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# Integration of perception, control and injury knowledge for safe human-robot interaction

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*Abstract*— **In the past few years the need for more flexibility in industrial production has implied a growing attention towards scenarios where humans work directly in touch with robots. In order to allow safe human-robot interaction, a methodology to evaluate the severity of an impact between a human worker and an industrial robot, based on related work on injury knowledge in human-robot contacts and relying on information coming from different exteroceptive sensors, has been developed in this paper. On the basis of this severity evaluation, the robot controller enforces a suitable safety-oriented strategy, ranging from on-path speed reduction to task-consistent evasive motion and protective stop. The safety evaluation methodology has been implemented in a dedicated software component, integrated with a video surveillance system and with the real time robot controller to obtain a complete HW/SW architecture named "Safety Controller". The system has been validated on an ABB IRB140 robot.**

## I. Introduction

It is today a common opinion that a more structured and fruitful human-robot cooperation will facilitate industrial robots to be massively used also in small companies. On the other hand, even the last safety regulations for using robots in industrial environments [1] impose strict requirements like for instance a maximum end-effector linear velocity of 250 mm/s. In order to address these limitations, while guaranteeing a certain level of safety, a twofold approach can be followed. First, a methodology to evaluate in real-time the severity of a possible impact between a robot and a human worker has to be established. On the other hand, safety-oriented control strategies, exploiting the computed severity measure, must be developed. Furthermore, both the severity evaluation and the control strategies must be based on the information coming from all the sensors available inside the robotic cell, both exteroceptive (i.e. surveillance cameras) and proprioceptive (i.e. joint encoders). Consequently, a significant effort must be made to integrate the available sensors and the control system into a single HW/SW architecture.

Evaluating the severity of an impact between a human being and a moving industrial robot consists in determining how dangerous the impact itself will be for the human involved. At first, methodologies borrowed from the automotive industry were used, like the Gadd Severity Index (GSI) [2] or the Head Injury Criterion (HIC) [3]. However, both

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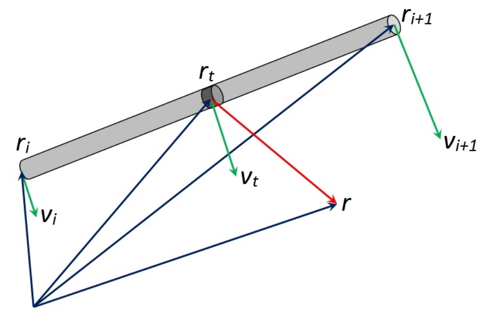


Fig. 1. Example of DF calculation for a single link.

the GSI and the HIC have been developed to deal with head injury, while in an industrial environment it is likely that a human-robot collision involves the worker's arm, his/her leg or thorax. More recently, new attempts were carried out to evaluate the severity of human-robot collisions using standard automotive crash-testing equipment and protocols. In [4] a large number of impact experiments and a wide basis of impact testing results are presented, mainly considering the contact forces and the acceleration of the human body parts involved in the collision.
In [5] and [6] Ikuta, Ishii and Nokata describe the first systematic severity evaluation methodology specifically developed for human-robot cooperation. Nevertheless, it is not explained how to implement this methodology for real-time severity computation. In [7] the "Impact Potential" is defined as the maximum impact force with which a mechanical moving system can hit a still obstacle. This approach to severity evaluation is computationally more effective, but it does not consider the case of human workers moving inside the cell. Finally, in [8] and [9] a methodology to use the information about severity to influence path planning and/or trajectory generation in real-time is presented.
Recently also the problem of detecting and reacting to collisions between a robot manipulator and a human being has been addressed [10] and sensor-based strategies for collision detection and reaction have been studied [11], [12].

This paper contributes to the field of safe human-robot interaction in many ways. At first, a severity evaluation strategy is presented and its real-time implementation is discussed. The main idea of this methodology is to use all the sensory information available, coming both from the robot's proprioceptive sensors (its internal encoders) and from all the exteroceptive sensors installed inside the robotic cell (typically distance sensors and/or surveillance cameras). Some "danger indices" are computed and are used to assess how dangerous a human-robot cooperation scenario is. In this way the severity measure not only depends on the robot's configuration (in terms of joint configuration, joint velocities, joint torques, and equivalent inertia), but it is also influenced by the human worker's behavior (in terms of position, velocity and estimated intention). Moreover, in the software implementation, the severity evaluation strategy is integrated into a comprehensive HW/SW architecture, named "Safety Controller", that comprises the robot, the exteroceptive sensors, the software components that acquire, process and provide the sensor measurements, the controller and the safety control strategy it implements.

## II. Methodology for severity evaluation

In order to guarantee a certain level of safety, the control system adopts different actions: speed reduction, protective stop and trajectory modification. To select the most suitable robot reaction, the controller needs to know the information regarding the human behavior, coming from the surveillance system (see Section IV-A), and an evaluation of the severity of a potential collision between the human worker and the manipulator. This Section explains how this severity evaluation is performed on the basis of two different quantities: the Danger Field and the Severity Index.

### A. Danger Field

The Danger Field (DF) is an artificial field that can be used to determine the danger level of a point in close proximity to the robot. This assessment has been introduced in [13] and is based on the idea that the robot, rather than the human, is a source of danger. A simplified model of the manipulator is considered, where every link is reduced to the segment connecting its end-points. For every infinitesimal element of the i-th link (Figure 1), the DF associated to the Cartesian position $\mathbf{r}_{3x1}$ can be expressed as:

$$DF(\mathbf{r},\mathbf{r_t},\mathbf{v_t}) \;=\; \frac{k_1}{||\mathbf{r}-\mathbf{r_t}||}+\frac{k_2\,||\mathbf{v_t}||\,[\gamma\,\cos\angle(\mathbf{r}-\mathbf{r_t},\mathbf{v_t})]}{||\mathbf{r}-\mathbf{r_t}||^2} \quad (1)$$

where parameters $k_1$ and $k_2$ are real positive constants, $\gamma \geq 1$ is a real constant, $\mathbf{r_t}$ and $\mathbf{v_t}$ are the position and velocity of a generic point on the i-th link respectively, expressed as a function of the link's natural coordinate $t$:

$$\mathbf{r_t} = \mathbf{r_i} + t(\mathbf{r_{i+1}} - \mathbf{r_i}) \qquad t \in [0,1] \quad (2)$$

$$\mathbf{v_t} = \mathbf{v_i} + t(\mathbf{v_{i+1}} - \mathbf{v_i}) \qquad t \in [0,1] \quad (3)$$

To obtain the DF value associated to the i-th link, it is necessary to integrate the infinitesimal DF over the entire link, thus obtaining:

$$DF_i(\mathbf{r}) \;=\; \int_0^1 DF(\mathbf{r},\mathbf{r_t},\mathbf{v_t})\,dt \quad (4)$$

The DF value related to the complete robot can be evaluated, in closed form, as the sum of all the contributions belonging to the $n$ links, or alternatively as the maximum value among them:

$$DF_{Sum}(\mathbf{r}) = \sum_{i=1}^{n} DF_i(\mathbf{r}), \quad DF_{Max}(\mathbf{r}) = \max_{i=1\dots n} DF_i(\mathbf{r}) \quad (5)$$

Finally, it is possible to transform the DF into a vector field, using its gradient:

$$\mathbf{DF}(\mathbf{r}) \;=\; DF(\mathbf{r})\frac{\nabla DF(\mathbf{r})}{||\nabla DF(\mathbf{r})||} \quad (6)$$

While the scalar DF only allows to determine the risk associated to a particular position, its vectorial counterpart can be effectively used to guide a safety control action. If we consider for instance a virtual impedance control scheme [14], the vector DF can be used as the virtual force that, once converted into a variation of the joint position and velocity references, causes the manipulator to keep a certain distance from the identified obstacles [15].

### B. Severity Index evaluation methodology

A specific injury criterion has been identified for every considered type of collision (free impact or clamping) involving a particular part of the human body (head, arm or thorax) [16]. As an example, the injury criterion associated to a free impact that involves a human arm is the plastic strain of the ulna bone, while the injury criterion that corresponds to a free impact that involves the thorax is the penetration inside the chest.

On the basis of the injury criterion, an injury risk curve can be determined. Introducing several threshold values on the injury probability, it is possible to discretize the severity measure into different levels, which are then represented, for convenience, using a color-code. The first level of severity (GREEN) starts from null injury probability and reaches up to a 30% injury risk. The second level (YELLOW) is defined between the load value corresponding to a 30% injury risk and the load value associated to a 50% probability of injury. The third level (ORANGE) ranges from the load corresponding to 50% injury risk to the upper tolerance limit (75% probability of injury). Finally, the fourth level (RED) includes everything above the upper tolerance limit.

In order to generalize the injury risk assessment to different kind of collisions and different involved body parts, a large number of simulations of collision between a mass, called "impactor", and a FE model of the human being have been done. The chosen Finite Element model of the human being is the THUMS model [17]. An experimental validation of these simulations has been also performed and can be found in [18].

The numerical simulations are based on the identification of a "collision configuration" [19]. Knowing the impact points both on the robot and on the human worker, the collision configuration consists in the combination of a set of indices which play a role in defining the severity of the potential collision:

- injury type: `FREE IMPACT` or `CLAMPING`;

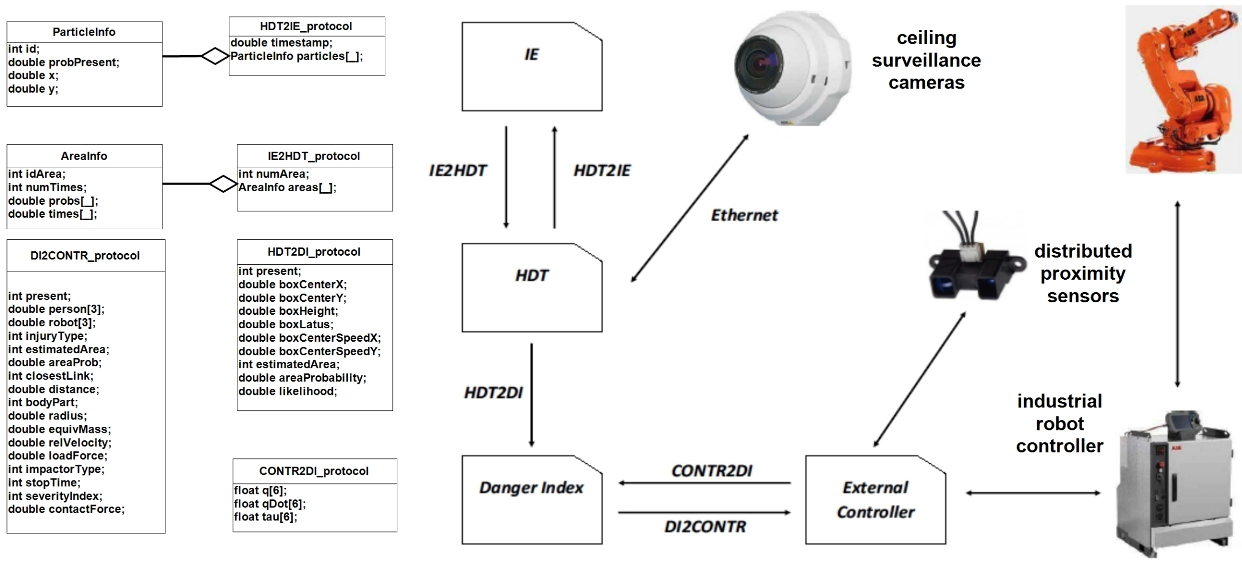


Fig. 2. Architectural scheme of ROSETTA Safety Controller. On the left side the UML diagram of the protocols used to exchange information between the different components.

- body part: part of the human body (HEAD or THORAX) hit by the robot;
- relative velocity: difference between the robot velocity and the human velocity along the direction identified by the robot velocity [0.00 - 0.75 m/s];
- equivalent mass: the effective mass of the robot in the direction of the linear velocity of the impact point [0.00 - 70.00 kg];
- load force: force exerted by the manipulator at the impact point [0.00 - 200.00 N];
- impactor radius: radius of the robot surface at the impact point [10.00 - 100.00 mm];
- material stiffness: stiffness of the robot surface at the impact point.

The severity index assessment consists, at first, in computing in real-time the values of these danger indices. Once all the indices have been evaluated a "Lookup Table" is queried. Tuples contained in this table relate a set of values of the danger indices to a particular value of the overall severity index (GREEN, YELLOW, ORANGE or RED), so that the result of the query is the value of the severity index associated to the current interaction situation.

## III. REAL-TIME SEVERITY INDEX EVALUATION

The proposed methodology for evaluating the severity index in real-time has been implemented into a software component named "Danger Index" (DI). DI mainly executes two different tasks: it computes the values of the danger indices and with these values it queries the Lookup Table to obtain the severity index value. More in depth, DI at first identifies the possible impact points both on the robot and on an identified person. For this a wire approximation of the links of the robot and a simplified approximation of the human body, as detected by some surveillance system, are used. Then DI computes the positional Jacobian matrix corresponding to the impact point on the robot $\mathbf{J}_p(\mathbf{q})$ and evaluates its linear velocity as:

$$\mathbf{v_{rob}} = \mathbf{J}_p(\mathbf{q})\,\dot{\mathbf{q}} \tag{7}$$

Then, normalizing the velocity $\mathbf{v_{rob}}$ and knowing the human's velocity $\mathbf{v_{obst}}$ it is possible to compute the **relative velocity** as:

$$\mathbf{u} = \frac{\mathbf{v_{rob}}}{||\mathbf{v_{rob}}||}, \quad \mathbf{v_{rel}} = (\mathbf{v_{rob}} - \mathbf{v_{obst}})\,\mathbf{u} \tag{8}$$

The **body part** index is a discretized quantity that is determined on the basis of the height of the impact point on the person.
The **injury type** is another discretized index depending on the destination area of the worker entering the cell (see Section IV).
The **equivalent mass** is evaluated using the following formula [20]:

$$\mathbf{m_{eq}} = (\mathbf{u}^T\,\mathbf{J}_p(\mathbf{q})\;\mathbf{B}(\mathbf{q})^{-1}\,\mathbf{J}_p^T(\mathbf{q})\,\mathbf{u})^{-1} \tag{9}$$

where $\mathbf{B}(\mathbf{q})_{nxn}$ is the robot's inertia matrix.
The **load force** is computed on the basis of the Principle of Virtual Works:

$$\mathbf{f_{load}} = \mathbf{u}^T\,\mathbf{J}_p^{\#}(\mathbf{q})\,\tau \tag{10}$$

where $\mathbf{J}_p^{\#}(\mathbf{q})_{nx3}$ is the Moore-Penrose pseudoinverse of $\mathbf{J}_p(\mathbf{q})$, and $\tau_{nx1}$ contains the joint torques.
A constant value of **impactor radius** is assigned to each link of the manipulator adopting a worst-case approach, i.e. considering the sharpest impact point on the link.
As for the **material stiffness** index, each link is assigned a particular discretized stiffness value and the **material stiffness** index is evaluated on the basis of the link to which the impact point belongs.

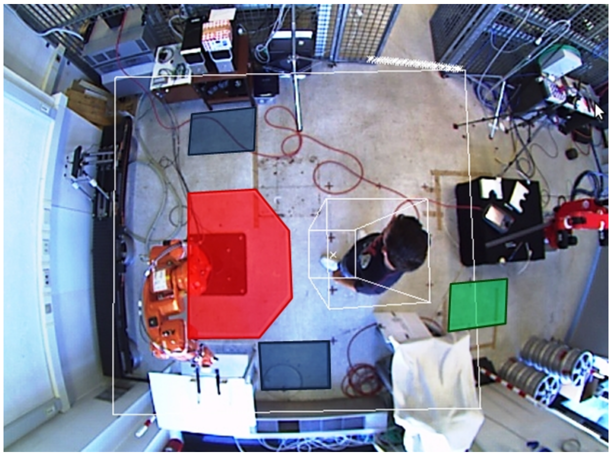

Fig. 3. Layout of the robotic cell and example of the tracking box.

After computing the values of all the danger indices, DI, exploiting the Lookup-Table, yields the value of the severity index that corresponds to the collision configuration.

## IV. Safety Controller System Integration

### A. Safety Controller Components and Connections

The overall HW/SW architecture of the Safety Controller is depicted in Figure 2. The main components are:

- Human Detection and Tracking (HDT): this software component and the two ceiling surveillance cameras are responsible for the detection and tracking of humans entering the robotic cell (see [21] for further details).
- Intention Estimation (IE): is the software component responsible for identifying the destination area a human entering the robotic cell is heading to (see [21] for further details);
- External Controller: a PC that communicates in real-time with the ABB IRC5 controller [22] in order to implement sensor-based control strategies;
- Exteroceptive distributed LED-based distance sensor: a set of LED-based distance sensors installed on the robot in order to measure the proximity of very close obstacles from different points on the manipulator (see [23]).

The complete HW/SW architecture of the Safety Controller is assembled by interconnecting all the components (Figure 2). IE receives the information computed by the tracking algorithm inside HDT and sends back to HDT the probability that a person entering the robotic cell stops inside one of the areas identified in the cell layout (see Figure 3). By considering the area with the highest probability the system predicts the human worker's destination, and, exploiting the fact that each area is classified either as a "free impact" or as a "clamping" area (see again Section V), determines what kind of injury will be caused by a possible collision with the robot. Provided that interaction areas are divided into free impact areas and clamping areas, the proposed severity evaluation strategy can be applied to any robotic cell. The HDT component sends to DI all the information regarding presence, position, speed, and most probable destination of each person.

The External Controller is already interfaced with both the ABB IRC5 Controller and the distributed distance sensor. One last communication channel allows DI to receive from the External Controller the information on the robot configuration and to send back all the information concerning the severity evaluation.

### B. Safety-oriented Control Strategy

The core of the Safety Controller Architecture is a safety-oriented real-time control strategy. This control strategy aims at allowing the robot to complete its task, while guaranteeing the human worker's safety during collaborative operations. More precisely, a task is defined by the $\mathbf{x_{ref}}$ vector

$$\mathbf{x_{ref}} = \left[ x_{ref},\ y_{ref},\ z_{ref},\ \varphi_{ref},\ \theta_{ref},\ \psi_{ref} \right]^T \qquad (11)$$

containing the six time-varying references that completely specify the desired TCP trajectory in the Cartesian Space.

The task can be divided into a primary task and a secondary task. The primary task consists in controlling the TCP position to the values that correspond, at each time step, to the first three elements of $\mathbf{x_{ref}}$. On the other hand, the secondary task consists in controlling the orientation of the tool frame, expressed in terms of XYZ Euler angles, to the values defined in the last part of $\mathbf{x_{ref}}$. The safety control strategy is articulated in the following steps:

1. Every time an obstacle (a human or an object) is perceived by the sensor system, its position is computed. In case the distance between the obstacle and the robot base is larger than 1.5 m, the Safety Controller is inactive. In this situations the vector DF is completely ignored, while the severity index is forced to **GREEN**.

2. If the distance, instead, decreases below the threshold value of 1.5 m, the control action to enforce is determined by the severity index and by the vector DF. In case DI computes a value of the severity index equal to **GREEN**, once again no control action is needed; while if the evaluated severity index is equal to **YELLOW**, the External Controller reduces the robot's speed by 50% in order to allow a safer human-robot cooperation.

3. Whenever the severity index determined by DI is equal to **ORANGE**, the External Controller enforces an evasive motion, i.e. a motion of the manipulator that essentially achieves a trade-off between keeping the robot far enough from the human and maintaining the manipulator TCP's main task, based on the vector DF. In this situation the vector DF is interpreted as a virtual force, that is mapped into displacements $\Delta\mathbf{p}_0$ of some points along the manipulator (Figure 4) through mechanical impedances, whose gains can be selected in software. These displacements are mapped at joint level and then differentiated, obtaining a variation of the joint velocity references $\dot{\mathbf{q}}_0$ that is fed to the CLIK control scheme shown in Figure 5 [15].

4. A threshold system determines how the evaluated displacements act on the reference computed by the standard

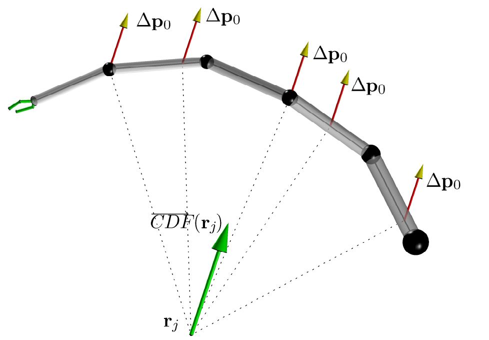


Fig. 4. Mapping the vector of the danger field into desired displacements $\Delta\mathbf{p}_0$ of several points of interest on the manipulator.

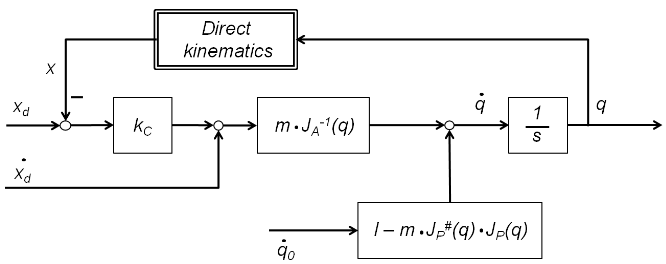


Fig. 5. CLIK Control Scheme.

robot controller. If the scalar DF value is below a certain threshold (experimentally determined), the value of the $m$ parameter (Figure 5) is set to 1 and the velocity references variation $\dot{\mathbf{q}}_0$ is projected into the null-space of the primary task (end-effector positioning). The result of this projection is finally summed with the velocity references computed by the standard robot controller. In this way the end-effector orientation is modified to allow the manipulator to assume a safer pose with respect to the human worker, determining a temporary suspension of the secondary task. On the other hand, if the DF value overcomes the previously mentioned threshold, the value of the $m$ parameter is set to 0. In this situation the standard control loop opens and the velocity references are computed on the basis of the vector DF. The resulting evasive motion consists in a full task suspension in terms of both position an orientation of the TCP. The complete release of the task allows the robot to avoid contact with the human worker by moving as far as possible from him. Only when the severity index decreases, the evasive motion is stopped and the main task of the manipulator is completely resumed.

5. Finally if the severity index is equal to **RED**, the External Controller enforces a protective stop. In this case the task must be resumed manually by the operator.

## V. Experimental Equipment

Both the software implementation of the severity evaluation methodology and the complete HW/SW architecture of the Safety Controller have been tested on the ABB IRB140 industrial manipulator installed inside the robotic cell. The experimental equipment consists of:

- ABB IRB 140 robot with ABB IRC5 controller: a 6-d.o.f. industrial manipulator with a reach of 810 mm and a maximum payload of 6 kg;
- distance sensors: LED-based distance sensors installed on the robot;
- surveillance cameras: two AXIS 212 PTZ surveillance cameras installed inside the cell and connected to the Safety Controller via Ethernet.

The robotic cell has a surface of approximately 32.5 square meters and is delimited on three sides by walls and by a gate on the fourth side. Surveillance cameras are installed at a height of approximately 3 metres.

Four different areas (corresponding to the highlighted zones in Figure 3) have been identified inside the cell:

- Area 1 (green): coexistence zone, where the human worker stays while performing actions that are completely independent from the main task of the robot;
- Area 2 (blue): cooperation zone at the bottom of the picture. Inside this area the human worker can actually cooperate with the robot;
- Area 3 (red): interference zone. If a worker enters this zone the probability of a collision with the robot is maximized. The robot is located inside this area;
- Area 4 (blue): cooperation zone in the upper part of the picture.

Considering the position of the tables with respect to the nearest areas (Figure 3), it is reasonable to assume that a collision between the robot and the person will result in a `FREE_IMPACT` if the person is located inside Areas 1, 2 and 3, while the collision will probably cause a `CLAMPING` injury when the human worker is in Area 4.

## VI. Experimental Verification

The control architecture described in the previous Sections has been experimentally tested. The robot has been assigned a typical "pick and place" task consisting in picking a box from the table near Area 2 (see Figure 3) and releasing it in Area 4. The experiments testing the four different safety behaviors of the Safety Controller are described below.

### *A. Human-robot coexistence - severity = `GREEN`*

Whenever the DI component computes a value of the severity index equal to `GREEN` or if the human worker stays at a distance of at least 1.5 m from the robot's base (i.e. when the person is located inside Area 1), the Safety Controller considers the severity index to be `GREEN` and, consequently, it does not adopt any particular control action to enforce safety, see Figure 6.

### *B. Human-robot cooperation - severity = `YELLOW`*

If the distance between the worker and the robot's base is less than 1.5 m (i.e. when the person is located inside either Area 2 or Area 4), whenever the DI component computes a value of the severity index equal to `YELLOW` the Safety Controller determines a speed reduction to allow a safe interaction with the human worker (Figure 7).

Fig. 9. Human-robot cooperation - severity = `ORANGE`: the first two screenshots are taken from the first cycle, with no human, while the other ones display the evasive motion due to the human presence. The IE is active, predicting the target area and the related probability.

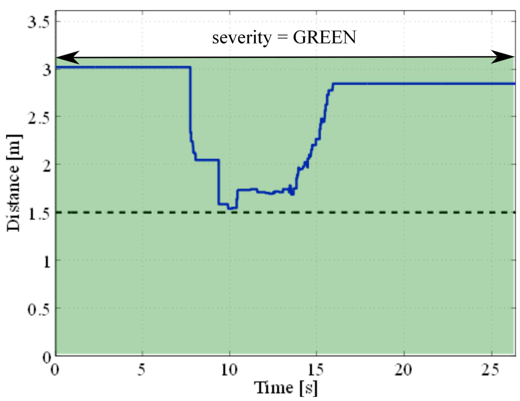


Fig. 6. Worker's distance to robot base (solid blue), distance threshold (dotted black)

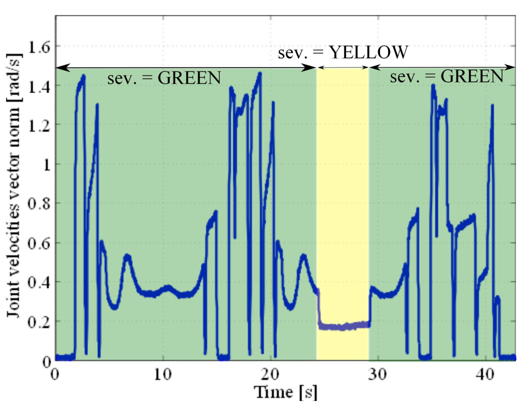


Fig. 7. Norm of the joint velocities vector (solid blue) reduced by a half when severity switches from `GREEN` to `YELLOW`

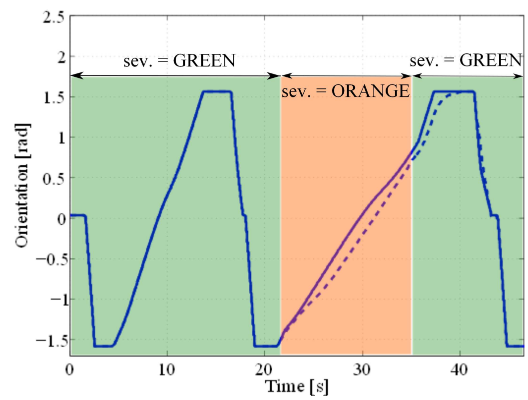


Fig. 8. Reference value for $\rho$ computed by robot controller (solid blue) and reference value for $\varphi$ computed by External Controller when severity = `ORANGE` and safety action is null-space projection

### C. *Human-robot cooperation - severity =* `ORANGE`

Whenever the computed severity index switches from `GREEN` to `ORANGE` and the value of the Danger Field is under the chosen threshold, the TCP's orientation task is suspended (Figure 8). This means that, while the end-effector maintains its position, its orientation references are modified by the Safety Controller. Considering the Euler angles $\varphi$, $\theta$ and $\psi$ (given in the XYZ convention), it can be noticed that the variation of the severity index causes the Safety Controller to modify the reference for the $\varphi$ angle computed by the robot controller in order to complete the TCP orientation task. When the severity index switches back to `GREEN`, the orientation task is recovered. For "task recovery" it is intended that the reference for $\varphi$ takes again the values computed by the robot controller making the manipulator resume the full task in terms of both position and orientation. In case the severity index is equal to `ORANGE`

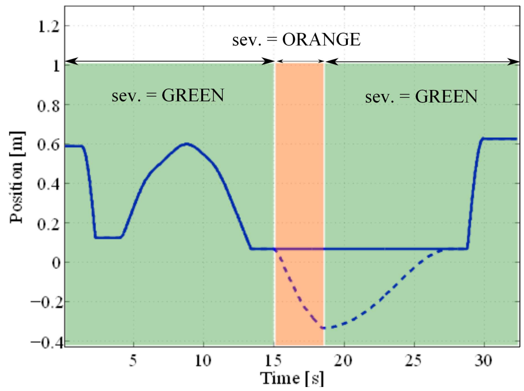


Fig. 10. Reference value for $x$ computed by the robot controller (solid blue) and reference value for $x$ computed by the Safety Controller when severity = ORANGE and the safety action is full evasive motion

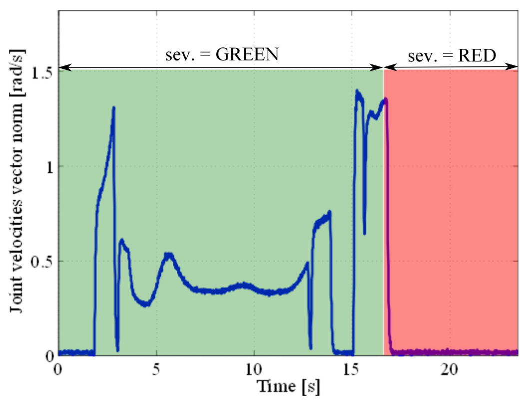


Fig. 11. Norm of the joint velocities vector (solid blue) reduced to zero when severity = RED - protective Stop

and the computed value of the DF overcomes the threshold, even the positioning task is suspended and later recovered. Figure 9 contains a series of screenshots of the experiment taken from HDT, while Figure 10 shows that the end-effector leaves its position to avoid contact with the human and tracks again the standard position reference only when the severity index diminishes again.

### D. Human-robot interference - severity = RED

If the human worker is too close to the robot (i.e. Area 3) and DI evaluates the severity index as RED, the safety action adopted by the External Controller is a protective stop (Figure 11), i.e. the robot is stopped as fast as possible.

## VII. Conclusions

A methodology for computing in real-time the severity of a possible collision between a robot and a human worker has been developed and implemented into a software component named "Danger Index". The DI component has been integrated within a comprehensive Safety Control architecture, together with the video-surveillance system, the intention estimation component and the sensor-based real-time control system. The overall architecture of the Safety Controller has been experimentally tested in a laboratory setup featuring an ABB IRB140 industrial robot.

## References


[1] ISO 10218-1:2012, *Robot and Robotic Devices – Safety Requirements for industrial robots – Part 1: Robots*. ISO, Geneva, Switzerland.

[2] C. W. Gadd, "Use of weighted-impulse criterion for estimating injury hazard," in *10th Car Crash Conf.*, 1966.

[3] J. Versace, "A review of the severity index," in *15th Stapp Car Crash Conf.*, 1971, p. 14.

[4] S. Haddadin, A. Albu-Schäffer, M. Frommberger, J. Rossmann, and G. Hirzinger, "The "DLR crash report": Towards a standard crash-testing protocol for robot safety - part I and II," in *IEEE Int. Conf. Robot. Autom.*, 2009, pp. 272–287.

[5] K. Ikuta, H. Ishii, and M. Nokata, "General danger evaluation method for control strategy of human-care robot," *J. Rob. Soc. Jpn.*, 2001.

[6] ——, "Safety evaluation method of design and control for Human-Care robots," *Int. J. Rob. Res.*, vol. 22, no. 5, pp. 281–297, 2003.

[7] J. Heinzmann and A. Zelinsky, "Quantitative safety guarantees for physical human-robot interaction," *Int. J. Rob. Res.*, vol. 22, no. 7-8, pp. 479–504, 2003.

[8] D. Kulić and E. Croft, "Pre-collision safety strategies for human-robot interaction," *Autonomous Robots*, vol. 22, no. 2, pp. 149–164, 2007.

[9] D. Kulic and E. Croft, "Affective state estimation for human-robot interaction," *IEEE Trans. Robot.*, vol. 23, no. 5, pp. 991–1000, 2007.

[10] S. Haddadin, A. Albu-Schäffer, A. De Luca, and G. Hirzinger, "Collision detection and reaction: A contribution to safe physical human-robot interaction," in *IEEE/RSJ Int. Conf. Int. Rob. Sys.*, 2008, pp. 3356–3363.

[11] S. Haddadin, M. Suppa, S. Fuchs, T. Bodenmüller, A. Albu-Schäffer, and G. Hirzinger, "Towards the robotic co-worker," in *Robotics Research*, ser. Springer Tracts in Advanced Robotics. Springer, 2011, vol. 70, pp. 261–282.

[12] S. Haddadin, S. Haddadin, A. Khoury, T. Rokahr, S. Parusel, R. Burgkart, A. Bicchi, and A. Albu-Schäffer, "On making robots understand safety: Embedding injury knowledge into control," *Int. J. Rob. Res.*, vol. 31, no. 13, pp. 1578–1602, 2012.

[13] B. Lacevic and P. Rocco, "Kinetostatic danger field - a novel safety assessment for human-robot interaction," in *IEEE/RSJ Int. Conf. Int. Rob. Sys.*, 2010, pp. 2169–2174.

[14] T. Tsuji, H. Akamatsu, and M. Kaneko, "Non-contact impedance control for redundant manipulators using visual information," in *IEEE Int. Conf. Rob. Autom.*, vol. 3, 1997, pp. 2571–2576.

[15] B. Lacevic, P. Rocco, and A. Zanchettin, "Safety assessment and control of robotic manipulators using danger field," *IEEE Trans. Robot.*, vol. 29, no. 5, pp. 1257 –1270, 2013.

[16] B. Matthias, S. Oberer-Treitz, H. Staab, E. Schuller, and S. Peldschus, "Injury risk quantification for industrial robots in collaborative operation with humans," in *41st Int. Symp. Rob.*, 2010.

[17] J. Maeno, T. adn Hasewaga, "Development of a finite element model of the total human model for safety (thums) and application to car-pedestrian impacts," in *2001, 17th Int ESV Conf.*, 2001.

[18] Z. Asgharpour, D. Baumgartner, R. Willinger, M. Graw, and S. Peldschus, "The validation and application of a finite element human head model for frontal skull fracture analysis," *J. Mech. Behav. Biomat.*, 2013, in press.

[19] S. Oberer-Treitz, A. Puzik, and A. Verl, "Measuring the collision potential of industrial robots," in *41st Int. Symp. Rob.*, 2010.

[20] O. Khatib, "Inertial properties in robotic manipulation: An object-level framework," *Int. J. Rob. Res.*, vol. 13, pp. 19–36, 1995.

[21] L. Bascetta, G. Ferretti, P. Rocco, H. Ardö, H. Bruyininckx, E. Demeester, and E. Di Lello, "Towards safe human-robot interaction in robotic cells: an approach based on visual tracking and intention estimation," in *IEEE/RSJ Int. Conf. Int. Rob. Sys.*, 2011, pp. 2971–2978.

[22] A. Blomdell, I. Dressler, K. Nilsson, and A. Robertsson, "Flexible application development and high-performance motion control based on external sensing and reconfiguration of ABB industrial robot controllers," in *Proc. ICRA 2010 Workshop on Innovative Robot Control Architectures for Demanding (Research) Applications*, 2010.

[23] N. Ceriani, G. Buizza Avanzini, A. Zanchettin, L. Bascetta, and P. Rocco, "Optimal placement of spots in distributed proximity sensors for safe human-robot interaction," in *IEEE Int. Conf. Rob. Autom.*, 2013.