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Survey on Human-Robot Collaboration in Industrial Settings: Safety, Intuitive Interfaces and Applications

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Abstract

Easy-to-use collaborative robotics solutions, where human workers and robots share their skills, are entering the market, thus becoming the new frontier in industrial robotics. They allow to combine the advantages of robots, which enjoy high levels of accuracy, speed and repeatability, with the flexibility and cognitive skills of human workers. However, to achieve an efficient human-robot collaboration, several challenges need to be tackled. First, a safe interaction must be guaranteed to prevent harming humans having a direct contact with the moving robot. Additionally, to take full advantage of human skills, it is important that intuitive user interfaces are properly designed, so that human operators can easily program and interact with the robot. In this survey paper, an extensive review on human-robot collaboration in industrial environment is provided, with specific focus on issues related to physical and cognitive interaction. The commercially available solutions are also presented and the main industrial applications where collaborative robotic is advantageous are discussed, highlighting how collaborative solutions are intended to improve the efficiency of the system and which the open issue are.

Keywords: Human-robot collaboration; collaborative robots; safety; user

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interfaces; intuitive robot programming; industrial applications.

1. Introduction

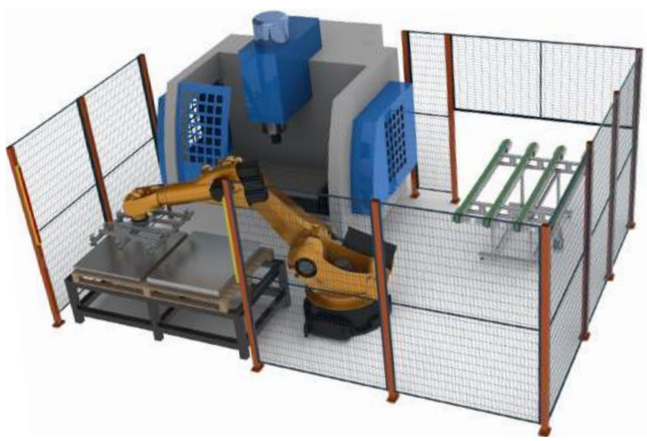
Much of the effort to design and develop today's safe, human friendly and adaptable robots comes from manufacturers of industrial robots. Robots play a pivotal role for today's manufacturing industry to be competitive. The last estimates by International Federation of Robotics report that until 2019 the worldwide annual supply of industrial robots will increase, on average, of 13% per year, with a final estimate of 2.6 million industrial robots in operation worldwide in 2019 [1]. Despite an increasing need of robots in all industrial sectors has been found in recent years, the strongest demand pertains to the automotive industry, followed by the electronics one, which has been experiencing an increasing high volume order since 2013 [1]. Moreover, it has been found that small and medium sized companies are increasingly using industrial robots thanks to the availability of affordable solutions and compact and easy-to-use collaborative robots [1]. Hence, collaborative solutions, where human workers and robots share their skills, are entering the market and becoming the new frontier in industrial robotics [1, 2]. The use of collaborative robotic solutions is also supported by the current trend of automation and data exchange in manufacturing technologies, the so called Industry 4.0 [3]. Ultimately, Industry 4.0 aims at achieving efficiency, cost reduction and productivity increases through integrated automation. In this novel scenario, future production systems will be characterized by individualized products under the conditions of a highly flexible mass production. Thus, new solutions for increased flexibility and interoperability, such as flexible robotic equipment and intelligent decision making software platforms, must be investigated. To this end, robots should be quickly and intuitively operated by humans, while guaranteeing a safe close interaction.

Collaborative robots, also called cobots [4], enable direct interaction between human operators and robots, thus overcoming the classical division of labour, still today prevalent on factory floors, which requires robots to be confined in safety cages far away from human workers. Being possible for the worker and the robot to work alongside each other in collaboration, the worker's productivity is enhanced, while her/his stress and fatigue are reduced. The greatest advantage brought by collaborative robots lies in the opportunity to combine the advantages of automation with the flexibility and cognitive and soft skills of human workers. Specifically, traditional industrial robots can perform the tasks they are programmed for continuously and with levels of accuracy, speed and repeatability impossible to achieve by humans. However, they lack in versatility and cannot efficiently adapt to dynamic working environments or changes in production, thus being unsuited for small batches of production. On the contrary, human workers have an innate flexibility and ability to adapt to unforeseen events and maintain strong decision making skills also in dynamic and complex environment.

Additionally, the use of collaborative robots in industrial processes proves beneficial also given the fact that they can be managed and taught through intuitive systems, based on augmented reality [5], walk-through programming [6, 7] or programming by demonstration [8], just to cite few examples. On the contrary, traditional non collaborative robots often need expert specialist engineers to program the robot since, according to traditional programming approaches, instructions to robots have to be explicit and motion oriented, basically specifying a set of points which the robot must pass through.

Further, a paramount limitation of non collaborative robots is related to safety issues. The existing applications separate the human worker from the robot's working area by means of physical or sensor-based barriers in order for the operators' safety to be ensured, as shown in Fig. 1(a). Such barriers are eliminated when collaborative robots are used since they host several safety mechanisms that prevent harming humans moving around (Fig. 1(b)). Typically these robots are lightweight and can be easily moved, and embed several sensors to detect and avoid collisions. Table 1 recalls the differences between traditional industrial robots and collaborative robots [9].

In addition to the economic and technical advantages mentioned above, a



(a) Non-collaborative robot: safety fences are required to prevent harming human operators.

(b) Collaborative robot allowing the human worker to stand in its proximity and work together at the same task.

Figure 1: Examples of traditional and collaborative industrial robots.

Table 1: Comparison between traditional industrial robots and collaborative robots (extended from [9]).

Traditional industrial robots	**Collaborative industrial robots**
Fixed installation	Flexibly relocated
Repeatable tasks, rarely changed	Frequent task changes
Lead-through and off-line programming	On-line programming (lead-through walk-through and PbD), supported by off-line programming and multi-modal interaction
Rarely interaction with the worker, only during programming	Frequent interaction with the worker, force/precision assistance
Worker and robot are separated through fence	Sharing workspace
Cannot interact with people safely	Safe interaction with
Profitable only with medium to large lot size	Profitable even at single lot production
Small or big and very fast	Small, slow and easy to use and easy to move

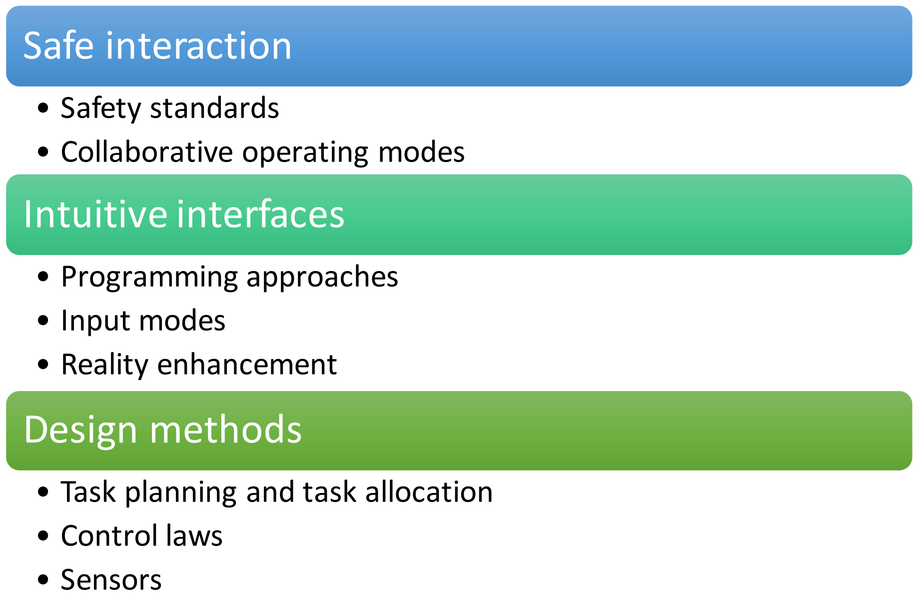


Figure 2: **Identified main challenges in HRC.**

concrete social impact of human-robot collaboration (HRC) has been reported in terms of a positive net effect on labour demand in Europe [1, 2]. Specifically, it is considered that new development in robotics have an impact on the creation of new jobs and opportunities, rather than replacement of workers [2, 10]. Accordingly, cobots can act as reliable and accurate co-workers for blue collars.

1.1. Main challenges in HRC

Considered the above motivation to the introduction of collaborative robots in industrial processes, the following main challenges in HRC, which are shown in Fig. 2, can be identified.

First of all, *safety* issues are the primary main challenge that must be tackled by any approach implementing collaboration between humans and robots. Indeed, being the intrinsic aim of HRC to allow a direct contact between them by eliminating fences, this must be achieved in a safe manner.

Moreover, to take full advantage of human skills, it is important that *intu-*

itive user interfaces are properly designed, so that human operators can easily interact with the robot. This requires that, on the one hand, providing inputs to the robot and programming it should be intuitive for the worker so that she/he is less concerned with how to communicate and is free to concentrate on the tasks and goals at hand. On the other hand, the information provided as a feedback by the robot should be adequate to provide the user with situation awareness needed to comprehend the current system behaviour and facilitate intervention in dynamic and unforeseen situations. To enable these features, the use of novel programming approaches, such as walk-through programming or learning by demonstration, and interaction modes, such as gestures or speech, and augmented reality have been introduced to avoid the bottleneck of traditional interaction means, e.g., keyboards, mice, screens and teach pendants [11, 12, 13].

Achieving these goals requires that proper *design methods* should be addressed, which means control laws, sensors and task allocation and planning approaches, that allow the human operator to safely stand close to the robot, actively sharing the working area and tasks and providing the interaction system with the required flexibility. For example, in [14] among the major design principles for workspace-sharing concepts, task identification and coordination aspects have been considered and included in the requirement analysis and functional specifications for assembly systems.

In this regard, it is worthwhile noting that the same key factors were considered in the framework of the recent EU project ROBO-PARTNER [15], which aims at integrating assembly systems and human capabilities. In particular, in the project the main enablers for effective HRC are considered to be intuitive interfaces, safe strategies and equipment, proper methods for planning and execution. In addition, the authors consider the use of distributed computing and of mobile robots acting as assistants to human operators. Also in [2] the main characteristics of collaborative robots in industrial scenario are reported to be safety features, user-friendliness and flexible use, which can be achieved by means of appropriate design methods.

1.2. Contribution

Moving along these lines, in this paper we will extensively review the state of the art of the literature with respect to safety and user interfaces for robotic industrial applications, highlighting the open issues that still need to be addressed in order to achieve a pervasive use of collaborative robots in such context. Specifically, since in the recent years increasing focus has been given to this topic and many different approaches have been proposed, a comprehensive survey is needed to provide an overview of the major findings, and understand which of them are actually used in industrial practice and where an action is still needed. Moreover, we aim at providing an overview about the application areas where approaches to HRC are currently mostly used in industry. Specifically, typical industrial robot applications that will be considered in the following sections are handling, surface polishing, welding, assembly and the automotive domain [16, 17, 18]. Since we aim at focusing on industrial applications of HRC, rather than on the general idea of HRC in broad sense, classical approaches and open issues related to design methods will not be addressed hereafter. A detailed review of control related aspects of HRC and approaches to sensing can be found in [19]. Moreover, the topic of task planning and allocation has been recently carefully detailed in [20] and, thus, will not be detailed hereafter. Briefly, here we just mention that it is possible to distinguish between static and dynamic optimization methods that either pre-define the collaborative optimal sequence of tasks or on-line adapt the operational sequence, respectively. Just to cite few examples, on the one hand, a static optimization method that accounts for changing of efficiency, due to parallel execution of operations, has been presented in [21]. On the other hand, the importance of dynamic sequencing and allocation of tasks between the human and the robot to minimize the risk and cycle time through selection of the optimal robot trajectories has been pointed out in [22, 23]. Over task planning, an increasingly important design aspect is selection of the appropriate robot for a safe execution of required collaborative task. A selection method relying on a knowledge-based expert system has been considered in [24]. Moreover, a systematic design approach for the implementation of HRC solution starting from existing manual processes has been proposed in [25]. The method presents a design framework based on qualitative evaluation of manufacturing goal, safety, accuracy and workload for the operations required, and it has been evaluated for assembly process of biomedical components.

Although several surveys on HRC in industrial applications have been proposed, to the best of the authors' knowledge, none of them covers the most relevant challenges of the topic in an exhaustive manner, but rather they consider only some of them, and focus on single application areas. Specifically, first reviews on HRC do not mention industrial applications as possible working scenarios of collaborative robots. Indeed, in [26], which represents one of the pioneering works reviewing HRC, the industrial context is not mentioned among possible application areas, probably due to the little relevance of collaborative industrial robotics at the time of the survey. Moreover, in [27], interestingly, in addition to safety, the issues related to cognitive engagement, and thus to user interfaces and intention estimation, in HRC are explicitly taken in consideration, but social robotics is considered as an application area, rather than the industrial scenario. Then, focusing on assembly lines, a detailed review on the collaboration between human and robot in industry was firstly provided in [17]. The oil and gas industry is considered in [28], where the authors mainly review the issues related to shared control between human and robot and multi-modal user interfaces. More recently, in [18] the focus was on automotive applications of HRC, with a specific distinction between industrial and academic research on the topic. Moreover, therein the authors did not provide a systematic analysis of the state of the art with respect to the main themes of HRC, such as safety, interfaces and task planning. In [20] the focus is put on task planning and programming methods for industrial collaborative robots.

1.3. Organization of the paper

The rest of the paper is organized as follows. In Section 2 the concept of HRC is delimited, thus distinguishing among safe coexistence and human-robot interaction. Then, Section 3 reports the main issues related to safety in HRC for industrial applications and provides an overview on current standards. In Section 4 we discuss the concept of HRC from the worker's point of view in terms of user interfaces, that is considering the currently available interaction means and how "easily" the user can deal with them in terms of cognitive workload. Then, Section 5 refer to the most common applications of industrial robots in today's industrial scenario and, finally, Section 6 follows with some concluding remarks.

2. Definition of HRC

The principles of HRC have found applications in different ways, considering varying levels of engagement of human operator and robot. In particular, a detailed taxonomy was proposed in [29], where HRC was classified in eleven categories, including task type, robot morphology, interaction roles, time, and space. However, this might sound inappropriate for the time being given the most recent advances in the state of the art.

More recently, the distinction between safety, coexistence and collaboration between human and robot has been pointed out in [30]. According to their framework, HRC spans from sharing only the physical workspace, but not the task, to sharing tasks, with cognitive engagement. In any condition, a safe behaviour must be inherently guaranteed and accomplished. Thus, they have proposed a nested framework consisting of three levels of interaction between a human and a robot, where any greater engagement requires that the features of lower levels of interaction are guaranteed, as summarized in Fig. 3. Specifically, to achieve *safety* in a scenario of HRC, where cages and barriers are inappropriate, several internal and external mechanical, sensory and control safety features can be merged. In this regard, in general collisions should be prevented, but if they accidentally occur, the robot should be able to react reducing forces at the impact, by using appropriate control laws [31] or using lightweight robots with compliant joints [32, 33, 34]. A further step into HRC according to [30] can be achieved by implementing *coexistence*. This approach considers that a robot and a human operator safely share the workspace and might also work on the same object, but without any mutual contact or coordination of actions and intentions. Beyond coexistence, *collaboration* approaches allow the robot and the human operator to perform a complex task together, that is with direct interaction and coordination [30]. This can be achieved intentionally establishing a physical contact with exchanges of forces between the two agents, or without contact, for example by the use of gesture or voice commands. Within the premises of such a framework, a control architecture that integrates collision avoidance, detection, and reaction capabilities, as well as collaboration between a human and a robot, has been proposed in [30].

This distinction somehow recalls the one in [27] where HRC is differentiated from human-robot interaction (HRI) based on the principle that in HRC the human and the robot work together aiming at reaching a common goal. On the other hand, in HRI they interact not necessarily with a common goal, thus falling in the definition of coexistence of [30].

Also in [35] the distinction is between safe coexistence, which pertains to safe (physical) HRI, and collaboration. In this context, a main challenge is to distinguish between accidental collisions and intentional contacts, which are associated to the human intention to start a physical collaboration phase [35].

3. Safety

Safety is a fundamental prerequisite in the design of products, machines and systems especially for collaborative workplaces, where humans work alongside robots. As reported in [36], both safety and dependability are the unified optimality criteria for future technical challenges in the design of robots for human environments. Safety standards provide unified requirements and design guidelines which help and simplify the development of new systems. From a formal point of view, compliance to standards is not mandatory to demonstrate the safety of a system [37]; however, it reduces the effort in safety compliance and

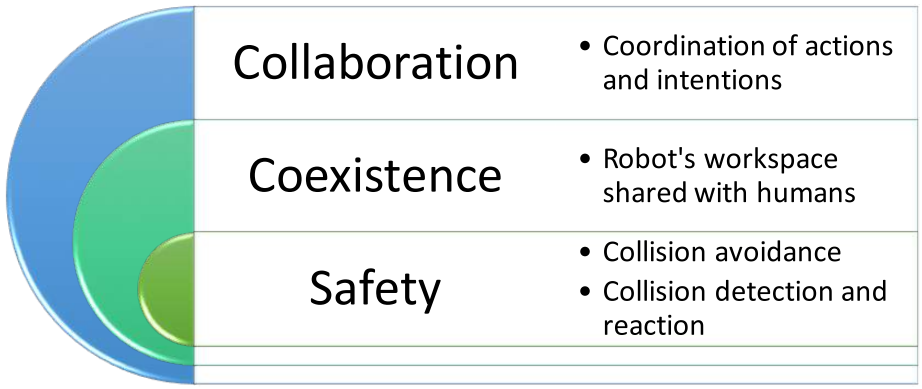


Figure 3: Nested levels for HRC, as proposed in the framework in [30].

certification with respect to Machinery Directive, which is the main European legislations for health and safety requirements for machinery [19]. Moreover, it speeds up the commissioning of new systems [37].

3.1. Classification of safety standards

The main standards for robotic solutions can be classified in three categories, which are shown in Fig. 4. Specifically, the distinction among such standards is as follows:

- the class of **Type A standard** collects the basic safety standards for general requirements that can be applied to machinery. ISO 12100 and IEC 61508 are the Type A standards that respectively define basic terminology and methodology used in achieving safety of machinery, i.e. risk assessment and risk reduction, and functional safety of electrical, electronic, and programmable electronic equipment;
- the class of **Type B standard** refers to generic safety standards; it is divided in the sub-categories B1 and B2. B1 safety standards address specific safety aspects: for example ISO 13849-1 and IEC 62061 refer to the design of low complexity safety system and “Safety PLCs”, respectively. B2 safety standards cover safety aspects of safeguarding, such as ISO

Table 2: Overview on the relevant literature for safety issues.

SAFETY	
SAFETY STANDARDS	**Type A** – basic safety standards for general requirements – **ISO 12100**, **IEC 61508**: terminology and methodology
	Type B – generic safety standards – **B1 standards** (ISO 13849-1, IEC 62061): specific safety aspects – **B2 standards** (ISO 13850, ISO 13851): safeguard
	Type C – safety countermeasures for specific machinery – prioritised over Type A and Type B standards – **ISO 10218**: safety of industrial robots – – **ISO 10218-1**: safety requirements for robot manufacturers (robot and controller) – – **ISO 10218-2**: safety requirements for system integrators (robot and ancillary devices) – **ISO TS 15066**: guidance on collaborative robot operations
COLLABORATIVE MODES	**Safety-rated monitored stop (SMS)** – the simplest type of collaboration
	– **Hand guiding (HG)** – **[46], [47]**: application to automotive assembly and production line – **[48]**: application to automated lifting and moving of heavy items – **[49]**: application to robotic welding
	– **Speed and separation monitoring (SSM)** – **[38]**: analytical analysis to implement SSM – **[51]–[56]**: dynamic safety space calculation – **[57]**: reactive planner for on-line selection of an avoidance trajectory
	– **Power and force limiting (PFL)** – **[61]–[64]**: variants implementing PFL – **[66], [74]**: analysis of collisions and risk assessment

13850 and ISO 13851, which describe the specific functional aspects of emergency-stop devices and two-hand control devices, respectively;

- the class of **Type C standard** collects individual safety standards that specify the safety countermeasures for specific machinery. If Type C standards are provided, these have priority over the Type B and Type A standards. Dedicated Type C standards that regulate the safety of industrial robots are the two parts of ISO 10218. ISO 10218-1 collects the safety requirements for robot manufacturers, and addresses the design of robot and its controller. ISO 10218-2 is intended for system integrators, and describes the safety requirements for an industrial robot system, consisting in the industrial robot and any ancillary devices [38]. The European Community adopts the ISO 10218, while the US follows the national standard ANSI/RIA R15.06 and Canada the CAN/CSA-Z434 standard, which have been both updated with the two parts of ISO 10218 [39]. Technical specification ISO TS 15066 provides additional information and guidance on collaborative robot operations.

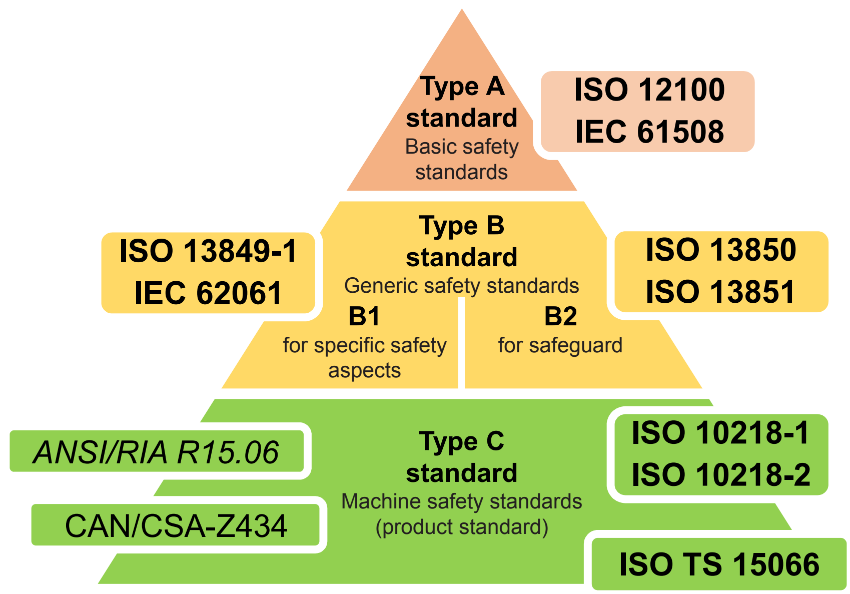


Figure 4: Categories for safety standards and specific references for robotic systems. The specifications of Type C category have priority over the other two categories.

3.2. Collaborative operative modes according to ISO 10218-1/2

As a consequence of the introduction of HRC technologies, great importance has been attributed to robot safety standards, which have been updated to address new co-working scenarios. ISO 10218-1/2 [40, 41] identify four collaborative modes, which are summarized in Fig. 5 and described as follows.

The first collaborative mode is "Safety-rated Monitored Stop" - SMS. It is the simplest type of collaboration. The operator performs manual tasks inside a collaborative area, which is an operative space shared between the human and the robot. Inside such collaborative area, both the human and the robot can work, but not at the same time since the latter is not allowed

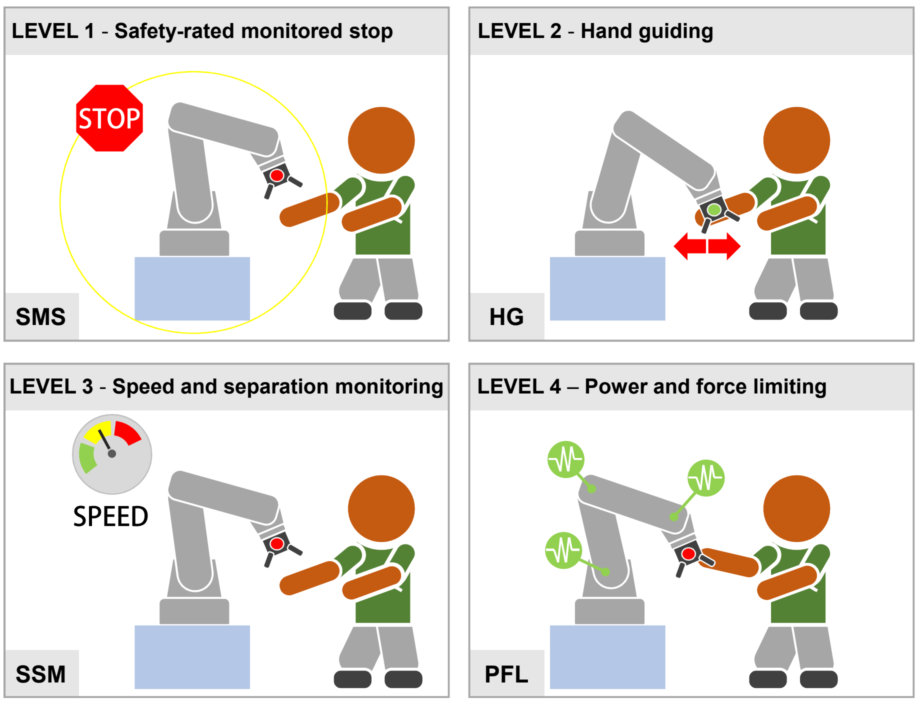


Figure 5: The four collaborative operative modes identified by robot safety standards 10218-1/2:2011.

to move if the operator occupies this shared space. This type of cooperation is suitable for manual placement of objects to the robot's end-effector, in visual inspection, for finishing operation or complex operations when human presence is required, or when the robot can help the operator to position heavy components [42]. Compared to traditional safety stop functions, SMS requires the additional retaining stopping function named "Stop Category 2", which is a *safety-rated monitored stop* leaving power available to the machine actuators after the movement ends [43]. Accordingly, when the human enters the collaborative area, the robot undergoes a "safe standstill" mode and its movement is paused through dedicated redundant software and electronics-based safety technology [44]. At the same time, the robot automatic cycle remains active and the program continues from interruption point after the worker has left the collaborative area. These functionalities are integrated in cobots and have been recently provided as an option for industrial robots [45].

The second mode is "Hand Guiding" - HG. Also known as "direct teach", in this collaborative mode the operator can teach the robot positions by moving the robot without the need of an intermediate interface, e.g. robot teach pendant. The weight of the robot arm is compensated to hold its position. The operator gets directly in touch with the machine through a guiding device that drives the robot motion. This is an enhanced collaborative scenario which requires robots equipped with both *safety-rated monitored stop* and *safety-rated monitored speed* functionalities. While the robot is inside the collaborative area, it executes the program in automatic mode; if the operator approaches this area, the robot program and movements interrupt. As the operator activates the hand guiding device, the robot state switches to safety-rated monitored speed functionality to allow direct movement of robot. When the operator releases the hand guiding device, the robot returns in safety-rated monitored stop and resumes previously interrupted program as soon as the operator leaves the collaborative area. An interesting application has been presented in [46, 47], regarding direct teach programming of collaborative operations in automotive assembly line. A similar solution has been presented in [48], where a two handed guiding tool is used to program an industrial robot as a lifting device for moving heavy components. In [49] a device for the direct teach of the robot for welding operations has been presented.

The third mode is "Speed and Separation Monitoring" - SSM. Also indicated as "Speed and Position Monitoring" (SPM) [50], it allows the human presence within the robot's space through safety-rated monitoring sensors. With reference to Fig. 5, the robot operates at full speed when the human is in the green zone, at reduced speed in the yellow zone, and it stops stop when the human moves into the red zone. These areas are inspected with scanners or a vision system. In areas out of the reach of the manipulator, where the operator does not get in contact with the robot but can be endangered with a dropped manipulated object, the robot is slowed down to a safe speed. If the robot's workspace is breached, the robot is stopped. As far as those two areas are clear, the robot can operate at maximal parameters [42]. As reported in [38], the research in the field of SSM collaboration type is suggesting many solutions for collision avoidance and maintaining safe operational distances between active robot systems and the surrounding objects. Therein, analytical analyses and test results of the current equation for implementing SSM in human-occupied environments have been provided [38]. An interesting SSM approach is the dynamical safety space calculation, which enables the user to utilize as much workspace as possible, since the minimal safety space is calculated according to robot encumbrance and position. In this regard, the application of a projection-based safety system has been presented in [51] to ensure hard safety in HRC and establish a minimal and well-shaped safety space around the robot at any time. The main target of [52] is safety of the shared workcell in the absence of physical fences between human and robot. Since safety options provided by basic infrared sensors are limited, the authors have designed a network architecture of these sensors, for tracking user positions, while avoiding collisions. A dynamic implementation of SSM and therefore on-line evaluation of the safety has been resented in [53]. In [54] a real-time SSM system for accurate robot speed adjustment has been introduced, which is based on the measurement of the human-robot separation distance. The approach compares the information on robot joint angles and the measure of the human positioning within robot workspace, available from the robot controller and an external system for human motion capture, respectively. Similar approach has been proposed in [55, 56], where three distributed sensors perceive unknown objects and obstacles in the work area of an industrial robot. The use of external sensor to detect obstacles within robot workspace and reactive planner of the KineoWorks^{TM} software for a fast selection of an avoidance trajectory has been combined in [57]. An external depth sensor has been exploited in [58], where a depth space approach for human and robot distance evaluations has been proposed. Finally, in [59] it has been presented a collaborative solution based on a dynamic safety system that reduces the speed and stops an industrial robot exploiting both a non-safe primary device, such as Microsoft Kinect, and a secondary certified safety system, which acts only if the primary one fails.

The fourth mode is "Power and Force Limiting" - PFL. This collaborative approach prescribes the limitation of motor power and force so that a human worker can work side-by-side with the robot. This level requires dedicated equipment and control models for handling collisions between the robot and the human with no harmful consequences for the latter. An overview of human-robot physical interaction control has been proposed in [60], which reports also a classification of contact types and related injuries as well as a description of collision handling methods. For the latter, four possible robot reactions in response to the contact are presented. The most obvious solution is activating robot's brakes after collision with immediate stop. Torque control mode with gravity compensation, torque and admittance reflex are improved strategies, which result in a safer behaviour such as decreasing the impact energy through counter-motion in the opposite direction. Other research works on PFL approaches are presented in the following. A mechanical spatial isotropic force module, which protects humans from physical overloads, has been described in [61]. In [62] focus has been put on control strategies and an adaptive damping controller that limit force, velocity, and power of the robot has been presented. Furthermore, focusing on tasks involving physical contact with the user, an approach to learn the robot behaviour along the task, including safety requirements into the stiffness learning process, has been proposed in [63]. A similar experience-based method has been considered in [64]: the approach exploits neural network models and data from robot's proprioceptive sensors to estimate the exchanged forces. In one of their recent works, Magrini et al. have developed an hybrid control that manages the relative motion and the exchanged contact forces during the physical contact between the human and the robot in collaborative tasks. Residual method and external sensors are respectively used for online estimation of the contact force and localization of the contact point, and the time-varying contact task frame is obtained analytically from this estimate [65].

It is worthwhile noting that the implementation of the described collaborative modes does not require dedicated robots, since it is possible to use also traditional industrial robots with enhanced control strategies and certified external sensing devices. Major producers of industrial robots provide dedicated safety-rated robot controller options, such as Safe Production (Reis Robotics), SafeMove 2 (ABB), Safe Operation (KUKA) and Dual Check Safety (Fanuc). These options are used in combination with external position monitoring sensors, such as security laser scanners or safe camera systems. Moreover, acting on joint torques, robot speed and the shape of contact surfaces allows to mitigate the effects of transient impact by limiting the energy transfer to the contacted body region [66].

Conversely, cobots are designed to work alongside the operator since they are equipped with dedicated sensing systems, such as forces and torques sensors in robot joints, control systems based on electric current drawn by actuators, measuring systems for reactions forces transmitted to the ground or tactile sensors all over the robot arm. The motion parameters of these robots are monitored with high precision and it is possible to change their values to accomplish safety requirements. As a result, it is possible to define a special automatic operation mode, called "collaborative operation", which allows the robot to perform intended tasks in cooperation with a person while sharing a workspace. Table 3 collects the main types of cobots with their main specifications.

3.3. Assessment and measure of the risk in collaborative environments

The ISO 10218-1/2:2011 safety standards underline the importance of hazard identification and set the mandatory of risk assessment, especially for collaborative robots and for those operations that dynamically involve the operator and the robot, such as SSM and PFL. The technical specification ISO TS 15066 provides additional information and further guidelines to evaluate the risk related to the four type of collaboration modes [72]. Assuming as fundamental requirement a maximum safe reduced speed of 250 mm/s over the collaborative operations [40], it presents the acceptable physical quantities for the collaborative modes of SSM and PFL, such as allowable minimum separation distances and limits of mechanical loadings over the human body. In the case of SSM, ISO TS 15066 extends the general calculation for minimum protective distance, S, provided by the EN ISO 13855, including the relative speed between the robot and the human operator.

The separation distance at a specific time t_0, namely $S(t_0)$, is dynamically computed by the following equation

$$S(t_0) = S_h[v_h(t_0)] + S_r[v_r(t_0)] + S_s[v_s(t_0)] + C + Z_d + Z_r \qquad (1)$$

The terms of Eq. (1) are distances expressed in mm, where the first term, S_h, returns the distance travelled by the operator until the robot complete stop, as provided by (2); conversely, the second term, S_r, returns the distance travelled by the robot before brakes activation, as in (3). The third term, S_s, is the distance that the robot travels during the breaking action, as in (4).

$$S_h = \int_{t_0}^{t_0+T_r+T_s} v_h(t)dt \qquad (2)$$

Table 3: Available commercial cobots (extended from [67, 68, 69, 70, 71]).

Manufacturers, robot models and specifications		*Manufacturers, robot models and specifications*	
ABB (Switzerland) ≀ YuMi - IRB 14000		**ABB (Switzerland) ≀ Roberta 1 / Roberta 2 / Roberta 3**	
	*DOFs:* 7+7 *Payload:* 0.5 kg *Reach:* 559 mm *Repeatability:* ±0.02 mm *Weight:* 38 kg *Velocity:* 1500 mm/s	ell 	*DOFs:* 6 *Payload:* 4 kg ‖ 8 kg ‖ 12 kg *Reach:* 600 mm ‖ 800 mm ‖ 1200 mm *Repeatability:* ±0.1 mm *Weight:* 14.5 kg ‖ 19.5 kg ‖ 30.5 kg *Velocity Joints:* 110°/s
FANUC (Japan) ≀ CR-35iA		**FANUC (Japan) ≀ CR4iA / CR-7iA / CR-7iA/L**	
	*DOFs:* 6 *Payload:* 35 kg *Reach:* 1813 mm *Repeatability:* ±0.04 mm *Weight:* 990 kg *Velocity:* 750 mm/s		*DOFs:* 6 *Payload:* 4 kg ‖ 7 kg ‖ 7 kg *Reach:* 550 mm ‖ 717 mm ‖ 911 mm *Repeatability:* ±0.02 mm ‖ ±0.02 mm ‖ ±0.03 mm *Weight:* 48 kg ‖ 53 kg ‖ 55 kg *Velocity:* 1000 mm/s
Rethink Robotics (Boston-USA) ≀ Baxter / Sawyer		**UNIVERSAL ROBOT (Denmark) ≀ UR 3 / 5 / 10**	
	*DOFs:* Baxter 7+7 ‖ Sawyer 7 *Payload:* 2.2 kg per arm ‖ 4 kg *Reach:* 1210 mm per arm ‖ 1260 mm *Repeatability:* ±0.1 mm *Weight:* 75 kg ‖ 19 kg *Velocity:* 1500 mm/s		*DOFs:* 6 *Payload:* 3 kg ‖ 5 kg ‖ 10 kg *Reach:* 500 mm ‖ 850 mm ‖ 1300 mm *Repeatability:* ±0.1 mm *Weight:* 11 kg ‖ 18.4 kg ‖ 28.9 kg *Velocity:* 1000 mm/s
MABI Robotics (Switzerland) ≀ SPEEDY 6 / 10 / 12		**KUKA (Germany) ≀ LBR IIWA**	
	*DOFs:* 6 *Payload:* 6 kg ‖ 10 kg ‖ 12 kg *Reach:* 800 mm ‖ 1384.5 mm ‖ 1250 mm *Repeatability:* ±0.1 mm *Weight:* 28 kg ‖ 28 kg ‖ 35 kg *Velocity Joints:* 145 → 275°/s ‖ 120 → 180°/s ‖ 75 → 275°/s		*DOFs:* 7 *Payload:* 7 kg ‖ 14 kg *Reach:* 800 mm ‖ 820 mm *Repeatability:* ±0.1 mm ‖ ±0.15 mm *Weight:* 22 kg ‖ 30 kg *Velocity Joints:* 90 → 180°/s ‖ 70 → 180°/s
Techman Robot (Taiwan) ≀ TM5-900 / 700		**Productive Robotics (Carpinteria-USA) ≀ OB7**	
	*DOFs:* 6 *Payload:* 4 kg ‖ 6 kg *Reach:* 900 mm ‖ 700 mm *Repeatability:* ±0.05 mm *Weight:* 22.5 kg ‖ 22 kg *Velocity Joints:* 180 → 225°/s		*DOFs:* 7 *Payload:* 5 kg *Reach:* 1000 mm *Repeatability:* ±0.1 mm *Weight:* 24 kg *Velocity:* 2000 mm/s
Yaskawa (Japan) ≀ Motoman HC10		**AUBO Robotics (China) ≀ AUBO-i5**	
	*DOFs:* 6 *Payload:* 10 kg *Reach:* 1200 mm *Repeatability:* ±0.1 mm *Weight:* 45 kg *Velocity Joints:* 130 → 250°/s		*DOFs:* 6 *Payload:* 5 kg *Reach:* 880 mm *Repeatability:* ±0.05 mm *Weight:* 24 kg *Velocity:* 2800 mm/s
FRANKA EMIKA (Germany) ≀ FRANKA ARM		**Precise Automation (Fremont-USA) ≀ PP100 - Cartesian**	
	*DOFs:* 7 *Payload:* 3 kg *Reach:* 855 mm *Repeatability:* ±0.1 mm *Weight:* 18 kg *Velocity Joints:* 2000 mm/s		*DOFs:* 3 *Payload:* 1 kg *Reach:* X 635 mm - Y 300 mm - Z 225 mm *Repeatability:* ±0.1 mm *Weight:* 20 kg *Velocity:* 1500 mm/s
Kawasaki Robotics (Japan) ≀ duAro – Dual-Arm SCARA Robot		**BOSCH (Germany) ≀ APAS**	
	*DOFs:* 4+4 *Payload:* 2 kg *Reach:* 760 mm *Repeatability:* ±0.05 mm *Weight:* 200 kg *Velocity:* N/A		*DOFs:* 6 *Payload:* 2 kg *Reach:* 911 mm *Repeatability:* ±0.03 mm *Weight:* 230 kg *Velocity:* 500 mm/s

$$S_r = \int_{t_0}^{t_0+T_r} v_r(t)dt \quad (3)$$

$$S_s = \int_{t_0+T_r}^{t_0+T_r+T_s} v_s(t)dt \quad (4)$$

The last terms take into account uncertainties related to the recognition system, such as the intrusion distance of a part of the body through the safety barriers prior the recognition of the hazard, C, and the positions of human, Z_d, and robot, Z_r. Accordingly, $v_h(t_0)$, and $v_r(t_0)$ respectively are the speeds of the robot and the human, while $v_s(t_0)$ is the speed of the robot during the breaking action.

Fig. 6 shows the trend of separation distance over time. The dotted lines refer to direct speeds of robot (green line) and human (yellow line); since the human and the robot move in opposite direction, the robot speed is considered negative. The continuous lines refer to separation distances. The grey horizontal lines identify constant distances as defined by the terms of Eq. (1), while the red line represents the trend of separation distance over the time.

The PFL scenario opens a novel kind of collaborative applications, where the interaction is based on the physical contact between the human and the robot. Both deliberate and unexpected human-robot contacts are eligible if they do not cause risks for the operator. Consequently, in the risk assessment, the evaluation of admissible limits of pressures and forces assumes fundamental importance in case of contacts on human body parts. The ISO TS 15066 proposes a formulation based on the relation between onset limit of pain and related biomechanical acceptable loads of the specific human body regions in case of transient and quasi-static contacts. In the first case, transient contact refers to short dynamic free contact ($< 50\ ms$) where the operator body part is not clamped and can recoil or retract from the moving part of the robot system. Power flux density is the physical quantity that quantifies the hazard of transient contacts, because of the possible high amount of energy transferred (which depends on relative contact speeds) in a short time on a little contact area. Conversely, in quasi-

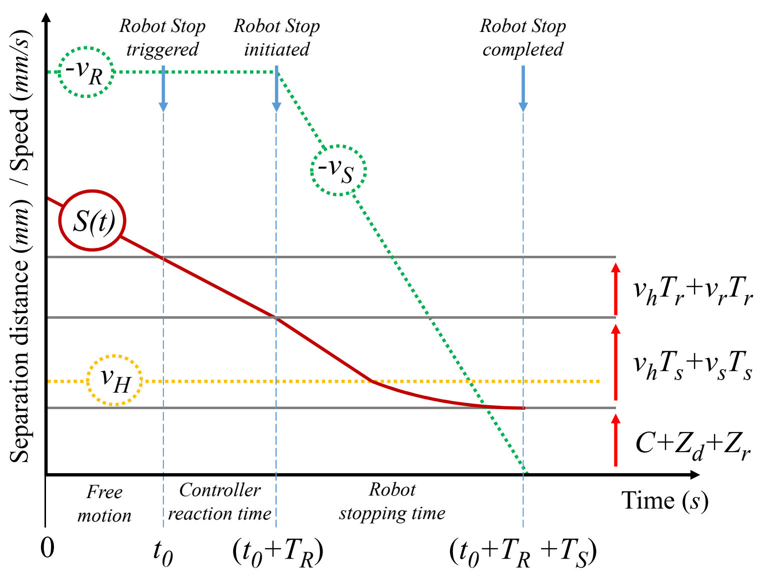


Figure 6: Trend of the separation distance between human and robot, as reported by ISO TS 15066:2016 [72].

static contact the operator body part can be clamped for an extended time between a moving part of a robot system and another fixed or moving part of the robot cell. Pressures and forces applied during the contact quantify the hazard, which depends on the size of the contact area and on the kinematics configuration of robot and human body at time of the contact. The curve shown in Fig. 7 provides the trend of force and pressure within the onset pain limit. ISO TS 15066 collects the admissible pressures and forces for 29 areas of human body for both the transient and quasi-static contact types. Moreover, it also provides a correlation between speed limit and mass of the robot for the maximum allowed energy transfer of a body region.

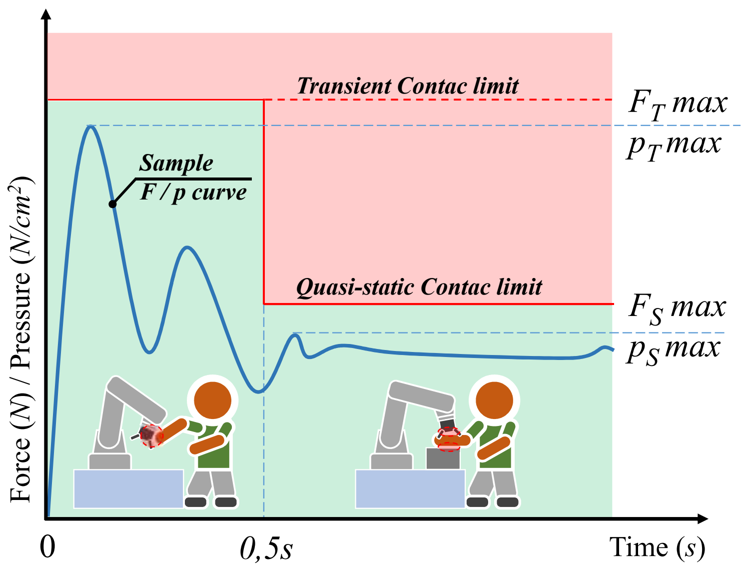


Figure 7: Sample force/pressure contact curve with acceptable and unacceptable zone, green and red area, respectively [72].

Therefore, ISO TS 15066, with the previous ISO 10218-1/2, provides the guidelines to calculate the direct data in the risk assessment process to evaluate the severity of risk and possibility of avoidance [73]. An example of evaluation method that identifies and characterizes the contact situations in PFL applications has been proposed by Matthias et al. [66, 74]. Moreover, software applications such as CAE tools dedicated to simulation and analysis of processes facilitate evaluation of the risk related to operations of the HRC application. Just to cite an example, Bobka et al. have presented the software tool called "Human-Industrial-Robot-Interaction-Tool" to evaluate both the productivity and safety of HRC systems in the planning process [75].

4. Intuitive user interfaces

One of the difficulties of using robots in industrial processes is often related to the way the human operator is supposed to interact with the robot, since it usually requires specialized knowledge. Conversely, the availability of intuitive ways to interact with robots and program them is one of the key enablers for a further adoption of the robotic technologies also by small companies. Specifically, simplified ways to interact with industrial robots in a reduced time, while minimizing user's errors and preserving situation awareness, are needed.

4.1. Human factors

In addition to guaranteeing the physical safety of human operators interacting with a collaborative robot, also issues related to mental safety, intended as mental stress and anxiety induced by close interaction with robot, needs to be considered. In particular, in [76] the operator's mental strain in collaborative robotic assembly tasks was measured by measuring relevant physiological parameters, such as the skin potential response. An increased mental strain was found when the robot moved closely towards the operator, with sustained approaching speed and without advance notice of motion. This kind of information about the underlying psychophysiological condition of the operator during interaction can be exploited in a framework of affective robotics, which consists in enhancing the interaction of a human with a robot by recognizing her/his affect [77]. Monitoring and interpreting nonverbal communication can provide important insights about a human interacting with the robot and, thus, implicit feedback about the interaction can be achieved. Accordingly, the aim of affective robotics is relieving user's cognitive burden when the task to accomplish overloads her/his mental capabilities, adapting the behaviour of the robot and implementing a sufficient level of autonomy [78]. However, current approaches based on affective robotics are mainly devoted to the field of socially interacting robots [77, 79] and, to a lesser extent, service robots [80]; they are not yet common in industrial practice. Preliminary attempts of introducing affective robotics in industrial environment are being considered in the framework of the INCLUSIVE EU project [10, 81, 82]. Moreover, in [83] the idea of allowing affective robotics with industrial manipulators by measuring mental strain by means of a common multi-purpose device, such as a smartwatch, has been proposed.

To reduce mental workload and increase reliability in robotic agents, human-robot interfaces based on the principles of human-centred design and cognitive engineering can be considered [84, 85]. Accordingly, the design of human-robot interfaces can be enhanced by taking human's cognitive information processing, decision making, perceiving and other capabilities or limitations into account [86, 87]. These general design recommendations are addressed by the branch of literature referring to concept of usability in human-computer interaction, whose pioneering reference works are [88, 89] and which is out of the scope of this survey.

4.2. Interfaces for robot programming

In practical industrial applications, most of the cognitive interaction effort of the human worker is devoted to robot programming tasks. Differently from instructing a (skilled) human worker how to carry a task, programming a robot requires providing the robot with explicit motion-oriented instructions, detailing the points and trajectories that the robot has to follow. Nonetheless, the goal is that of explicitly instructing the robot in a human friendly manner and without negatively affecting the productivity of the system. It is worthwhile noting that in the following interfaces for robotic production processes will not be addressed, since their design and use follow general methodologies and principles for the design of good operator interfaces, such as those in [88, 90, 91], just to cite some examples.

Traditionally, robot programming approaches can be classified in on-line programming, such as traditional lead-trough and walk-trough, and off-line programming (OLP), which use software tools without occupying the robot, thus being a first attempt to minimize downtime for robot programming [13, 16, 92].

The approaches described below, and their respective advantages and disadvantages, are reported in Fig. 8 and summarized in Table 4. As will be discussed below, the most novel approaches offer great intuitiveness and ease of use, thus not reducing the operator's cognitive burden and being accessible to low skilled users. However, unfortunately, such approaches are still quite limited in terms of possible operations to perform and working scenarios, and they have been mostly validated at experimental level. This applies also to human-friendly interaction modes, which allow to establish a more natural communication with the robot, but suffer from severe limitations that hinder a fast use of industrial practice. In particular, novel approaches, such as walk-through programming, programming by demonstration and the use of multi-modal interfaces and augmented/virtual reality, are characterized by high intuitiveness since they constitute instances of natural and tangible user interfaces (NUIs and TUIs, respectively). The main idea of a NUI is that of allowing a direct expression of mental concepts by intuitively mimicking real-world behaviour. NUIs offer a natural and reality-based interaction by exploiting users' pre-existing knowledge and using actions that correspond to daily practices in the physical world [93]. To achieve this, NUIs allow users to directly manipulate and interact with robots rather than instruct them to do so by typing commands. Thus, they represent an evolutionary paradigm that overcomes the access bottleneck of classical interaction devices such as keyboards, mice and joysticks, by resorting to voice, gestures, touch and motion tracking [94]. The term TUI encompasses a great variety of interaction systems relying on a coupling between physical objects and digital information, which is physically embodied in concrete form in the environment [95]. Thus, TUIs provide direct mapping between the behaviour of the robot and usage of

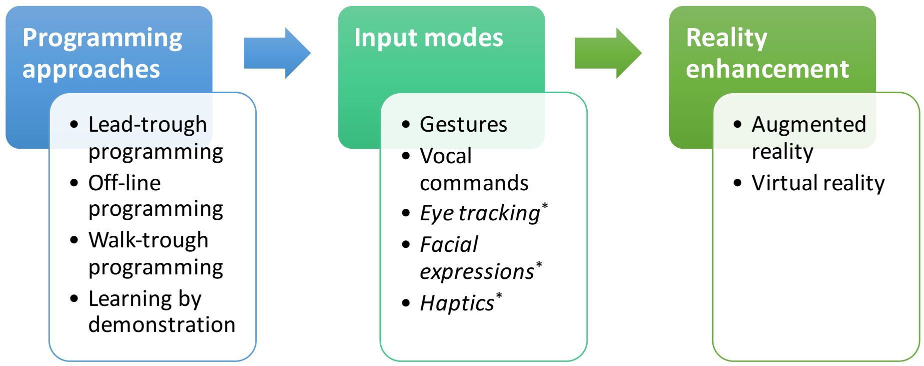


Figure 8: Overview of state-of-the-art approaches for robot programming (*: *not reviewed in this paper*).

such a robot, and between the behaviour of control devices and resulting digital effects. In other words, the pillars of TUIs are embodied interaction, tangible manipulation, physical representation of data and embeddedness in real space.

4.2.1. Traditional lead-through programming

The first approach to robot programming relies on the use of the teach pendant for on-line moving the robot through the required motion cycle by jogging, as shown in Figure 9. Trajectories and endpoints are then recorded into controller memory for later playback. When played back the end effector appears to follow a continuous smooth path. During the programming session, the robot's control is placed in a "teach" mode and the person performing the teach function can be within the robot's working envelope, with operational safeguarding devices deactivated or inoperative.

Although the concept is simple and does not require strong technical expertise, some programming skills are still required and teaching trajectories to the robot in this way turns out to be a tedious and time-consuming task, as shown in usability assessments reported, e.g., in [96, 97, 98]. Moreover, it is only suitable for programming simple tasks on workpieces with a simple geometry, with programming complexity dramatically increasing when complex geometries are involved. Further, this method requires reprogramming for each new

Table 4: Overview on the relevant literature for robot programming methods.

INTERFACES FOR ROBOT PROGRAMMING	
ROBOT PROGRAMMING	**Lead-through programming** – standard used in industrial settings, together with OLP – **[96]–[98]**: usability assessment – **[100]–[103]**: improved with intuitive input devices (comparative overview in [13])
	Off-line programming – standard used in industrial settings – refinements with lead-through programming still necessary – **[13], [104]**: review of the method and its variants – **[106]–[109]**: approaches and issues related to robot calibration
	Walk-through programming – **[6], [12], [110]–[120], [124], [125], [127], [128]**: force/torque sensing – – **[6], [12], [113]–[117], [124], [125]**: admittance/impedance control schemes – – **[118], [119], [127], [128]**: variable admittance/impedance control – – **[120]**: force control – **[110], [124], [125]**: introduction of a virtual tool – **[35], [130], [131]**: techniques alternative to force/torque sensing to detect intentional interaction – **[121]–[123]**: preliminary industrial applications
	Programming by demonstration – **[8], [139]**: overview and classification – **[133], [134]**: symbolic encoding – **[135], [136]**: trajectory encoding – **[145]**: preliminary industrial applications
MULTI-MODAL INTERFACES	**Vision based** – **[150], [151]**: recognition based on markers – **[155], [157], [159]**: markerless recognition – **[158]**: stereo 3D vision – **[151]–[154]**: hybrid vision/force approaches
	Vocal commanding – **[162], [163]**: use of simple and limited voice commands – **[148]**: vocal commanding combined with gesture recognition – **[164]**: quasi-natural speech language – **[165]**: issues related to environmental noise in industrial settings
ENHANCEMENT OF REALITY	**Augmented reality (AR)** – **[180], [182], [183]**: robot programming by AR – **[5], [184]–[186]**: robot programming by AR combined handheld devices – **[5], [149]**: robot programming by AR combined with gestures – **[187]**: robot programming by AR combined with speech
	Virtual reality (VR) – **[181]**: robot programming by VR

Figure 9: Lead-through programming by teach pendant.

task, even in case of little changes, thus stopping the production every time. As a consequence, in industry this type of robot programming can be justified economically only for production of large lot sizes and is not suited for small and medium sized enterprises, where small production batches require frequent task reprogramming and such a time-consuming and demanding procedure is unaffordable [99].

To overcome the limitations of this classical approach to robot programming, several other approaches, which are addressed in the subsections below, have been proposed. Nevertheless, on-line programming by jogging is still necessary in some specific situations, such as when it is needed to *in situ* verify and manually adjust programs generated off-line (see section below), or when 3D models are unavailable, or still in presence of complex tasks that can be only be programmed by the human operator close to the robot [16, 100]. To this end, a few new programming methods have been proposed to alleviate the burden of jogging assisted by implementing additional sensors and control technologies [101, 13, 102, 100, 103]. As an example, in [101] a programming solution has been introduced that relies on the use of a 6-DOF motion tracking device that is mounted on the end-effector of a robot to recognize the lead-through teaching. Also, the authors in [100] have proposed a modular on-line programming environment, which represents a first attempt of integrating the power of OLP tools with the on-line programming based methods. Specifically, the proposed environment consists of a user interface to control the movement of the robot using a mobile guiding device, a geometric model representing the environment given by CAD or sensor data and assisting algorithms working on the geometric model supporting the user while moving the robot.

4.2.2. Off-line programming

Given the disadvantages listed above, nowadays on-line robot programming by teach pendant has become quite unusual and is being replaced by OLP [104]. This approach resorts to remotely simulating the task in the 3D model of the complete robot workcell. Specifically, the robot can be programmed from a computer rather than on the robot itself, thus virtually replicating the system in the shop floor. Additionally, these programming tools come with a set of modelling and simulation functions that allow for graphical representation of the robot cell, automated program generation and simulation of robotic tasks, with the possibility to check for possible collisions [105, 104]. Moreover, most advanced today's OLP tools offer modules for specific processes, such as coating, welding or polishing. Thus, feedback is immediately given to the user about the programmed path, thanks to its simulation. After simulation and testing, the program is then exported from the computer to the robot, usually via Ethernet, and some final tuning of the program with the teach pendant might be required. A careful review of all the steps required by OLP methods has been provided in [13], whereas CAD-based robot programming approaches have been reviewed in [104].

Unfortunately, typically each robot manufacturer has its own specific OLP software, whose licence is usually very expensive, and employing an OLP system requires great programming effort. Indeed, OLP approaches move the burden of programming from the robot operator in the shop floor to the software engineer in the office [13]. Time required to program the robot is still remarkably long, but the production does not need to be stopped during programming, thus the uptime can be maximized. Moreover, it is fundamental to perform a robot calibration step when off-line generated program is transferred onboard the robot in order to compensate for any positioning error due to a mismatch of coordinate systems between real and virtual world. Several approaches have been proposed for robot calibration, such as those in [106, 107, 108, 109].

4.2.3. Walk-through programming

The basic idea behind this robot programming method is that the user is allowed to physically move the end-effector of the robot through the desired positions in a free way. At the same time the robot's controller records the desired trajectory and the corresponding joints coordinates, and is then able reproduce the trajectory thereafter. Thus, the robot can be programmed in a very intuitive manner and no knowledge of the robot programming language is requested to the operator. Specifically, robot programming by walk-through programming constitutes a NUI and TUI, as introduced in Subsec. 4.2.In addition to intuitiveness of interaction, this implies also that, thanks to tangible manipulation, that is the possibility of moving the robot along the desired path, the operator manipulates the robot, having tactile contact and feeling haptic feedback. Feedback about the trajectory that is being recorded is rapidly and constantly given to the user (according to the so-called lightweight interaction feature of TUIs [95]). Moreover, as opposed to lead-through programming, it is straightforward for the user to understand the relation between programming instructions (that is how the robot is moved) and their effect in terms of programmed trajectory (isomorph effects typical of TUIs [95]).

Clearly, in this scenario safety issues related to physical HRI become of paramount importance and appropriate motion control strategies are needed [11]. Most control approaches rely on the use of a force/torque sensor typically mounted on the robot wrist, which measures the forces and torques occurring during the interaction. Such forces and torques can be then exploited by closing a control loop that provides inputs to the position control system of the robot, in order to accommodate the forces applied by the operator [110, 111, 112]. This is typically achieved by means of compliant control schemes, such as admittance/impedance control [6, 12, 113, 114, 115, 116, 117, 118, 119] or force control [120]. In the very recent paper [121], walk-through programming for spray painting with industrial collaborative robots has been proposed. Moreover, walk-through programming in welding applications is considered in [122, 123], exploiting the impedance control with zero stiffness but without taking into account the tool emulation or compensation. Indeed, the main limitation of these methods is that they require a robust dynamic model of the robot and its tool. For example, in the approaches by Al-Jarrah and Zheng [114, 115, 116] the weight of the tool is simply shared between the robotic arm and the human operator, but the forces/torques due to the motion of the tool are neglected.

To partially overcome these issues, the concept of virtual tool has been introduced, which gives the operator an impression the closest possible to that felt when the task is performed without the robot assistance. To this end, by modelling the end-effector as a virtual point of given mass, the operator feels she/he is moving a tool of reduced mass instead of an heavy and stiff robot. This idea is exploited in [124, 125] together with an impedance control scheme. In [110] an admittance control is designed, considering a nonlinear model of the dynamics of the virtual tool, with the same weight and inertial properties of the real one, in order to ensure that this virtual dynamic behaviour associated to the virtual tool is achieved. However, the approach based on virtual tool is not appropriate in some industrial applications, where the operator needs to program the robot by moving directly the real tool, in order to see the final result of the operation. In this case the end-effector of the robot may have to carry a not negligible payload. This condition has been tackled in [126] and [6], where impedance control schemes are adopted and modified to include the dynamic of the load, thus allowing the use of the real tool in the teaching phase.

Other approaches resort to variations of admittance and impedance control. Specifically, the concept of variable impedance is introduced in [127], where the impedance parameters are varied depending on the speed of the operation, whereas in [128] an adaptive admittance control is proposed that provides compliance to external forces. In [129] the admittance control is coupled with virtual

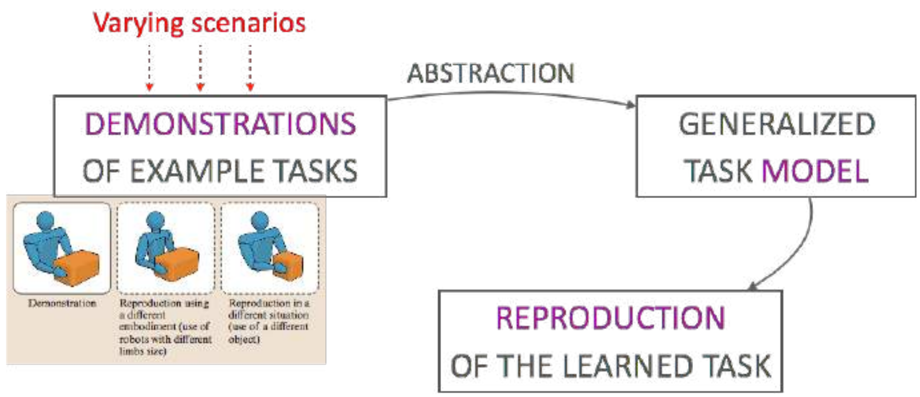


Figure 10: Overview of robot programming by demonstration.

fixtures that constrain the motion of the robot, thus providing a vision-based guidance.

For the sake of completeness, some approaches not relying on the use of a force/torque sensor should be mentioned. Basically, they consist in detecting human intentional interaction, which can ultimately be used to achieve manual guidance in a scenario of walk-through programming. Examples can be found in [35, 130, 131].

Finally, in [132] interestingly the human side of physical HRI in a scenario of walk-trough programming is considered: which kind of response of the robot is preferred by the human user is studied and a trade-off between the conflicting goals of naturalness of motion and positioning accuracy is found to be needed.

4.2.4. Programming by demonstration

A further extension to walk-through programming is provided by the concept of programming by demonstration (PbD). Indeed, while the former allows the mere reproduction of motions performed by the human operator, the latter considers the possibility for the robot to learn the movements to perform under varying conditions and to generalize them in new scenarios. Accordingly, the robot is endowed with some learning skills, rather than pure imitation. Figure 10 shows the principles of this approach. From the human operator's perspective, this approach allows an easy and natural interaction, without requiring any experience in robot programming, as in the case of walk-through programming. Thus, it provides the same advantages of being a natural and tangible user interface as discussed for walk-through programming.

The most investigated issues in PbD refer to how to generalize across demonstration in the demonstration phase and how to generalize the movement to new situations during reproduction. As regards the first one, mainly two approaches have been proposed to extract the relevant features of a given task, namely symbolic and trajectory encoding. Basically, in symbolic encoding, a set of task-dependent primitives is derived based on a priori knowledge and a task is recognized as a sequence of symbolic primitives [133, 134]. In the case of trajectory encoding, the demonstrated trajectory, and the applied force if necessary, is directly transformed to the robot motion [135, 136]. The choice of which encoding approach to consider strongly depends on the the task to perform: for example, hierarchical tasks, such as assembly, have been tackled by resorting to symbolic encoding, enhanced with information extracted from the CAD model of the workpieces [61, 137]. On the contrary, simpler tasks, such as pick and place or peg-in-hole, have been solved by means of trajectory and force encoding based on dynamic movement primitives framework [138].

A complete overview of PbD has been provided in [8], and a full classification can be found in [139]. However, most of works related to PbD consist in theoretical and experimental approaches, and appear far to be ready for everyday implementation in industrial practice [140, 141, 142, 143, 144]. In [145] an approach for PbD in industrial welding applications is presented. However, the definition of robot paths is performed by walk-through programming, thus the robot can only imitate demonstrated trajectories. The ability to generalized is referred to the fact the robot can rather predict next welding tasks, based on a probabilistic approach making use of hidden Markov models. In other works, such as [137], PbD is improperly claimed, but rather manual guidance methods allowing only motion imitation are considered, in conjunction with multi-modal interfaces based on speech or gesture recognition.

4.3. Multi-modal interfaces

Regardless of the approaches used for robot programming, sensing has been recently applied to enhance the interaction of a human operator with a robot. Indeed, apart from aspects related to safety features, the use of additional sensors has been considered for using interaction modes that make robots behave more like humans do, or alternatively to make them complement human abilities. This alleviates the burden of communication with the robot and, as a consequence, people with no previous experience or knowledge in HRI can easily and effectively interact with robots. The ultimate goal is to help users to control and program a robot by means of high-level behaviours that abstract from the robot language [146, 147]. This can be achieved by considering human-friendly input modes, such as speech, gesture, eye tracking, facial expression, haptics, in addition to the traditional ones, namely keyboard, mouse, monitor, touchpad and touchscreen [20].

In the following, interaction modes based on vision and vocal guidance, as used in the industrial practice, are reviewed. It is worthwhile noting that in some applications, such as in [148], these interaction modes are considered combined and sometimes are integrated in approaches based on augmented reality [5, 149].

4.3.1. Vision based

Generally speaking, vision systems are used for object and environment recognition, and to recognize the human body gestures and the facial expressions. Thus, they can be used for recognising the demonstrator's actions and tranferring them to the robot for motion imitation. Typically, the recognized scene is shown to the user and/or a proper acoustic or visual feedback is provided to the user to reduce risks of miscrecognitions.

In [150] the authors have proposed a robot programming approach based on the recognition of marks manually made by the human operator on the workpiece. Depending on the type of tasks needed, the worker marks differently the areas that need additional robot working; such marks are then detected by a vision system and are translated in instructions to the robot. Similarly, in

[151] a robot path generation method to automatically generate robot paths to accomplish the deburring process has been presented. This is a hybrid approach combining visual and force servoing. The desired tool path is marked manually on the wheel and is then identified using an eye-in-hand camera mounted on the robot end-effector. Force sensing guarantees a continue contact of the robot with the workpiece. Many other hybrid vision/force approaches have been proposed starting from [152, 153, 154].

In [155], instead of drawing marks on the workpiece, the path is shown to the robot by using a laser that projects structured light on the surface. The vision system does not require calibration and an impedance control is implemented in order to regulate the interaction forces generated by the contact between the robot end-effector and the work surface where the trajectory is traced. Structured light 3D machine vision is used also for object profile perception in [156], where the problem of automated leather surface roughing has been addressed.

A vision-based markerless human–robot interface has been proposed in [157] and it has been used to control dual robot manipulators by tracking the motion of operator's hands, without any contact devices or markers. The approach has the advantage of being completely noninvasive, however it requires that the operator stands in a fixed position in front of the camera. Thus, it is suited only for static HRI tasks.

Stereo vision has been used also in this context: for example, in [158] coordinates for welding robot programming are acquired by means of stereo vision. The system uses two cameras for 3D coordinates and edge detection with other image processing algorithms to find the welding path in the image.

In [159] vision based robot programming has been explored in combination with a digital pen that recognizes the marks drawn by the operator on a special digital paper and processes them in order to derive the robot program. Specifically, welding trajectories can be automatically extracted by the CAD files of the workpiece.

Vision based human-robot collaborative handling of dangerous liquid has been considered in [160]. Collaboration is based on gestures. Interestingly, the proposed approach starts from the observation and analysis of human-human-interaction during collaborative assembly scenarios and the identified gestures are properly transferred in the interaction with the robotic system, according to human-centred design principles.

Visual commands are combined with voice commands in [148] to program a pick-and-place application simply by pointing to objects in the work area and speaking simple and intuitive natural language commands. Then, a camera is used to recognize deictic gestures and implement finger pointing.

However, it is worthwhile noting that the solutions proposed in the literature in this regard, as those mentioned above, are still limited to the research ground and currently do not find much application in the industrial practice [13]. This is mainly due to cost reasons and to the fact that such approaches have validity limited to the experimental setup, thus they cannot easily and straightforward extended to other applications, scenarios and instrumentations.

4.3.2. Vocal commanding

Voice guidance proves very useful when hands-free interaction is required: that is, for example, when the user's hands are not free or when classical interaction systems do not fit the situation, such as the case of interaction with service mobile robots. Indeed, one major advantage of voice communication is that it does not restrict operator's mobility and operator can remain focused on the tasks, without taking her/his eyes off. However, very few systems for speech recognition and natural language processing in industrial scenario exist. Basically, the poor diffusion of vocal commanding systems for industrial environment is due to the lack of reliable solutions and to the fact that in this context any misrecognition would have non negligible side effects, in terms, for example, of production, efficiency and safety.

In general terms, when considering the use of speech interfaces two main aspects need to be addressed: speech recognition, involving phoneme or word recognition, and language processing, which includes parsing and semantic analysis [161]. The ultimate goal is that of establishing a natural bidirectional communication that allows natural language to be understood and generated by the robot. To this end, providing users with proper feedback during interaction is a key issue for the success of these systems. Specifically, operators should be informed about the outcome of speech recognition, in order to prevent that any misrecognition is further processed by the system. In this regard, feedback can be provided to the user by letting the interface repeat the recognized commands. However, if an audio feedback is provided to the operator by the interface, issues related to background environmental noise must be considered.

In practical industrial applications a vocal communication based on quasi-natural language might be sufficient, instead of the natural language, since the lexicon to be used is quite limited and users should be (at least partially) expert of the interaction. Despite of this, the existing approaches are usually based on a very limited number of simple voice commands [162, 163], which is quite limiting, as reported in [161]. A web-based remote voice control of robotic cells has been proposed in [164] and it is based on quasi-natural language. However, the implementation and validation of the approach are still at a laboratory level. As mentioned above, voice command is used in [148] in combination with finger-pointing commands. Recognized voice commands trigger the vision component to capture what a user is pointing at. Also in this work, some effort has been put in enabling the use of natural language and a noisy manufacturing environment has been used for testing.

In [165] the problem of environmental noise in industrial robotic control is considered and a multichannel signal enhancement methodology has been proposed to improve the performance of commercial speech recognizers.

4.4. Augmented reality and virtual reality

In recent years, a lot of interest in robot interfaces has been devoted to the application of augmented reality (AR) and virtual reality (VR) in manufacturing practice. The first results of the integration of these methodologies in traditional interaction approaches have shown that they can increase system productivity while enhancing human safety [167, 168]. As described in Fig. 11, the difference

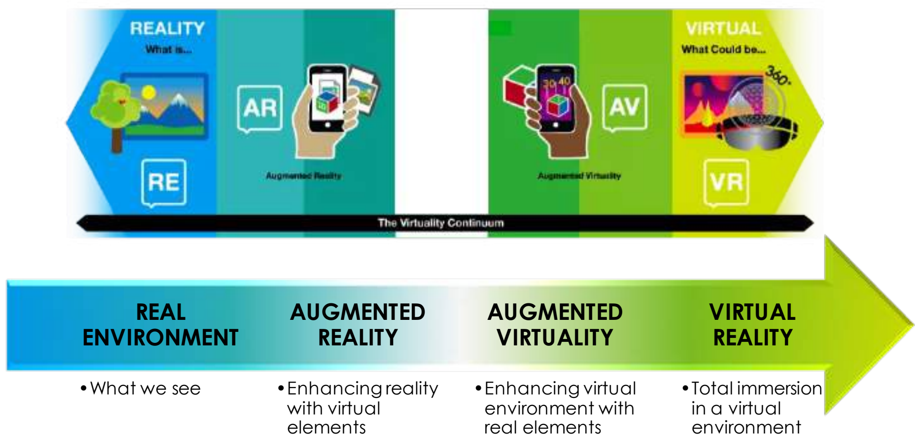


Figure 11: Augmented and virtual reality as part of the virtuality continuum introduced in [166]. Image adapted from `http://smartideasblog.trekk.com/augmented-or-virtual-how-do-you-like-your-reality`.

between augmented and virtual reality is that in the former the real world scene is augmented by virtual elements and, thus, the user maintains a sense of presence in real world, whereas the latter provides a totally immersive environment where the user's senses are under control of system [166]. These technologies allow to embody the interaction objects and information in the real world, by supporting intuitive use and exploiting human spatiality, humans' innate ability to act in physical space and interact with physical objects. Ultimately, they provide a tangible interaction that overcomes the access bottleneck of other interaction modes [95, 169].

A detailed review about AR technologies and applications in design and manufacturing has been provided in [170]. Specifically, the most promising uses of AR and VR in industrial applications are related to design, assembly and maintenance since they allow to display synoptic information onboard the robot and in the field of vision, such as performance values, catalogue spare part codes and work instructions [167, 168, 171]. Thus, tasks such as assembly design, where the optimal assembly operation sequence that minimizes completion time and effort must be found [172], planning [173] and guidance [174] can be enhanced. The added value of the use of both AR and VR in these operations is that proper real-time training is given to operators, providing them with cues and guidance. The same applies in the case of maintenance tasks, where real-time troubleshooting and spare parts purchase actions with all relevant information and functions are enabled to maintenance personnel [170, 175]. Also, AR and VR for ergonomic assessment of assembly tasks have been proposed [176, 177, 178].

Additionally, AR and VR have been applied also to robot programming [179, 180]. Generally speaking, reality enhancement by AR and VR can be applied to any of the programming approaches discussed above, to increase intuitiveness and provide rapid feedback to the user. Specifically, the first attempts in this regard, such as that proposed in [181], considered VR as an alternative approach to OLP that allows safe robot programming in a more intuitive manner than traditional OLP. However, approaches based on VR require to extensively model the environment entities and to calibrate the model when it is applied in the real environment. Thus, robot programming using AR (RPAR) techniques were introduced, which implement a sort of OLP without the need for a model of the workpiece in the virtual environment [13]. One of the former works in this regard were performed in the framework of the MORPHA research project [182] and in [183] the potential of AR-based HRI was discussed, together with the basic requirements for an AR system from the robot manufacturer's perspective. Specifically, RPAR brings the same advantages as walk-through programming, such as intuitive programming and spatial interaction, and OLP, namely the possibility to run simulations of the planned paths to check for collision and to program the robot without stopping the production [13]. In addition, RPAR allows the programming of large robots where the walk-through method is unfeasible, such as is the case of airplane washing robots considered in [180].

In several works, RPAR has been proposed in combination with handheld devices, typically tablets, since they easily allow for small batch industrial applications that need fast and easy to use tools to program the robots [5, 184, 185, 186]. In [5, 149] AR is combined with gestures for a very intuitive spatial programming, whereas RPAR is proposed jointly with modular multimodal inputs, such as mouse and speech, in [187], and is tested with pick-and-place tasks of different complexity. Moreover, in [186] the perceived workload of industrial robot programmers and their task completion time were investigated when using a tablet-based AR approach. The mental demand was found to be decreased with respect when not using AR, but an increase in task completion time was however found.

5. Applications

In this section we provide an overview on the main industrial applications where collaborative robotic is advantageous. Specifically, it is discussed how HRC might improve the efficiency of the selected tasks and which are the open issues. The automotive domain is considered separately, since it currently represents the strongest demand of collaborative robots, as shown in [1].

Table 5 reports a synthetic overview on the relevant literature for the industrial applications of HRC discussed hereafter.

As discussed below with respect to specific instantiations, in most of the currently available cooperative applications robots are mainly used to perform dull tasks, such as helping operators moving materials, holding heavy objects or performing sample tests. In these working scenarios, the robot has the role of a tool that eases the operator's burden of physical labour and is given little autonomy [28]. However, this kind of cooperation still proves advantageous for the human worker, since she/he is relieved assisted of distressful tasks by acting through the robot to accomplish her/his work in a more natural fashion [28]. A step further would be conceiving the robot as a collaborative workmate, thus being endowed with greater autonomy and offering proactive assistance to the human.

Table 5: Overview on the relevant literature for industrial applications of HRC.

APPLICATIONS	
HANDLING	– [**160**]: dangerous material handling – [**16**]: food and aseptic material handling – [**188, 189**]: collaborative surface polishing
WELDING	– [**190**]: overview on current technological solutions – [**122, 123, 145**]: walk-through programming for welding robots – [**157**]: dual arm system taught by hands movements (using a Leap Motion) – [**158**]: welding path reconstruction by stereo vision
ASSEMBLY	– [**16, 17, 191**]: hybrid assembly robotic cells – [**17, 191**]: extensive analysis of HRC in assembly cells – [**192**]: discussion on hand guided assembly – [**193**]: discussion on automotive assembly lines
AUTOMOTIVE	– [**194**]: review on automotive assembly technologies – [**195**]: HRC to relieve workers' strain in BMW plants – [**196**]: ergonomically optimal position of workers in Audi plants – [**197**]: heavy tools handling in Ford plants – [**198**]: ergonomic workplace layout in Volkswagen plants – [**199**]: high-precision tasks in ŠKODA plants

5.1. Handling

Handling probably represents the largest application of robotics in general, since it can be found in all branches of manufacturing and logistics. Moreover, it comprises a great variety of processes, such as grasping, transporting, packaging and palletizing [16]. Essentially, applications such as product testing, assembly, and pick and place are all applications that are simply manipulating a part for another step in the manufacturing process. Robotic material handling is advantageous to reduce the worker efforts in lifting and moving materials or when material cannot be handled by a human for hygiene, such as in the case of food presented in [16], or because of danger, as the case in [160].

While these motivations do not prescribe collaboration between the human worker and the robot, using collaborative robotic system for handling applications allows to satisfy current industrial requirements on shorter product lifecycles, reduced time-to-market and customization [200]. Indeed, cobots allow for quick and agile in-process reconfiguration and set-ups, thus they can be easily relocated and reprogrammed to do a wide variety of tasks. Such applications are suited for automotive and general industries where robots work alongside human workers and can use the same setup as if a human worked there. Therefore, current applications of collaborative robotics for handling processes fall in the robot-as-tool approach, and most of the cognitive effort, which depends on the application, is left to the user. A first attempt of robots as collaborative workmate for these applications has been proposed in the framework of the SYMPLEXITY EU project [189]. The project considers the use of collaborative robots in surface finishing applications, where the worker is in charge of the final phases of the process, which require human skills and sensitivity [188]. In this scenario, collaborative robots are required when the work piece has to be hold in a precise position or orientation and presented to the worker. Building upon this idea, in the project a collaborative robotic system is being developed, which performs rough robot polishing and allows the user to perform some final corrective polishing steps, based on the results of an interferometer that measures surface quality. Thus, the collaborative robot is able to present the work piece to the human worker in the exact orientation where imperfection lies and additional corrective polishing is required [189].

5.2. Welding

Welding represents one of the leading uses of industrial robots. However, its effective application in practical production is still limited by the complexity and uncertainty of welding process [190]. Welding robots currently used in industrial environment follow traditional interaction approaches based on lead-through and off-line programming, which cannot cope with diverse requirements of welding production in real working conditions, due for example to errors of pre-machining and fitting workpiece or distortions induced by heat [190]. To overcome these issues, intelligent technologies for welding robots are considered in [190], such as vision sensing, automatic programming, guiding and tracking, and real-time intelligent control of welding process. In addition, using collaborative robots allows to tackle such complexity and uncertainty by relying on human skills.

Moving along these lines, the approaches presented in [122, 123, 145], which have been discussed above, propose the use of walk-through programming for welding robots. A similar approach has been described also in [16]. Additionally, in [157] and in [158], multi-modal (vision based) interaction has been proposed for welding applications. All these approaches implement collaborative robotics in terms of robot-as-tool approach and little autonomy or cognitive capabilities are provided to the robot.

5.3. Assembly

Assembly robots are used for lean industrial processes and have expanded production capabilities in the manufacturing world. The most common use of collaborative robots for assembly in manufacturing lines are hybrid assembly robotic cells [16, 17, 191]. Indeed, automated assembly system are advantageous since, on the one hand, the use of robots prevents workers from tedious jobs and increases productivity for simple assembly tasks. On the other hand, human workers are able to handle complex tasks and can quickly adapt to new process sequences. Specifically, cooperative assembly work stations are suited for sequential assembly, that is when the robot first performs the simple tasks and the complex frequently varied tasks that give the assembled products their individual features are performed at the end of the line by human operators [17]. Conversely, parallel cooperative assembly is required when many parts have to be assembled at the same time or for precision tasks. In this case, timing and coordination between the human and the robot are critical factors that might severely affect the acceptability and effectiveness of HRC.

The works presented in [17] and [191] provide an extensive analysis of HRC in an assembly cell. Moreover, in the benefits of using collaborative robots in hand guided assembly operations that require lifting and handling large and heavy objects have been discussed in [192]. The specific case of automotive assembly lines, and its related issues, has been discussed in [193].

Further, in advanced assembly processes the physical contact between the joined workpieces can be controlled by means of a robot implementing compliant motion control that measures joint torques or contact forces using a torque-force sensor mounted on the robot flange [16, 201].

5.4. Automotive

The automotive domain is worthy of a dedicated discussion, since a great interest has been put in this application domain both by industries and academia. Specifically, most of the applications are devoted to assembly tasks [194]; however, in [202] and [18] a lack of high-level collaboration between the human and the robot is pointed out, and collaboration collapses to robot-as-tool scenarios, meant as intelligent lift assistants, such as the one proposed in [203]. Nevertheless, the advantage brought by such underuse of cobots in this domain is still relevant since very often the tasks delegated to robots require lifting heavy objects and, if performed by human workers, such tasks would require assuming non ergonomic positions and inducing strain in the worker.

In recent years several automotive manufacturers have been introducing collaborative robots in producing lines: this is the case, for example, of BMW, Audi, Ford, Volkswagen and ŠKODA. The industrial application of collaborative robots by Universal Robots in BMW assembly lines has been presented in [204, 195]: robots are used in the production line to roll a layer of protective foil over electronics on the inside of a door, which is a task that could cause workers repetitive strain injury when done by hand. Audi's human-robot cooperation in production processes relies on the robot "PART4you". It embeds a camera and a suction cup to assist human workers in picking up the components from boxes and to pass them to the assembly workers, without any safety barrier, at the right time and in an ergonomically optimal position [196]. As regards Ford, KUKA collaborative robots are being used on an assembly line helping workers install shock absorbers: rather than use a heavy shock absorber installation tool, the workers have the robot lift and automatically position the shock into the wheel arch before pushing a button to install the component [197]. Robotic arms by Universal Robots are used also in Volkswagen plant, where they are in charge of handling delicate glow plugs into the cylinder heads, thus allowing a ergonomic workplace layout of the plant where the employee can complete the task of fixing the glow plugs and insulating the cylinder head in an upright healthy posture, with the robot standing in the close vicinity and serving as a colleague [198]. Also ŠKODA production employees are working alongside robots on high-precision tasks, such as inserting the gear actuator piston, which is one of the most delicate processes in transmission manufacturing [199].

6. Conclusion and future directions of research

Given the great importance that collaborative robots have been gaining in recent years in industrial setting, in this paper we have reviewed the HRC approaches existing in the literature, in order to provide an overview of the state of the art and its current limitations. In particular, we have addressed the two most important challenges that arise when using collaborative robots in industrial applications, namely safety and intuitive ways to program and interact with robots. Specifically, the safety standards have been recalled, and it has been discussed to what extend they allow to implement collaboration. As regards user interfaces, despite the traditional lead-through and off-line programming are still the most used in industrial practice, many more intuitive approaches have been introduced, which rely also on multi-modal interaction and augmented and virtual reality.

Finally, in the last part of this survey paper, we have discussed which are the commercially available solutions are also presented and the main industrial applications where collaborative robotic is advantageous have been presented, highlighting how collaborative solutions are intended to improve the efficiency of the system and which are the open issue.

Future directions of research should push strongly towards a pervasive integration of HRC solutions in industries. In general terms, we refer to the need for safe and easy to use collaborative robotic solutions that really allow for robots working together with human operators, as co-workers, each complementing the skills of the others, as discussed in Sec. 1. In this regard, we currently identify four major specific goals to achieve such objective.

First, safety issued should be addressed by identifying performance oriented solutions. In other words, the approach should change from considering safety as a requirement that limits performance, but rather performances should be optimized subject to the constraint of safety.

Second, as remarked in Sec. 4, most of the novel and advanced, in terms of intuitiveness and ease of use, user interfaces for robot programming currently pertain mostly to laboratory research and have not found yet concrete application in industry, despite of being quite mature technologies. To overcome such a gap, specific effort in terms of technology transfer is required, to bring solid user interfaces used at research level to shopfloors. To this end, robots retrofitting represents an important step, to allow the integration of novel interaction solutions in deprecated robots. In particular, this is needed to introduce collaborative solutions also in small and medium-sized companies that might have limited budget for investing in innovation.

Moreover, the last step to make HRC effective in real industrial scenarios is the introduction of adaptive solutions for inclusive robotics. Specifically, we refer to the need for taking into account vulnerable users and, in general, the different skills and capabilities of users and in the design of collaborative solutions, as discussed in [82].

Finally, the overview on current industrial applications of HRC presented in Sec. 5 has highlighted that collaborative robots in industry are mostly under-used, since they are mainly regarded as tools that relieve workers of physical fatigue and enhance their capabilities, but enjoy very limited autonomy and intelligence. As a future target, we point out the need for endowing robots with proper cognitive processing skills and shared autonomy capabilities, so that they can take over some tasks, thus relieving human operators of cognitive effort, especially in complex tasks and scenarios.

[1] Executive summary world robotics 2016 industrial robots, Tech. rep., International Federation of Robotics (IFR) (Sep. 2016).

[2] L. Probst, L. Frideres, B. Pedersen, C. Caputi, Service innovation for smart industry - human-robot collaboration, Tech. rep., European Union, Business Innovation Observatory (Feb. 2015).

[3] H. Kagermann, J. Helbig, A. Hellinger, W. Wahlster, Recommendations for implementing the strategic initiative industrie 4.0: securing the future of german manufacturing industry; final report of the industrie 4.0 working group, Tech. rep., acatech – National Academy of Science and Engineering (Apr. 2013).

[4] J. Colgate, W. Wannasuphoprasit, M. A. Peshkin, Cobots: robots for collaboration with human operators, in: Int. Mechanical Engineering Congress and Exhibition, Vol. 58, 1996, pp. 433–439.

[5] J. Lambrecht, J. Krüger, Spatial programming for industrial robots based

on gestures and augmented reality, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2012, pp. 466–472.

[6] C. Talignani Landi, F. Ferraguti, C. Secchi, C. Fantuzzi, Tool compensation in walk-through programming for admittance-controlled robots, in: Annu. Conf. IEEE Ind. Electron. Soc., Italy, 2016.

[7] S. Farsoni, C. T. Landi, F. Ferraguti, C. Secchi, M. Bonfè, Compensation of load dynamics for admittance controlled interactive industrial robots using a quaternion-based kalman filter, IEEE Robotics and Automation Letters 2 (2) (2017) 672–679.

[8] A. G. Billard, S. Calinon, R. Dillmann, Learning from humans, in: B. Siciliano, O. Khatib (Eds.), Springer Handbook of Robotics, 2nd Edition, Springer, 2016, Ch. 74, pp. 1995–2014.

[9] A. M. Djuric, R. Urbanic, J. Rickli, A framework for collaborative robot (CoBot) integration in advanced manufacturing systems, SAE Int. J. of Materials and Manufacturing 9 (2016) 457–464.

[10] V. Villani, L. Sabattini, J. N. Czerniak, A. Mertens, B. Vogel-Heuser, C. Fantuzzi, Towards modern inclusive factories: a methodology for the development of smart adaptive human-machine interfaces, in: IEEE 22nd Int. Conf. Emerging Technologies and Factory Automation (ETFA), IEEE, 2017.

[11] A. Gupta, S. Arora, Industrial automation and robotics, Laxmi Publications, 2009.

[12] L. Bascetta, G. Ferretti, G. Magnani, P. Rocco, Walk-through programming for robotic manipulators based on admittance control, Robotica 31 (7) (2013) 1143–1153.

[13] Z. Pan, J. Polden, N. Larkin, S. V. Duin, J. Norrish, Recent progress on programming methods for industrial robots, Robotics and Computer-Integrated Manufacturing 28 (2) (2012) 87 – 94.

[14] Y. Shen, G. Reinhart, M. M. Tseng, A design approach for incorporating task coordination for human-robot-coexistence within assembly systems, in: 9th Annu. IEEE Int. Systems Conf. (SysCon), IEEE, 2015, pp. 426–431.

[15] G. Michalos, S. Makris, J. Spiliotopoulos, I. Misios, P. Tsarouchi, G. Chryssolouris, ROBO-PARTNER: Seamless human-robot cooperation for intelligent, flexible and safe operations in the assembly factories of the future, Procedia CIRP 23 (2014) 71–76.

[16] M. Hägele, K. Nilsson, J. N. Pires, R. Bischoff, Industrial robotics, in: B. Siciliano, O. Khatib (Eds.), Springer Handbook of Robotics, 2nd Edition, Springer, 2016, Ch. 54, pp. 1385–1418.

[17] J. Krüger, T. K. Lien, A. Verl, Cooperation of human and machines in assembly lines, CIRP Annals-Manufacturing Technology 58 (2) (2009) 628–646.

[18] A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, P. Fraisse, Collaborative manufacturing with physical human–robot interaction, Robotics and Computer-Integrated Manufacturing 40 (2016) 1–13.

[19] B. Siciliano, O. Khatib, Springer handbook of robotics, 2nd Edition, Springer, 2016.

[20] P. Tsarouchi, S. Makris, G. Chryssolouris, Human-robot interaction review and challenges on task planning and programming, Int. J. Computer Integrated Manufacturing 29 (8) (2016) 916–931.

[21] H. Ding, M. Schipper, B. Matthias, Optimized task distribution for industrial assembly in mixed human-robot environments-case study on IO module assembly, in: IEEE Int. Conf. on Automation Science and Engineering (CASE), IEEE, 2014, pp. 19–24.

[22] S. Pellegrinelli, F. L. Moro, N. Pedrocchi, L. Molinari Tosatti, T. Tolio, A probabilistic approach to workspace sharing for human–robot cooperation

in assembly tasks, CIRP Annals - Manufacturing Technology 65 (1) (2016) 57–60.

[23] S. Pellegrinelli, A. Orlandini, N. Pedrocchi, A. Umbirco, T. Tolio, Motion planning and scheduling for human and industrial-robot collaboration, CIRP Annals - Manufacturing Technology (in press).

[24] S. Keller, R. Hausmann, L. Kressner, A. Koenig, An approach of a computerized planning assistant to the system design of collaborative robot installations, in: IEEE 21st Int. Conf. Emerging Technologies and Factory Automation (ETFA), IEEE, 2016, pp. 1–4.

[25] F. Pini, F. Leali, M. Ansaloni, A systematic approach to the engineering design of a HRC workcell for bio-medical product assembly, in: IEEE 20th Int. Conf. Emerging Technologies and Factory Automation (ETFA), IEEE, 2015.

[26] M. A. Goodrich, A. C. Schultz, Human-robot interaction: a survey, Foundations and trends in human-computer interaction 1 (3) (2007) 203–275.

[27] A. Bauer, D. Wollherr, M. Buss, Human-robot collaboration: a survey, Int. J. Humanoid Robotics 5 (01) (2008) 47–66.

[28] C. Heyer, Human-robot interaction and future industrial robotics applications, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2010, pp. 4749–4754.

[29] H. A. Yanco, J. Drury, Classifying human-robot interaction: an updated taxonomy, in: IEEE Int. Conf. Systems, Man and Cybernetics (SMC), Vol. 3, IEEE, 2004, pp. 2841–2846.

[30] A. De Luca, F. Flacco, Integrated control for pHRI: Collision avoidance, detection, reaction and collaboration, in: IEEE RAS & EMBS Int. Conf. Biomedical Robotics and Biomechatronics (BioRob), IEEE, 2012, pp. 288–295.

[31] B. Vanderborght, A. Albu-Schäffer, A. Bicchi, E. Burdet, D. G. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh, et al., Variable impedance actuators: A review, Robotics and autonomous systems 61 (12) (2013) 1601–1614.

[32] G. Hirzinger, A. Albu-Schaffer, M. Hahnle, I. Schaefer, N. Sporer, On a new generation of torque controlled light-weight robots, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 4, IEEE, 2001, pp. 3356–3363.

[33] M. Zinn, B. Roth, O. Khatib, J. K. Salisbury, A new actuation approach for human friendly robot design, The Int. J. Robotics Research 23 (4-5) (2004) 379–398.

[34] A. Bicchi, G. Tonietti, Fast and "soft-arm" tactics, IEEE Robotics & Automation Magazine 11 (2) (2004) 22–33.

[35] M. Geravand, F. Flacco, A. De Luca, Human-robot physical interaction and collaboration using an industrial robot with a closed control architecture, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2013, pp. 4000–4007.

[36] A. De Santis, B. Siciliano, A. De Luca, A. Bicchi, An atlas of physical human–robot interaction, Mechanism and Machine Theory 43 (3) (2008) 253–270.

[37] C. Harper, G. Virk, Towards the development of international safety standards for human robot interaction, Int. J. Social Robotics 2 (3) (2010) 229–234.

[38] J. A. Marvel, R. Norcross, Implementing speed and separation monitoring in collaborative robot workcells, Robotics and Computer-Integrated Manufacturing 44 (2017) 144–155.

[39] J. Fryman, B. Matthias, Safety of industrial robots: From conventional to collaborative applications, in: 7th German Conf. Robotics (ROBOTIK), VDE, 2012, pp. 1–5.

[40] ISO 10218-1:2011 - Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots, ISO, 2011.

[41] ISO 10218-2:2011 - Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration, ISO, 2011.

[42] A. Vysocky, P. Novak, Human-robot collaboration in industry, Modern Machinery Science J. (2016) 903–906.

[43] IEC 60204-1:2016 Safety of machinery - Electrical equipment of machines - Part 1: General requirements, IEC, 2016.

[44] S. Kock, J. Bredahl, P. J. Eriksson, M. Myhr, K. Behnisch, Taming the robot, ABB Review (4) (2006) 11–14.

[45] ABB - safemove2 data sheet. URL `https://library.e.abb.com/public/f049eac4c4cb431a9bb22f0a5d97433a/safemove2_9AKK106713A6908.pdf`

[46] Y. Ogura, M. Fujii, K. Nishijima, H. Murakami, M. Sonehara, Applicability of hand-guided robot for assembly-line work, J. Robotics and Mechatronics 24 (2012) 547–552.

[47] M. Fujii, H. Murakami, M. Sonehara, Study on application of a human-robot collaborative system using hand-guiding in a production line, IHI Engineering Review 49 (1) (2016) 24–29.

[48] V. Gopinath, K. Johansen, Risk assessment process for collaborative assembly - a job safety analysis approach, in: Procedia CIRP, Vol. 44, 2016, pp. 199–203.

[49] S. Choi, W. Eakins, G. Rossano, T. Fuhlbrigge, Lead-through robot teaching, in: IEEE Conf. Technologies for Practical Robot Applications (TePRA), 2013.

[50] J. A. Marvel, Performance metrics of speed and separation monitoring in shared workspaces, IEEE Trans. Automation Science and Engineering 10 (2) (2013) 405–414.

[51] C. Vogel, C. Walter, N. Elkmann, A projection-based sensor system for safe physical human-robot collaboration, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2013, pp. 5359–5364.

[52] N. Pedrocchi, F. Vicentini, M. Matteo, L. M. Tosatti, Safe human-robot cooperation in an industrial environment, Int. J. Advanced Robotic Systems 10 (1).

[53] F. Vicentini, M. Giussani, L. M. Tosatti, Trajectory-dependent safe distances in human-robot interaction, in: IEEE 19th Int. Conf. Emerging Technologies and Factory Automation (ETFA), IEEE, 2014, pp. 1–4.

[54] P. A. Lasota, G. F. Rossano, J. A. Shah, Toward safe close-proximity human-robot interaction with standard industrial robots, in: IEEE Int. Conf. Automation Science and Engineering (CASE), 2014, pp. 339–344.

[55] C. Lenz, M. Grimm, T. Röder, A. Knoll, Fusing multiple kinects to survey shared human-robot-workspaces, Tech. rep., Technische Universität München (2012).

[56] C. Lenz, A. Knoll, Mechanisms and capabilities for human robot collaboration, in: 23rd IEEE Int. Symp. Robot and Human Interactive Communication, IEEE, 2014, pp. 666–671.

[57] G. Dumonteil, G. Manfredi, M. Devy, A. Confetti, D. Sidobre, Reactive planning on a collaborative robot for industrial applications, in: 12th Int. Conf. Informatics in Control, Automation and Robotics (ICINCO), Vol. 2, 2015, pp. 450–457.

[58] F. Flacco, T. Kroeger, A. De Luca, O. Khatib, A depth space approach for evaluating distance to objects: with application to human-robot collision avoidance, J. Intelligent and Robotic Systems 80 (2015) 7–22.

[59] T. Salmi, I. Marstio, T. Malm, J. Montonen, Advanced safety solutions for human-robot-cooperation, in: 47th Int. Symp. Robotics (ISR), VDE, 2016, pp. 1–6.

[60] S. Haddadin, Physical safety in robotics, in: Formal Modeling and Verification of Cyber-Physical Systems, Springer, 2015, pp. 249–271.

[61] J. Zhang, Y. Wang, R. Xiong, Industrial robot programming by demonstration, in: Int. Conf. Advanced Robotics and Mechatronics (ICARM), IEEE, 2016, pp. 300–305.

[62] B. Navarro, A. Cherubini, A. Fonte, R. Passama, G. Poisson, P. Fraisse, An ISO10218-compliant adaptive damping controller for safe physical human-robot interaction, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2016, pp. 3043–3048.

[63] L. Rozo, S. Calinon, D. G. Caldwell, P. Jiménez, C. Torras, Learning physical collaborative robot behaviors from human demonstrations, IEEE Trans. Robotics 32 (3) (2016) 513–527.

[64] E. Berger, D. Vogt, S. Grehl, B. Jung, H. B. Amor, Estimating perturbations from experience using neural networks and information transfer, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2016, pp. 176–181.

[65] E. Magrini, A. De Luca, Hybrid force/velocity control for physical human-robot collaboration tasks, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2016, pp. 857–863.

[66] B. Matthias, T. Reisinger, Example application of ISO/TS 15066 to a collaborative assembly scenario, in: 47th Int. Symp. Robotics (ISR), VDE, 2016, pp. 1–5.

[67] A. Khalid, P. Kirisci, Z. Ghrairi, K.-D. Thoben, J. Pannek, A methodology to develop collaborative robotic cyber physical systems for production environments, Logistics Research (2016) 9–23.

[68] H. Bo, D. M. Mohan, M. Azhar, Human-robot collaboration for tooling path guidance, in: IEEE RAS & EMBS Int. Conf. on Biomedical Robotics and Biomechatronics (BioRob), 2016, pp. 1340–1345.

[69] R. Bogue, Europe continues to lead the way in the collaborative robot business, Industrial Robot: An Int. J. 43 (1) (2016) 6–11.

[70] J. Teiwes, T. Bänziger, A. Kunz, K. Wegener, Identifying the potential of human-robot collaboration in automotive assembly lines using a standardised work description, in: 22nd Int. Conf. Automation and Computing (ICAC), 2016, pp. 78–83.

[71] Cobotsguide web site.
URL `http://cobotsguide.com`

[72] ISO/TS 15066:2016 - Robots and robotic devices - Collaborative robots, ISO, 2016.

[73] M. Bélanger-Barrette, ISO/TS 15066 and collaborative robot safety, In-Tech Magazine.
URL `https://www.isa.org/intech/20160803/`

[74] B. Matthias, S. Oberer-Treitz, Ding, Experimental characterization of collaborative robot collisions, in: 45th Int. Symp. Robotics (ISR), VDE, 2014, pp. 778–783.

[75] P. Bobka, T. Germann, J. K. Heyn, R. Gerbers, F. Dietrich, K. Dröder, Simulation platform to investigate safe operation of human-robot collaboration systems, Procedia CIRP 44 (2016) 187–192.

[76] T. Arai, R. Kato, M. Fujita, Assessment of operator stress induced by robot collaboration in assembly, CIRP Annals-Manufacturing Technology 59 (1) (2010) 5–8.

[77] C. Braezal, K. Dautenhahn, T. Kanda, Social robotics, in: B. Siciliano, O. Khatib (Eds.), Springer Handbook of Robotics, 2nd Edition, Springer, 2016, Ch. 72, pp. 1935–1971.

[78] S. Stork, C. Stobel, H. Muller, M. Wiesbeck, M. Zah, A. Schubo, A neuroergonomic approach for the investigation of cognitive processes in interactive assembly environments, in: 16th IEEE Int. Symp. Robot and Human Interactive Communication (RO-MAN), IEEE, 2007, pp. 750–755.

[79] R. Kirby, J. Forlizzi, R. Simmons, Affective social robots, Robotics and Autonomous Systems 58 (3) (2010) 322–332.

[80] D. Kulic, E. A. Croft, Affective state estimation for human–robot interaction, IEEE Trans. Robotics 23 (5) (2007) 991–1000.

[81] L. Sabattini, V. Villani, J. N. Czerniak, A. Mertens, C. Fantuzzi, Methodological approach for the design of a complex inclusive human-machine system, in: 13th IEEE Conf. Automation Science and Engineering (CASE), IEEE, 2017.

[82] V. Villani, L. Sabattini, J. N. Czerniak, A. Mertens, C. Fantuzzi, MATE robots simplifying my work: benefits and socio-ethical implications, IEEE Robot. Automat. Mag. (2018) .

[83] C. Talignani Landi, V. Villani, F. Ferraguti, L. Sabattini, C. Secchi, C. Fantuzzi, Relieving operators' workload: Towards affective robotics in industrial scenarios, Mechatronics this issue.

[84] P. A. Hancock, D. R. Billings, K. E. Schaefer, J. Y. Chen, E. J. De Visser, R. Parasuraman, A meta-analysis of factors affecting trust in human-robot interaction, Human Factors 53 (5) (2011) 517–527.

[85] B. Keyes, M. Micire, J. L. Drury, H. A. Yanco, Improving human-robot interaction through interface evolution, in: Human-robot interaction, In-Tech, 2010.

[86] O. Ogorodnikova, Human weaknesses and strengths in collaboration with robots, Periodica Polytechnica. Engineering. Mechanical Engineering 52 (1) (2008) 25.

[87] F. Nachreiner, P. Nickel, I. Meyer, Human factors in process control systems: The design of human–machine interfaces, Safety Science 44 (1) (2006) 5–26.

[88] J. Nielsen, Usability engineering, Morgan Kaufmann Publishers, 1993.

[89] D. A. Norman, The design of everyday things: Revised and expanded edition, Basic books, 2013.

[90] B. Shneiderman, Designing the user interface: strategies for effective human-computer interaction, Pearson Education India, 2010.

[91] Building an hmi that works: New best practices for operator interface design, Tech. rep., Opto 22 (2014).

[92] OSHA technical manual, industrial robots and robot system safety (Section IV, Chapter 4), 2017, Occupational Safety and Health Administration (OSHA), U.S. Department of Labor Occupational Safety & Health Amdinistration, NW, Washington, DC.

[93] R. J. Jacob, A. Girouard, L. M. Hirshfield, M. S. Horn, O. Shaer, E. T. Solovey, J. Zigelbaum, Reality-based interaction: A framework for post-WIMP interfaces, in: SIGCHI Conf. Human Factors in Computing Syst. (CHI), ACM Press, 2008, pp. 201–210.

[94] G. M. Bandeira, M. Carmo, B. Ximenes, J. Kelner, Using Gesture-Based Interfaces to Control Robots, Vol. 9170 of Lecture Notes in Computer Science, Springer International Publishing, 2015, Ch. Human-Computer Interaction: Interaction Technologies, pp. 3–12.

[95] E. Hornecker, J. Buur, Getting a grip on tangible interaction: A framework on physical space and social interaction, in: A. Press (Ed.), SIGCHI Conf. Human Factors in Computing Systems (CHI), 2006, pp. 437–446.

[96] S. Gray, J. Wilson, C. Syan, Human control of robot motion: orientation, perception and compatibility, in: Human-Robot Interaction, Taylor & Francis, London, 1992, pp. 48–64.

[97] H. Brantmark, A. Lindquist, U.-G. Norefors, Man/machine communication in asea's new robot controller, Asea J. 55 (6) (1982) 145–150.

[98] E. C. Morley, C. S. Syan, Teach pendants: how are they for you?, Industrial Robot: An Int. J. 22 (4) (1995) 18–22.

[99] T. Dietz, U. Schneider, M. Barho, S. Oberer-Treitz, M. Drust, R. Hollmann, M. Hägele, Programming system for efficient use of industrial robots for deburring in SME environments, in: 7th German Conf. Robotics (ROBOTIK), VDE, 2012, pp. 1–6.

[100] B. Hein, M. Hensel, H. Worn, Intuitive and model-based on-line programming of industrial robots: A modular on-line programming environment, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2008, pp. 3952–3957.

[101] L. Qi, D. Zhang, J. Zhang, J. Li, A lead-through robot programming approach using a 6-dof wire-based motion tracking device, in: IEEE Int. Conf. Robotics and Biomimetics (ROBIO), IEEE, 2009, pp. 1773–1777.

[102] N. Pires, T. Godinho, K. Nilsson, M. Haage, C. Meyer, Programming industrial robots using advanced input-output devices: test-case example using a CAD package and a digital pen based on the anoto technology, Int. J. Online Engineering 3 (3).

[103] B. Hein, H. Wörn, Intuitive and model-based on-line programming of industrial robots: New input devices, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2009, pp. 3064–3069.

[104] P. Neto, N. Mendes, Direct off-line robot programming via a common CAD package, Robotics and Autonomous Systems 61 (8) (2013) 896–910.

[105] X. Zha, H. Du, Generation and simulation of robot trajectories in a virtual CAD-based off-line programming environment, The Int. J. Advanced Manufacturing Technology 17 (8) (2001) 610–624.

[106] L. Beyer, J. Wulfsberg, Practical robot calibration with ROSY, Robotica 22 (05) (2004) 505–512.

[107] A. Nubiola, I. A. Bonev, Absolute calibration of an ABB IRB 1600 robot using a laser tracker, Robotics and Computer-Integrated Manufacturing 29 (1) (2013) 236–245.

[108] F. Leali, M. Pellicciari, F. Pini, A. Vergnano, G. Berselli, A calibration method for the integrated design of finishing robotic workcells in the aerospace industry, in: Communications in Computer and Information Science, Vol. 371, 2013, pp. 37–48.

[109] M. J. Hwang, S. Y. Chung, K. Lee, I. J. Song, H. I. Son, Registration between robot and workpiece in virtual environment for off-line programming, in: 42nd Annu. Conf. IEEE Industrial Electronics Society (IECON), IEEE, 2016, pp. 779–784.

[110] G. Ferretti, G. Magnani, P. Rocco, Assigning virtual tool dynamics to an industrial robot through an admittance controller, in: IEEE Int. Conf. Advanced Robotics (ICAR), IEEE, 2009, pp. 1–6.

[111] M. H. Choi, W. W. Lee, A force/moment sensor for intuitive robot teaching application, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 4, IEEE, 2001, pp. 4011–4016.

[112] R. D. Schraft, C. Meyer, The need for an intuitive teaching method for small and medium enterprises, in: ISR Robotik, 2006.

[113] N. Hogan, Impedance control: An approach to manipulation: Part II – Implementation, J. Dynamic Systems, Measurement, and Control 107 (1) (1985) 8–16.

[114] O. M. Al-Jarrah, Y. F. Zheng, Arm-manipulator coordination for load sharing using compliant control, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 2, IEEE, 1996, pp. 1000–1005.

[115] O. M. Al-Jarrah, Y. F. Zheng, Arm-manipulator coordination for load sharing using reflexive motion control, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 3, IEEE, 1997, pp. 2326–2331.

[116] O. M. Al-Jarrah, Y. F. Zheng, Arm-manipulator coordination for load sharing using variable compliance control, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 1, IEEE, 1997, pp. 895–900.

[117] D. Massa, M. Callegari, C. Cristalli, Manual guidance for industrial robot programming, Industrial Robot: An Int. J. 42 (5) (2015) 457–465.

[118] C. Talignani Landi, F. Ferraguti, L. Sabattini, C. Secchi, C. Fantuzzi, Admittance control parameter adaptation for physical human-robot interaction, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2017.

[119] C. Talignani Landi, F. Ferraguti, L. Sabattini, C. Secchi, C. Bonfé, Marcello Fantuzzi, Variable admittance control preventing undesired oscillating behaviors in physical human-robot interaction, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2017.

[120] B. Siciliano, L. Villani, Robot force control, Vol. 540, Springer Science & Business Media, 2012.

[121] F. Ferraguti, C. Talignani Landi, C. Secchi, M. Nolli, M. Pesamosca, C. Fantuzzi, Walk-through programming for industrial applications, in: 27th Int. Conf. Flexible Automation and Intelligent Manufacturing (FAIM), 2017.

[122] M. H. Ang Jr, W. Lin, S.-Y. Lim, A walk-through programmed robot for welding in shipyards, Industrial Robot: An Int. J. 26 (5) (1999) 377–388.

[123] M. H. Ang, L. Wei, L. S. Yong, An industrial application of control of dynamic behavior of robots-a walk-through programmed welding robot, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 3, IEEE, 2000, pp. 2352–2357.

[124] K. Kosuge, Y. Fujisawa, T. Fukuda, Control of robot directly maneuvered by operator, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), Vol. 1, IEEE, 1993, pp. 49–54.

[125] K. Kosuge, N. Kazamura, Control of a robot handling an object in cooperation with a human, in: 6th IEEE Int. Workshop Robot and Human Communication (RO-MAN), IEEE, 1997, pp. 142–147.

[126] F. Aghili, M. Namvar, Scaling inertia properties of a manipulator payload for 0-g emulation of spacecraft, The Int. J. Robotics Research 28 (7) (2009) 883–894.

[127] R. Ikeura, H. Inooka, Variable impedance control of a robot for cooperation with a human, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 3, IEEE, 1995, pp. 3097–3102.

[128] K. P. Tee, R. Yan, H. Li, Adaptive admittance control of a robot manipulator under task space constraint, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2010, pp. 5181–5186.

[129] P. Marayong, G. D. Hager, A. M. Okamura, Control methods for guidance virtual fixtures in compliant human-machine interfaces, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2008, pp. 1166–1172.

[130] A. De Luca, A. Albu-Schaffer, S. Haddadin, G. Hirzinger, Collision detection and safe reaction with the DLR-III lightweight manipulator arm, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2006, pp. 1623–1630.

[131] Z. Chen, P. Kazanzides, Force control of a non-backdrivable robot without a force sensor, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2013, pp. 3570–3575.

[132] M. Lopez Infante, V. Kyrki, Usability of force-based controllers in physical human-robot interaction, in: 6th Int. Conf. Human-Robot Interaction (HRI), ACM, 2011, pp. 355–362.

[133] R. Zoliner, M. Pardowitz, S. Knoop, R. Dillmann, Towards cognitive robots: Building hierarchical task representations of manipulations from human demonstration, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2005, pp. 1535–1540.

[134] T. Abbas, B. A. MacDonald, Generalizing topological task graphs from multiple symbolic demonstrations in programming by demonstration (PbD) processes, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2011, pp. 3816–3821.

[135] A. J. Ijspeert, J. Nakanishi, S. Schaal, Movement imitation with nonlinear dynamical systems in humanoid robots, in: IEEE Int. Conf. Robotics and Automation (ICRA), Vol. 2, IEEE, 2002, pp. 1398–1403.

[136] S. Calinon, F. Guenter, A. Billard, On learning, representing, and generalizing a task in a humanoid robot, IEEE Trans. Systems, Man, and Cybernetics, Part B (Cybernetics) 37 (2) (2007) 286–298.

[137] N. J. Pires, G. Veiga, R. Araújo, Programming-by-demonstration in the coworker scenario for SMEs, Industrial Robot: An Int. J. 36 (1) (2009) 73–83.

[138] F. J. Abu-Dakka, B. Nemec, A. Kramberger, A. G. Buch, N. Krüger, A. Ude, Solving peg-in-hole tasks by human demonstration and exception strategies, Industrial Robot: An Int. J. 41 (6) (2014) 575–584.

[139] B. D. Argall, S. Chernova, M. Veloso, B. Browning, A survey of robot learning from demonstration, Robotics and autonomous systems 57 (5) (2009) 469–483.

[140] D. Aarno, D. Kragic, Motion intention recognition in robot assisted applications, Robotics and Autonomous Systems 56 (8) (2008) 692–705.

[141] J. Saunders, C. L. Nehaniv, K. Dautenhahn, Teaching robots by moulding behavior and scaffolding the environment, in: ACM SIGCHI/SIGART Conf. Human-Robot Interaction (HRI), ACM, 2006, pp. 118–125.

[142] M. Pardowitz, R. Zollner, S. Knoop, R. Dillmann, Using physical demonstrations, background knowledge and vocal comments for task learning, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2006, pp. 322–327.

[143] A. Ude, A. Gams, T. Asfour, J. Morimoto, Task-specific generalization of discrete and periodic dynamic movement primitives, IEEE Trans. Robotics 26 (5) (2010) 800–815.

[144] G. Maeda, M. Ewerton, G. Neumann, R. Lioutikov, J. Peters, Phase estimation for fast action recognition and trajectory generation in human–robot collaboration, The Int. J. Robotics Research.

[145] R. Hollmann, A. Rost, M. Hägele, A. Verl, A HMM-based approach to learning probability models of programming strategies for industrial robots, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2010, pp. 2965–2970.

[146] P. Neto, J. Norberto Pires, A. Paulo Moreira, High-level programming and control for industrial robotics: using a hand-held accelerometer-based input device for gesture and posture recognition, Industrial Robot: An Int. J. 37 (2) (2010) 137–147.

[147] V. Villani, L. Sabattini, G. Riggio, C. Secchi, M. Minelli, C. Fantuzzi, A natural infrastructure-less human–robot interaction system, IEEE Robotics and Automation Letters 2 (3) (2017) 1640–1647.

[148] S. van Delden, M. Umrysh, C. Rosario, G. Hess, Pick-and-place application development using voice and visual commands, Industrial Robot: An Int. J. 39 (6) (2012) 592–600.

[149] J. Lambrecht, M. Kleinsorge, M. Rosenstrauch, J. Krüger, Spatial programming for industrial robots through task demonstration, Int. J. Advanced Robotic Systems 10 (5) (2013) 254.

[150] B. Solvang, G. Sziebig, P. Korondi, Robot programming in machining operations, INTECH Open Access Publisher, 2008.

[151] H. Zhang, H. Chen, N. Xi, G. Zhang, J. He, On-line path generation for robotic deburring of cast aluminum wheels, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2006, pp. 2400–2405.

[152] V. Lippiello, B. Siciliano, L. Villani, Robot interaction control using force and vision, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2006, pp. 1470–1475.

[153] J. Baeten, J. De Schutter, Hybrid vision/force control at corners in planar robotic-contour following, IEEE/ASME Trans. Mechatronics 7 (2) (2002) 143–151.

[154] D. Xiao, B. K. Ghosh, N. Xi, T. J. Tarn, Sensor-based hybrid position/force control of a robot manipulator in an uncalibrated environment, IEEE Trans. Control Systems Technology 8 (4) (2000) 635–645.

[155] I. Bonilla, M. Mendoza, E. J. Gonzalez-Galvan, C. Chavez-Olivares, A. Loredo-Flores, F. Reyes, Path-tracking maneuvers with industrial robot manipulators using uncalibrated vision and impedance control, IEEE Tran. Systems, Man, and Cybernetics, Part C (Applications and Reviews) 42 (6) (2012) 1716–1729.

[156] Z. Hu, C. Marshall, R. Bicker, P. Taylor, Automatic surface roughing with 3D machine vision and cooperative robot control, Robotics and Autonomous Systems 55 (7) (2007) 552–560.

[157] G. Du, P. Zhang, A markerless human–robot interface using particle filter and Kalman filter for dual robots, IEEE Trans. Industrial Electronics 62 (4) (2015) 2257–2264.

[158] B. Takarics, P. T. Szemes, G. Nemeth, P. Korondi, Welding trajectory reconstruction based on the intelligent space concept, in: IEEE Conf. Human System Interactions (HSI), IEEE, 2008, pp. 791–796.

[159] O. Madsen, J. Pires, T. Godinho, R. Araújo, Using digital pens to program welding tasks, Industrial Robot: An Int. J. 34 (6) (2007) 476–486.

[160] T. Ende, S. Haddadin, S. Parusel, T. Wüsthoff, M. Hassenzahl, A. Albu-Schäffer, A human-centered approach to robot gesture based communication within collaborative working processes, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), IEEE, 2011, pp. 3367–3374.

[161] A. Rogowski, Industrially oriented voice control system, Robotics and Computer-Integrated Manufacturing 28 (3) (2012) 303–315.

[162] J. N. Pires, Robot-by-voice: Experiments on commanding an industrial robot using the human voice, Industrial Robot: An Int. J. 32 (6) (2005) 505–511.

[163] G. Veiga, J. Pires, K. Nilsson, Experiments with service-oriented architectures for industrial robotic cells programming, Robotics and Computer-Integrated Manufacturing 25 (4) (2009) 746–755.

[164] A. Rogowski, Web-based remote voice control of robotized cells, Robotics and Computer-Integrated Manufacturing 29 (4) (2013) 77–89.

[165] K. Y. Chan, C. K. Yiu, T. S. Dillon, S. Nordholm, S. H. Ling, Enhancement of speech recognitions for control automation using an intelligent

particle swarm optimization, IEEE Trans. Industrial Informatics 8 (4) (2012) 869–879.

[166] P. Milgram, H. Takemura, A. Utsumi, F. Kishino, Augmented reality: A class of displays on the reality-virtuality continuum, in: Photonics for industrial applications, International Society for Optics and Photonics, 1995, pp. 282–292.

[167] G. Michalos, P. Karagiannis, S. Makris, Ö. Tokçalar, G. Chryssolouris, Augmented reality (AR) applications for supporting human-robot interactive cooperation, Procedia CIRP 41 (2016) 370–375.

[168] D. van Krevelen, R. Poelman, A survey of augmented reality technologies, applications and limitation, Int. J. Virtual Reality 9 (2) (2010) 1–20.

[169] E. Sharlin, B. Watson, Y. Kitamura, F. Kishino, Y. Itoh, On tangible user interfaces, humans and spatality, Personal and Ubiquitous Computing 8 (5) (2004) 338–346.

[170] A. Y. Nee, S. Ong, G. Chryssolouris, D. Mourtzis, Augmented reality applications in design and manufacturing, CIRP Annals - Manufacturing Technology 61 (2) (2012) 657–679.

[171] A. G. De Sa, G. Zachmann, Virtual reality as a tool for verification of assembly and maintenance processes, Computers & Graphics 23 (3) (1999) 389–403.

[172] S. Ong, Y. Pang, A. Nee, Augmented reality aided assembly design and planning, CIRP Annals-Manufacturing Technology 56 (1) (2007) 49–52.

[173] A. Seth, J. M. Vance, J. H. Oliver, Virtual reality for assembly methods prototyping: a review, Virtual reality 15 (1) (2011) 5–20.

[174] M. Yuan, S. Ong, A. Y. Nee, Assembly guidance in augmented reality environments using a virtual interactive tool, Innovation in Manufacturing Systems and Technology.

[175] G. Chryssolouris, D. Mavrikios, D. Fragos, V. Karabatsou, K. Alexopoulos, A hybrid approach to the verification and analysis of assembly and maintenance processes using virtual reality and digital mannequin technologies, in: Virtual and augmented reality applications in manufacturing, Springer, 2004, pp. 97–110.

[176] D. Mavrikios, V. Karabatsou, M. Pappas, K. Alexopoulos, G. Chryssolouris, An integrated VR-based simulation environment for the assessment of process and human factors in assembly, in: 1st CIRP Int. Seminar on Assembly Systems, 2006, pp. 301–305.

[177] C. Pontonnier, A. Samani, M. Badawi, P. Madeleine, G. Dumont, Assessing the ability of a VR-based assembly task simulation to evaluate physical risk factors, IEEE Trans. Visualization and Computer Graphics 20 (5) (2014) 664–674.

[178] M. Pappas, V. Karabatsou, D. Mavrikios, G. Chryssolouris, Ergonomic evaluation of virtual assembly tasks, in: Digital enterprise technology, Springer, 2007, pp. 511–518.

[179] S.-K. Ong, J. Chong, A. Y. Nee, Methodologies for immersive robot programming in an augmented reality environment, in: 4th Int. Conf. Computer Graphics and Interactive Techniques (SIGGRAPH), ACM, 2006, pp. 237–244.

[180] J. W. S. Chong, S. Ong, A. Y. Nee, K. Youcef-Youmi, Robot programming using augmented reality: An interactive method for planning collision-free paths, Robotics and Computer-Integrated Manufacturing 25 (3) (2009) 689–701.

[181] J. Aleotti, S. Caselli, M. Reggiani, Leveraging on a virtual environment for robot programming by demonstration, Robotics and Autonomous Systems 47 (2) (2004) 153–161.

[182] K. Lay, E. Prassler, R. Dillmann, G. Grunwald, M. Hägele, G. Lawitzky, A. Stopp, W. Von Seelen, MORPHA: Communication and interaction with intelligent, anthropomorphic robot assistants, in: Int. Status Conf. Lead Projects "Human-Computer-Interaction", 2001, pp. 67–77.

[183] R. Bischoff, A. Kazi, Perspectives on augmented reality based human-robot interaction with industrial robots, in: IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), Vol. 4, IEEE, 2004, pp. 3226–3231.

[184] S. M. Abbas, S. Hassan, J. Yun, Augmented reality based teaching pendant for industrial robot, in: 12th Int. Conf. Control, Automation and Systems (ICCAS), IEEE, 2012, pp. 2210–2213.

[185] C. Mateo, A. Brunete, E. Gambao, M. Hernando, Hammer: An Android based application for end-user industrial robot programming, in: IEEE/ASME 10th Int. Conf. Mechatronic and Embedded Systems and Applications (MESA), IEEE, 2014, pp. 1–6.

[186] S. Stadler, K. Kain, M. Giuliani, N. Mirnig, G. Stollnberger, M. Tscheligi, Augmented reality for industrial robot programmers: Workload analysis for task-based, augmented reality-supported robot control, in: 25th IEEE Int. Symp. Robot and Human Interactive Communication (RO-MAN), IEEE, 2016, pp. 179–184.

[187] B. Akan, A. Ameri, B. Cürüklü, L. Asplund, Intuitive industrial robot programming through incremental multimodal language and augmented reality, in: IEEE Int. Conf. Robotics and Automation (ICRA), IEEE, 2011, pp. 3934–3939.

[188] A. Wilbert, B. Behrens, O. Dambon, F. Klocke, Robot assisted manufacturing system for high gloss finishing of steel molds, in: Springer (Ed.), Intelligent Robotics and Applications. ICIRA 2012. Lecture Notes in Computer Science, Vol. 7506, Springer, 2012, pp. 673–685.

[189] SYMPLEXITY EU project.
URL http://www.symplexity.eu/

[190] S. Chen, T. Qiu, T. Lin, L. Wu, J. Tian, W. Lv, Y. Zhang, Robotic Welding, Intelligence and Automation. Lecture Notes in Control and Information Science, Vol. 299, Springer, 2004, Ch. Intelligent technologies for robotic welding, pp. 123–143.

[191] P. Tsarouchi, A.-S. Matthaiakis, S. Makris, G. Chryssolouris, On a human-robot collaboration in an assembly cell, Int. J. Computer Integrated Manufacturing 30 (6) (2017) 580–589.

[192] S. Grahn, B. Langbeck, K. Johansen, B. Backman, Potential advantages using large anthropomorphic robots in human-robot collaborative, hand guided assembly, Procedia CIRP 44 (2016) 281–286.

[193] V. V. Unhelkar, J. A. Shah, Challenges in developing a collaborative robotic assistant for automotive assembly lines, in: 10th Annu. ACM/IEEE Int. Conf. Human-Robot Interaction (HRI), ACM, 2015, pp. 239–240.

[194] G. Michalos, S. Makris, N. Papakostas, D. Mourtzis, G. Chryssolouris, Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach, CIRP J. Manufacturing Science and Technology 2 (2) (2010) 81–91.

[195] Innovative human-robot cooperation in BMW group production.
URL https://www.press.bmwgroup.com/global/article/detail/T0209722EN/innovative-human-robot-cooperation-in-bmw-group-production?language=en

[196] New human-robot cooperation in Audi production processes (feb. 2015).
URL https://www.audiusa.com/newsroom/news/press-releases/2015/02/new-human-robot-cooperation-in-audis-production-processes

[197] Ford shows how humans and robots work hand-in-hand on its assembly line (Jul. 2016).
URL https://techcrunch.com/2016/07/14/ford-shows-how-humans-and-robots-work-hand-in-hand-on-its-assembly-line/?ncid=rss&utm_source=feedburner&utm_medium=feed&utm_campaign=sfgplus&sr_share=googleplus&%3Fncid=sfgplus

[198] First robot collaborates directly with employees at Volkswagen plant.
URL http://www.businesswire.com/news/home/20130829005825/en/Robot-Collaborates-EmployeesVolkswagen-Plant

[199] Intelligent assistants: New cooperating robot facilitates production of direct shift transmissions at vrchlabí (Dec. 2015).
URL https://media.skoda-auto.com/en/_layouts/Skoda.PRPortal/pressrelease.aspx?ID=953

[200] E. Gambao, M. Hernando, D. Surdilovic, A new generation of collaborative robots for material handling, Gerontechnology 11 (2) (2012) 368.

[201] S. Kock, T. Vittor, B. Matthias, H. Jerregard, M. Källman, I. Lundberg, R. Mellander, M. Hedelind, Robot concept for scalable, flexible assembly automation: A technology study on a harmless dual-armed robot, in: IEEE Int. Symp. Assembly and Manufacturing (ISAM), IEEE, 2011, pp. 1–5.

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

[203] A. Levratti, A. De Vuono, C. Fantuzzi, C. Secchi, TIREBOT: A novel tire workshop assistant robot, in: IEEE Int. Conf. Advanced Intelligent Mechatronics (AIM), 2016, pp. 733–738.

[204] W. Knight, How human-robot teamwork will upend manufacturing (Sep. 2014).

URL https://www.technologyreview.com/s/530696/how-human-robot-teamwork-will-upend-manufacturing/