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On the improvement of the combination of Power and Force Limiting and Speed and Separation Monitoring for an effective Human Robot Collaboration

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Abstract

In industrial human-robot collaborative tasks it is of paramount importance to guarantee safety, productivity and fluency. To this scope, beyond the two collaborative modalities introduced by the ISO/TS 15066 (Speed and Separation Monitoring - SSM and Power and Force Limiting - PFL), a modality that combines SSM and PFL to further enhance productivity of a collaborative task has been proposed in literature. However, such method, while guaranteeing an improvement with respect to the two modalities foreseen by the ISO/TS 15066, relies on some conservative assumptions that limit its potentialities. In this work, a method to overcome these limitations is presented and its effectiveness is validated through numerical simulations. Results show that the novelty introduced in this paper leads to an improvement in terms of productivity, fluency of the operation and in usage of the robot, without affecting the safety of the collaborative tasks.

Keywords: Human-Robot Collaboration; Collaborative Robotics; ISO/TS 15066

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1. Introduction

Collaborative robots are gaining more and more importance in industrial environments [1] thanks to their capability of operating in a fenceless and shared workspace. To foster the implementation of such devices it is of paramount importance to develop algorithms capable of ensuring two different aspects, which several times are contrasting one with the other: safety and productivity [3, 5].

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It is possible to group the scientific works trying to tackle this problem in two categories: the ones which develop a strategy based on the ISO/TS 15066 [2] and the ones that don't. Concerning the second group, it is worth mentioning those relying on potentials fields [6, 7, 10, 13], which proved to be particularly effective. However, such methods don't ensure the fulfilment of the ISO/TS 15066 [2], which establishes the conditions under which a safe human-robot collaboration can take place, thus limiting the potentialities when considering their implementation in a real-world industrial scenario.

Concerning the first group, instead, several works based on the ISO/TS 15066 [2] can be found in literature. Such technical specification foresees 4 modalities to implement a fenceless human-robot interaction (HRI): *safety-rated monitoring stop*, *hand guiding*, *speed and separation monitoring* (SSM) and *power and force limiting* (PFL). Among those, actually, only SSM and PFL are regarded as truly 'collaborative' modalities and they will also be the two criteria allowed to implement a collaborative application by the future version of the ISO 10218 standard. For this reason, the vast majority of the scientific works focus on those two modalities or on their combination.

The PFL criterion admits possible collision between the robot and the human operator if they take place under safe conditions, i.e. the collision will not cause an injury to the operator. In particular, it is foreseen that a possible human-robot collision must take place at a relative speed smaller than a limit velocity v_{PFL} defined as:

$$v_{PFL} = \frac{F_{max}}{\sqrt{k}} \sqrt{m_R^{-1} + m_H^{-1}} \tag{1}$$

where d is the distance between the operator and the robot, T_s the stopping time of the robot, F_{max} and k are, respectively, the maximum allowable contact force and the effective spring constant for a specific body region (their reference values are defined in [2]), while m_R and m_H are, respectively, the effective mass of the robot and of the human operator.

The SSM criterion, instead, establishes that the manipulator must operate at a combination of relative distance and velocity with respect to the human operator which ensures that the robot can slow down its speed and stop its motion before a collision could take place. In particular, SSM foresees that the minimum human-robot distance must be larger than a limit protective distance. The limit protective distance d_l is defined as:

$$d_l = S_h + S_r + S_s + C + Z_d + Z_r \tag{2}$$

where S_h is the space covered by the operator, S_r and S_s are, respectively, the space covered by the robot during the reaction time and during the braking phase, C is the contribution for intrusion before detection, Z_d and Z_r are, respectively, the operator's and robot's position uncertainty.

In [12] the implementation of the SSM is improved by considering the minimum stopping time of the robot instead of the maximum stopping time reported in the datasheet of the manipulator. The minimum stopping time is computed taking into account kinematic and dynamic conditions and capabilities of the manipulator. In [4], the maximum allowable speed that ensures a safe human-robot collaboration is computed by rearranging the formula foreseen by the norm. In [8] a method based on the explicit representation of danger zones is presented which aims at maximizing the speed of the manipulator while fulfilling the SSM paradigm is presented. In [11], instead, a collision avoidance methodology based on the SSM criterion is proposed.

A first attempt to combine the PFL and SSM criteria has been presented in [9]. The idea is that the robot is allowed to operate at a combination of speed and distance such that the manipulator is capable of reducing its speed, in case of a possible collision, up to a speed lower with respect to the limit speed v_{PFL} defined by the PFL criterion. Consequently, by reducing the speed, it is ensured that, if a collision happens, it takes place in 'safe' conditions, i.e. without entailing an injury for the operator. In mathematical terms, the combination of PFL and SSM was formulated as:

$$v \leq \frac{d}{T_s} + \frac{F_{max}}{\sqrt{k}} \sqrt{m_R^{-1}} \tag{3}$$

where d is the distance between the operator and the robot, T_s the stopping time of the robot, F_{max} and k are, respectively, the maximum allowable contact force and the effective spring constant for a specific body region (their reference values are defined in [2]), while m_R is the effective mass of the robot. In particular, $\frac{F_{max}}{\sqrt{k}}\sqrt{m_R^{-1}}$ is the maximum allowable contact speed according to the PFL criterion defined in ISO/TS 16055 [2] under the assumption of an infinite mass of the human operator ($\frac{F_{max}}{\sqrt{k}}\sqrt{m_R^{-1}+m_H^{-1}}, m_H = \infty$). It is important observe that assuming an infinite mass of the operator reduces the maximum allowable contact speed, thus resulting more conservative with respect to the technical specification. Even if such work improved the effectiveness of a human robot collaboration with respect to the adoption of the PFL or the SSM criteria, such a method assumes that the deceleration time is equal to the stopping time T_s, which, according to the definition, is the time required by the manipulator to completely stop its motion. When considering the combination of PFL and SSM, however, the manipulator doesn't have to stop its motion before a collision could take place, it has to slow down its speed up to the limit one (v_{PFL}). Therefore, it would be possible to adopt a less conservative approach by considering the 'deceleration time' T_d required by the manipulator to reduce its speed up to the limit speed v_{PFL} instead of considering the stopping time of the manipulator T_s.

The main contributions of this work are: (1) development of a less conservative method to combine the PFL and SSM criteria based on the 'minimum deceleration time' instead of the 'maximum stopping time' to fully exploit the potentialities of their combination and (2) investigate the effects of the introduction of such novelty on the effectiveness of the human-robot collaboration in terms of safety, productivity and fluency of the operation with numerical experiments.

The remainder of this work is organized as follows: in Sec. 2 once an overview of the developed method is given, the method is detailed. Then, in Sec. 3 implementation and effectiveness evaluation are presented. Finally, in Sec. 4, conclusions are drawn and possible future works mentioned.

2. Method

2.1. Overview of the Method

The developed safety method addresses the problem of guaranteeing a safe HR collaboration while the manipulator is executing a task by moving along a predefined nominal trajectory. Such a method is structured in three parts:

- At every time-step it is computed the minimum possible 'deceleration time' T_d required by the robot to slow down the quickest part of the robot along the predefined path up to the limit speed v_{PFL} defined by the PFL criterion by considering the dynamic and kinematic capabilities of the manipulator. The robot, then, reaches a 'safe' speed at time $t = t_{safe} = t_0 + t_r + T_d$, where t_r is the reaction time, i.e. the time distance between the moment a command is defined and the moment in which the robot initiates the action.
- it is computed the volume covered by the robot during the deceleration phase, i.e. up to the time-point where the speed is lower than the limit one (Fig. 1, yellow area). This space is a region where the manipulator is moving with a velocity higher than the 'safe' one (v_{PFL}). Consequently, if a collision would happen in this area, it would happen at a speed of the robot higher with respect to the limit one. In other words, this volume is a 'danger zone'.
- it is computed the volume which could be occupied by the human operator within the deceleration time (Fig. 1, blue area). If the possible future human encumbrance intersects the robot's 'danger zone', the operation of the robot is interrupted, otherwise the manipulator's movement continues along the nominal trajectory.

2.2. Method

In this subsection the three phases in which the developed method is structured are presented in detail. In particular, in Subs. 2.2.1 it is explained how the deceleration time is computed, while in Sub.s 2.2.2 and 2.2.3 it is presented, respectively, the computation of the robot's danger zone and of the human's future occupancy zone.

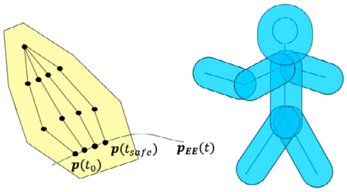


Fig. 1: Representation of the robot's 'danger zone' (yellow) and the possible future human encumbrance (blue).

2.2.1. Evaluation of the deceleration time

Let's consider the movement of the manipulator along the predefined path $\mathbf{q}(s(t))$. At each time step t_0, the manipulator has to compute the minimum deceleration time T_d which allows the manipulator to slow down its speed by moving along its predefined path. To do so, it is necessary to find a deceleration trajectory $\mathbf{q}_{(}s_d(t))$ with the following characteristics:

- the boundary conditions at the beginning of the deceleration trajectory must match the state of the robot at this moment:

$$\begin{aligned}\mathbf{q}(s(t_0+t_r)) &= \mathbf{q}(s_d(t_0+t_r))\\ \dot{\mathbf{q}}(s(t_0+t_r)) &= \dot{\mathbf{q}}(s_d(t_0+t_r))\\ \ddot{\mathbf{q}}(s(t_0+t_r)) &= \ddot{\mathbf{q}}(s_d(t_0+t_r))\end{aligned} \tag{4}$$

- the cartesian speed of all robot points P_r at the end of the deceleration phase must be lower than the limit speed defined by the PFL criterion (v_{PFL}):

$$|\mathbf{v}_{\mathbf{P}_r}(t_0+t_r+T_d)| = |\mathbf{J}^{\mathbf{P}_r}\dot{\mathbf{q}}(t_0+t_r+T_d)| \leq v_{PFL} \quad \forall \quad \mathbf{P}_r \tag{5}$$

where T_d the deceleration time of the manipulator, i.e. the time required to slow down the speed from the actual to the safe one, and $\mathbf{J}^{\mathbf{P}_i}$ the position Jacobian associated with point $\mathbf{P}_i$.

Evaluating this second condition for every robot's point is time consuming and, consequently, a strategy to reduce the computational complexity must be adopted. To achieve this goal, let's consider a generic linear link i of the manipulator (if they would be non-linear, it would be possible to approximate them by means of a set of linear links) having as initial and final points, respectively, $\mathbf{r}_a$ and $\mathbf{r}_b$, and a generic point $\mathbf{r}_s$ belonging to that link (Fig. 2):

$$\mathbf{r}_s = \mathbf{r_a} + s\,(\mathbf{r}_b - \mathbf{r}_a)\,, \qquad s \in [0,1] \tag{6}$$

the speed $\mathbf{v}_s$ of a generic point of the link can be computed as:

$$\mathbf{v}_s = \frac{d\mathbf{r}_s}{dt} = \mathbf{v}_a + s\,(\mathbf{v}_b - \mathbf{v}_a) \tag{7}$$

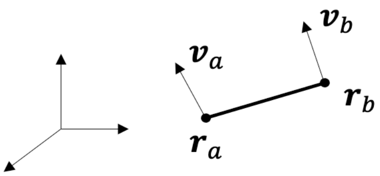


Fig. 2: Representation of a generic linear link of the manipulator.

Eq. 7 proves that the speed of a generic point belonging to the link is linear with respect to s. Consequently, it is possible to state that:

$$\max_s(v_s) = \max(v_a, v_b) \tag{8}$$

or, in other words, the maximum speed of a robotic link is equal to the maximum of the speeds of its extreme points. This result is particularly useful for such a method because it implies that the maximum speed of the manipulator can be found only in a finite number of points of the manipulator (at the beginning and at the end of each link). Therefore, it has been proven that the constraint reported in eq. 5 has to be verified only for the set of extreme points of all the manipulators' links Φ:

$$|\mathbf{v}_{\mathbf{P}_i}(t_0 + t_r + T_d)| = |\mathbf{J}^{\mathbf{P}_i}\dot{\mathbf{q}}(t_0 + t_r + T_d)| \leq v_{PFL} \quad \forall \quad \mathbf{P}_i \in \Phi \tag{9}$$

Finally, the deceleration time can be computed by means of the following optimization model:

$$\min T_d \tag{10}$$

$$\text{s.t.} \quad |\tau\,(\ddot{\mathbf{q}}(s_d(t)), \dot{\mathbf{q}}(s_d(t)), \mathbf{q}(s_d(t)), \tau_{ext})\,| \leq \tau_{max} \tag{11}$$

$$|\mathbf{v}_{\mathbf{P}_i}(t_0 + t_r + T_d)| \leq v_{PFL} \quad \forall \quad \mathbf{P}_i \in \Phi \tag{12}$$

where $\tau\,(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}, \tau_{ext})$ is the inverse dynamic model of the manipulator and τ_{max} the vector of limit torques of the manipulator. The goal of the optimization (eq. 10) is to find the minimum deceleration time T_d which ensures that the Cartesian speed of every critical point at the end of the deceleration phase is smaller than the limit one without exceeding the torque limits of the manipulator (eq. 11).

2.2.2. *Robot's danger zone*

Once the deceleration time has been determined, it is possible to define the 'danger zone' of the robot, i.e. the zone occupied by the manipulator before reducing its speed under the safe limit speed. In particular, the 'danger zone' is defined as the union of all space occupied by the robot from time $t = t_0$ to the end of the deceleration phase ($t = t_0 + t_r + T_d$).

2.2.3. *Human's occupancy zone*

Based on the kinematic state of the operator, it is possible to generate the volume of space which might be occupied by the human within the completion of the robot's deceleration phase by considering a radius r_{SSL} around the human skeleton/obstacle points, which is given by:

$$r_{SSL} = r_i + C + Z_d + Z_r \tag{13}$$

where r_i is the minimum radius which allows to enclose the i^{th} body part considered. Then, possible intersections between the robot's danger volume and the human occupancy zone are investigated. If an intersection is found, the human operator might get in touch with the robot in non-safe conditions and, consequently, the motion of the robot is interrupted, otherwise the manipulator can execute the nominal path.

In Fig. 3 a graphical representation summarizing the the developed algorithm is reported.

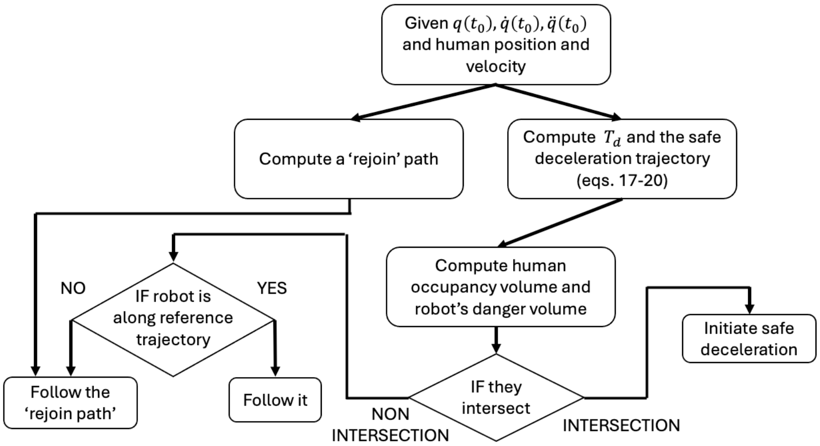


Fig. 3: Representation of the developed algorithm.

3. Implementation and Validation

3.1. *Implementation*

The developed algorithm has been implemented and tested in a simulation environment developed in Matlab. The manipulator used to test and validate this work is the UR5e (produced by Universal Robots), which is characterized by 6 degrees of freedom and by a maximum payload of $5kg$. The collision geometries, the kinematic and the dynamic parameters adopted are the ones that can be retrieved by the model of the Matlab Robotics Toolbox's UR5e model. To solve the optimization problem (eq.s 10-12), the Matlab Optimization Toolbox's *fmincon* function has been used.

In the simulation scenario the manipulator interacts with an obstacle point which is moving along a fixed and predefined path. Such an obstacle point has the goal of simulating the actions of a human operator.

In Fig. 4 it is possible to observe the simulation environment in which the robot and the obstacle point (surrounded by its possible future occupancy volume) are interacting. In particular, in Fig. 4a, the 'danger zone' of the robot and the human possible occupancy do not intersect each other, thus implying a 'safe' condition. On the contrary, in Fig. 4b, the two volumes intersect each other, denoting a 'dangerous' condition which will lead to the interruption of the robot's motion.

(a) (b)

Fig. 4: Representation of the simulation environment representing a safe condition (a) and a dangerous one (b).

3.2. Validation

To validate the method the following test scenario is considered: a robot is controlled while it moves along a predefined nominal trajectory which simulates a pick-and-place application executed 5 times. In the meanwhile, the obstacle point, which simulates a HR interaction, is moving in the robot's workspace.

To evaluate the effectiveness of the developed method, which exploits the minimum deceleration time T_d, its effectiveness is compared with the one of using the maximum stopping time T_s as in [9]. Moreover, the test has been executed with four different combinations of human-robot velocities, to take into account the possible effects due to velocity. In particular, the manipulator's nominal pick-and-place trajectory (Fig. 5, orange curve) is executed in $t_R = 10s$ (which corresponds to a maximum absolute cartesian velocity of $0.39m/s$) and in $t_R = 20s$ ($0.19m/s$), while the human trajectory (Fig. 5, blue line) is executed in $t_H = 3s$ and in $t_H = 6s$.

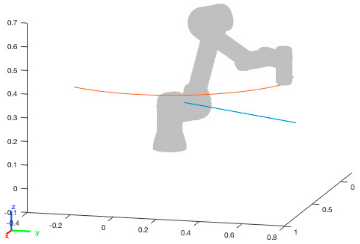


Fig. 5: Representation of the robot's (orange) and human's (blue) path.

To quantitatively measure and compare the effectiveness of the two solutions, the following metrics are considered:

- E-TIME: it is the average time required to execute a pick-and-place cycle by the robot. Consequently, the lower the E-TIME value, the higher it is the productivity. This metric aims at measuring the productivity associated with the deployment of an algorithm.
- R-STOPS: it consists of the number of times the robot stopped its action. This metric has the goal of quantifying the fluency of a collaborative operation. In fact, the lower the number of robot stops, the more fluent the collaboration is.
- R-IDLE: it is defined as the percentage of time in which the robot is stopped, i.e. not moving/executing an action. The metrics evaluates the exploitation of the robot. The lower the R-IDLE value, the more the manipulator is used to generate value.

New Method						
	E-TIME		R-STOPS		R-IDLE	
	$t_H = 3s$	$t_H = 6s$	$t_H = 3s$	$t_H = 6s$	$t_H = 3s$	$t_H = 6s$
$t_R = 10s$	10 s	10,8 s	0	4	0	0.074
$t_R = 20s$	23.4 s	24.2 s	9	10	0.077	0.082
Constant Stopping Time						
	E-TIME		R-STOPS		R-IDLE	
	$t_H = 3s$	$t_H = 6s$	$t_H = 3s$	$t_H = 6s$	$t_H = 3s$	$t_H = 6s$
$t_R = 10s$	12.2 s	11.8 s	6	5	0.098	0.085
$t_R = 20s$	23.8 s	24.4 s	15	11	0.126	0.090

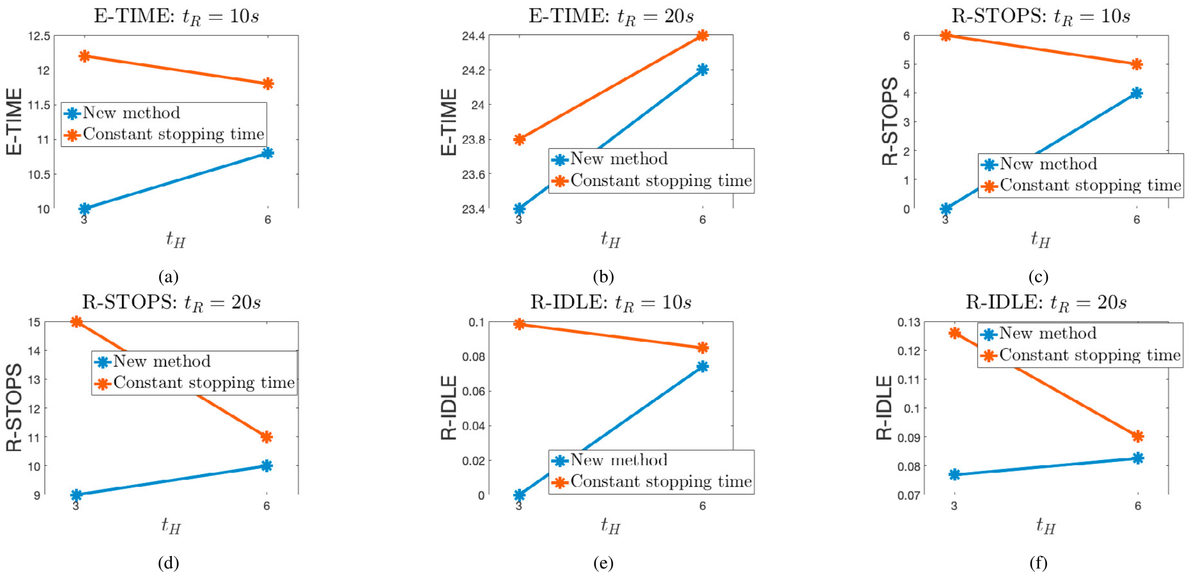
Table 1: numerical results of the numerical comparison.

In Fig. 6, the results of such a comparison are reported. In particular, in Fig.s 6a and 6b it is possible to observe that the evaluation of the minimum deceleration time (new method, blue curve) leads to a lower value of 'E-TIME', thus improving the productivity associated with the HR collaborative operation.

An improvement can be observed also when considering the fluency of the collaborative operation. In fact, as it is possible to observe in Fig.s 6c and 6d, the number of robot stops are in all scenarios reduced, thus ensuring a smoother collaboration.

In Fig.s 6e and 6f, instead, it is possible to observe the results describing the exploitation of the robot: the exploitation of the newly developed method still entails a reduced robot idle time, which implies a higher usage of the manipulator.

Moreover, with respect to safety, both methods ensure that a possible collision would take place at a speed of the manipulator smaller than the limit one. Consequently, from the point of view of safety, the two methods can be both considered as 'safe' and compliant with the ISO/TS 15066 [2].



(a) (b) (c)

(d) (e) (f)

Fig. 6: Results of the comparison analysis.

4. Conclusion

This paper proposes a new way to improve the combination of PFL and SSM. In particular, the developed method foresees that, at every time step, it is computed the trajectory which slows down the robot from its actual speed to the safe speed defined by the PFL criterion in the minimum possible time by moving along the nominal path of the manipulator. Then, it is computed the volume of space occupied by the robot in the 'deceleration' phase. Finally, the volume which might be occupied by the human within the deceleration phase of the robot is computed. If it intersects the 'danger' volume associated with the robot motion, the motion of the robot is stopped, otherwise it can continue its motion. The effectiveness of the algorithm, which exploits the minimum deceleration time, instead of the maximum stopping time of the robot (as the state of the art work does) has been evaluated through numerical simulations. Results show that the introduced method leads to an improvement in terms of safety, productivity, fluency of the collaborative operation while guaranteeing the same level of safety with respect to the scenarios in which the maximum stopping time is considered.

Possible future works are related to the implementation and evaluation of such an algorithm in a real-world scenario based on a real production cycle and its assessment with respect to a broader variety of metrics also related to the cognitive ergonomics domain.

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