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Experiences in Safe Physical Human-Robot Interaction

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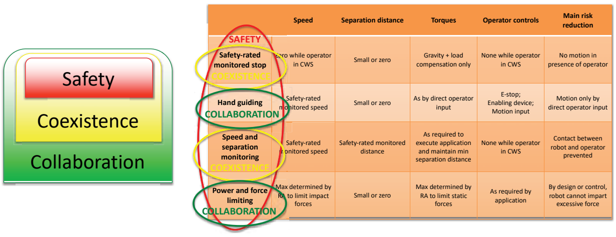
***Abstract*— We review our research results on safe control of physical Human-Robot Interaction to handle collision detection/classification, coexistence in the workspace, and collaboration with intentional contacts or by visual coordination, using model-based techniques and real-time monitoring by sensors.**

I. CONTROL OF HUMAN-ROBOT INTERACTION

The capability of handling tasks that involve interaction between humans and robots has become nowadays a highly desirable feature in both industrial and service environments. Robot co-workers should be able to share their workspace and collaborate safely with humans, combining and enhancing the skills of both parties. In the last few years, we have proposed and developed a control framework that considers physical Human-Robot Interaction (pHRI) in an integrated way, defining a hierarchy of functional behaviors that must be guaranteed in a consistent way during robot operation [1]. With reference to Fig. 1, the three nested layers of our control architecture are concerned with *safety*, *coexistence*, and *collaboration*, which easily map into the four forms of 'collaboration' modes of the ISO 10218 standard (enhanced by the technical specification TS 15066). Each layer contains specific methods related to its objectives, with their associated sensory requirements and control algorithms. In the next sections, we illustrate how these layers have been populated during our research path. The accompanying video shows a selection of results.



	Speed	Separation distance	Torques	Operator controls	Main risk reduction
Safety-rated monitored stop	Zero while operator in CWS	Small or zero	Gravity + load compensation only	None while operator in CWS	No motion in presence of operator
Hand guiding	Safety-rated monitored speed	Small or zero	As by direct operator input	E-stop; Enabling device; Motion input	Motion only by direct operator input
Speed and separation monitoring	Safety-rated monitored speed	Safety-rated monitored distance	As required to execute application and maintain min separation distance	None while operator in CWS	Contact between robot and operator prevented
Power and force limiting	Max determined by RA to limit impact forces	Small or zero	Max determined by RA to limit static forces	As required by application	By design or control, robot cannot impart excessive force

(a) (b)

Fig. 1. (a): The three nested layers of the hierarchical control architecture for pHRI proposed in [1]; (b) The mapping of the three control layers into the four modes of the ISO standards on robot safety.

II. SAFETY LAYER

Safety is the most important feature of a robot that works close to human beings, and should always be enforced in any condition. In case of an unforeseen collision, the safety layer should immediately detect the situation and let the robot react properly. In [2], [3], we have introduced a model-based method to detect collisions and isolate the link subject to the contact force which does not need exteroceptive or distributed tactile sensors. The method works for robots with rigid or with flexible joints, in the latter case both with and without joint torque sensing [4]. Consider the robot dynamics

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{\tau}_F = \boldsymbol{\tau} + \boldsymbol{\tau}_e(\boldsymbol{q}) + \boldsymbol{\tau}_{ext}(\boldsymbol{q}), \quad (1)$$

where $\boldsymbol{q} \in \mathbb{R}^n$ is the link position vector, $\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{S}\dot{\boldsymbol{q}}$ are the (suitably factorized) Coriolis and centrifugal terms, $\boldsymbol{g}$ is the gravity vector, and $\boldsymbol{\tau}_F$ is the friction torque. Moreover, $\boldsymbol{\tau}$ is either the commanded torque $\boldsymbol{\tau}_m = \boldsymbol{K}_m \boldsymbol{i}_m$ (proportional to the motor current), in case of rigid joints, or the (measurable) elastic transmission torque $\boldsymbol{\tau}_J$, in case of flexible joints, $\boldsymbol{\tau}_e = \boldsymbol{J}_e^T(\boldsymbol{q})\boldsymbol{F}_e$ is the torque resulting from a force $\boldsymbol{F}_e$ acting at the end-effector and measured by a F/T sensor, while $\boldsymbol{\tau}_{ext} = \boldsymbol{J}_c^T(\boldsymbol{q})\boldsymbol{F}_c$ is the unknown torque due to a collision/contact force $\boldsymbol{F}_c$ with the human/environment at a generic robot location. Knowing all terms in (1), *except* for $\boldsymbol{\tau}_{ext}$, the so-called *residual* $\boldsymbol{r} \in \mathbb{R}^n$ is given by

$$\boldsymbol{r} = \boldsymbol{K}_I \left[\boldsymbol{p} - \int_0^t \Big(\boldsymbol{\tau} + \boldsymbol{\tau}_e(\boldsymbol{q}) + \boldsymbol{S}^T(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{\tau}_F + \boldsymbol{r} \Big) ds \right], \quad (2)$$

where $\boldsymbol{p} = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}}$ is the momentum of the robot, and $\boldsymbol{K}_I > 0$ is a diagonal gain matrix. The residual provides an approximation (a first-order, stable, filtered version) of the unknown torque $\boldsymbol{\tau}_{ext}$, with $\boldsymbol{r} \simeq \boldsymbol{\tau}_{ext}$, for sufficiently large $\boldsymbol{K}_I$. The critical aspects of friction and payload estimation in (2) have been analyzed in [5]. The model-based terms in the residual can be efficiently computed via a Newton-Euler implementation following [6]. When the robot dynamics is poorly known, an alternative signal-based method for detecting collisions (though without their isolation) relies on processing the motor currents $\boldsymbol{i}_m$ [7]. A logic based on high-pass and low-pass filtering of motor currents has been used to distinguish the nature of the detected impact, i.e., a soft/slow contact (possibly signifying the start of an intentional collaboration) or a hard/fast collision (always undesired). The same can be performed with two residuals $\boldsymbol{r}_L$ and $\boldsymbol{r}_H$, having low and high bandwidths, i.e., two different gain matrices $\boldsymbol{K}_{I,L}$ and $\boldsymbol{K}_{I,H}$ in (2). Soft contacts will excite similarly both residuals, while in hard collisions $\boldsymbol{r}_H$ will be excited more than $\boldsymbol{r}_L$. The various possible implementations and a comparison of these approaches have been described in [8].

III. COEXISTENCE LAYER

Coexistence occurs when the robot shares the workspace with humans, without requiring mutual contact. This is probably the most common situation in an Industry 4.0 environment, when a lightweight robot and human operator should work side-by-side. Safety requirements must still be guaranteed, obtaining thus a safe coexistence. Monitoring the workspace with exteroceptive (camera, depth laser) sensors and computing online relative distances between the full body of the robot in motion and the operator is fundamental to prevent collisions and to reduce the speed of the robot TCP in potentially critical situations. This should be obtained without giving up robot mobility and dexterity, by oversizing the safety areas. In [9], [10], we have introduced an efficient robot-human distance computation that works directly in the depth space of a RGB-D sensor, achieving collision avoidance with real time (300 Hz) performance. To avoid gray zones or sensor occlusion, the algorithm has been extended to the case of multiple depths sensor [11]. The optimal placement of multiple (depth and/or presence) sensors in the workspace was investigated in [12]. A GPU implementation of the algorithm [13] allows to preserve

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efficiency while computing distances with any moving object or any human part. More recently, this safe coexistence approach has been implemented in a full-size industrial cell with a large ABB robot, where the depth space method using two Kinects was combined/integrated with additional laser scanners for ISO compliance [14]. Pure collision avoidance, however, is just the simplest way to achieve coexistence. Using the same techniques, one can also realize visual coordination tasks [15] in which the robot end-effector follows in a prescribed way the motion of a human body part (e.g., the left hand or by pointing at the user head), while preserving a safe distance.

IV. COLLABORATION LAYER

Collaboration occurs when the robot performs complex tasks with direct human interaction and coordination, the most demanding and critical feature in safe pHRI. During a physical collaboration, there is an explicit and intentional contact with controlled exchange of forces between human and robot. According to our hierarchy, safety and coexistence should also be guaranteed during physical collaboration. For example, if the human is collaborating with the robot using his/her right hand, contact between the robot and the left hand or the rest of the human body is undesired, and therefore such accidental contacts are treated as potential collisions that must be avoided. The basic ingredient in our collaborative control approach has been the estimation of contact forces at a generic point of the robot without using force/torque sensing [16]. This *virtual* force sensing is obtained determining first the localization of the contact point $\boldsymbol{p}_c$ on the robot body, by combining the information from an external RGB-D sensor (when the distance computed by the algorithm in [9] is close to zero) with the residual-based contact detection algorithm [8] (when at least one residual component crosses a small threshold). Once the contact point has been determined, it is possible to extract from the residual $\boldsymbol{r}$ also an estimate of the contact force $\boldsymbol{F}_c$ as

$$\widehat{\boldsymbol{F}}_c = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)^{\#}\boldsymbol{r}, \tag{3}$$

namely by pseudoinversion of the transpose of the $3 \times n$ Jacobian matrix $\boldsymbol{J}_c = (\partial \boldsymbol{p}_c/\partial \boldsymbol{q})$ related to the contact point. When the contact occurs far down the serial chain of the robot links (at a link $k \geq 6$) the action line of the contact force can be estimated also without the external sensor [8]. Combining the virtual sensing information given by the residuals with real measurements of a force/torque sensor placed at the robot base provides an efficient way to estimate an external wrench acting on the robot, together with the contact position [17]. This method uses the recursive Newton-Euler algorithm for dynamic computations.

At this stage, the knowledge of the estimate $\widehat{\boldsymbol{F}}_c$ of the Cartesian contact force can be used for designing a number of classical control laws, regulating or tracking reference values for motion and/or force quantities. However, this occurs in a generalized *whole-body* sense, namely the desired behavior is not imposed at the joint or end-effector level, but directly at the level of the detected contact position in the robot structure. In [16], human-robot collaboration has been realized using the estimated contact force in an admittance scheme, with the robot controlled in position mode. Torque control laws based on generalized impedance and task-consistent force control [18], as well as hybrid force-velocity control [19], have also been implemented. With a F/T sensor, it is possible to handle simultaneously and separately both intentional contacts at the end-effector and reaction to undesired collisions on the robot body [20]. To this end, kinematic redundancy of the robot can be exploited together with the relaxation of multiple tasks with priority [13]. A similar approach works also when a dynamic model is not available, using the motor currents as proxies of the residuals [21].

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