

Research on cobotics at the LIRMM IDH group

Andrea Cherubini, André Crosnier, Philippe Fraisse, Benjamin Navarro, Robin Passama, Mohamed Sorour

▶ **To cite this version:**

Andrea Cherubini, André Crosnier, Philippe Fraisse, Benjamin Navarro, Robin Passama, et al.. Research on cobotics at the LIRMM IDH group. ICRA Workshop IC3 – Industry of the future: Collaborative, Connected, Cognitive, Jun 2017, Singapore, Singapore. hal-01523305

HAL Id: hal-01523305
https://hal.science/hal-01523305

Submitted on 16 May 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Research on cobotics at the LIRMM IDH group

Andrea Cherubini, André Crosnier, Philippe Fraisse, Benjamin Navarro, Robin Passama and Mohamed Sorour

***Abstract*—This paper summarizes recent (2011-2016) research carried out within the LIRMM IDH group, to address the development of collaborative robots for industrial applications. The presented works have been carried out in the frame of various projects, involving major European industrial actors such as PSA Peugeot Citroën, Airbus, and the Tecnalia Foundation.**

***Index Terms*—Factory of the Future; Collaborative robots for manufacturing industry; Enhanced human-machine interaction; Safe Physical Human-Robot Interaction.**

I. Introduction

This paper presents our recent research on *Collaborative industrial manipulation with safe physical human-robot interaction (pHRI)*. The motivation of all presented works is to provide industrial robots with the three fundamental requirements of pHRI: the human intention should be easy to infer by the robot, control should be intuitive from the human viewpoint and the designed controller should be safe for both human and robot.

The research was carried out in the frame of French Projects ANR ICARO (2011-2014), ANR SISCob (2014-2017) and Cobot@LR (2014-2017), and has lead to three main results:

1) A unified controller for collaborative interaction, merging vision and force with smooth transitions and weighted combinations of the sensor tasks [1], [2].
2) The design and validation of a robot manufacturing cell, for homokinetic joint assembly [3].
3) The design and validation, on a hand-arm robot, of an adaptive damping controller that fulfills the ISO10218 safety standard [4].

The rest of the paper is organized as follows: first we present the motivation and objectives (Sect. II), and the current state of art in collaborative industrial robotics (Sect. III). Then, we present the contribution of our work in Sect. IV, and we conclude in Sect. V.

II. Objectives and Motivation

The concept of *cobots*, i.e., robots collaborating with human workers in manufacturing assembly lines, dates back to the pioneer work [5]. In fact, cobots – designed for the assembly line worker - can reduce ergonomic concerns that arise due to on-the-job physical and cognitive loading, while improving safety, quality and productivity. This is a key issue, since according to statistics of the Occupational Safety and Health Department of the US Department of Labour, more than 30% of European manufacturing workers are affected by lower back pain, leading to enormous social and economic costs. Thorough surveys on human-machine cooperation in manufacturing lines are provided in [6], [7]. Both underline the absence of high level human-robot collaboration (if one excludes "Intelligent Lift Assistants") and to the need for more advanced collaboration: although humans remain indispensable in many assembly operations, ergonomic tools assisting their duties are fundamental. Although some automotive manufacturers are gradually introducing robots in their production line [8], [9], a crucial question persists: how should a collaborative robotic cell be designed? The ultimate goal would be to have the adaptability of humans merged with the high performance of robots in terms of precision, speed and payload [10].

Furthermore, robots must behave safely, especially when operators are present in their workspace. Higher safety levels need to be attained when physical contact occurs between the two. This makes it indispensable to define safety and dependability metrics [11], [12], [13]. These can contribute to the definition of standards, such as the recent ISO 10218 "Safety requirements for industrial robots" [14], that imposes velocity, power and contact force bounds to the robot tool control point (TCP), in the presence of a human.

To guarantee safety, particularly during physical contact phases, human-robot interaction has largely relied on the use of force/torque control [15]. Even when there is no direct contact, the robot should reactively adapt to sudden changes in the environment, especially because of unpredictable human behaviour [16]. This can be done through vision, which is also useful to infer/guess the underlying intention behind motion, as done in [17], to track the human hand during hand-over. Hence, vision and force should be used concurrently, since the information they provide is complementary. The integration of the two however requires operating different modes and managing sudden signal changes from heterogeneous sensor data. Important research problems include: What information would be helpful? How can this information be reliably obtained in the context of the task and platform? How/where should this information be used?

In summary, the motivation behind the research presented here is the design of *collaborative industrial robot cells*, with *safety* and *ease of use* as fundamental requirements.

III. State of art

In the field of collaborative robotics, many solutions for realizing safe collaborative tasks have been explored in recent years. Although few of these solutions have been transferred to the industry, we hereby list some of the most relevant theoretical works. In [18], a deformation-tracking impedance control strategy is designed to enable robot interaction with environments of unknown geometrical and mechanical properties. For successful interaction with unknown environments

All authors are with Interactive Digital Human group IDH, Laboratory for Computer Science, Micro-electronics and Robotics LIRMM, University of Montpellier CNRS, 860 rue Saint Priest, 34090 Montpellier, France.firstname.lastname@lirmm.fr

and operators, the robot should behave in a human-like manner. This is the target of the research in [19] and [20]: a human-like learning controller is designed, to minimize motion error and effort during interaction tasks. Simulations show that this controller is a good model of human-motor adaptation, even in the absence of direct force sensing. A robust controller for a collaborative robot in the automotive industry, is extended in [21], to manage not only the interaction between an industrial robot and a stiff environment, but also human-robot-environment interactions.

Other researchers have focused on industrial applications. For example, an industrial robot controller, incorporating compliance of the joints with the environment, is presented in [22]. The desired pose of the TCP is computed from the force error. Parallel control considers a reference trajectory, while allowing feedforward in force-controlled directions. Although the method is designed for industrial assembly tasks, it does not take into account the presence of humans in the loop. In contrast, Erden and colleagues [23], [24], [25] have thoroughly studied an industrial task that directly involves a human operator: manual welding. In [23], a physically interacting controller is developed for a manipulator robot arm: the human applies forces on the robot, to make it behave as s/he likes. The assistant robot is then designed in [24]: as the human controls the welding direction and speed, the robot suppresses involuntary vibrations. The results show a considerable improvement in the welders performance when they are assisted. Finally, [25] presents a study of end-point impedance measurement at human hand, with professional and novice welders. The results support the hypothesis that impedance measurements could be used as a skill level indicator, to differentiate the welding performance levels. Similar works are presented in [26] and [27]. In [26], an operator teaches tasks to a robotic manipulator, by manually guiding its TCP. For this, the authors design a virtual tool, whose dynamics the operator should feel when interacting with the robot. An admittance controller driven by the measurements of a force/torque sensor is designed to ensure the desired virtual dynamic behaviour. The second paper [27] addresses the problem of controlling a robot arm, executing a cooperative task with a human, who guides it physically. This problem is tackled by allowing the TCP to comply according to an impedance controller [28] defined in the Cartesian space. Redundancy ensures the stability of the human-robot system through inertial decoupling at the TCP.

As already mentioned, safety is a crucial element in the design of all these collaborative industrial robotic cells. To our knowledge, present-day collaborative robot manufacturers [29] fulfill the ISO10218 standard by saturating the velocity, stopping the robot, or using expensive hardware solutions. Although novel safe actuation systems have been recently proposed in the literature [30], [31], [32], these are not always easily affordable or adapted for any robotic system. An alternative comes from control, although, to the best of our knowledge, the only work that tackles the ISO1028-2011 is [33], where only the force limitation is considered. As for most of the works cited above, a solution comes from impedance control [28] and its modified versions for force tracking [34], force limitation [35], adaptive damping [36] or exploiting redundancy [37].

In general, having a human being as a physical collaborator requires revisiting some aspects, such as the choice of the impedance parameters. For instance, variable impedance control is used for human-robot collaboration in [38], [39], with parameters obtained from human-human experiments. In fact, mechanical impedance was shown to provide a good model of the human being in [40]. A variable damping controller is defined in [41] using the derivative of the interaction force. A method for improving impedance control consists in utilizing an estimate of the human intended motion [42]. An example is [43], where machine learning is used to obtain a model of the task, then input to an adaptive impedance framework.

IV. Contribution

The research described in this paper targeted three applications: collaborative screwing (case study proposed by AIRBUS [1], [2]), collaborative assembly of a homokinetic joint (proposed by PSA, Peugeot Citroën [3]) and collaborative drilling, complying with the ISO10218 standard [4]. These applications are shown in Figures 1-3, and in videos on the IDH LIRMM youtube channel[1]. For the first two scenarios, we only utilized a Kuka LWR arm, whereas in the third one a Shadow robotic hand was also mounted on the arm. In the first two scenarios, the control relied on *force proprioception* (external wrench estimated, via the FRI Interface[2].) and *vision* (including a kinect, in the first one), whereas in the third scenario, we used *force proprioception* and *touch*, measured by the BioTac on the robot hand. The contributions of the three works have respectively been: a unified multimodal control framework for pHRI, the design of a collaborative cell with the robot alternating proactive and compliant behaviors, and a safe damping controller. These are detailed hereby.

A. Unified multimodal control for pHRI

In the first application (Fig. 1), the robot aids a human operator in a screwing operation. The two operate on opposite sides of a flank, where a series of screws must be inserted. The required operations are: the human inserts the screws in the holes; the robot touches the screws with its TCP properly aligned (bolt tightening is out of scope). In such an application (which resembles "peg-and-hole", but adding the human-in-the-loop), it seems natural to exploit vision and force complementarity. Indeed, while the robot is far from any physical constraints, image-based control is useful for nearing the parts to be mated, but as the robot tip approaches the environment, unpredicted contacts can occur. Then, a force controller can intervene on some degrees of freedom to provide compliance and guide the manipulator to the desired pose.

Inspired by inverse kinematic control [44], [45], we have designed a unified task formalism. The contributions, with regards to classic hybrid vision-force-position control (typically

[1]https://www.youtube.com/watch?v=P8wfQ5tOa5E
https://www.youtube.com/watch?v=3KWduKKSyy8
https://www.youtube.com/watch?v=iOuhFKp31xY
[2]http://cs.stanford.edu/people/tkr/fri/html/

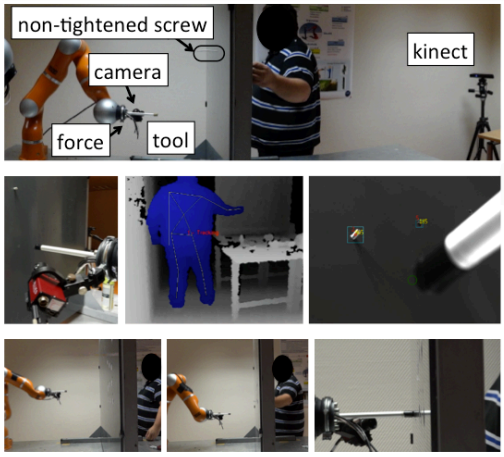


Fig. 1: Collaborative screwing (Airbus application).

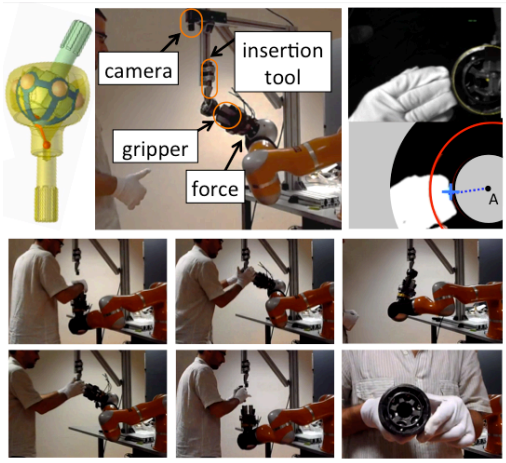


Fig. 2: Assembly of a homokinetic joint (PSA application).

to [46]), is that we can guarantee global asymptotic stability, while enabling smooth transitions (homotopies) and weighted combinations (even on the same degrees of freedom) of the different sensor tasks.

We hereby recall the formulation of our approach (further details are in [1]). Let $k \leq 6$ be the dimension of the operational space associated to the TCP. Consider n senses and, for each sense, the task vector $\mathbf{s}_m \in \mathbb{R}^k$, with $m = 1, \ldots, n$ (e.g., if vision and force are used, $n = 2$). A combination of tasks defined by different senses is realizable as long as its size is also k. The tasks are selected via n positive definite square diagonal selection matrices, denoted $\mathbf{S}_m$. The k-dimensional hybrid task $\mathbf{s}$ *to be realized* is:

$$\dot{\mathbf{s}} = \mathbf{S}\dot{\bar{\mathbf{s}}}, \tag{1}$$

with $\mathbf{S} = [\mathbf{S}_1 \ldots \mathbf{S}_n] \in \mathbb{R}^k \times \mathbb{R}^{kn}$ and $\bar{\mathbf{s}} = \left[\mathbf{s}_1^\top \ldots \mathbf{s}_n^\top\right]^\top \in \mathbb{R}^{kn}$.

If the m-th sensor provides less than k measures, the missing components can be deselected by zeroing the corresponding rows in $\mathbf{S}_m$. Matrix $\mathbf{S}$ can also be used to weigh/combine outputs from different sensors in a single task. Each task is related to the Cartesian velocity of the TCP $\mathbf{v} \in \mathbb{R}^k$ by the $k \times k$ Jacobian $\mathbf{J}_m$:

$$\dot{\mathbf{s}}_m = \mathbf{J}_m \mathbf{v}. \tag{2}$$

In [1], we proved that the optimal controller[3] ensuring convergence of $\mathbf{s}$ to $\mathbf{s}^*$ is[4]:

$$\mathbf{v} = (\mathbf{SJ})^{-1} (\mathbf{s}^* - \mathbf{s}), \quad \text{with} \quad \mathbf{J} = [\mathbf{J}_1 \ldots \mathbf{J}_n]^\top \in \mathbb{R}^{kn} \times \mathbb{R}^k. \tag{3}$$

Furthermore, the use of homotopies (differentiable time-varying expressions for the selection matrices $\mathbf{S}_i$) smoothens the transitions between sensor tasks, to guarantee safer operation. We show experimentally, in the mentioned collaborative screwing setup, that vision and force tasks can be realized either exclusively or simultaneously with our controller. To this end, we utilize a fixed Kinect and a black and white camera mounted on the robot, so as to respectively track the human hand position (using OpenNI[5]) and newly inserted screws on the flank. To properly align tool and screw, the external wrench on the TCP is estimated via the FRI Interface. The robot infers the - unpredictable - human intentions using only low-cost sensors, without the need for structuring neither the environment nor the operator (in contrast, e.g., with [47]).

B. Collaborative assembly cell

The second target application (Fig. 2) is the assembly of an Rzeppa homokinetic joint. In particular, we focus on the insertion of six steel balls in the joint grooves. This is currently done manually by the PSA operators, using an *insertion tool* and a *gripper* to incline the joint cage and insert the balls. The cage opening should be automated, to alleviate the worker from musculoskeletal disorders, while ball insertion requires very high precision and adaptability skills, not attainable by present-day industrial robots.

To fulfill these requirements, in [3] we proposed a novel design of the Rzeppa assembly cell. The lower part of the joint is held by the robot, while the insertion tool is fixed to a rigid support. Hence, most of the required movements are carried out by the robot, with the human intervening only to position the balls. By relying on force and vision, we successfully manage direct physical contact between robot and human, and between robot and environment. In fact, vision stops robot operation in case of danger for the operator hand (as in the images in Fig. 2, top right), while the external forces are used by an admittance controller that deforms the robot nominal trajectory for collision/blockage avoidance.

Although the applications targeted by most of the works cited in Sect. III also fall in the *shared workplace* paradigm evoked in [6], they differ from the one treated here, since the robot motion is driven only by the human worker. Instead, in our work the robot alternates active (i.e., autonomous) and passive (compliant) behaviors, to lighten him/her in the first case and to follow his/her needs in the latter.

Furthermore, in contrast with most similar works (e.g., [27]), our approach can be applied to standard

[3]By optimal, here, we mean it minimizes the task error 2-norm.

[4]Assuming matrix $\mathbf{SJ}$ is invertible.

[5]https://github.com/OpenNI/OpenNIhttps://github.com/OpenNI/OpenNI

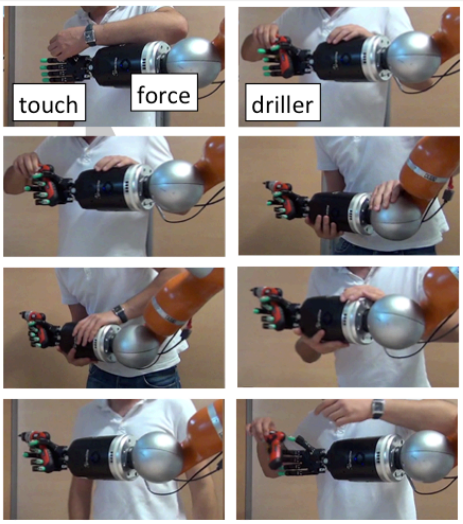


Fig. 3: Collaborative drilling complying with ISO10218.

position (and not torque) controlled robots, common in the industry. From the end user's (PSA) viewpoint, two aspects were particularly noteworthy. First, since the operator load is reduced by approximately 60%, the proposed assembly cell can be reclassified in the PSA ergonomics scale. Second, a complete risk analysis by PSA indicates that this setup is compatible with the safety standards and can be certified.

C. A safe adaptive damping controller

Following that work, we pursued research on manually guided collaboration, on the one hand focusing on the requirements of the ISO10218 safety standard, on the other, exploring the features of direct force measurement via *touch* [4]. This research has been carried out on a hand-arm robotic system, in a mock-up drilling application, shown in Fig. 3. Here, as for the Rzeppa assembly, the robot operates as an enhanced weight compensator, by alternating active and passive modes. Touch (via tactile sensing) provides an intuitive interface for the operator, enabling it to easily switch between modes.

The ISO10218 standard specifies that in presence of a human being, any robot must respect contact force, velocity and power limits at the TCP. In [4], we have designed and validated an adaptive damping controller that limits online (only when needed) the force, velocity and power at the TCP.

Although we did not apply our control framework directly to the robot hand, we did guarantee safety of its use by exploiting tactile data in two ways. First, we designed a simple grasp strategy that is driven by tactile measures. In fact, we use them to modify online the desired articular configuration of each finger to regulate the contact pressure between finger and object. Second, we exploit the thumb BioTac as an intuitive interface for the operator. This BioTac is used as a button, to trigger some events (e.g., to start grasping a tool). The implemented switch is based on a comparator with hysteresis. With this system, the operator can interact with the robot without a sophisticated interface. This solution improves both the ergonomy, and the time required to perform the task.

V. Conclusions

This paper has outlined our main research results in the field of collaborative industrial robotics. The three case studies were application-driven, and have required us to address two crucial specifications from the industry: safety and robustness.

Currently, we are in the process of enhancing the mobility of our cobotic solutions. To this end, we have designed the BAZAR[6] platform shown in Fig. 4. This robot combines the last generation sensors and actuators, and will be utilized in the context of European Project H2020 VERSATILE (2017-2020), to address the industrial case studies proposed by our partners PSA, Airbus and BIC.

Preliminary works on BAZAR consisted in controlling its steerable wheels [48], [49], in view of sensor-based control, as the robot behavior is not preplanned and will be driven by unexpected events (e.g., obstacles, or interacting humans).



Fig. 4: The BAZAR robotic platform.

References

[1] A. Cherubini, R. Passama, P. Fraisse, and A. Crosnier, "A unified multimodal control framework for human-robot interaction," *Robotics and Autonomous Systems*, vol. 70, pp. 106–115, 2015.

[2] A. Cherubini, R. Passama, A. Meline, and P. Fraisse, "Multimodal control for human-robot cooperation," in *IEEE/RSJ Int. Conf. on Robots and Intelligent Systems*, nov JTCF Novel Technology Paper Award for Amusement culture finalist, 2013.

[3] A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, and P. Fraisse, "Collaborative manufacturing with physical human-robot interaction," *Robotics and Computer-Integrated Manufacturing*, vol. 40, pp. 1–13, August 2016.

[4] B. Navarro, A. Cherubini, A. Fonte, R. Passama, G. Poisson, and P. Fraisse, "An ISO10218-compliant adaptive damping controller for safe physical human-robot interaction," in *IEEE Int. Conf. on Robotics and Automation*, May 2016.

[5] P. Akella, M. Peshkin, E. Colgate, W. Wannasuphoprasit, N. Nagesh, J. Wells, S. Holland, T. Pearson, and B. Peacock, "Cobots for the automobile assembly line," in *IEEE Int. Conf. on Robotics and Automation*, 1999.

[6] J. Kruger, T. K. Lien, and A. Verl, "Cooperation of human and machines in assembly lines," *CIRP Annals - Manufacturing Technology*, vol. 58, pp. 628–646, 2009.

[7] J. Shi, G. Jimmerson, T. Pearson, and R. Menassa, "Levels of human and robot collaboration for automotive manufacturing," in *Workshop on Performance Metrics for Intelligent Systems, PerMIS*, 2012, pp. 95–100.

[6]Bimanual Agile Zany Anthorpomorphic Robot.

[8] W. Knight, "How Human-Robot teamwork will upend manufacturing - MIT Technology Review - www.technologyreview.com."

[9] "New human-robot cooperation in Audi's production processes" - Feb 16, 2015 - www.audi.com.

[10] C. Heyer, "Human-robot interaction and future industrial robotics applications," in *IEEE/RSJ Int. Conf. on Robots and Intelligent Systems*, 2010, pp. 4749–4754.

[11] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, "Requirements for safe robots: Measurements, analysis and new insights," *Int. Journal of Robotics Research*, 2009.

[12] J. Fryman and M. Bjoern, "Safety of industrial robots: From conventional to collaborative applications," in *7th German Conference on Robotics ROBOTIK*, 2012.

[13] F. Flacco and A. De Luca, "Safe physical human-robot collaboration," in *IEEE/RSJ Int. Conf. on Robots and Intelligent Systems*, 2013.

[14] "ISO 10218-1:2011 Robot for industrial environments - Safety requirements - Part 1 : Robot," International Organization for Standardization, Geneva, Switzerland, Tech. Rep., 2006.

[15] L. Villani and J. De Schutter, "Force Control," in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Springer, 2008, ch. 7, pp. 161–185.

[16] F. Flacco, T. Kroger, A. De Luca, and O. Khatib, "A Depth Space Approach to Human-Robot Collision Avoidance," in *IEEE Int. Conf. on Robotics and Automation*, 2012.

[17] D. Song, N. Kyriazis, I. Oikonomidis, C. Papazov, A. Argyros, D. Burschka, and D. Kragic, "Predicting human intention in visual observations of hand/object interactions," in *IEEE Int. Conf. on Robotics and Automation*, 2013, pp. 1608–1615.

[18] L. Roveda, F. Vicentini, and L. M. Tosatti, "Deformation-tracking impedance control in interaction with uncertain environments," in *IEEE/RSJ Int. Conf. on Robots and Intelligent Systems*, 2013.

[19] G. Ganesh, A. Albu-Schäffer, M. Haruno, M. Kawato, and E. Burdet, "Biomimetic motor behavior for simultaneous adaptation of forcen impedance and trajectory in interaction tasks," in *IEEE Int. Conf. on Robotics and Automation*, 2010.

[20] C. Yang, G. Ganesh, S. Haddadin, S. Parusel, A. Albu-Schäffer, and E. Burdet, "Human-like adaptation of force and impedance in stable and unstable interactions," *IEEE Trans. on Robotics*, 2011.

[21] D. Surdilovic, G. Schreck, and U. Schmidt, "Development of collaborative robots (cobots) for flexible human-integrated assembly automation," in *41st International Symposium on Robotics, ISR*, 2010.

[22] F. Lange, W. Bertleff, and M. Suppa, "Force and trajectory control of industrial robots in stiff contact," in *IEEE Int. Conf. on Robotics and Automation*, 2013.

[23] M. Suphi Erden and T. Tomiyama, "Human intent detection and physically interactive control of a robot without force sensors," *IEEE Trans. on Robotics*, vol. 26, no. 2, pp. 370–382, 2010.

[24] M. Suphi Erden and B. Maric, "Assisting manual welding with robot," *Robotics and Computer Integrated Manufacturing*, vol. 27, pp. 818–828, 2011.

[25] M. Suphi Erden and A. Billard, "End-point impedance measurements at human hand during interactive manual welding with robot," in *IEEE Int. Conf. on Robotics and Automation*, 2014.

[26] G. Ferretti, G. Magnani, and P. Rocco, "Assigning virtual tool dynamics to an industrial robot through an admittance controller," in *Int. Conf. on Advanced Robotics, ICAR*, 2009.

[27] F. Ficuciello, A. Romano, L. Villani, and B. Siciliano, "Cartesian impedance control of redundant manipulators for human-robot co-manipulation," in *IEEE/RSJ Int. Conf. on Robots and Intelligent Systems*, 2013.

[28] N. Hogan, "Impedance control: an approach to manipulation: parts I-III," *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 107, pp. 1–24, 1985.

[29] Robotiq, "Collaborative robot ebook - 3rd edition - http://blog.robotiq.com."

[30] M. Zinn, O. Khatib, B. Roth, and J. Salisbury, "Playing it safe," *IEEE Robotics and Automation Magazine*, vol. 11, no. 2, pp. 12–21, 2004.

[31] A. Albu-Schaffer et al., "Soft robotics," *IEEE Robotics and Automation Magazine*, vol. 15, no. 3, pp. 20–30, 2008.

[32] R. Schiavi, G. Grioli, S. Sen, and A. Bicchi, "VSA-II: A novel prototype of variable stiffness actuator for safe and performing robots interacting with humans," in *IEEE Int. Conf. on Robotics and Automation*, 2008.

[33] A. Vick, D. Surdilovic, and J. Krüger, "Safe physical human-robot interaction with industrial dual-arm robots," in *9th IEEE Workshop on Robot Motion and Control (RoMoCo)*, 2013, pp. 264–269.

[34] S. Jung, T. Hsia, and R. Bonitz, "Force tracking impedance control of robot manipulators under unknown environment," *IEEE Trans. on Control Systems Technology*, vol. 12, no. 3, pp. 474–483, May 2004.

[35] F. Almeida, A. Lopes, and P. Abreu, "Force-impedance control: A new control strategy of robotic manipulators," in *Recent Advances in Mechatronics, Springer, Singapore*, 1999, pp. 126–137.

[36] V. Duchaine and C. Gosselin, "Safe, stable and intuitive control for physical human-robot interaction," in *IEEE Int. Conf. on Robotics and Automation, ICRA*, 2009, pp. 3383–3388.

[37] H. Sadeghian, L. Villani, M. Keshmiri, and B. Siciliano, "Experimental study on task space control during physical human robot interaction," in *2nd RSI/ISM Int. Conf. on Robotics and Mechatronics (ICRoM)*, Oct 2014, pp. 125–130.

[38] R. Ikeura and H. Inooka, "Variable impedance control of a robot for cooperation with a human," in *IEEE Int. Conf. on Robotics and Automation*, vol. 3, 1995, pp. 3097–3102 vol.3.

[39] R. Ikeura, T. Moriguchi, and K. Mizutani, "Optimal variable impedance control for a robot and its application to lifting an object with a human," in *IEEE Int. Symposium on Robot and Human Interactive Communication*, 2002, pp. 500–505.

[40] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance," *Nature*, vol. 414, no. 6862, pp. 446–449, 2001.

[41] V. Duchaine and C. M. Gosselin, "General model of human-robot cooperation using a novel velocity based variable impedance control," in *EuroHaptics Conf. and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 2007, pp. 446–451.

[42] B. Corteville, E. Aertbeliën, H. Bruyninckx, J. De Schutter, and H. Van Brussel, "Human-inspired robot assistant for fast point-to-point movements," in *IEEE Int. Conf. on Robotics and Automation*, 2007, pp. 3639–3644.

[43] E. Gribovskaya, A. Kheddar, and A. Billard, "Motion learning and adaptive impedance for robot control during physical interaction with humans," in *IEEE Int. Conf. on Robotics and Automation*, 2011, pp. 4326–4332.

[44] B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, *Robotics: Modelling, Planning and Control*. Springer, 2009.

[45] N. Mansard, O. Stasse, P. Evrard, and A. Kheddar, "A versatile generalized inverted kinematics implementation for collaborative working humanoid robots: The stack of tasks," in *Int. Conf. on Advanced Robotics, ICAR*, 2009.

[46] M. Prats, P. J. Sanz, and A. P. Del Pobil, "Reliable non-prehensile door opening through the combination of vision, tactile and force feedback," *Autonomous Robots*, vol. 29, no. 2, pp. 201–218, 2010.

[47] J. A. Corrales, G. J. Garcìa Gòmez, F. Torres, and V. Perdereau, "Cooperative tasks between humans and robots in industrial environments," *Int. Journal of Advanced Robotic Systems, IJARS*, 2012.

[48] M. Sorour, A. Cherubini, R. Passama, and P. Fraisse, "Kinematic modeling and singularity treatment of steerable wheeled mobile robots with joint acceleration limits," in *IEEE Int. Conf. on Robotics and Automation*, May 2016.

[49] ——, "Motion Discontinuity-Robust Controller for Steerable Mobile Robots," *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 452–459, 2017.