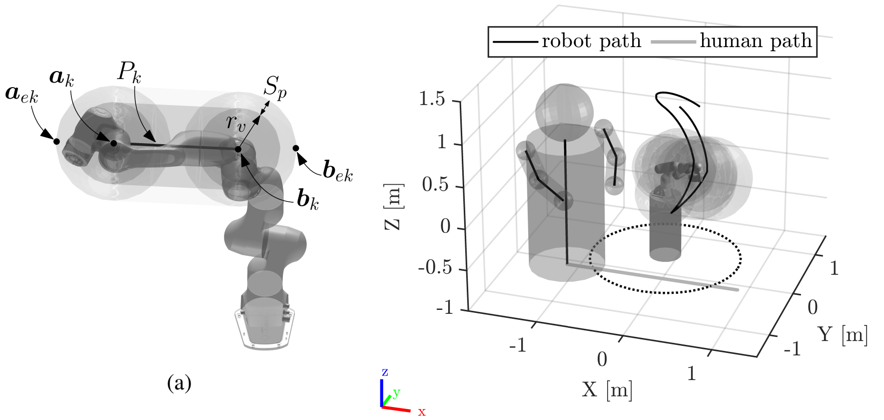
Conversely, collision avoidance methods include strategies that prevent any contact between human and moving robot, as in the speed and separation monitoring (SSM) paradigm [8]. As for instance, in [1], the robot velocity is continuously adapted in response to the relative operator and robot motion. Moreover, in [2], an algorithm for adaptive obstacle avoidance is presented, which considers cylindrical safety region wrapping each link of the manipulator.

In [13], the authors introduce an approach based on the scaling of dynamic safety zones using bounding volumes as sphere swept lines (SSLs) to perform intersection tests between human and robot. That method defines a potential stop trajectory by searching among a pre-defined set of stop times, and results in discontinuous safety zones over time. The method is further improved in [14], where an optimization problem is solved online to compute optimally scaled smooth stop trajectories. The robot dynamics and its torque limits are considered to minimize the stop time, and consequently the size of the dynamic safety zones that enclose the manipulator. However, that approach does not preserve path consistency during safety stops.

In case the robot must follow the path accurately during safe deceleration and stop, the nominal motion law of the robot should be scaled in time to meet the robot constraints. Several examples of trajectory scaling methods for path tracking can be found in the present literature. A method for path-accurate online trajectory generation is illustrated in [10], where a forward scaling and backtracking is applied to obtain a feasible trajectory. Further approaches for path-consistent trajectory scaling while respecting joint and torque limits are based on look-ahead approaches, as in [16]. Moreover, in [3], a method that modifies the velocity profile based on an approximated look-ahead criterion is adopted to scale the nominal trajectory in time to meet the robot constraints and preserving the assigned path as much as possible.

In this paper, we present a method for the online planning of path-consistent stop trajectories for collaborative robotics. The proposed approach considers the manipulator to be enclosed in dynamic safety zones, whose sizes are minimized online accounting for the robot dynamics and its torque constraints. In case a collision danger between bounding volumes enclosing human and robot is detected, the robot is guided to stop along a safe trajectory that preserves the geometrical path. Simulation results on validated model of a manipulator with 7 degrees of freedom (DOFs) show the feasibility of the method and its superiority with respect to the similar approach proposed by the same authors in [14] that does not preserve path consistency during safety stops. In particular, we show the effectiveness of the here proposed approach using metrics directly related to fluency in the collaboration [7] as e.g., the task execution time and the number of stops.

The paper is organized as follows: Sect. 2 details the addressed problem, whereas Sect. 3 presents the proposed approach. Simulation results are shown in Sect. 4, and the conclusion follows in Sect. 5.



(a)

(b)

Fig. 1: A SSL and its corresponding safety zone (a); simulation test bed (b).

2 Problem statement

In this work, a supervisory controller verifies online the possible collision between robot links and operator, and steers the robot to stop when needed along a stop trajectory. The bounding volumes enclosing both robot and human are chosen to be SSLs, which are defined as the Minkowski sum of a sphere and a line segment. The SSL for the k-th link is defined by points $\boldsymbol{a}_k$ and $\boldsymbol{b}_k$, and the radius r_v (Fig. 1a), which is the minimum one to enclose the link geometry.

According to the ISO/TS 15066 [8], a protective separation distance S_p can be calculated as the minimum distance that a robot must keep with respect to an operator. Therefore, the radius r_{SZ} of a SSL that represents the safety zone enclosing a link can be computed as:

$$r_{SZ} = r_v + S_p = r_v + S_r + S_s + S_h + \xi \tag{1}$$

where S_r and S_s are the space covered by the robot during the reaction time t_r and the stop time t_s, respectively. $S_h = v_h\,(t_r + t_s)$ is the distance covered by the human computed with the worst-case human velocity $v_h = 1.6\ m/s$, and ξ collects multiple error contributions. The term S_{r_k} related to the k-th robot link is calculated with the speed v_{r_k} from the initial time of the safety test t_0 to $t^* = t_0 + t_r$ as:

$$S_{r_k} = \int_{t_0}^{t^*} v_{r_k}(t)\,dt \tag{2}$$

On the other hand, once t_s is defined, the space S_{s_k} covered by the k-th link to stop is given by the following equation, where v_{s_k} is the speed of the link being stopped:

$$S_{s_k} = \int_{t^*}^{t^*+t_s} v_{s_k}(t)\, dt \tag{3}$$

Having computed r_{SZ}, the intersection test verifies the collision danger between each robot safety zone and the human SSLs. The closest points of each couple of line segments defines the human-robot distance d_{hr}. Being r_h the radius of a human link, the SSM criterion is satisfied if $d_{hr} < r_{SZ} + r_h$, or if the robot is stopped.

3 Proposed approach

In this work, the nominal trajectory $\boldsymbol{q}(\gamma)$ is considered to be a joint-space curve parametrized by means of the variable $\gamma \in \mathbb{R}$. The nominal timing law $\gamma(t)$ is assumed to be twice differentiable, and can be described as $\gamma : [0, t_n] \rightarrow [0, 1]$, where t_n is the final time of the nominal trajectory. During the stop trajectory starting at t^*, i.e., when $t \in [t^*, t^* + t_s]$, a new parameterization $\gamma_s(t)$ is adopted, as a three-degree polynomial. The following boundary conditions can be applied to determine the four coefficients of the three-degree polynomial that ensure continuity up to the acceleration: $\gamma_s(t^*) = \gamma(t^*)$, $\dot{\gamma}_s(t^*) = \dot{\gamma}(t^*)$, $\ddot{\gamma}_s(t^*) = \ddot{\gamma}(t^*)$, $\dot{\gamma}(t^* + t_s) = 0$. Clearly, $\gamma_s(t^*+t_s)$ is not fixed. In this way, the final joint position $\boldsymbol{q}_s(\gamma_s(t^*+t_s))$ is determined analytically, once the stop time is chosen. The motion law during the stop trajectory is given by:

$$\begin{aligned} \boldsymbol{q}_s(t) &= \boldsymbol{q}(\gamma_s) \\ \dot{\boldsymbol{q}}_s(t) &= \dot{\boldsymbol{q}}(\gamma_s)\, \dot{\gamma}_s \\ \ddot{\boldsymbol{q}}_s(t) &= \ddot{\boldsymbol{q}}(\gamma_s)\, \dot{\gamma}_s{}^2 + \dot{\boldsymbol{q}}(\gamma_s)\, \ddot{\gamma}_s \end{aligned} \tag{4}$$

The proposed approach aims at minimizing the size of the safety zones enclosing the robot, by solving online an optimization problem that defines the minimum stop time t_s needed to stop the robot without violating the joint torque limits $\tau_{i,max}$. The formulation of the problem is the following:

$$\min_{t_s} \quad w_0\, t_s + w_1\, |t_s - t_{s,prev}| \tag{5}$$

subject to

$$\begin{gathered} |\tau_i(\boldsymbol{q}_s(t), \dot{\boldsymbol{q}}_s(t), \ddot{\boldsymbol{q}}_s(t))| \leq \tau_{i,max} \\ t \in [t^*,\ t^* + t_s], \quad i = 1, ..., N \end{gathered} \tag{6}$$

In (5), w_0 and w_1 are positive weights. $t_{s,prev}$ is the stop time found at the previous safety check, which is used to penalize discontinuities between successive iterations. τ_i represents the torques at the i-th joint, and N is the number of DOFs. The torques $\boldsymbol{\tau}$ during the stop trajectory are evaluated by using a recursive Newton-Euler algorithm for efficient computation of the robot dynamics:

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q}_s)\ddot{\boldsymbol{q}}_s + \boldsymbol{C}(\boldsymbol{q}_s, \dot{\boldsymbol{q}}_s)\dot{\boldsymbol{q}}_s + \boldsymbol{F}_v\dot{\boldsymbol{q}}_s + \boldsymbol{f}_c\text{sign}(\dot{\boldsymbol{q}}_s) + \boldsymbol{g}(\boldsymbol{q}_s) \tag{7}$$

where $\boldsymbol{M}(\boldsymbol{q}_s)$ is the mass matrix of the manipulator, $\boldsymbol{C}(\boldsymbol{q}_s, \dot{\boldsymbol{q}}_s)\dot{\boldsymbol{q}}_s$ accounts for Coriolis and centrifugal terms, $\boldsymbol{F}_v$ and $\boldsymbol{f}_c$ include the viscous and Coulomb friction coefficients, respectively, whereas $\boldsymbol{g}(\boldsymbol{q}_s)$ represents gravity. In our approach, the dynamic model of the robot is considered to be well-known. However, in case of uncertainties or inaccuracies in the dynamics, alternative approaches can be adopted, e.g., using a recursive Newton-Euler algorithm based on interval arithmetic [5].

Once the optimal t_s is defined, the contribution S_{s_k} in (3) can be computed by considering the velocity of the spherical end-caps $\dot{\boldsymbol{a}}_{e_k}$ and $\dot{\boldsymbol{b}}_{e_k}$, being $\boldsymbol{a}_{e_k}$ and $\boldsymbol{b}_{e_k}$ the extreme points that over-approximate the k-th link of the robot (Fig. 1a). In particular, we define the maximum linear velocity of a link v_{s_k} during t_s as:

$$v_{s_k}(t) = \max(|\dot{\boldsymbol{a}}_{e_k}(t)|, |\dot{\boldsymbol{b}}_{e_k}(t)|) \tag{8}$$

Please refer to [13] and [14] for a complete description of the computation of the maximum linear velocities. With respect to those works, we proceed differently in the design of the stop trajectory, making it path consistent yet preserving smoothness, as described above.

4 Simulation results

The proposed approach is validated through numerical simulations of the 7-DOF Panda arm by Franka Emika GmbH. The dynamic parameters of this robot were experimentally identified in [4]. The simulations are implemented in Matlab™/Simulink® using a laptop running Windows 10 Pro with an Intel i7-8565U CPU and 16 GB of RAM. The problem (5) is solved online with the optimization function *fmincon*, choosing the sequential quadratic programming algorithm, and limiting to 10 the number of iterations. A sampling time of 1 ms is set for the tracking controller of the robot, and the reaction time is set equal to 5 ms.

The proposed approach is compared with the previous method in [14]. For the sake of simplicity in the following, we name these two strategies as:

- Approach (1): the proposed approach based on path-consistent stop trajectories;
- Approach (2): the method in [14] that considers, instead, the stop trajectory $\boldsymbol{q}_s(t)$ to be a non path-consistent five-degree polynomial defined starting from the current joint variables $\boldsymbol{q}_{s,i}$, $\dot{\boldsymbol{q}}_{s,i}$, and $\ddot{\boldsymbol{q}}_{s,i}$ at time $t_0 + t_r$, to the final joint coordinates, defined by $\boldsymbol{q}_{s,f} = \boldsymbol{q}_{s,i}$, $\dot{\boldsymbol{q}}_{s,f} = 0$, and $\ddot{\boldsymbol{q}}_{s,f} = 0$ at time $t_0 + t_r + t_s$.

For each of the two methods, 100 simulations are evaluated. In each simulation, the robot performs random trajectories and the human moves back and forth along a straight path, so as to intrude in the robot workspace. Each nominal trajectory for the robot is defined by five random points in the joint space, of which each pair is linked by a five-degree polynomial trajectory 2 s long, for a total time of $t_n = 10$ s, without considering possible safety stops due to human intrusions.

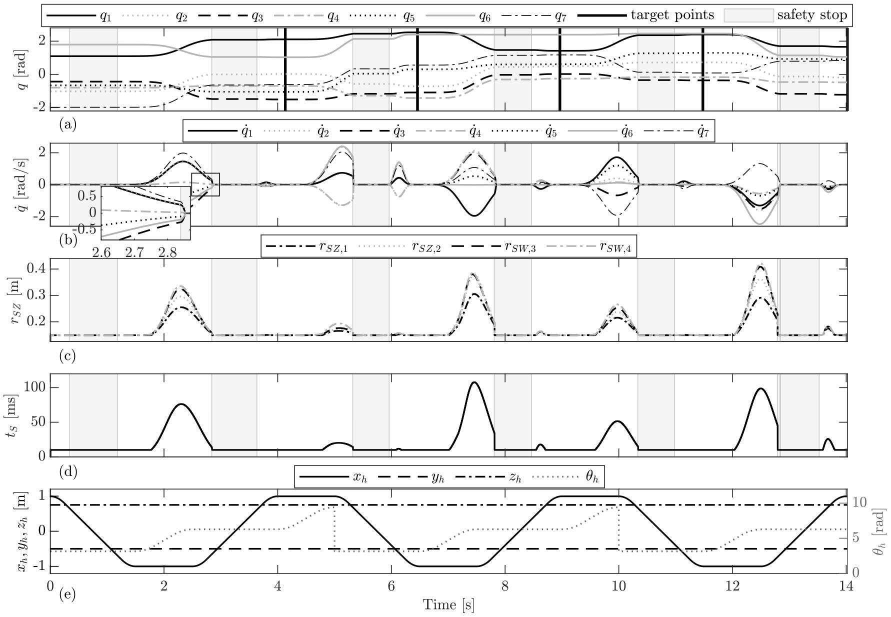
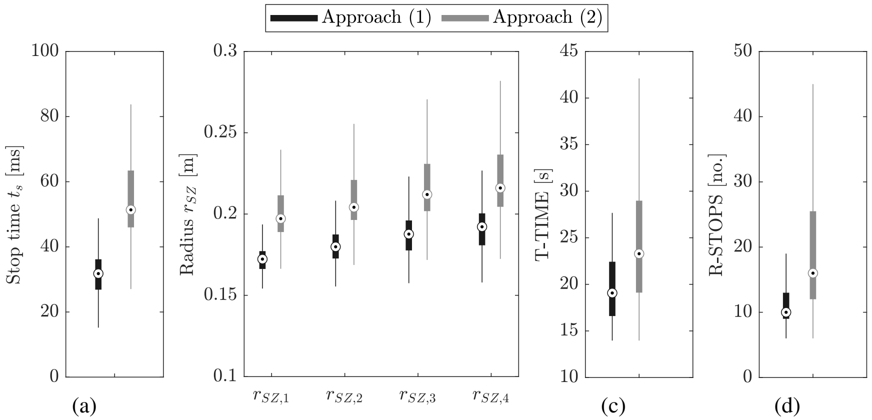


Fig. 2: Example trajectory: joint positions (a); velocities (b); radius of the safety zones (c); stop time (d); and human coordinates (e).

The simulated human is modeled as a simple kinematic tree with a chest, a head and two arms (Fig. 1b), following the approximation in [12]. Six bounding volumes enclose the human. A replicable motion model is implemented for the human, considering a linear path of length 2 m, and distant 0.50 m from the robot base. At the end of each path, the human rotates $\pi\ rad$ and comes back. The motion law for the human is a trapezoidal speed profiles that brings its speed to $v_h = 1.6\ m/s$. The human completes the path two times in $t_n = 10\ s$. However, the robot keeps moving until the robot end-effector has not reached the last way point.

Figure 2 reports an example trajectory performed by the robot. The plots show the joint positions, velocities, radius of the safety zones, stop time, and human coordinates over time. The vertical black lines indicate target achievements, whereas shaded areas represent safety stops. From Fig. 2 it can be seen that the radii of the safety zones changes according to the stop time minimized online. Furthermore, during safety stops the path is preserved according to the parameterization (4).

Figure 3 reports the box plot representation of the numerical results, where the two approaches that differently plan the stop trajectories are compared. In Figs. 3a and 3b, the root mean square values for the stop time and the radius of the safety zones of each of the 100 simulations are reported in aggregate form. The stop times computed with Approach (1) are lower with respect to those computed with Approach (2). Accordingly, the safety zones results to be smaller in terms of radius. Indeed, in Approach (1) the robot generally travels a shorter path to come to a stop



(a) (b) (c) (d)

Fig. 3: Box plot representation of the simulation results: stop time (a); radius of the safety zones (b); total task time (c); number of stops (d).

Table 1: Simulation results reported as mean ± standard deviation.

Approach	t_s [ms]	$r_{SZ,1}$ [m]	$r_{SZ,2}$ [m]	$r_{SZ,3}$ [m]	$r_{SZ,4}$ [m]	**T-TIME** [s]	**R-STOPS** [no.]
(1)	317 ± 83	0.17 ± 0.01	0.18 ± 0.01	0.19 ± 0.03	0.19 ± 0.02	19.82 ± 4.05	11.2 ± 3.4
(2)	532 ± 131	0.20 ± 0.02	0.21 ± 0.02	0.22 ± 0.02	0.22 ± 0.02	24.45 ± 6.66	20.5 ± 12.0

and avoids performing kind of a loop as in Approach (2), where the stop trajectory is a five-degree polynomial that brings the robot back to $\boldsymbol{q}_{s,i}$.

Furthermore, Fig. 3c and 3d reports the results in terms of *total task time* (T-TIME) and *number of robot stops* (R-STOPS), which are directly related to the evaluation of fluency in human-robot collaboration. T-TIME for Approach (1) is generally lower than in Approach (2). Moreover, the number of stops when engaging path consistent stop trajectories is lower with respect to the previous approach that does not preserve the robot path. The results (also reported in numeric form in Tab. 1) show the highest performance of the proposed method with respect to Approach (2) in ensuring safety and fluency in the collaboration, while satisfying the robot dynamic constraints.

5 Conclusion

In this paper, a method for the online planning of path-consistent stop trajectories for collaborative robotics has been presented. The approach considers the manipulator to be enclosed in bounding volumes, whose sizes account for a protecting separation distance and are minimized online considering the robot dynamics and its torque constraints. In case a collision danger between bounding volumes enclosing human and robot is detected, the robot is steered to stop along a path-consistent trajectory. The approach has been tested on a validated model of the 7-DOF Franka Emika Panda arm. Results have shown the feasibility of the method and its superiority with respect to a similar approach that does not preserve path consistency during safety stops. The effectiveness of the approach has also been verified using metrics related to the collaboration fluency, e.g., the task execution time and the number of stops. Future works will see the experimental validation of the approach and its extension to mobile manipulators to ensure safety in more challenging scenarios.

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