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SURVEY PAPER

Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017

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ABSTRACT

Currently, a large number of industrial robots have been deployed to replace or assist humans to perform various repetitive and dangerous manufacturing tasks. However, based on current technological capabilities, such robotics field is rapidly evolving so that humans are not only sharing the same workspace with robots, but also are using robots as useful assistants. Consequently, due to this new type of emerging robotic systems, industrial *collaborative robots* or *cobots*, human and robot co-workers have been able to work side-by-side as collaborators to accomplish tasks in industrial environments. Therefore, new human–robot interaction systems have been developed for such systems to be able to utilize the capabilities of both humans and robots. Accordingly, this article presents a literature review of major recent works on human–robot interactions in industrial collaborative robots, conducted during the last decade (between 2008 and 2017). Additionally, the article proposes a tentative classification of the content of these works into several categories and sub-categories. Finally, this paper addresses some challenges of industrial collaborative robotics and explores future research issues.

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1. Introduction

Industrial robots are flexible machines, equipped with various sensors and tools, that can be adapted to a wide variety of production tasks [1,2]. In the last 30 years, such autonomous robots have been a thriving research area with a great progress [3,4]. These robots were seen as substitutes and have been deployed to replace or assist humans in performing various repetitive/hazardous and tedious manufacturing tasks with a high accuracy [5]. They were installed away from humans in physically separated workspaces. However, based on current technological capabilities, such robotics field is rapidly evolving so that humans are not only sharing the same workspaces with robots, but also are considering them as useful collaborators at home and at work [6]. Additionally, there are some tasks that may be too complex to be fully achieved by robots or too expensive to be fully automated. Therefore, a human worker assisting and sharing the execution of such tasks with robots is the most flexible and affordable solution. In this context, the interaction and safety between the human and the robot (*Human–Robot Interaction*) are relevant goals to be reached.

Schmidtler et al. [7] defined the *Human–Robot Interaction* (*HRI*) as '*a general term for all forms of interaction between humans and robots*' [8]. Fang et al. [9] defined HRI as '*the process of conveying human intentions and interpreting task descriptions into a sequence of robot motions complying with robot capabilities and working requirements*'. The interaction can be also defined as a situation where many actors (humans and/or robots) react or communicate with each other [10].

Interaction with industrial robots is traditionally considered as a *Human–Machine Interaction* (*HMI*) because of their lower level of autonomy and complexity [11]. Shared workspace [12], teach by demonstration [13], all these improvements in industrial robotics require different interaction levels and which are identified depending on two principles [9]: (i) autonomy degree of the robotic system, and (ii) proximity of human and robot during operation. As a result, the need for better and more intuitive user interfaces and interactions for industrial robots is increasing [14]. In addition, it must be determined whether contact between the entities is desirable or if it has to be avoided by all means [15].

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The authors in [7] decomposed these human–robot hybrid systems into several sub-categories depending on the following four criteria [8]:

- *Workspace*: the overlapping space in the working range of human and robot is described as the common workspace,
- *Working time*: it is defined as the time the participant is working inside the workspace,
- *Aim*: every entity of the interacting team has an aim to achieve. This aim can match or mismatch with the other one,
- *Contact*: since human and robot share the same workspace, they may come into contact with each other either [16] (i) occasionally or by accident if normal operation is intended to be without contact, or (ii) on purpose if the operator is supposed to work in contact with the robot, exchanging forces and cooperating in action upon on the environment.

In terms of the previous four criteria, HRI can be classified into three categories as follows:

- *Human–Robot Coexistence* (*HRCx*), also called *coaction*, is defined [17] as the capability of sharing the dynamic workspace between humans and robots without a common task (operate on dissimilar tasks) [18,19] or, without requiring mutual contact or coordination of actions [20] and intentions (human and robot may have different aims) [21]. It is generally limited to collisions avoidance.
- *Human–Robot Cooperation* (*HRCp*) acts on a higher level [22] than *HRCx*. In such a case, humans and robots are working on the same purpose and fulfill the requirements of time and space, simultaneously. The cooperation requires thus advanced technologies such as force-feedback sensing or advanced machine vision [1,17], and far more sensing techniques for collision detection and avoidance.
- *Human–Robot Collaboration* (*HRC*) is the feature of performing a complex task with direct human interaction in two different modalities [21]: (i) *Physical collaboration* where an explicit and intentional contact with forces exchange exists between human and robot [23]. By measuring or estimating these forces/torques [10], the robot can predict human motion intentions and react accordingly [24,25]. (ii) *Contactless collaboration* where no physical interaction exists. In such a case, actions are coordinated from information exchange which can be achieved via *direct communication* (speech, gestures, etc.), or *indirect communication* (intentions recognition, eye gaze direction, facial expressions, etc.) [26,27]. In such scenarios, the operator performs task parts requiring dexterity or decision-making, while the robot realizes parts that are not well suited to direct human involvement (repetitive or high-force applications, chemical deposition, precision placement, etc.) [7,28].

Currently, HRI becomes easier and safer with the emergence of *Collaborative robots*, also known as *Cobots*, that enable safe interaction between the robots and the humans. *Cobots* were introduced firstly as *Intelligent Assist Devices* (*IAD*) to support the human by utilizing power assistance or force amplification [29–32].

It is only since 2008, that this new technology started to come out in the industry with many cobots such as *UR5* of *Universal Robots* [33], *Robonaut* of *NASA* [34], *Baxter* of *Rethink Robotics* [35], and *LBR iiwa* of *Kuka* [36]. After that, most manufacturers have released their own cobots [37]. Table 1 shows examples of deployed collaborative robots in the industry with their main specifications.

In parallel, a large number of scientists from the research community have been interested in aspects related to HRI, which has given rise to a large number of developed systems and publications. In addition, a lot of research and works dealt with industrial collaborative robotics (safety, human gestures and face recognition, fault detection, programming approaches, control architectures, etc.). Thus, a general review of such systems can bring a great benefit to the related research and academic field. Therefore, this article presents a review of the literature of peer-reviewed publications referring to HRI in industrial collaborative robotics realized during the last decade (i.e., 2008–2017).

The organization of this review paper is given as follows. Section 2 gives definitions of *collaborative robots* (*cobots*) and *collaborative robotics* (*cobotics*). Additionally, it provides the search methodology conducted in this article. Section 3 proposes a tentative classification of the content of selected recent works and research on HRI in industrial cobotics. Besides that, for each examined article, this section summarizes the treated problem, describes the proposed approach and gives main results. Section 4 identifies some potential trends and challenges for future research in this area. Section 5 presents discussions on HRI in industrial cobotics. Finally, Section 6 presents the summary and some conclusions.

2. Industrial collaborative robotics

This new type of emerging industrial robotic systems, *industrial cobots*, make human and robot co-workers able to work shoulder-by-shoulder as collaborators to accomplish tasks in industrial environments. Some studies are

Table 1. Examples of deployed collaborative robots in the industry with their main specifications.

Robot	Company, Country	Specifications	Sensors	Applications	Program.	Ref.
Yumi IRB 14000	ABB, Switzerland	Dual-arm body (7-dof each); Action resumption only by human through remote control; Collision-free path	Camera-based object tracking; Collision detection through force sensor	Mobile phone; Electronic and small parts assembly lines	RobotWare	[38–41]
LBR iiwa	Kuka, Germany	Contact detection; Velocity and force reduction on collision; Single arm with 7-axis	Torque sensors; Force sensors	Machine tending; Palletizing; Handling; Fastening; Measuring	Kuka Sunrise API (Java)	[36,42]
Baxter	Rethink Robotics, USA	Dual-arm (7 + 7-dof)	Embedded torque sensors; Integrated camera per arm; Vision-guided movement and object detection; 360 degrees sonar; Front camera	Pick-and-place; CNC machine tending; Metal stamping & Press tending; Plastic Injection & Blow Molding; Packaging; Testing & quality inspection	N/A	[35]
UR3 &5&10	Universal Robots, Denmark	6-dof in single arm; Collision detection; Robot stops upon collision; Speed reduction to 20%	Force sensors; Speed reduction in directly programming	Packaging; Palletizing; Food handling; Pick-and-place parts in optimized production flows	PolyScope	[20,21,33]
Robonaut	NASA, USA	Dual arms with complete hands and fingers; Each arm has 7-dof; Each finger has 3 dof; Elastic joints	Stereo-vision camera; Infrared camera; High-resolution auxiliary cameras; Miniaturized 6-axis load cells; Force sensing in joints	International space station; Space robotics	VxWorks real-time	[34]
APAS	Bosch, Germany	6-dof	Touchless triggering sensor; 3D stereo camera; 2D monochrome camera	Pick-and-place; Assembly; Machine tending; Packaging	N/A	[43]
COMAU dual-arm robot	COMAU, Italy	Dual anthropomorphous arms with 6-dof	Proximity and tactile sensors; Vision system; Force/torque sensor	Handling heavy and complex geometry parts; Handling flexible parts from different materials; Large pick-and-place; Automotive industry	ROS; Card with a communication rate @ 400us	[44,45]
Rob@Work 3	Fraunhofer IPA, Germany	6-dof arm; Omnidirectional mobile base	3D camera; Stereo-camera systems; Laser scanners	All industrial tasks	ROS	[46]
DLR-LWR III	Institute of Robotics and Mechatronics, Germany	7-dof	Joint torque sensors; Redundant position sensing; Wrist force-torque sensor	Assembly; Mobile service robotics applications	Matlab/ Simulink; RealTime Workshop	[47–51]
DLR LWR 4 + &5	Kuka-DLR, Germany	7-dof	Torque sensors	Automate complex; Delicate assembly tasks	Kuka Sunrise (Java)	[49,52,53]

designed to be easy-to-use applications of various robot systems to interact with humans. These applications include an interactive conversation robot (verbal and/or non-verbal cues [24]), which collects multi-modal data and links with human partners [54] (Figure 1).

The main advantages of such a collaboration lies on the combination of the cognitive skills, intelligence, flexibility and ability to act when confronted with unexpected events of the humans [55] and advantages of the robots such as high precision, repeatability and strength (as synthesized in Table 2) [1,56,57]. Thus, industrial cobots leverage the '*strength and endurance of robots*' with the '*flexibility and decision-making of humans*' [58]. (The *availability of a human* is related to both his presence and interruptibility [59]. On the other hand, *flexibility* is the capability of humans to define and perform new tasks).

2.1. Definition of industrial collaborative robots

The definition of *collaborative robots* or *cobots* has evolved into different definitions depending on the application context. It can be defined as a robot that has been

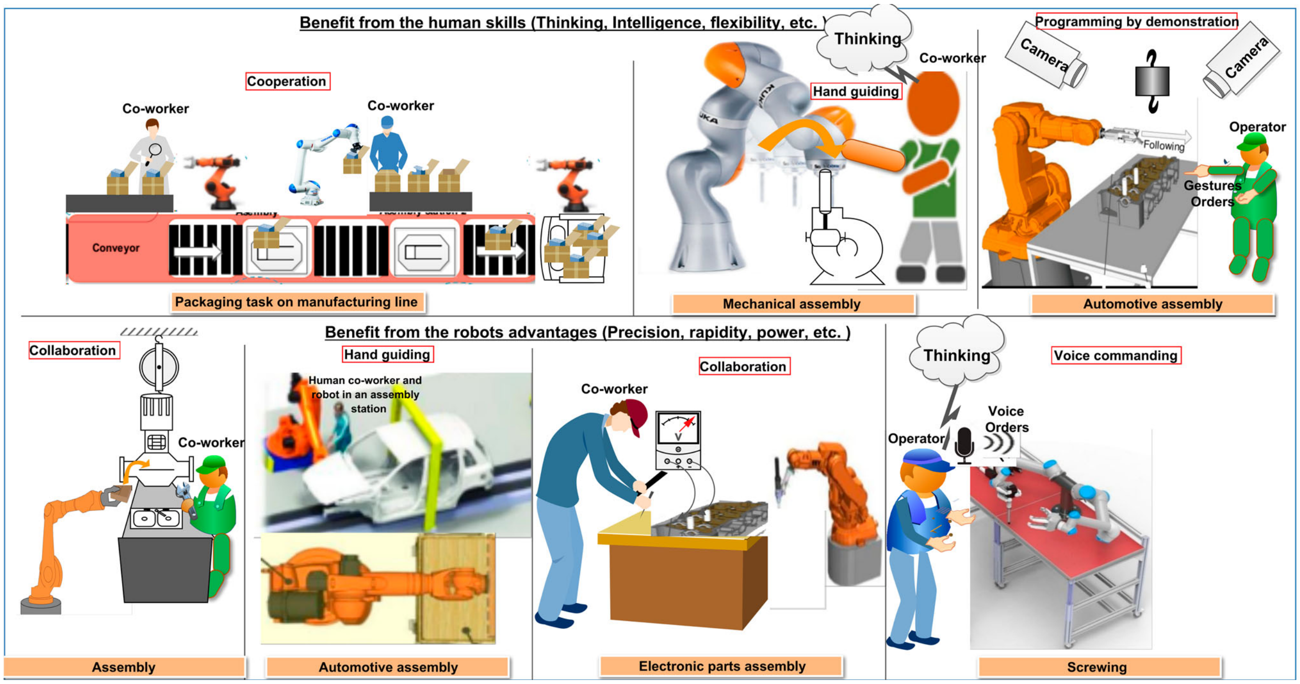

Figure 1. Several examples of human–robot interaction and collaborative human–robot tasks.

Table 2. The skills of humans and advantages of robots [1,56,57].

Skills of humans	Advantages of robots
High availability	Integrated process control
Handling of complex components	Handling heavy, sharp-edged components
Reliable execution of complex joining processes	Exact playback of defined paths
Simple magazine loading of components	Reliable performance of repetitive activities
Provide motive power	Provide guidance through the use of servomotors
Flexible in tasks	

designed and built to collaborate with humans [37,60]. A *cobot* can also be considered as a robot intended to physically interact with humans in a shared workspace [60,61].

On the other hand, *cobotics* is a neologism formed by the two terms *collaborative* and *robotics*. *Cobotics* was used firstly by Edward Colgate and Michael Peshkin [31] to conceptualize the direct interaction between a robot and a human on a dedicated workstation [62,63]. *Cobotics* is defined by the science and techniques of design, construction, study and evaluation of a *cobotic system*. This latter consists of a workstation comprising a robot and a collaborating human [63,64].

An *industrial cobot* is designed for direct actuation with human co-workers in the industry to provide flexible manufacturing environment of future mixture of humans and robots [65] and to assist them during tasks accomplishment (by reducing physical effort and cognitive overload) [66]. Additionally, industrial cobots are used to help the co-workers to lift, move production workloads and track assembly line. They can also support and relieve human operators [67], and place the loads quickly, precisely and safely [68].

This type of systems has been adopted in several industries [69] such as food-processing industry [33], aerospace exploration [34,70], health industry, automotive [71], construction industry [72] and assembly systems [73].

Table 3 synthesizes the characteristics of industrial cobots and compares them with existing industrial traditional robots (synthesized from [1,53,58,60,74,75]):

2.2. Search methodology

The objective of this review article is being to provide enough information to draw a broad picture of the state-of-the-art on HRI in industrial cobotic field without intending to be exhaustive. For this aim, the contents of more than 300 papers that presented solutions dealing with HRI-related problems, were carefully studied and reviewed. In addition, these papers are classified into 39 research categories and sub-categories as shown in Table 4. This table also gives the list and number of respective studied publications in each category/sub-category.

As Table 4 shows, this paper classifies the selected works into the following possible categories ranked from an architectural vantage point, from hardware to functional profiles: '*Hardware and software design*

Table 3. Comparison between *Industrial traditional robots* and *Industrial collaborative robots* [1,53,58,60,74,75].

Industrial traditional robots	Industrial collaborative robots (Light-weight cobots)
Fixed installation	Flexibly relocated (manually or on mobile robots)
Heavy structure; weights around 250 kg for 3 kg payload	Light-weight structure; Weights as little as 11 kg for 3 kg payload
Periodic, repeatable tasks; infrequently changes	Frequent task changes; Tasks infrequently repeated
On-line and off-line programming by a robot specialist	On-line instructed by a process expert and supported by off-line methods
Not easy to teach	Easy to teach
Rarely interaction with the human, only during programming	Frequent interaction with the human, even force/precision assistance
Human and robot separated through perimeter safeguarding	Workspace sharing with human
Hazards prevented by not allowing access	Safe interaction with human
Profitable only with medium to large lot size	Profitable even at small lot size
Cannot reduce cost and footprint to justify new applications	Reduce cost and footprint to justify new applications
Not requested risk assessment	Requested risk assessment
Usually 6-axis with last three intersecting in wrist	Usually 6 and 7-axis with many offsets
No ability to provide support to the human	Provide power support to the human
Do not provide a virtual surface to constrain and guide human motion	Provide a virtual surface to constrain and guide human motion
Cannot adjust their configurations in real-time to fit with the human physique	Automatically adjust their configurations in real-time to best fit with the human physique and fastening task features
Do not provide an artificial force to the human	Provide an artificial force to the human to perform hazardous activities
Not able to reduce the ergonomic risk of strenuous tasks	Reduce the ergonomic risk of strenuous tasks
Setting up takes days or over weeks	Quick set up (less than a day)
Need for a robotic programmer to be hired which might require additional investment	Easy to program without special skills; Anyone who can work on smartphone can use it
Requires large and separate enclosures	Requires less floor space
Small or big and fast	Small, slow and easy to use and easy to move

of cobotic systems', '*Safety in industrial cobotics*', '*Cognitive human–robot interaction*', '*Robot programming approaches*', '*Fault tolerance*', '*Virtual & augmented reality*' and '*Human–robot task allocation*'. The categories/sub-categories describe illustrative research studies performed during the last decade from 2008 to 2017.

Table 5 lists and distributes the publications studied in this review article on the years from 2008 to 2017. It can be seen that the number of publications in the last three years, i.e. 2015–2017, doubled compared with those of the previous years. However, this cannot be considered as an absolute metric of the relative importance. But overall, the distribution of publication years indicates that *HRI in industrial cobotics* has attracted much attention during this period.

3. Human–robot interaction in industrial collaborative applications

This section presents the content of selected recent articles on HRI in industrial cobotics. It also proposes a tentative classification of these works into several categories and sub-categories (Figure 2) since it is clear that a single methodical classification does not exist. Indeed, there are different classification methods to distinguish cobotic systems. In these methods, morphology and role of the operator are important [284].

The proposed classification is based on many keywords: *collaborative robots* combined with *actions recognition*, *gestures and faces recognition*, *pre-collision and post-collision*, *human–robot interfaces*, *human–robot task allocation and planning*, *safety*, etc. For each selected article, the problem, the description of the proposed approach and the main obtained results are summarized.

3.1. Hardware and software design of collaborative robotic systems

As stated by Ferland et al. in [76], the design of industrial cobots is one of, if not, the most challenging problem in this field. Consequently, many attempts of designing such systems have been carried out during these recent years [78]. This can be justified by the fact that most of industrial cobots operate the tasks in complex working conditions and must be able to move efficiently in their crowded environments while facing unexpected events (obstacles, etc.) [77]. For this reason, cobots are generally designed with 7 *degree-of-freedom* (*dof*) to be able to collaboratively carry and manipulate objects (tools, products, etc.), avoid singularity and obstacles, and increase flexibility, dexterity and manipulability [70]. Figure 3 summarizes the different sub-categories of '*hardware and software design of collaborative robotic systems*' as considered in this article.

3.1.1. Design of cobotic systems

An industrial cobotic system may include one/several robot(s) and one/several human(s) collaborating in synergy to accomplish tasks. As indicated in [62], to characterize a cobotic system, it is necessary to pay attention to humans, tasks, robots and system interactions.

Authors in [62] introduced a method of designing cobotic systems based on several stages with increasing complexity: activity analysis, basic design, detailed design

Table 4. Possible research categories/sub-categories and number of the studied publications from 2008 to 2017.

Research categories	Research sub-categories	Studied references: References	Nb. pub.
Hardware and software design of cobotic systems		[70,76–78]	**04**
	Design of cobotic system	[62,79,80]	03
	Software architectures for cobotic systems	[21,23,72,81–88]	11
	Cloud-based robotics and fog-based robotics	[40,89–93]	06
	Low-control of industrial robots	[49,52,55,94–98]	08
Safety in industrial cobotics		[32,70,99–104]	**08**
	Design of intrinsically safe cobots	[16,61,68,70,97,100,105–116]	21
	Pre-collision approaches	[15,18,117–120]	06
	Reactive control strategies	[52,117,119,121–123]	06
	Proprioceptive sensor-based strategies	[124–129]	06
	Exteroceptive sensor-based control	[68,103,130–132]	05
	Post-collision approaches	[48,50,51,96,107,110,133–140]	14
	Cyber-physical-based safety approaches	[100,141–147]	08
	Virtual and augmented reality-based approaches	[42,148–158]	12
	Prediction of human intentions	[15,24,136,159–171]	16
	Risks analysis approaches	[102,106,159,172]	04
	Developing metrics and standards for safety	[101,173]	02
	Developing metrics for safety	[101,174–181]	09
	Developing standards for safety	[32,58,154,182–187]	09
Cognitive human–robot interactions		[188–191]	**04**
	Human actions recognition	[192–194]	03
	Gestures recognition	[195–201]	07
	Faces recognition	[190,202–205]	05
	Voice commanding	[195,206–209]	05
	Social gaze and social acceptance	[190,195,210–214]	07
Robot programming approaches		[207,215]	**02**
	Generation of robotic skills	[216]	01
	Augmented reality & Virtual reality	[215]	01
	On-line programming	[217]	01
	Programming by demonstration	[9,38,66,218–220]	06
Human–robot tasks allocation		[99,221]	**02**
	Ontology-based knowledge	[40,41,93,222–226]	08
	Creating high-level tasks plans	[67,227–231]	06
	Tasks allocation and scheduling	[44,45,56,197,221,232–238]	12
Virtual & augmented reality		[239–241]	**03**
	Augmented reality	[128,152,155,239,240,242–245]	09
	Virtual reality	[9,17,42,246,247]	05
Study of physical interactions between humans		[46,248–255]	**09**
Fault tolerance		[256–261]	**06**

and realization. In addition, they involved many experts from three different disciplines: ergonomics for analyzing tasks variability, cognitive engineering for HRI and robotics for the robot itself.

Maurice et al. [79,80] presented a method for performing detailed ergonomic assessments of collaborative manipulation activities and its application to optimal design of cobots. They considered four components: (i) multiple ergonomic indicators were defined to estimate the different bio-mechanical demands which occur during manual activities; (ii) These indicators were measured for each activity through dynamic simulation framework, for varying human and robot features; (iii) A sensitivity analysis framework to quantify the influence of each parameter and identify those which should mainly be modified to enhance ergonomic performance; and finally (iv) A framework is used to optimize, based on multi-objective evolutionary algorithm, the design parameters with respect to most relevant ergonomic indicators. This scheme was applied to optimize a robot morphology for assisting a drilling activity.

3.1.2. Software architectures for cobotic systems

The control architecture represents a vital part of a cobotic system, which integrates all the necessary high-level and low-level software modules (sensor management, communication, safety, planning, (re) programming, decision-making, etc.) [72].

Recently, several technical architecture paradigms have been proposed to support developing industrial cobotic systems. Object-oriented, component-based and service-oriented approaches are among the latest models of heterogeneous software products that require complex interoperability and synchronization. As indicated by Amoretti and Reggiani in [81], understanding the characteristics, advantages and disadvantages of different paradigms is crucial for the design, implementation and successful use of cobotic software architectures.

In this sub-area, the use of *Multi-Agent Systems* (*MAS*) in industrial applications is recommended especially when decentralized decision-making and control are required [82]. This may have many important advantages in terms of modularity, robustness, flexibility and

Table 5. Distribution and list of studied publications on the years from 2008 to 2017.

Year	References	Nb. pub.
2008	[16,52,61,73,103,114,132,138,157,202,217,237,244,254, 259,262–265]	19
2009	[1,3,18,25,48,50,86,105,113,122,135,141,153,160,201, 212,215,247,266–270]	23
2010	[27,53,81,118,120,121,133,172,173,179,186,236,249, 250,271–273]	17
2011	[83,134,140,152,159,162,168,181,235,238,239,274–277]	15
2012	[4,11,13,15,17,21,26,29,41,72,77,112,119,125,139,167,177, 185,187,195,223,240,245,251,278,279]	26
2013	[2,12,24,38,49,65,84,85,101,111,123,150,171,198,200,207, 218,242,252,253,255,280–283]	25
2014	[8,9,14,46,68,79,89,91,95,104,115,117,130,131,158,178, 180,203,204,206,228,233,284–289]	28
2015	[5,7,10,19,23,40,44,64,82,87,90,92,93,96,99,108,124,128,129,142,151, 154,156,163,170,192–194,196, 199,209,211,224,225,227,234,248,256,258,260,290–293]	44
2016	[28,55,56,58,70,75,88,97,98,102,106,107,116,143–146,148,149,155, 161,164,165,184,191,208,210, 213,216,219–221,231,241,243,294–300]	42
2017	[32,37,42,45,57,62,66,67,69,74,76,78,80,94,100,109,110,136,137,147,166,169, 175,176,188–190,197, 205,214,222,226,229,230,232,246,301–303]	40
Websites	[33,36,43,174,182,183,304–308]	11

adaptability to change, durability, reuse and scalability [83–85]. The power of such a technology mainly stems from the fact that MAS approaches rely on decentralized decision-making; this means that the loss of a single entity can cause local challenges but does not risk the overall operation. Additionally, MAS are pluggable systems that allow smoothly changes to production facilities, such as adding, removing, or modifying software and modules, migration or updating old technologies, without the need for shutting down, reprogramming and resetting the system [86].

Another functional system architecture to control cobotic systems, based on a standard hierarchical robot control, *ESA Functional Reference Model* (*FRM*), is developed in [72]. The authors developed a modular flexible collaborative robot prototype for material handling, although without any perception sensors for capturing the working environment [87]. They decomposed a complex activity at lower-layer components that can be executed by various algorithms and assigned to specific sub-systems. This model provided a hierarchical multi-layer control framework and assumed horizontal and vertical layers assembly process control. According to the authors, to improve reconfigurability and flexibility of existing robots, modular approach is the best solution.

In [20,21], the authors proposed a control architecture organized in three functional layers for HRI within the *EU SYMPLEXITY* project. The human–robot safety is handled in the lowest layer. The coexistence is realized in the intermediate layer by featuring on-line collision avoidance capabilities, based on workspace monitoring by external sensors (cameras or RGB depth devices) [23,88]. The collaboration is addressed in the top layer. This architecture is validated for the collaborative polishing task on the *Universal Robots 6R UR10* lightweight manipulator mounting an *ATI 6D Force/torque* sensor.

3.1.3. Cloud-based robotics and fog-based robotics

Cloud/fog robotics is defined as an emerging field of robotics rooted in cloud/fog computing, cloud/fog storage, and other internet technologies centered around the benefits of converged infrastructure and shared services (powerful computational, storage and communications resources of modern data centers, etc.) [89,90].

The cloud-based or fog-based control model for industrial cobots allows analyzing wide data from additional sensors (e.g., cameras, power sensors). The availability of external algorithms such as fog-based and cloud-based services makes it possible to use industrial robots as an intelligent tool. This will also creates suitable interfaces for connecting the robots to *Internet of Thing* (*IoT*) and accessing them from different locations [91].

Fog-/cloud-based robotics allows to create modular systems that has a potential in different HRI scenarios able to serve as common platforms for researchers. Further, this technology removes overheads for maintenance and updates, and reduces dependence on custom middlewares. Magyar and Vircikova [90] stated that, from HRI perspective, such robotic systems can benefit from the knowledge of quasi-unlimited number of human experts.

Vick et al. [92] proposed an open framework based on services instead of a closed monolithic architecture. Services can be run independently of hardware over a cloud infrastructure allowing rapid reconfiguration of control modules and their multiple uses in different tasks. The authors studied and documented the effects on control performance, availability, and scalability. Measured time values showed that this approach allowed combining low-power components with reduced functionality with an on-demand scalable computing infrastructure, which could result in significant savings of energy and resources.

In addition, Stenmark et al. [93] proposed an industrial robotic applications and shared knowledge base store. The authors concluded that distributed approaches

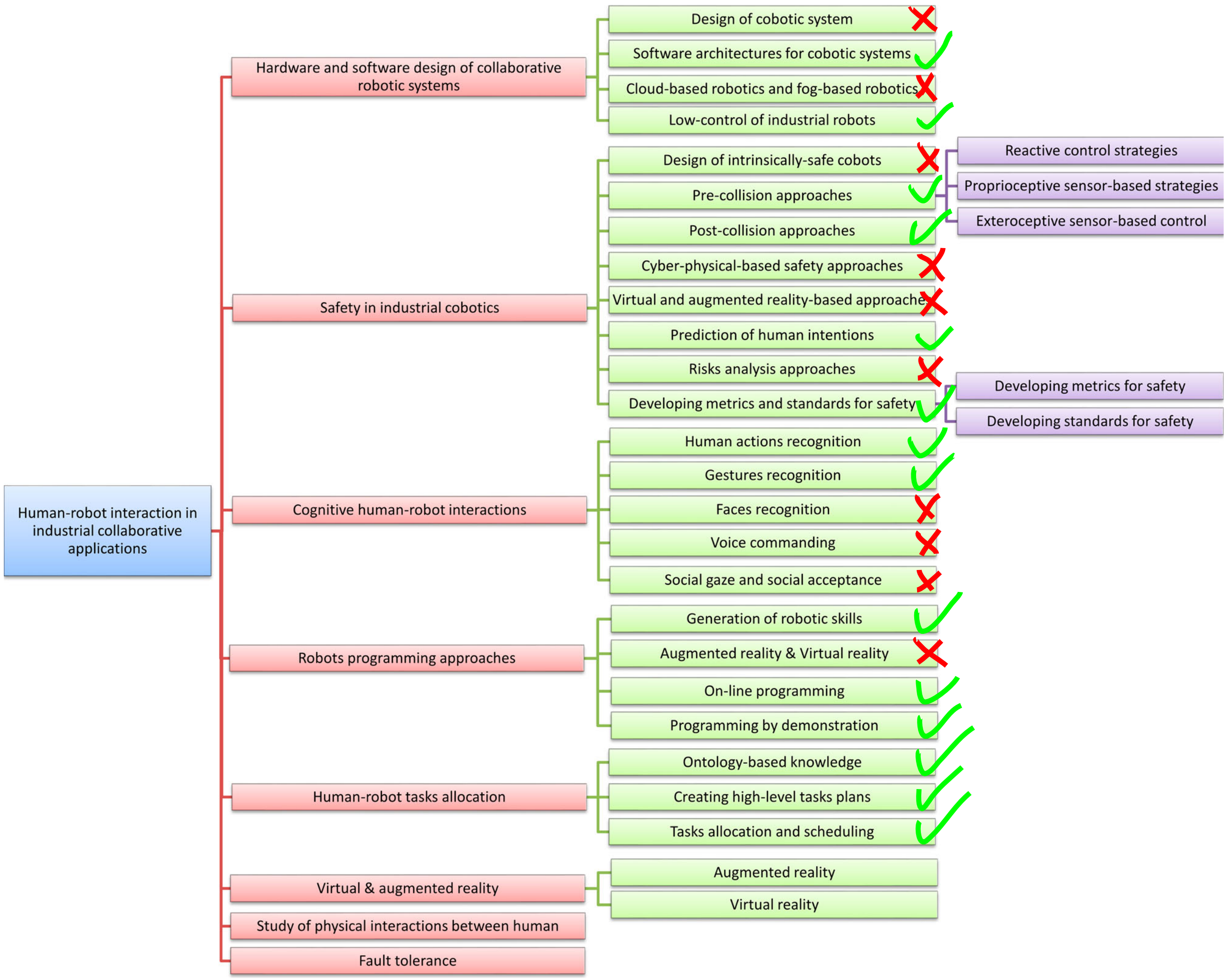

Figure 2. Summarized and classified related works into several possible categories and sub-categories.

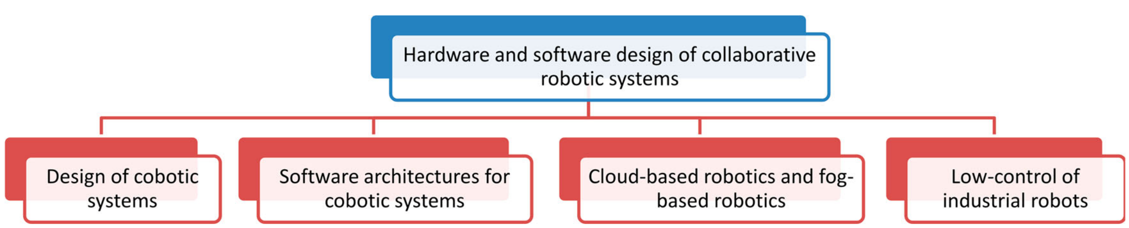

Figure 3. Sub-categories of *Hardware and software design of collaborative robotic systems*.

based on the cloud offer many possibilities, but there is still a need for additional research and better infrastructure before this approach can become industrially attractive. As they stated in another work [40], cloud robotics is a key factor for automation in intelligent manufacturing environments: (i) cloud robotics can provide an ecosystem for solution distribution, similar to an application store, (ii) collect and store data on-line to improve skills and learn settings, improving the robot capabilities over time, (iii) user interaction procedures (natural language, image processing) and learning algorithms can use this data, or even weighty computing procedures, during configuration and adaptation, and (iv) there are still many unresolved issues related to reliability, consistency or legal responsibility.

3.1.4. Low-control of industrial robots

HRI is a very complex issue and the choice of the control logic is relevant. In addition, many impedance control schemes have been studied in the literature (hybrid impedance, force impedance, etc.) to overcome the limitations of classical impedance control strategies [94].

An intelligent HRI is introduced by Modares et al. [55], with adjustable automatic behavior, to help humans performing tasks with minimum workload requirements, and improve the overall performance of the system. The control structure consists of two control loops: (i) The inner loop is made up of a robotic neuro-adaptive controller designed to ensure that unknown non-linear robot acted as a model of the robotic impedance described by the operator; (ii) The task-specific outer-loop controller is designed to find optimal parameters for the robotic impedance model described to adjust robot dynamics to operator skills and minimize tracking error. Hence, the authors shifted the problem of finding the optimal parameters of the robotic impedance model into the *Linear Quadratic Problem* (*LQR*) [96], which reduced human effort and improved the closed loop behavior. In addition, the authors used integral reinforcement learning to solve the assigned LQR problem to avoid the requirements of the human model.

The basic problem of rapid detection and robot reaction to unexpected collision situations has been addressed on advanced research robots equipped with torque sensors, with a precise available dynamic model. This is the case of Geravand et al. [49] who introduced an end-user approach to detecting a whole body collision and reaction on HRI for industrial robots with closed control structure and no additional sensors. They considered only the external outer joint velocity reference to the robot manufacturer controller, as well as the measurements available for the currents and joint positions of the motor. No a priori information about the robot dynamic model and low-level joint controllers is required [95]. As well, the authors provided examples of reaction schemes for collaboration, where the user pushed/pulled the robot at any point in its structure or with a compliant-like robot behavior in response to the forces applied by the human. The authors performed this method on *KUKA KR5* manipulator using the RSI interface. They also compared with *DLR LWR-III* [47] and *KUKA LWR4+* [52].

The authors in [97] proposed an impedance (specifically, a closed-loop adaptive damping) controller that automatically adapted to the external wrench, guaranteeing that ISO10218 standard (force, velocity, and power limitations) are respected (see Subsection 3.2.8) [98]. The developed controller has been validated on a *Kuka LWR4* robot, with a Shadow right hand mounted on its end-effector.

3.2. Safety in industrial cobotics

The first law of '*Three Laws of Robotics*' is defined as '*A robot may not injure a human-being or, through inaction, allow a human-being to come to harm*'. This means that in any case, safety is the foremost consideration factor [70].

Industrial cobots are able to interact with humans and perform tasks shoulder-by-shoulder with humans [99]. However, this evolution means breaking with established safety procedures and removing physical separation of workspaces between robots and humans [100]. The robots can move their arms or their bodies by force, very quickly, and often deal with dangerous and sharp tools. This represents a threat to all humans surrounding robots [32,101]. In addition, the dangerous behavior of these systems, caused by failure or extreme environmental conditions, can have catastrophic consequences [102].

As expressed by Santis and Siciliano in [103], three steps can be considered for safety tactics: (i) those related to intrinsic safety, (ii) those which can prevent collisions (pre-collisions), and (iii) those activated in the event of collisions (post-collisions) [104,309]. Figure 4 gives the different sub-categories of '*safety in industrial cobotics*' as considered in this work.

3.2.1. Design of intrinsically safe cobots

'*How to design cobotic systems safely?*' is very important. So far, no industrial safety standards and regulations are present for developing such collaborative systems [105]. Moreover, it is difficult to assess these systems with all their capabilities before commissioning [106].

A critical issue with industrial cobots is to make them intrinsically safe and dependable [107]. However, as reported by Bicchi et al. in [16], making rigid and heavy conventional industrial robots behaving gently and safely (especially when a human is present inside their workspace) is an almost hopeless task if realistic conditions are taken into account. Therefore, many attempts have been done to design intrinsically safe robots in various ways. Hirzinger et al. [310] affirmed that reducing the weights of the moving parts of the robot consists of one of the principal factors in designing intrinsically safe cobots. In addition, the risk while interacting with such robots may be mitigated by increasing their sensorial apparatus [16], using proximity-sensitive skins or torque/force sensors to detect collisions [108,109], increasing energy-absorbing properties of protective layers, adding enough soft and compliant coverings, placing airbags around the robot [16,110], limiting the robot velocity and maximum energy in the system by human capability [61], limiting strength and contact force [70], etc. [97].

Some researchers tried to realize intrinsically safe cobots thanks to mechanisms integrated within the robotic structure able to efficiently handle collisions with their surrounding environment. A largely studied solution consists of introducing *Variable Impedance Actuators*

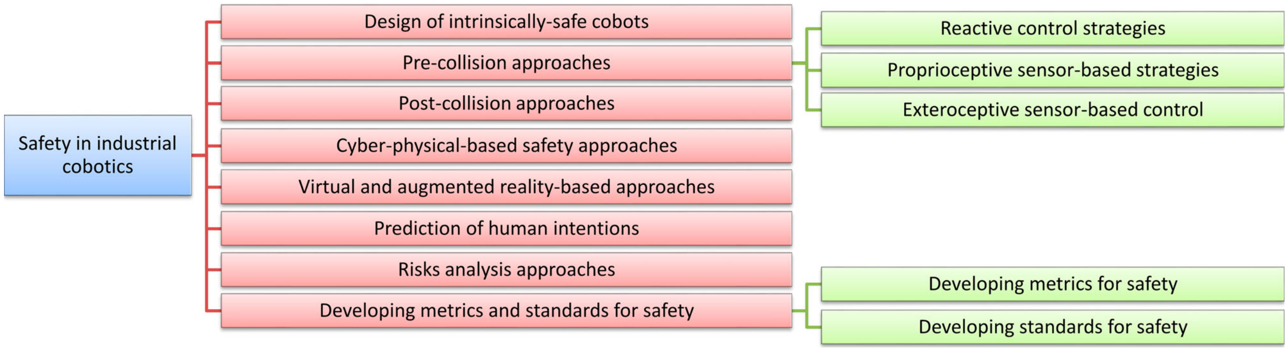

Figure 4. Sub-categories of *Safety in industrial cobotics*.

(*VIA*) [111,311], *Active Impedance Control* (*AIC*) or *Passive Compliance* (*PC*) [112] within actuators. VIA-based approaches consist of a mechanical/control co-design that exploits rapid and continuous variations of transmission impedance during task execution (by varying stiffness, damping or gear ratio) [107,113]. AIC-based approaches suffer from relatively low bandwidth, since they involve accumulative delays generated by the control loop components, in response to fast collisions [114,115]. PC-based approaches are commonly composed of mechanical elements including springs to absorb the joint kinetic energy in collision, known that an elastic joint is capable of decoupling the next link inertia from the base link [115,116].

In [312], authors used viscoelastic coverings around link surfaces to eliminate all risky elements around the robot links. They also used mechanical measures such as spherical joints to prevent mechanical shearing, and mechanical stoppers to limit the motion range of each joint [100].

According to Sghaier and Charpentier [278], collision between robot parts and human limbs is the most common accident in the industry [68]. Pervez et al. [263] stated that light-weight structures may assure better safety performances, in case of collisions thanks to modern materials in axes and links. In this trend, Bicchi et al. [262] described a way to increase the safety level of robot arms, which is to introduce compliance at the level of mechanical design. The authors discussed some possible concepts for safely actuating joints, and focused on implementation aspects of the mechanics and control of this class of cobots.

3.2.2. *Pre-collision approaches*

As stated in [15], in industrial collaborative systems, a contact with the other teammate may be desirable (e.g., for objects handling). However, unplanned collisions between the humans and cobots must be avoided. *Pre-collision systems* use proprioceptive/exteroceptive robot sensors to detect humans or obstacles presence to stop the robot or modify its trajectory to prevent collisions and avoid contact [18,117–120].

(a) *Reactive control strategies*

Some reactive control strategies may be applied to ensure collision detection and avoidance enhancing thus human safety during collaborative tasks execution.

Haddadin et al. [52] showed how reactive control strategies can help to ensure human safety during physical interaction by using a light-weight robot. Further, they performed several collision tests for interactive and cooperative tasks. The robot is able to detect and distinguish unexpected collisions from a planned cooperation, in which a human stretching his arm, attempted to catch the robot. The proposed detection and response methods allow the operator to feel that he has total control of the robot. The authors concluded that users feel self-sustaining when they can naturally stop the robot in self-movement.

A distributed real-time approach based on a 3D simulation of the robotic cell has been proposed in [117] to avoid overloading the robot controller. Based on appropriate speed priority control, the strategy evaluated the distances between robot and obstacles in the workspace, according to the cell simulation. The calculated distance is used to move the robot at a reduced speed in the event of impending collisions. Finally, the authors proposed to host the *ROS* module in the *C5G Open architecture* [121,304] to open the control, to ROS-compliant sensors, drivers and other robotic platforms [122,123].

In [119], the authors presented a real-time collision avoidance approach based on depth sensor for safe HRI. The proposed method evaluates distances between the robot and the moving obstacles (including humans) to generate repulsive vectors based on an estimation of their velocities. A repulsive action is designed for the end-effector and other control points on the manipulator to be able to avoid collisions while executing at best the original Cartesian motion task. This framework is validated by a series of experiments on a *7-dof Kuka LWR4* using *Microsoft Kinect*.

(b) *Proprioceptive sensor-based strategies*

An overall procedure for collision detection between an industrial robot and the environment has been proposed in [124]. The procedure, directly implemented in the internal software architecture of the controller, did not use any particular parameters related to the robot or external sensor, and did not rely on particular information concerning the specific robot to which it was applied. The robot used only the information already available from proprioceptive sensors and the dynamic model used for the control. Experimental tests, carried out during real work cycles, confirmed the absence of false collision detections.

Some researchers suggested improving existing approaches by adding different pose estimation methods [125], EKF [126] and Hybrid EKF [127,128]. Whereas, [129] suggested using coordinated motions to reduce task completion time on bi-manual collision-free motion planning.

(c) *Exteroceptive sensor-based control*

Exteroceptive sensor measurement-based active control is a viable approach to improving safety in industrial environments [130].

Since it is very difficult (even impossible) to obtain a detailed description of the environment, De Santis and Siciliano [103] proposed to use a precise sensors system along with virtual reality to simulate a realistic HRI task, including collisions and injected errors. In addition, subjective comfort procedures related to the use of manipulators, which are also related to observed safety during robot motion, can be achieved depending on the robot shape, speed and posture.

In the same trend, a hardware/software solution to improve safety is provided by Avanzini et al. in [130]. The authors developed an initial model of the distributed distance sensor, to be integrated in industrial robots. Sensor output was used as part of the control strategy to improve human safety by assessing the risk level caused by the robot. The feasibility of this module has been demonstrated through experimental scenarios on the *ABB IRB140* industrial robot [131].

Meziane et al. [68] combined the *Inertial Measurement Unit* (*IMU*) and *Received Signal Strength Indication* (*RSSI*) to recognize human activities and localize the human position in real-time using industrial wireless equipment. A hybrid workspace with a flexible manufacturing system has been designed to practice experiments in an industrial environment.

Other systems create large zones around the operator and the robot; in case of overlapping between zones, the robot decreases its velocity or stops. Accordingly, research in this category focused on reducing the size of the zones or modifying the robot behavior only if a near collision is detected. Examples include *Bosch APAS system* [43] and *ABB SafeMove* [132].

3.2.3. Post-collision approaches

Post-collision schemes react after collisions occur to reduce the impact/injury after an unexpected collision has occurred [52,133]. For such schemes, the human safety is assured by limiting the maximum energy of the impact [50], thanks to the robot compliant structure or by using the measured force in the control scheme [313,314].

A robot could injure a human by two different manners [136]: (i) *physical injuries* caused by unintentional or unwanted contact between the human and robot if the exerted forces exceed a certain threshold. (ii) *indirect or psychological injuries* caused by many factors such as robot appearance, embodiment, gaze, speech, posture [134,315]. Additionally, many types of injuries could occur [135]: (a) contact with a sharp or abrasive surfaces may cause cuts or abrasions, (b) manipulator pinch points or direct crush loads may cause serious injuries such as bone fracture, and (c) potential impact with large loads may cause more serious injury or even death.

Many works have been realized to evaluate maximum contact forces and pressure levels for quasi-static and transient contacts that robots can apply against each relevant part of the human body [137]. In this context, Yamada et al. [316] introduced human-pain tolerance as a criterion for safe robot impact behavior. Haddadin et al. [50,138] analyzed injuries with different robots considering the severity of injuries to a human caused by a collision with a robot. Obtained results showed that the severity of an injury depends on the mass, geometry and velocity of the colliding objects [110,139].

Haddadin et al. [48] made a systematic assessment of safety in HRI, covering various aspects of the most important injury mechanisms. The authors performed various tests using *DLR-Lightweight Robot III* [51] to determine the potential risk of injury from such a robot. Based on these tests, the researchers evaluated several industrial robots of different weights and studied the effect of their mass and velocity from different points of view. As well, they analyzed, in simulation, the quasi-static constrained impact problem; this can pose a serious hazard to humans even for low-inertia robots under certain conditions (near-singular configurations in case of constrained impacts, etc.). Additionally, the authors demonstrated the effectiveness of a collision detection and reaction scheme, which is capable of dealing with this hazard.

Matthias et al. [140] presented two approaches to risk assessment for HRI scenarios and a more detailed future methodology that would better address the risk of low-level injuries. The authors considered the results as a systematic step towards applying safety in the common workspace and as a contribution to new standards defining HRI from a safety perspective.

To provide low levels of injury risk at any time during motion and minimize negative effects on control performance, Courreges et al. [107] proposed a simple biologically-inspired non-linear elastic force-deformation response model for a safety mechanism. This model exploited rapid and continuous variations of transmission impedance during task execution (by varying stiffness, damping, or gear ratio).

3.2.4. Cyber-physical-based safety approaches

The advent of computing, sensors and integrated wireless technologies has become the key technologies for real-time control interaction and construction of physical engineering systems applied to robotics [142].

Lee et al. [143] defined *Cyber-Physical Systems* (*CPS*) as an emerging approach to physical processes, computing and networking, which emphasizes the interactions between cyber and physical elements in time and space [141,144]. In such an approach, physical processing systems are equipped with sensors attached to communication networks [145]. CPS monitor and control physical infrastructures, which have a significant impact on industrial automation [146].

As indicated in [100], safety issues in HRI in industrial environments fall within the scope of CPS. In [147], authors implemented safety strategies based on CPS by combining different sensors including laser scanners, proximity sensors, vision systems and force sensors.

Robla-Gómez et al. [100] discussed the use of CPS approach in HRI, underlining the current technological constraints and challenges associated with its real-time implementation in such a field. Additionally, the authors described various mechanical systems and safety strategies for collision detection, which reduced injuries in case of collisions.

3.2.5. Virtual and augmented reality-based approaches

Augmented reality (*AR*) is a set of techniques which refers to embedding additional computer-generated information into real-world environments [152,157] and into the user current surroundings view [158]. On the other hand, *virtual reality* (*VR*) can be defined as an approach to user-computer interface that involves real-time 3D computer simulation of an environment, scenario or activity that allows for user interaction via multiple sensory channels [153]. Both technologies (VR and AR) represent an effective tool capable of simulating industrial cobotic systems with a high-level of immersion [42].

Vogel et al. presented in [148] a solution for safeguarding HRI workplaces with high payload robots. The approach consisted of a tactile floor with spatial resolution acting as a hard-safety sensor for workspace monitoring together with a three-color (red, orange and green) projection system as a soft-safety component to visualize the safety zones boundaries. The authors also proposed hints and algorithms to dynamically define these zones around the robot regarding its current direction and target position which will be safeguarded by the tactile floor and displayed for the human co-worker by the projection system [149].

A similar work has been carried by Schmidt and Wang in [150]. The authors considered a shared workplace in close proximity, where real data driven 3D model of a robot and a single or multiple depth camera system images of the workplace are used for monitoring and decision-making to perform a task with emergency stops. The strategy for robot control depends on the current task and information about human presence and position. They also mentioned a camera-projector system which creates a dynamic safety zone boundaries [151].

Michalos et al. [156] suggested introducing AR techniques that allow visualizing the robot operating workspace rather than the safe areas for the operator while performing collaborative tasks. Additionally, other researchers [155] proposed to use augmented reality glasses that meet industrial standards.

Hernoux et al. [154] tried to improve the human safety by considering pre-collision algorithms and virtual reality tools (e.g., *Kinect2* device). This allowed to detect in advance potential collisions, secure an area and act on the industrial robots before any injury occurs. By using a markerless motion capture system, the researchers were able to detect the presence of operators in the robots vicinity based on (i) real-time detection and localization of humans in the robot workspace, and (ii) reactive planning algorithms to avoid collision.

3.2.6. Prediction of human intentions

The HRI is not always explicit, neither physical, nor synchronous. The goal is to provide the robot with the three fundamental requirements of HRI [161]: (i) the human intention should be easy to infer by the robot, (ii) the control should be intuitive from the human viewpoint and (iii) the designed controller should be safe for both human and robot. Moreover, robots should not only consider the environment and monitor the human teammate actions, but also process those actions to anticipate his knowledge, state of mind and contribution to the collaborative task [136]. The use of such anticipated knowledge in the robot decision-making mechanism depends on the adaptation of these cobots to various types of humans, their dynamic behaviors and requirements. Realizing such adaptivity would result in cobots working more efficiently and seamlessly with their human co-workers, increasing overall productivity [162–166].

Other researchers dealt with this question by modeling and predicting the human behaviors to safely and efficiently interact with the industrial cobots. The challenge is that humans tend to follow different motion patterns, depending on their intention and environment structure.

As indicated in [24], the robot must be able to infer human intentions during task by using acquired sensors data to enable safe HRI in industrial scenarios. In [167], the authors aimed to realize this without structuring neither environment nor operator and by only deploying low-cost sensors. The validation task consisted of a series of screws to be collaboratively inserted by a human and a robot operating on the opposite sides of a flank. To perform this, the authors utilized a Kinect to observe the work scene and a camera placed on the robot end-effector.

In [168] and [317], the authors addressed the operator intention estimation as the problem of predicting on-line the trajectory, given a set of human trajectories learnt off-line using an unsupervised classification algorithm. The current 3D position of the human and his intended position are thus considered to modify the robot behavior.

In [169], the authors provided a formulation for both SEA-driven robots used in HRI and integrated it into a single controller: (i) *robot-in-charge mode* where the robot plays the dominant role during task execution; and (ii) *human-in-charge mode* in which the human plays a dominant role to guide the robot. The authors illustrated the performance of the proposed controller via simulation and experimental results.

Ding et al. [159] proposed a method based on *Hidden Markov Models* (*HMMs*) [160] to predict the workspace region that will possibly be occupied by the human within a prediction horizon, where the two entities (human and robot) shared a common workspace. The researchers tried to increase the efficiency of the system by informing the robot about the most probable human motion to sufficiently warrant it to re-plan its trajectories. Therefore, the necessary safety reactions (such as, stopping the robot) that would imply higher robot idle times (reducing the system efficiency) could be averted [15]. The authors demonstrated the practicability of this approach by predicting the motion of a human arm in two scenarios involving multiple motion patterns.

The authors in [170] extended the safety measure described in [171] and proposed a trajectory scaling approach to take into consideration more complex obstacles for safe human–robot collaboration. This method is based on real-time prediction of human occupancy in terms of a series of swept volumes. Knowing the space that the human will occupy within the robot stopping time, the controller can scale the robot velocity to allow safe collaboration and avoid task interruption.

3.2.7. Risks analysis approaches

Guiochet [102] proposed to extend or modify the well-known risk analysis methods used in other vital areas (aeronautics, nuclear, medical, transport, etc.). As he indicated, the main challenge is therefore to develop viable methods at the beginning of the development process, making it possible to identify the risks posed by automated tasks and their interactions with humans. Here, the author introduced a method for the security analysis based on an adaptation of *Hazard Operability* (*HAZOP*) [172], along with *Unified Modeling Language* (*UML*) [305]. This process produced lists of risks, recommendations and assumptions.

Additionally, Bobka et al. [106] proposed specialized simulation software tools that could be used to build and simulate models of safety systems, *Human–Industrial-Robot-Interaction-Tool* (*HIRIT*). Their objective was to assess the safety and productivity of HRI systems in the planning process. The authors used geometric data in the real world to study various safety algorithms and strategies (genetic algorithm to avoid collision, process data quantities in short times, etc.). The special feature of *HIRIT* is to find safety distances between humans and robots, robots and robots, robots and environment, thus simulating adaptive speed motion regulation in assembly applications. Another important capacity is to create dynamic models, such as the *Head Injury Criterion* [266], the recording of realistic human motion sequences, etc.

3.2.8. Developing metrics and standards for safety

Most of collaborative tasks involve close interactions between humans and robots, thereby making safety a crucial parameter. Erroneous interactions that inevitably arises between the co-workers cause accidents in collaborative applications. Mohan et al. [173] affirmed that currently, there are no metrics available in the HRI community for analyzing erroneous interactions.

Vasic and Billard [101] stated that scientific and industrial community must urgently address developing context-specific safety guidelines and metrics for industrial HRI. Although robot safety is always a concern, the accidents of this type of interactions are likely to increase as the number of cobotic systems grows. To avoid accidents, it is important to identify possible sources of damage and workers near the most vulnerable robot, and assess the type of injuries that those robots can cause to humans.

(a) *Developing metrics for safety*

In the United States, the *National Institute of Standards and Technology* (*NIST*) [174] is developing performance metrics for cobotic systems for smart manufacturing applications. Using a series of sensor platforms, feedback mechanisms and new test artifacts, *NIST* seeks to provide the industry with tools to characterize the performance of robots collaborating with humans and other robots [175].

Bdiwi et al. [176] developed an HRI taxonomy to improve safety procedures which are recommended in the ISO standards concerning HRI in industrial cobotic systems. They classified the interaction into four levels ($Level_1 \ldots Level_4$) based on the interaction level and the required task with heavy-load industrial robots. In every level, different kinds of safety functions has been introduced and tested to ensure human safety during any possible interaction. Depending on this taxonomy, authors were able to define which human features should be detected and which robot parameter should be monitored and/or controlled in every level of interaction.

Mohan et al. [173] proposed and validated a class of false alarm metrics to define, classify and quantify the effects of erroneous interactions in human–robot teams. They also explored relationship between false alarms and safety in service robots. For this, they extended the *Receiver Operating Characteristics* (*ROC*) curve [177] to classify robots based on their associated risks.

Additionally, the authors proposed in [178] a safety index based on the distance from robot to humans and robot link momentum. This index is evaluated in the ellipsoid coordinates attached to the robot links, and the formulated non-linear and non-convex optimization problem is approximated by a quadratic formulation. The researchers implemented and simulated this approach on a two-link planar robot and a *ITRI 7-dof manipulator*.

In [179], authors evaluated the danger within manipulator workspace based on *kinetostatic danger field concept* (a generalization of potential field approach). It represents the quantity that captures the complete state of the robot from its proprioceptive sensors only (configuration and velocity). Finally, authors in [180] developed the safety field which is an extension of the cumulative danger field concept [179,181] to moving surfaces or bodies (obstacle or human).

(b) *Developing standards for safety*

The standards ISO 10218-1 [182] and ISO 10218-2 [183] (established in 2011) are designed to evaluate and ensure the safety while working with cobots [32]. The first part of this standard, *ISO 10218-1*, is regarding the robot itself; it specifies how a robot cooperates with a human in a collaborative operation and, also, specifies all limitations depending on how the collaboration is designed. The second part, *ISO 10218-2*, is regarding robot systems and its safety requirements for an integration of HRC [184,318]. Recently, a new standard, *ISO/TS 15066*, [308] has been announced to specify safety requirements for such systems [319]. According to *ANSI/RIA R15.06-2012* standard [185], robot collaboration with humans can be divided into many types of applications. Thus, a robot must satisfy at least one of the four following criteria [154] (considered as a set of requirements for achieving safety goals and risk reduction in automatic modes): (i) hand guiding, (ii) safety-rated monitored stop, (iii) speed and separation monitoring, and/or (iv) power and force limiting [58,186,187,320] as shown in Figure 5 [321].

- *Safety-rated Monitored Stop (SMS)*: inside the collaborative workspace, both human and robot can work, but not at the same time; indeed, the robot stops immediately when an operator enters this area. Accordingly, dedicated software and electronic technology are designed to pause the robot motion when a human enters the shared area and restarts after the operator has left it.
- *Hand Guiding (HG)*: here, the robot is controlled by the operator through a hand-guiding device. When the operator releases *HG* device, the robot returns in *SMS* and resumes previously interrupted program as soon as the operator leaves the collaborative area.
- *Speed and Separation Monitoring (SSM)*: the robot and the operator can move concurrently in the same workspace but the robot motion is allowed only when the minimum separation distance limit is not exceeded. The operator is monitored continuously for moving at a safe speed with respect to the operator.
- *Power and Force Limiting (PFL)*: the robot motion is limited by an inherent control strategy while using its sensors so that the motion is stopped upon collision. The speed is controlled or limited so that forces and momentum upon impact with the operator are within the limits to avoid injury.

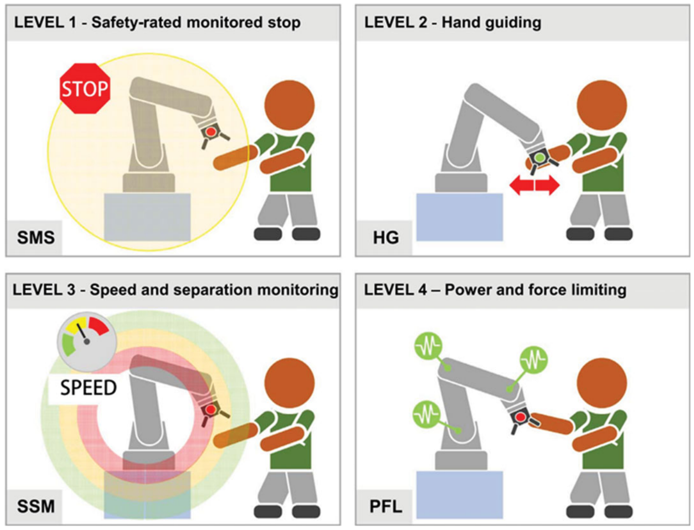

Figure 5. The four modes identified by robot safety standards 10218-1/2:2011 [321].

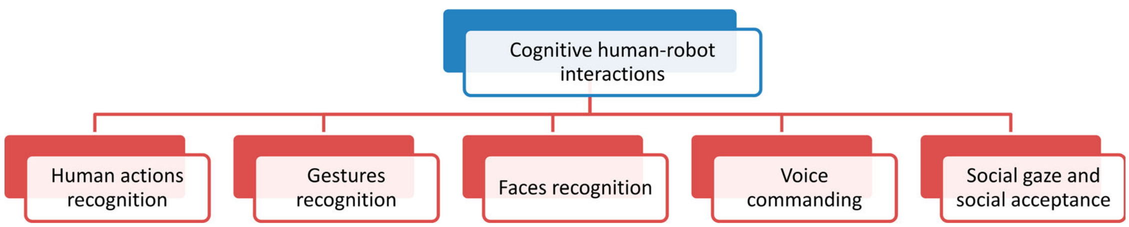

Figure 6. Sub-categories of '*Cognitive human–robot interaction*'.

3.3. *Cognitive human–robot interactions*

A better and more efficient HRI in industrial settings requires a good communication between human and robot partners. Thus, the robot should be able to manage a number of behaviors and social components, voices, gestures and faces [188–190] to facilitate fluid and safe collaborations [191]. Figure 6 shows the different subcategories of '*Cognitive human–robot interaction*' as considered in this article.

3.3.1. *Human actions recognition*

Human actions recognition plays a vital role in HRI and is widely investigated due to its potential applications. Research works in this area principally focused on using cameras (or other devices) to observe human actions. The main purpose is being to develop robots capable of understanding the human actions.

Akkaladevi and Heindl presented in [192] a multi-label human actions recognition framework for HRI in industrial applications with real-time capability to detect multiple actions simultaneously. They learnt a set of key descriptors from a set of weak spatio-temporal skeletons descriptors using randomized forests. The obtained recognition accuracy is sufficient for the classification of actions and can be used with a high-level learning/reasoning system to handle actions/activities with larger temporal variations.

Ramirez-Amaro et al. [193] developed a framework that combined several observable inputs together with reasoning tools through ontologies to interpret, learn, and understand human actions. The authors presented a method to extract semantic rules of human everyday activities. Namely, they extracted low-level information from the sensor data; then, they inferred the high-level by reasoning about the intended human behaviors. The authors also addressed this aspect in [194] while focusing on generating compact semantic models for inferring human coordinated activities, including tasks that require understanding dual arms sequencing.

3.3.2. *Gestures recognition*

Gesture is an embodied form of interaction that people naturally use in their social communications. The gestures detected through augmented gloves or computer vision have been used to control industrial robots [201].

The development of effective HRI involves the research and design of human gestures to develop as basic set of commands as possible through arms and hands movements. The relationship of this aspect with technical evaluation of available scientific tools can confirm the potential candidates to unify gesture-based HRI, while the gestures must also be understood by the robot to reduce the error rates of interpretation [195].

Peppoloni et al. [196] integrated a control interface allowing the user to teleoperate the robot based on hand gestures using *Robot Operating System* (*ROS*) [304]. The operator could adjust robot autonomy between two levels: direct control and way-point following. Hand tracking and gesture recognition features of the *Leap Motion device* are used to generate control commands [198,199]. The user received 3D real-time augmented visual feedback from the environment via *Kinect* and *Head-Mounted Display* (*HMD*) sensors. The authors presented experimental results on *KUKA Youbot*, to evaluate the performance and practicability of their system. Tasks can be successfully executed with the current system, although the performance is affected by the workspace and dexterity of the remote robot.

Additionally, Tsarouchi et al. [197] developed a system based on relatively unusual body gestures for HRI to control and guide robots, specifically start or stop motion or action.

Barattini et al. [195] introduced design limitations between different sets of requirements and a technical solution for automatic identification using imaging hardware. The authors illustrated the concepts of *human-to-robot* and *robot-to-human communication* on a real industrial scenario, with a focus on defining a set of gestures to communicate in automotive industry. Further, the authors used the gestures recognition algorithm based on *dynamic time warping* [200] to demonstrate the feasibility of distinguishing these gestures by automatic processing.

3.3.3. Faces recognition

Faces recognition plays an important role in building efficient HRI that allow humans to interact with cobotic systems in a natural way [202]. Overall, faces recognition along with fingerprint scanning are mainly used for identifying human operators inside factories that are allowed (have required skills) to work side-by-side with cobots.

El Makrini et al. [190] proposed to endow the cobotic system with face recognition capacities to personalize the robot for each operator, whereby the user is identified and greeted. The main purpose is being to allow only authorized/qualified operators to interact with the robot. For this, they developed a recognition system using the *Kinect2* camera; images are processed by the *IAI Kinect2 ROS* package [204] and the face detection algorithm used the *ProcRob ROS* package [205]. Finally, the acquired face is compared to workers faces of a database.

Bdiwi [203] proposed a cobotic system integrating several kinds of sensor (vision, force, sensitive skin sensors) to ensure safe HRI. Using the Kinect camera, the robot was able to detect and recognize the human face, load-free human hand and any hand-carried object. The author implemented this solution on a *Stäubli RX90* robot with a *JR3 multi-axis force/torque* sensor together with an eye-in-hand camera system. However, the face recognition approach was not reliable enough if the human face is covered by glass or hat; further, the human should directly face the camera to make recognition.

3.3.4. Voice commanding

The ability to communicate in natural language and manifesting responsive behavior is essential in social communities [206]. In general, voice commands channel remains the most preferred method to communicate with another assistant or co-worker (human or robot) [208] thanks to many factors (voice is faster, etc.) [209].

In this trend, a system was introduced in the *RobotStudio* environment using a natural language to programming assembly tasks for industrial robots [207]. From the input sentence, the processing pipeline applied a series of operations to analyze the sentence, produce a set of predicate-argument structures, and create an executable code for virtual and physical robots with real-time constraints. The semantic module used statistical methods to extract structures from grammatical functions automatically. After that, the system mapped the predicate and arguments into robot actions and objects of the simulated environment.

Additionally, Niculescu et al. [206] created a human–robot interface for welding robots using natural language to demonstrate responsive behavior in interaction with human co-workers. Based on the results of two data sets, the authors argued that these capabilities can be very useful in industrial environments, improving HRI and contributing to the transformation of the interaction paradigm from industrial towards social.

The measurements done on the sound landscape of the test factory considered in [195] indicated that human co-worker can only voice-command the robot within a range of 3 m. Barattini et al. pointed out that this range was not a strong limitation; indeed, this range offers humans a comfort zone to interact vocally. They concluded that, to maintain the capacity of using the robotic assistant, gesture-visual communication channel is a valuable option, leaving to the worker the freedom of being enough far away from the robot than 3 m voice control range.

3.3.5. Social gaze and social acceptance

Most of cobots working alongside humans on factory floors do not have mechanisms for communicating with human co-workers. Additionally, cobots likeability is usually not a design concern. On the other hand, most of socially expressive robots do not have required capacities to perform industrial tasks with high precision and repeatability required in such applications [210].

Explored in [211], how the social gaze in the aggregation robot affects how naïve users interact with it. For their experimental study, 30 participants asked an industrial robot to get the parts needed to assemble a wooden toolbox. The participants interacted with the robot using a simple look that followed the movements of his arm, or either with the robot after his movements during the tasks, but which also gazed at the participant between instructions [212]. Qualitative and quantitative analysis showed that people in a social gaze are much faster to engage the robot, and can better understand where the robot is looking. In addition, the authors found that people in social gaze condition feel more responsible for the task performance. They summarized that social gaze in assembly scenarios fulfilled the floor management functions and provided an indicator of the robot affordance, without influencing its sympathy, mutual interest, and supposed skill.

Additionally, Barattini et al. [195] respected the principle of social acceptance, for establishing basic connections with industrial cobots. The authors also illustrated the concepts of *human-to-robot* and *robot-to-human communication* on real industrial scenarios, while defining a set of gestures for *human-to-robot communication* in automotive manufacturing.

Elprama et al. [213] realized a study with factory workers on social gaze and acceptance. They found that humans expressed concerns of robots taking over their jobs while, at the same time, believing that cobots can be of great benefit for physical demanding tasks.

El Makrini et al. [190] conducted other experiments using multiple methods (surveys, experiments and interviews) to investigate HRI using gestures and assess the importance of social cues [214]. Obtained results indicated that humans are more willing to work with cobots when showing more social cues such as head nodding and eye gaze.

3.4. Robots programming approaches

The problems of HRI in industrial cobots have been largely confined to finding better ways of reconfiguring or programming such systems [215]. Further, in automatic control, computer vision, machine learning, optimization algorithms and data mining are widely used [207]. Figure 7 summarizes the '*Robot programming approaches*' sub-categories as considered in this paper.

3.4.1. Generation of robotic skills

Currently, new robots programming methods are needed, allowing shop-floor workers to program and teach robots. One possible technique is to develop robotic skills, which are pre-programmed software packages that only need to be parametrized by the user [216].

Steinmetz and Weitschat [216] have introduced a software architecture that combined generations of robotic skills (action blocks), aimed at robustness and HRI. Besides, the user has full control over execution and all events are managed in a specific way. The authors described four basic questions about defining the skills to be implemented to speed-up the process and increase the user ease-of-use. Finally, they implemented the screwing skill and pick-and-place skill in two cases to show how to reduce the number of parameters while maintaining general efficiency and adapting them to different scenarios.

3.4.2. Augmented reality & virtual reality

Fang et al. [215] proposed an *Augmented-Reality-based Robot Programming* system (*RPAR-II*) to assist users with remote programming, selection and installation. Virtual robot is used in a real environment to perform and simulate task and trajectory planning. An interaction device is also used to allow them interacting with the virtual robot during programming process from scheduling tasks to execution. For remote operations, authors installed many cameras at a remote location (stereovision) to obtain remote work environment information, virtual objects recording, and interactive position tracking devices. Another interaction device (joystick, PHANTOM, etc.) replaced the marker cube to allow operators to manipulate the virtual robot in the remote site to perform planning tasks. The system can be used to help operators determine the best location of the robot before final installation and select the appropriate robot configuration among available robots.

3.4.3. On-line programming

An on-line programming environment (software and hardware), supporting an intuitive way to move and teach industrial robots, while supporting the user with assisting algorithms (collision avoidance, automatic path planning, etc.), was proposed in [217]. For this, authors combined different methods such as teleoperation, *Programming by Demonstration* (*PbD*) and off-line programming. The operator works in a robot cell and the motion of the guiding device is instantly interpreted and executed as a robot motion (except automatic path planning module). Therefore, human interacts directly with the robot, assisted by the proposed algorithms.

3.4.4. Programming by demonstration

Programming by Demonstration (*PbD*) is an on-line programming approach where a human performs a task

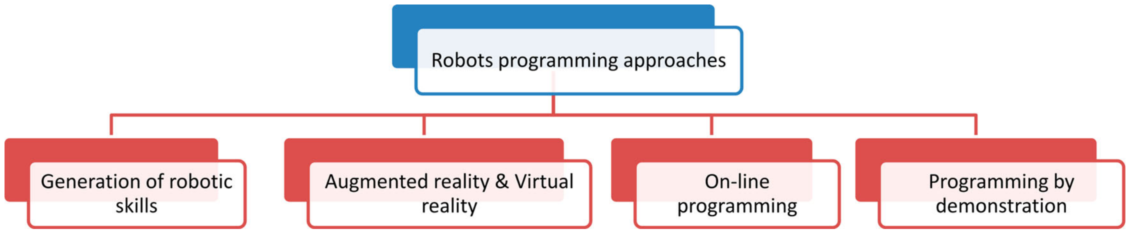

Figure 7. Sub-categories of *Robot programming approaches*.

manually; in parallel, the robot is observing, following and learning demonstrations in real-time [9]. The main idea behind this is to free the human from tedious robot programming tasks on any machine-code level [220]. The first advantage is that *PbD* allows accelerating programming task and reducing learning difficulty of robot programming by just giving a demonstration of how carrying out the operations sequence. In addition, *PbD* allows any user (even with no robotic skills) to program a robot. Likewise, it allows saving investment for dual-arm robot or multi-robot programming by reducing customized installations. Another advantage is that it is possible to program more than one robot simultaneously and make robot programming more intuitive and easier [38].

Lambrecht et al. [218] showed a programming system of industrial robots using the recognition of markerless gestures and the mobile *AR* in terms of *PbD* on modern smartphones and tablets. The authors provided a prototype for programming an assembly sequence consisting of several pick-and-place tasks. The reconstruction of the presented scene allowed estimating the pose of known objects using a hand-held 2D camera in *AR* application. The program can be adapted with gestures and then transmitted to a robot controller using a unified interface.

Restrepo et al. [66] described an iterative approach that allowed human co-worker to program and locally modify the virtual guides through physical interaction with the cobot. In this work, only one demonstration without assistance is needed. The proposed scheme was implemented using kinesthetic teaching [219] and Akima splines [322]. Experimental evaluation was carried with an expert user via a sanding task with a cobot; the task changed and the virtual guides must be reprogrammed by the operator.

Ge [38] implemented a *PbD* approach with an optical tracking system and *ABB YuMi dual-arm robot* [39]. The human demonstrated the task to be carried out. Simultaneously, the human motion is observed and transferred to robot; this latter is able to imitate 6D motion of operator arm and hand.

3.5. *Human–robot tasks allocation*

The capability of cobots to work closely with humans is identified as a significant advantage of such systems; however, this advantage is only realized in case cobot and human tasks are well-defined and optimized [99,221]. Figure 8 shows the '*Human–robot task allocation approaches*' sub-categories.

3.5.1. *Ontology-based knowledge*

When robots work in dynamic environments, close to humans lacking extensive knowledge of robotics, there is a strong need to simplify user interaction and ensure that the system works as autonomously as possible, as long as it is feasible [93]. By using knowledge management systems, the usefulness of cobots can be improved inside the corporate organizations. This will improve the quality and quantity in a shorter time and with minimal maintenance costs or even unnoticeable [222]. Further, the use of semantic tools and clear knowledge in industrial robotics is still in its early stage, with only a few other published examples [223]. In recent years, ontologies have been ofttimes used as a knowledge modeling method by many researchers [225].

Stenmark and Malec [40] provided a generic knowledge-based system architecture for industrial cobotic systems. They used their approach to represent and implement force-controlled tasks and creat composable representations of non-trivial assembly skills, which can be reused between different models of *ABB* [41] and *KUKA LWR4* [224] robots in an industrial setting.

Schou et al. [226] described the design and implementation of a proof-of-concept configurator with a graphical user interface aiming to help the user for selecting feasible configurations based on process and product input. To evaluate the feasibility of this framework, the authors examined the response of the configurator and determined the candidate list, skill list, and primitive list through three industrial assembly tasks. Results indicated that the configurator did produce the expected output within the defined scope.

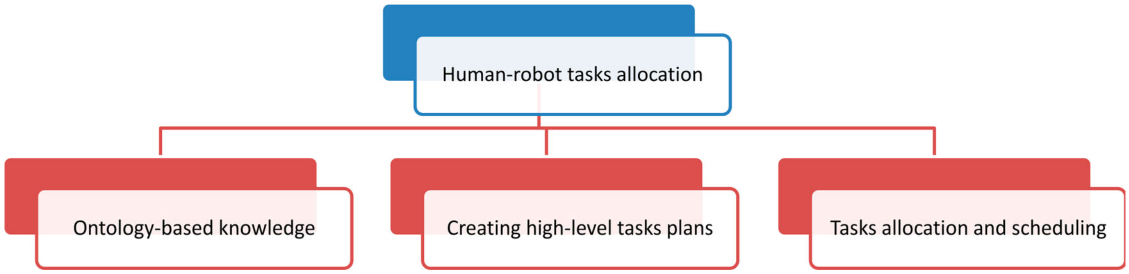

Figure 8. Sub-categories of *Human–robot task allocation approaches*.

3.5.2. Creating high-level tasks plans

Guerin et al. [227] designed a system for *Small and Medium Enterprise* (*SME*) that has useful capabilities for a wide range of tasks, powerful and easy to use, allowing grounded actions and capable of accumulating and abstraction reusing taught plans. In addition, the authors provided an extension of the *Behavior Trees* [228] to represent the capabilities of the robot system in form of a set of generalizable operations for the end user to create task plans. Additionally, the authors implemented this framework in *CoSTAR* (*Collaboration System for Task Automation and Recognition*) [229]. They demonstrated its effectiveness with two case studies of industrial tasks: (i) a complex tool-based object manipulation task in a laboratory setting, and (ii) machine tending task in an *SME* that was not possible with current off-the-shelf robots.

The authors in [67] developed a *Skill-Based System* (*SBS*) software which runs on *ROS* [304]. *SBS* is structured in four levels: (i) mission level, (ii) task level, (iii) skill level and (iv) motion primitive level. The operator can execute a task, which consisted of smaller predefined blocks called skills; for example, to execute '*place the object into the box*' task, *pick* and *place* skills are used. Consequently, the human can execute previously programmed tasks or create new tasks using available skills. This system has been applied on the *Kuka LWR4+* manipulator on the industrially task of screwing.

In another work, Pichler et al. [230] presented *XRob* platform for HRI, making it possible to build applications in an intuitive way. Using this platform, the operator can follow different levels of human-robotic autonomy that require customized interaction models. The researchers described how processes in industrial settings can be implemented with an increasing degree of autonomy from co-existence to collaboration with applications from quality inspection to collaborative manufacturing in the same workspace.

Additionally, the authors in [231] described the development of an architecture for interactive multi-modal industrial HRI to facilitate programming and allow easy adjustment of changes in robot task without needing skilled personnel. The programming approach offered, through the use of intuitive text programming interface and, hand-gestures and speech recognition, the ability to provide interactive feedback to the industrial robot at any specified time. The demonstrator checked the communication with the robot controller and the effectiveness of text and partial hand gestures in the multi-modal programming and execution approach, including the ability to interrupt commands preemptively. The user can express preferences for one or more interaction methods to suit the user's personal needs.

3.5.3. Tasks allocation and scheduling

In this field, another HRI aspect is related to decomposition, allocation to humans and robots, and scheduling manufacturing tasks to improve productivity and efficiency [232,323].

As specified by Gombolay and Shah in [233], the first step in designing such a system to coordinate the activities of the industrial cobot team is to understand the role of the human and that of the robot within the decision-making loop. As well, the decision-making authority should be shared on planning decisions among team co-workers and must include their preferences and competences [234].

Tsarouchi et al. [197] proposed a decision-making method that allows human–robot task allocation integrated within *ROS* [304]. This algorithm allowed *human-to-robot* and *robot-to-robot* sequential task allocation and cooperation in the shared workspace. This framework is implemented in the case of manual assembly lines for the automotive industry which concentrate on assembling hydraulic pumps by robots and humans. In another work [44], the authors described an approach for collaborative assembly tasks accomplished by an operator and a dual-arm robot in a shared workspace. The assembly sequence is modeled in a XML format generated off-line. The *COMAU dual-arm robot* is simulated using ROS for different modules to communicate and coordinate their actions through messages exchange [45].

The authors in [56] presented an approach to assign the assembly sequence tasks to the human or robot depending on product and process. They also implemented a simplified skills-oriented assembly sequence planning for autarkic and synchronized HRI operating modes. Their method was validated using an assembly process of the aircraft industry example.

Chen et al. in [235] examined a scheme for allocating tasks to humans and robots for cell manufacturing. In their approach, the evaluation and generation of alternatives were based on '*Dual GSPN Model*' (stochastic petri net).

Heydaryan et al. [324] studied HRI for the case of an automotive brake disc assembly. They used the *Analytic Hierarchy Process* (*AHP*) [236] as a decision-making approach and applied the detailed *Hierarchical Task Analysis* (*HTA*) [237] to allocate tasks to humans and robots.

The authors in [238] presented a method for task allocation in human and robot hybrid assembly systems. This approach selected an initial allocation pattern that can potentially minimize the expected total production costs while taking into consideration possible changes in the product models and the volumes demanded in the future [221].

3.6. Virtual & augmented reality

Most interfaces designed to control or program industrial cobots are complex and require special training for the user. This complexity, associated with a changing environment, has led to the absence of such systems from *SME*. Moreover, the costs of reprogramming and training the users of cobots exceed the initial installation costs [239]. Consequently, researchers have appealed other simpler and easier techniques and technologies: *Augmented reality* and *Virtual reality*.

In this trend, Nee et al. [240] concluded that *the use of virtual robot models enables the operators to program the robot by guiding the virtual models without having to interact physically with the real robots* [241].

3.6.1. Augmented reality

As the authors stated in [242], AR can help close the gap between product development and manufacturing operation. This can mainly be justified by the ability to reuse and reproduce digital data and knowledge while supporting human operators. It has been used in factory and assembly planning [240], assembly guidance [242,243], product design [244,245], etc.

Akan et al. [239] proposed an interface using AR and multi-modal HRI running on a mobile tablet device. They demonstrated that such an approach allowed easier handling of robots in industrial environments.

Additionally, Ibari et al. [128] presented a simulation and manipulation of a 6-dof manipulator using the kinematic model and an AR world. This system is based on a multi-modal user interface to overlay virtual objects on the real-world scene. The authors determined the camera pose in the AR system using *ARToolKit* marker detection method [306] and *OpenGL* library [307]. The analysis of the experimental results revealed that the system is effective in terms of accuracy and stability of the camera location using enhanced reality targets.

Makris et al. [155] presented an AR system to assist operators working in collaborative industrial environment by providing them with immersive assembly instructions along with necessary production information [152]. They used ROS topics and services [304] to exchange messages with the resources. Similarly, other researchers presented in [243] an AR system for visualizing assembly process, video and text-based instructions and production status updates. The system also provided a hardware landscape including the AR equipment and markers, hand-held devices and network infrastructure for interfacing the robot and the storage database. The developed systems have been applied to a case study from the automotive sector in executing different scenarios, improving the integration of operators in the assembly process.

3.6.2. Virtual reality

Gammieri et al. [42] provided a VR model to control a redundant manipulator in task and joint spaces and optimize HRI. The authors proposed a digital model for *KUKA LBR iiwa* redundant robot starting with kinematic modeling and then coupled with the real robot. Their approach allowed simulating HRI in several scenarios, to reproduce safe behavior on the real robot, as well as to train operators.

Matsas and Vosniakos [246] proposed the interactive and immersive *Virtual Reality Training System* (*VRTS*) to facilitate training operators of simple manufacturing tasks. In this study, '*beWare of the Robot*' system simulates real-time industrial-manipulators and humans cooperation with information feedback while considering safety issues (contacts, collisions, etc.).

Di Gironimo et al. [247] proposed an assembly process for trains based on VR technology which focused on human factors and their interaction with robots. The collision-free paths were planned for multiple robots in virtual environments while considering operator safety. Results showed that virtual simulation can improve the railway manufacturing system design not only in terms of time and cost but also in terms of quality improvement.

Andrisano et al. [17] designed and optimized a reconfigurable system through virtual prototyping and digital manufacturing methods, offering support to efficient HRI in hybrid industrial environments [9].

3.7. Study of physical interactions between humans

The introduction of cobots in industrial settings provides an opportunity to better understand humans interactions and perceptions. This will moreover help modernizing work in such workspaces and adapting humans to interact with robot co-workers in real manufacturing environments [248].

The authors in [254] studied human–human interaction to define the distance that humans prefer to keep from the robot during HRI. They concluded that this distance is equal to those that humans usually hold while interacting with unknown persons.

In [46], the researchers compared the performances of a robot assistant vis-a-vis human assistant during the delivery phase of fetch-and-deliver tasks. They concluded that a smooth HRI requires awareness and anticipation of intent by both actors. To this end, both humans and robots should communicate their status, location and intent, either explicitly through certain cues (audio or visual) or implicitly via their actions and motion paths [255]. For their experiments, they used the *Fraunhofer IPA Rob@Work platform* as an assistant.

Glasauer et al. [249] studied how hand-over tasks between humans are achieved without verbal communication. The authors confirmed that this simple task proved to be an excellent example of how humans interact effectively by predicting the outcome of actions, how to implement actions through smooth transitions instead of sudden sequences, and how continuous learning and adaptation together with reasonable a priori expectation shapes human interaction behavior. The results with humans as receiver and both humans and robots as delivering agent revealed that partner location and kinematics are used to increase confidence in predicting hand-over in time and space. The proposed decision-theory-based probabilistic model can simulate the results to predict timing of the next hand-over action depending on the task complexity. The results confirmed that for successful joint action, the robot must function in a predictable manner for the partner. Further, researchers investigated and implemented assembling tasks where industrial robots are considered as manufacturing assistants for humans using important aspects (continuous learning, natural hand-over position, human-like movement profiles, etc.) [250].

Charalambous et al. [252] identified a range of human factors that may influence HRI as well as evolving methodology for data collection and analysis to test the suitability of these factors for industrial contexts (level of trust of human to robotic teammate [251,253], etc.). Moreover, authors explored different types of production processes in terms of stage of maturity to test the validity of these factors. They also gathered data through a series of semi-structured interviews with shop-floor operators, engineers, system designers and management staff.

3.8. Fault tolerance

Fault tolerance is a central and critical problem facing the development of reliable cobotic systems [260]. It means the ability of the system to carry out assigned tasks despite any accidental failure that could happen to the system [256]. Additionally, both aspects, fault handling and fault-tolerant control, have to be considered as fundamental functionalities [257–259]. Fault tolerance is traditionally based on three main principles: *error detection*, *error diagnosis* and *recovery*.

Crestani et al. [260] studied the fault-tolerance paradigm for such industrial systems. Experience showed that industrial robots often fail because they are not designed to deal effectively with erroneous or unexpected situations. Although research studies exist, there is still a lack of a global approach that actually incorporated reliability, especially fault tolerance in such robots design and robotic control architectures. In addition, the authors arrived to the conclusion that different stages (prediction, detection, diagnosis and recovery) are rarely studied together, while joint design will improve the efficiency of each.

Additionally, a structured approach to integrating the principles of fault tolerance into the design of robot real-time control architecture to overcome the constraints has been proposed in [260]. The authors performed a failure mode analysis, obtained with *FMECA* (*Failure Mode, Effects, and Criticality Analysis*) [261], to identify and characterize the most appropriate defects: (i) *Fault detection* is based on dedicated software components to analyze faulty behaviors; (ii) *Diagnosis* depends on the residual principle and signature analysis to determine the defective software or hardware components and behaviors; and finally (iii) *Mechanism of fault recovery* is based on modality principle while integrating autonomy level adaptation.

4. Challenges and open issues of industrial collaborative robotics

Nowadays, cobotic systems have been developed to be able to exploit the capabilities of both humans and robots.

However, from this literature review, it can be clearly seen that there are several challenges for highly advanced HRI in industrial cobotics that still needs to be addressed. Most of them have been posed by the authors of the studied research works [325]. Figure 9 separates the most important open issues into different classes and subclasses:

4.1. Collaborative robots design

Contrarily to classical robot design, a cobot must be designed in such a way that it optimizes the quality of task execution, ergonomic situation of human co-worker [291] and assure his safety.

4.1.1. Design of industrial cobots

Different aspects must be taken into account when designing and building industrial cobots. The analysis of current standards, available techniques and human acceptance has identified many interdependent elements; the major challenges are given in the following [76,156]:

- action (manipulation, mobility),
- type of robot (dual arm, single arm),
- perception (environment, etc.),
- interaction (information exchange modalities, interpretation of perceptual cues, etc.),
- systems (mechatronics, control, software, cognition),
- payload, power and force,
- part characteristics (geometry, weight),
- end-effector and robot motion,
- sensors (torque, etc.),
- form, shape and material of mechanical components.

4.1.2. Development of new sensors and algorithms

As reported in [101], other limitations related to the design of new sensing technology, fast sensor fusion algorithms to track multiple moving targets in real-time, etc. still remain problematic to develop advanced industrial cobotic systems.

4.1.3. Social acceptance

Four key questions about social acceptance by human operators of industrial cobots raised; they can be outlined as follows [248]:

- social relationship that operators built with robots,
- attributions of positive and negative human-like characteristics to the robots,
- wide range of social interactions that workers have with the robots for problem-solving and coordinating work,
- worker responses to morphological and behavioral characteristics of the robot design.

4.1.4. Energy autonomy

Reducing the energy consumption for current industrial cobots is a priority in the development of green production and manufacturing systems. This will automatically reduce operating costs and CO_2 emissions. Hence, methods of reducing energy consumption of such robots and developing more energy-efficient manufacturing systems are required [292].

4.2. Safety and security

Safety and security issues related to industrial cobots should be introduced while developing control architectures [268] so as not to harm human co-workers during tasks accomplishment (handling, etc.). Despite the fact that this aspect has been tackled by numerous research studies so far [221] (as reported in Subsection 3.2), and some cobots (equipped with vision capabilities and force-sensing features) are considered safe enough to work alongside humans [99], it is still an open research field. In the next solutions, the design of intrinsically safe robots will focus on safety and sophisticated control will provide accuracy [264].

4.3. From industrial robots towards industrial cobots

According to [287,288], many millions of industrial robots are already deployed in manufacturing environments worldwide. Thus, instead of replacing all these traditional robots by safe cobots which will require colossal cost, it would be more attractive to develop technologies that can turn them into human-safe robotic systems with no hardware modifications [300]. Some tentatives were recently carried out on *ABB IRB-120* [287] and *Motoman SDA10F* [303] traditional industrial robots with no built-in safety systems.

4.4. Cognitive human–robot interactions

The cognitive interaction between humans and robots in cobtic systems still remains an important research topic as it is essential for accomplishing collaborative tasks in industrial settings.

4.4.1. Perception and interpretation of human behaviors

In order to efficiently realize operations with cobots, the first step consists of analyzing the human behaviors [294]. In addition, industrial cobots must be able to detect

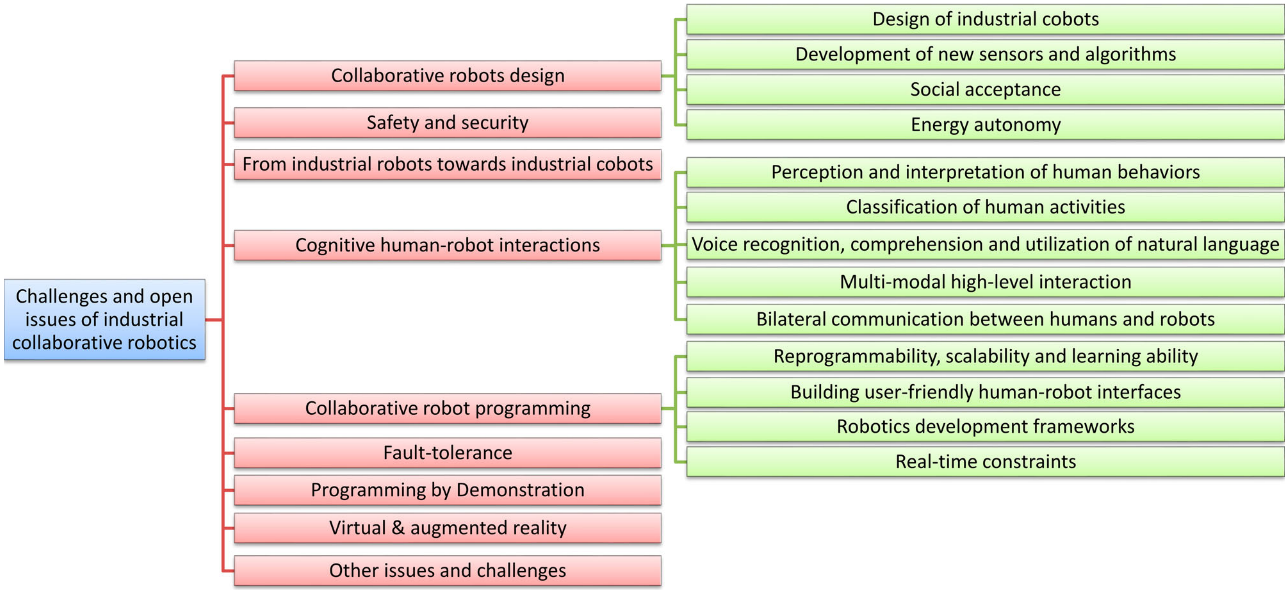

Figure 9. Different classes for the identified challenges and open issues of industrial collaborative robotics.

human presence, identify and determine requests based on body language, hand gestures, etc. A promising trend here consists of examining the markerless recognition; this will lead to better and more robust recognition since the correct visualization depends on the marker recognition [155].

4.4.2. Classification of human activities

Another extension would be to examine the classification of human activities that include interaction with other objects and subjects. This will be realized with an on-line learning/reasoning system [192]. Applied to the cobotic systems, the resulting ones will be better and more reliable.

4.4.3. Voice recognition, comprehension and utilization of natural language

It is clear that the use of natural language to interact with industrial cobots still remains an open issue. Some of these robots must identify the speaker, understand the sentences, appropriately and efficiently connect them to the physical world and identify commands and orders in the speech stream.

4.4.4. Multi-modal high-level interaction

Humans naturally interact with the world using multiple resources, simultaneously [301]. Consequently, it should be easier for them to interact with cobotic systems similarly. Hence, to facilitate HRI in such systems, it is essential to integrate many modalities with high-level interfaces to support robots programming and control and, to guide the humans in performing operations [269]. This can be done by incorporating voice commands which are concurrent with gestures [195], overlay virtual objects on the real-world scene [128], projection system and manual guidance [188], physical interaction and haptics, etc.

4.4.5. Bilateral communication between humans and robots

One of the major challenges in an industrial HRI is how to transfer information between the humans and robots using existing equipments and approved by security [286,298]. On the one hand, the data concern, for example, human's positions, his movements, behaviors, activities, etc. to be transferred toward the robot. On the other hand, the operator is able to know subsequent robot location or movement, to stay inside the workspace or to move away.

4.5. Collaborative robots programming

Cobots require fast and easy robotic systems programming. Additionally, the human operator is often not a robotics expert, and teach-pendant programming has become a time-consuming and demanding task to be performed [293].

4.5.1. Reprogrammability, scalability and learning ability

Industrial cobots should be reprogrammable machines, able of performing predefined tasks and learning to carry out new tasks by imitation and/or demonstration [302]. Moreover, these robots must be designed to be scalable; this means that new features can be integrated to their capabilities, new control algorithms can be tested, etc. without the need to modifying those already in place.

4.5.2. Building user-friendly human–robot interfaces

Most of the human–robot interfaces designed to control or program industrial cobots are complex and not easy-for-use [282]. In addition, these interfaces require special training for the user [239]. Moreover, the cobotic systems can be used by unqualified and unskilled persons who may have disabilities. Therefore, it is very important to develop more intelligent and natural interfaces for these robots to simplify their use and exploitation [265]. These interfaces should include the use of physical interaction objects, gesture-based interaction and, virtual and augmented reality to help interpreting data in a spatial context [158]. Finally, developers should carry out quantitative analysis of time and level of difficulties in the user operations [275] before deploying such control interfaces.

4.5.3. Robotics development frameworks

Despite the popularity of industrial cobots, many SME still hesitate with their adoption [69]. In addition, only few cobotic system have become commercially available. This is largely due to their long development process and high costs. Moreover, the fact that each manufacturer develops and uses its own operating systems, middlewares, and development tools, further complicates their development [37,299]. The use of open-source shared robotic development frameworks will significantly reduce the required development time and resources. This will also make the development of industrial cobots easier and and less expensive [283].

4.5.4. Real-time constraints

Real-time constraints are among the main requirements of HRI in industrial cobotics. If some computations exceed a specific barrier, the resulting behavior is indeterministic and can lead to system failures with unacceptable consequences [270]. These limitations are of key importance for recognizing human actions, the ability to detect multiple actions simultaneously, anti-collision approaches, control architecture, 3D vision, etc.

4.6. Fault tolerance

One of the major problems in the development of HRI in industrial cobotic systems is fault-tolerance paradigm [260]. This should integrate diagnostics and re-planning capacities and adapt the needs dynamically depending on the embedded resources and reliability. The fault-tolerance model has led to a great deal of research and study. Nevertheless, there is still a lack of a general approach that integrates this paradigm into the design of HRI and control architectures.

4.7. Programming by demonstration

Usually, the human behavior is very complex. Since *PbD* requires tracking his behaviors and actions, one single sensor is not enough. Consequently, more sensors (force, tactile, accelerometer, etc.) must be integrated and fused for more reliable and efficient *PbD* [38]. Moreover, since operator hands are supposed to be used for demonstrating the task, more interaction methods (voice, etc.) combined with machine learning and *Artificial Intelligence* (*AI*) are mandatory. Additionally, the future enhancement of *PbD* should include [289]: (i) use of voice to command the robot, (ii) use of visual programming techniques such as vision-based posture/motion recognition systems [273] and (iii) use of force/tactile sensors to control the robot [277].

4.8. Virtual & augmented reality

The development of industrial cobotic systems in a shared workspace that combines *VR* and *AR* continues to be an open problem. During the human–robot operation, humans will be able to obtain virtual objects, graphics instructions and information on the robot motion through AR/VR technology. Additionally, the robot will receive control commands from the human operator to help transfer virtual objects, etc. [152].

Finally, the types of HRI that can be realized highly depend on the progress in the computer vision domain [9]. Besides hardware-related limitations, there exist numerous software-based issues that still delay the spread of VR and AR technologies [38,242].

4.9. Other issues and challenges

HRI should be safe and efficient. This means that the robot should not injure the operator [48,279]. Additionally, imposed production constraints should be respected [170]. Other constraints and challenges related to industrial cobotic systems can be outlined as follows [101]:

- achieve robust detection of human motion to build good predictive systems,
- ensure robust detection of contact between robots and surrounding living agents in multiple points,
- develop fast responsive controllers that can re-plan trajectories in complex and cluttered environment in real-time.

5. Discussions

This literature review represents efforts to cover up the growing number of research on HRI, interfaces and solutions related to industrial cobots design and implementation. It reveals that researchers developed, and still developing very complex and sophisticated interaction systems.

To enhance the performances of existing manufacturing settings, several works investigated the integration of collaborative systems in which humans collaborate with robots in carrying out tasks. To this end, many issues need to be addressed. Some researchers [178,179,290] investigated essential standardizations to restructuring plants for accommodating changes, developing skills and training to assist the labor force for increasing productivity. Other works [147,151,287,288] presented solutions accompanied by a set of sensors (light beams, vision system, infrared system, etc.) to monitor human position in relation to robot. Other researchers [21,23,72,81,129] introduced hardware and software architectures while addressing a number of assembly-related issues (workspace optimization, compensation, position-based force control, etc.). Most of HRI works studied in this review used *AI* techniques to allow making user interaction, system configuration and performing tasks as profitable as possible [38]. Further, these techniques allow industrial cobots to share knowledge and access remote reasoning and computing, which rely on large amounts of data or computing power [280]. Additionally, they are needed to reduce the demand for programming time and system integration experience.

It is clearly seen that HRI can effectively contribute in developing future industrial factories, where humans and robots can share tasks and work shoulder-by-shoulder. To achieve this objectively, HRI should respect the following: *safety*, *flexibility*, *dexterity*, *perception* and *intelligence*. Indeed, the cobotic systems need to be safe, reduce human physical effort [276] and cognitive overload, and take advantages of the human gestures expertise. Further, cobots have to be flexible enough to handle mutable process and uncertainty, while being intuitive enough to be set and programmed by non-robotic experts [66].

Noted that a great number of studied works dealt with safety and security in cobotic systems using different technologies and approaches (e.g., light-weight robots with collision detection features, safeguarding and complementary protective measures [272] and energy limitation). This can be justified by the fact that, to interact with robots and perform tasks side-by-side, traditional established safety procedures and workspaces separation between robots and humans were removed, which represents a big hazard to all humans in the robots vicinity. Additionally, when humans need to physically interact with robots, the standard of normal and effective performance is based on their daily experience interactions with humans. This goal is still far away to be achieved, despite the great advances in HRI [249].

To summarize, present trend in industrial cobotics is to obtain flexible systems in which humans and robots can safely interact to achieve assigned tasks. This will encourage industrials to integrate such cobotic systems in current factories. As in [295], cobots will be of a paramount importance in incoming years, such a technology will become the dominate one in next decades for some selected applications and fill parts of the remaining 90% of workstations [70].

6. Conclusion

Human–robot interaction in industrial collaborative robotics has received significant attention in this last decade since it represents a very important research field. This paper presented a literature review and proposed a tentative classification (into many categories/subcategories) of major works and recent research realized in this area between 2008 and 2017. For each selected article, the problem, proposed approach, main obtained outcomes and future works are summarized. The review indicated that this theme got much consideration from academia during this period. The authors also noticed that a large gap exists between the carried research and deployed efforts in the real industrial environments, to bring laboratory-based cobotic technology to smart factories. At the end of the paper, some challenges and issues faced by researchers dealing with human–robot interaction in industrial cobots were identified and highlighted.

Disclosure statement

No potential conflict of interest was reported by the authors.

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