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A Systematic Review of Augmented Reality Interfaces for Collaborative Industrial Robots

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Abstract

Industry 4.0 is moving factories towards a high level of collaboration between human workers and industrial robots, with the aim of improving efficiency and productivity. Among other technologies, Augmented Reality (AR) is one of the most researched in recent years to provide novel user interfaces that could easily blend the real world with additional information. This literature review aims at identifying the main strengths and weaknesses of AR with industrial robots in human-robot collaborative scenarios. The term industrial robot is meant according to the ISO 8373:2012 definition. To this end, starting from 3734 initial works, 63 papers have been selected and analysed. The results suggest that AR technology shows its effectiveness also in this particular domain. With respect to traditional approaches, AR systems are faster and more appreciated by users. Nonetheless, the use of AR in human-robot collaborative scenarios is so cutting edge that not all the considered works have properly evaluated the proposed user interfaces. Future research should improve the qualitative evaluation in order to clearly point out both limitations and strengths of the proposed systems, involving also expert users in tests.

Keywords: Augmented Reality, Human-Robot Collaboration, Collaborative Robot, Industrial Robot, User Interface

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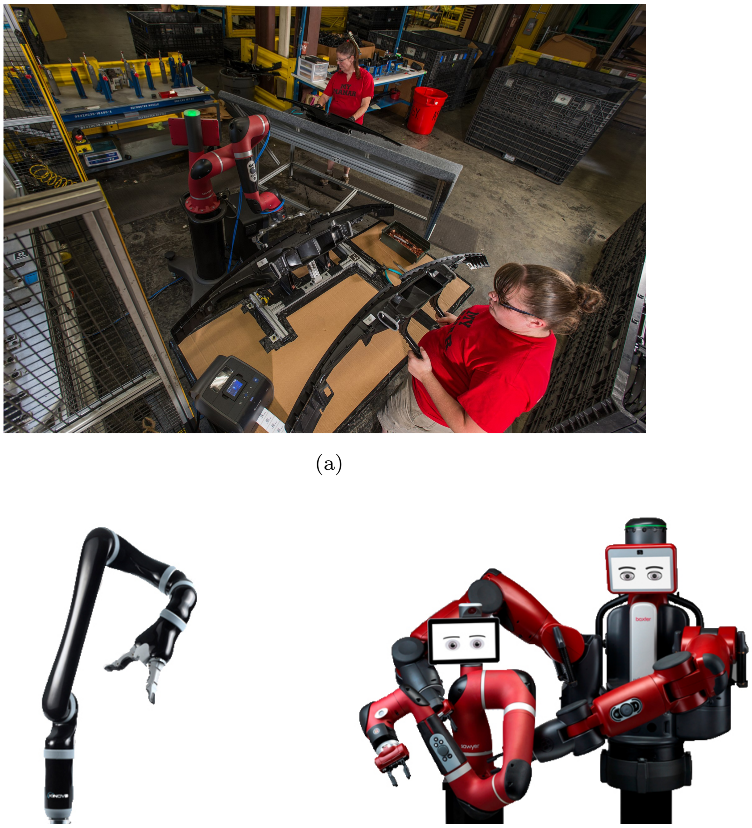
1. Introduction

The fourth industrial revolution is changing the very nature of factories: in order to manage the demand of innovative products and to cope with an increasingly competitive market, industries are expected to keep a high level of production without decreasing their overall quality. Industrial robots, *automatically controlled, reprogrammable, multipurpose manipulators, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications* [1], can be effectively employed on the production lines to meet these requirements. Their high precision and velocity make them a fundamental element of the productive processes.

Since the capabilities of the industrial robots are steadily improving, the degree of collaboration between human operators (HOs) and robots is expected to increase in order to enhance the manufacturing processes (Fig. 1 shows a collaborative robot working side-by-side with human operators and two examples of collaborative robots).

Creating a collaborative environment suitable for both HOs and industrial machines is a challenging goal. Lemoine et al. [2] highlight that the human-machine collaboration involves two different dimensions: the *know-how* (KH) and the *know-how-to-cooperate* (KHC). The former refers to the agent's (human or machine) capability to control a process, the latter to the agent's ability to cooperate with other agents. KH and KHC are linked in a shared space where agents can exchange information and data using different interfaces (e.g. audio, haptic) [3]. Since in such a space humans and machines are in close contact, humans should find acceptable to work with machines if the task to be shared is well defined and there are no safety concerns for the operators [4]. Moreover, in order to properly cooperate, agents should be able to recognize each other's intentions, to adapt their own actions to the partners' goals [5]. Thus, the development of new interaction paradigms should be pursued to allow technicians to safely carry out their tasks near industrial robots, highlighting the role of each agent to avoid any possible concerns that can affect the collaboration



(a)

(b)

(c)

Figure 1: (a): the collaborative robot Sawyer on the factory floor at Tennplasco in Lafayette, TN. Credits to Jeff Green/Rethink Robotics / CC BY 4.0. (b): the Kinova collaborative robot. Credits to Mgomezrobotnik / CC BY-SA. (c): the Sawyer and Baxter collaborative robots. Credits to Jeff Green/Rethink Robotics / CC BY.

between machines and humans (see [4] for a discussion related to the ethical risks of human-machine cooperation in Industry 4.0). Human-Robot Collaboration (HRC) seeks to improve the collaboration between humans and machines through the development of innovative user interfaces. Several technologies can be used to enhance the collaboration between HOs and robots [6]: as an example, Gely et al. [7] combine visual and text-to-speech technologies to cooperate during a maintenance of an autonomous train as well as Lemoine et al. [8] propose a brain-computer interface to control a mobile robot. Among these different interfaces, Augmented Reality (AR) results to be an effective technology to improve the collaboration [9].

AR dates back to the sixties when Sutherland developed the first acknowledged AR prototype [10]. However, the fundamental ideas of Sutherland's novelty were only formalized in the nineties. In [11], the Mixed Reality continuum was introduced by Milgram and Kishino. Since AR devices are part of this continuum, they allow users to augment the real environment using virtual assets. Technological improvements have lowered the production costs of AR devices and AR has begun to be used in several scientific areas. Smartphones and tablets are assembled with sensors required by AR applications and they are equipped with processing units powerful enough to display in real-time computer-generated contents. Technological innovations developed for the hand-held devices have been applied to improve AR ad-hoc portable equipment, commonly called Head Mounted Displays (HMDs) or wearable devices. It is currently possible to find several wearable AR devices on the market, the most known are the Vuzix Blade 3000 AR glasses[1], the Meta 2 AR headset[2], the Moverio BT-300[3] or the Microsoft HoloLens[4] glasses. It is expected that through 2021, 67.2 million of HMD devices will be sold[5] and the AR market will increase from $5.91 billion to more than $198 billion[6]. The AR technology should reach the plateau of productivity in 5-10 years[7], thus it is expected that AR will be effectively adopted in the Industry 4.0 domain. Due to this spread, AR technology has started to be used to improve the interaction and the collaboration with industrial robots, creating new interaction paradigms based on innovative user interfaces.

The use of industrial robots is continuously increasing. It is expected that

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[1] `https://www.vuzix.com/Products/Series-3000-Smart-Glasses`

[2] `http://www.metavision.com/`

[3] `https://tinyurl.com/ybo5ac4d`

[4] `https://www.microsoft.com/it-it/hololens`

[5] `https://tinyurl.com/y64scp8z`

[6] `https://tinyurl.com/y32v35ru`

[7] `https://tinyurl.com/y5csl8wf`

there will be more than 1.4 million of active industrial robots by the end of 2020 [12]. Thus, the development of new technologies should be pursued in order to give technicians the capabilities to properly interact and cooperate with industrial manipulators. Since during a cooperative task HOs and robots share the same workspace, humans should be aware of the robot intentions to trust them. Moreover, they also necessitate to be able to control the robot receiving an immediate feedback on the control itself. The amount of papers collected for this work seems to confirm that AR can be employed to meet these requirements. In [13], the usage of AR in the whole Industry 4.0 is addressed and a brief section is dedicated to AR for programming robots. Villani et al. [14] discussed in depth the whole HRC context, giving also an overview of the current AR technologies used to collaborate with industrial robots. However, due to the increasing interest of both academic and industrial research centres in the use of AR technologies with industrial robots, this new research area deserves a more in-depth analysis to clarify the current state of the art. Although this research context is so cutting edge that it is still not always possible to collect complete and consolidated results, it is interesting to analyse what has been done in research so far to truly identify which are the strengths and weaknesses of the use of AR systems with industrial manipulators[8] and to foresee the future developments.

Starting from a rigorous definition of the meaning of the term *collaboration* and clearly indicating the methodology we have adopted for collecting the papers, this article proposes a systematic literature review of AR interfaces for industrial robots in collaborative environments.

2. Definitions

The term *collaborative robot* is being increasingly used to indicate “a robot that can work side by side with humans”. Considering that this definition

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[8] In this work, the terms *industrial robot*, *manipulator*, *robot*, *robotic arm* are interchangeably used to refer to a generic industrial robot arm.

is too vague to give a precise description of the human-robot collaboration concept, a more accurate definition is presented. In 2011, the International Organization for Standardization (ISO) [15] provided some regulations to define both the safety requirements for industrial robots and the concept of collaboration in the European Union. The ISO 10218, part 1 and part 2 [16, 17], defines the guidelines for the use of industrial robots: "*[...].It describes the basic hazards associated with robots and provides requirements to eliminate, or adequately reduce, the risks associated with these hazards*". Moreover, for the first time the concept of collaborative robot along with two other important terms, collaborative operation and collaborative workspace, appeared. In 2016, in order to provide a standard definition of the above terms, the technical specification document ISO/TS 15066 [18] has been integrated into the ISO 10218. This regulation specifies the "*safety requirements for collaborative industrial robot systems and supplements the requirements and guidance on collaborative industrial robot operation given in ISO 10218 1 and ISO 10218 2*". It is important to notice that both ISO 10218 and the ISO/TS 15066 "*apply to industrial robot systems and they do not apply to non-industrial robots, although these principles can be useful for other areas of robotics*" [16, 17, 18]. The collaborative robot, operation and workspace are defined as follows [18]:

- "*A collaborative robot is a robot that can be used in a collaborative operation*";
- "*A collaborative operation is a state in which purposely designed robots work in direct cooperation with a human within a defined workspace*";
- "*A collaborative workspace is a workspace within the safeguarded space where the robot and human can perform tasks simultaneously during production operation.*

Since the HO and the robot share the same workspace, the so called "collaborative work space" (CWS), a list of possible collaborative operations has been chosen to reduce risks when humans and robots work closely together. A collaborative operation has to use at least one of the following techniques [18] (Fig. 2):

1. “*Safety-rated monitored stop*”: if the worker is in the CWS, the robot cannot move;
2. “*Hand guiding*”: HO controls the robot with an input device;
3. “*Speed and separation monitoring*”: as the distance between the robot and the worker reduces, the speed of the robot reduces too;
4. “*Power and force limiting*”: contact between the human and the robot is allowed.

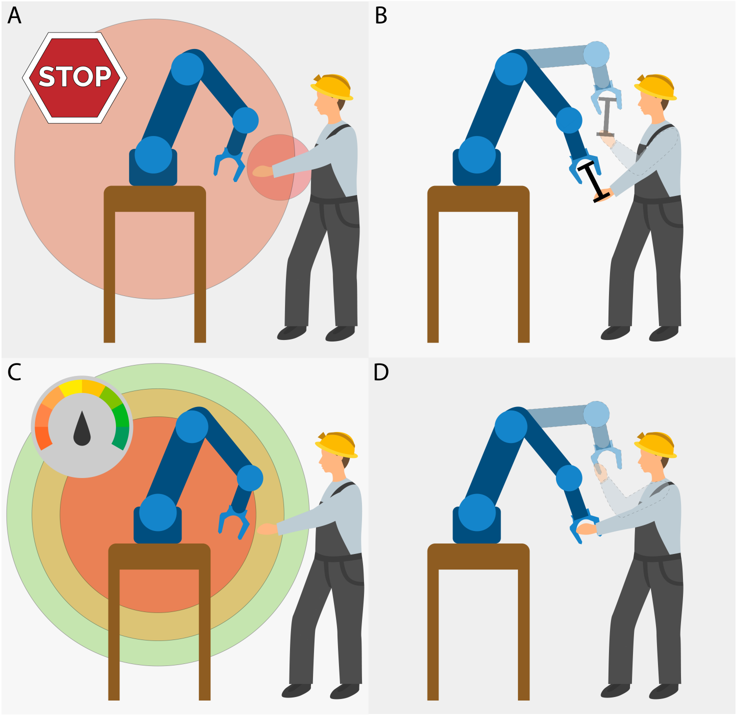


Figure 2: A: safety-rated monitored stop. B: hand guiding. C: speed and separation monitoring. D: power and force limiting.

One of the most important consideration is that a collaborative operation is not determined by the robot itself, it is defined by the task and the working space. Guided by this criterion, papers that explicitly confirm the adoption of the ISO standard and those that present tasks and/or working spaces that can be considered suitable for a human-robot collaborative operation have been taken into consideration for this literature review (the concept of collaborative robot or cobot appeared for the first time in literature in 2001, see section 3.3).

3. Methodology

In order to assess the current use of the AR technologies in human-robot collaborative operations, a Systematic Literature Review (SLR) approach has been adopted. Booth et. al [19] defined the SLR approach as a *"systematic, explicit, and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work made by researchers, scholars, and practitioners"*. The SALSA Framework [20] can be adopted to classify the current state of the art of a particular technology. It ensures replicability of the study and it helps to categorize and analyse the reviewed articles. It is composed by 4 different steps that are summarized in Table 1. It also presents the methodology that has been adopted in each step along with the expected outcome.

Step	**Outcome**	**Method**
Protocol	Scope	PICOC Framework
Search	Potential Data	Literature Search
Appraisal	Selected Data	Selected Data Evaluation
Synthesis and Analysis	Data Taxonomy	Data Features Extraction and Analysis

Table 1: The adopted SALSA Framework.

3.1. Step 1 - Protocol

The protocol step implies the definition of the research scope. Since the PICOC Framework has been already employed in similar works [21, 22, 23] and it has been identified as a useful strategy to determine the main research areas for a SLR [19], it has also been adopted for this work. The PICOC Framework is shown in Table 2. Each PICOC area is presented and briefly described. The main outcome of the PICOC Framework employment is presented in the form of research questions:

1. Q1: what are the main uses of AR technologies in the HRC context?
2. Q2: what are the main strengths and weaknesses of the AR technologies in the HRC context?
3. Q3: what are the potential future developments of AR technologies in the HRC context?

Area	**Description**
Population	AR technologies for the HRC area
Intervention	Tools and techniques for the use of AR with robotic arms
Comparison	Differences among different techniques
Outcomes	Quantitative and qualitative performance indicators
Context	AR technologies in the Industry domain

Table 2: The PICOC Framework used in this SLR.

Having defined the main goals of this SLR, the paper collection procedure and the analysis of the selected works are introduced in the following sections.

3.2. Step 2 - Search

In this step, the search of the potential data is performed. It consists in the definition of the potential databases and the search string. Among all the different available databases (Google Scholar, IEEE Xplore Digital Library, Science Direct, etc.), it has been decided to narrow the search down to only the Scopus database. The reasons behind this choice are the following:

- It provides a high customization degree of the search strategy;
- It encompasses several digital libraries such as IEEE, ACM, etc. Hence, it provides a basis selection.
- It provides all the research papers that are Scopus indexed.

Search String	**Database**	**Date**	**Found**
TAK(robot OR cobot OR manipulator OR automaton OR operator) AND TAK(collaborat* OR interact* OR coaction OR cooperat*) AND TAK(“augmented reality” OR projecti* OR projected OR “see-through” OR “hand-held” OR “mobile device” OR “personal device”)	Scopus	15/10/2019	3734

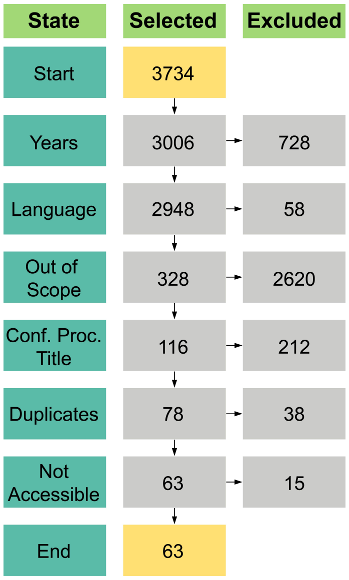
Table 3: The search string and the initial number of collected papers.

The search string has been constructed on the basis of the requirements obtained in 3.1. Starting from three main key-words *Augmented Reality* - *Collaboration* - *Robot*, the search string has been constructed using all possible combinations of the key-words synonyms and it has been applied to the Title, Abstract and Key-words (TAK) fields of each paper. Table 3 shows the search string and the number of initially collected papers. Due to the great number of collected papers, a selection criterion has been applied in Sec. 3.3 to discard all works not related to the research scope.

3.3. Step 3 - Appraisal

The appraisal step involves the selection and evaluation of the collected papers. As stated in [22, 23], the main goal of a quality assessment procedure is to identify a paper selection criterion in case two or more studies present quite similar approaches or conflicting ideas/results. In order to make the selection process repeatable, a set of pre-determined exclusion criteria has been defined. The six different criteria are the following:

- Years: papers dated before the 2001 have been excluded. This year has



State	Selected	Excluded
Start	3734	
Years	3006	728
Language	2948	58
Out of Scope	328	2620
Conf. Proc. Title	116	212
Duplicates	78	38
Not Accessible	63	15
End	63	

Figure 3: The selection procedure along with the excluded papers.

been chosen because the first paper related to the concept of collaborative robot has been published in 2001 [24];

- Language: papers written in languages different from English have been excluded;
- Not Accessible: papers not accessible have been excluded;
- Duplicates: duplicated papers have been excluded;
- Conference Proceeding Title;
- Out of Scope: papers that are not concerned with the use of AR technologies with a robotic arm in a collaborative environment for the industry domain have been excluded.

Starting from 3734 initial papers, a set of 63 relevant works has been selected (see Fig. 3).

Afterwards, a quality assessment procedure has been applied to evaluate the selected papers. Table 4 shows the Quality Criteria (QC).

Quality Criteria	**Name**
QC1	Q1 or Q2 Journal
QC2	Full Paper
QC3	Test
QC4	Citations/Year
QC5	State of the Art

Table 4: Quality criteria applied to the 63 papers selected for the SLR.

For QC1 and QC2 a score equal to 0 or 1 has been assigned depending on whether:

- QC1: the paper has been published in a Q1 or Q2 journal or not (Q1 and Q2 are the quartile scores);
- QC2: the paper is composed by more than 3 pages or not.

The QC3 score is represented by a number between 0 and 1 that describes whether a paper has performed tests using unskilled or expert users and collecting objective or subjective parameters. It is worth noticing that in this quality assessment an expert user is defined as a user expert in the domain for which the AR system has been implemented. The QC3 score has been computed as:

$$QC3_i = (U_i + E_i + OB_i + SUB_i)/4, i = 1, ...N,$$

where N is the number of selected papers, U and E represent the fraction of unskilled and expert users with respect to their maximum number, OB and SUB indicate whether a paper has collected objective or subjective parameters. The U and E values are numbers between 0 and 1: they are proportional to the number of unskilled (NU) and expert (NE) users employed to evaluate the proposed system. U and E have been computed as:

$$U_i = \frac{NU_i}{max_{NU}}; E_i = \frac{NE_i}{max_{NE}},$$

where max_{NU} and max_{NE} represent the maximum number of unskilled and expert users among all the collected papers, respectively. For OB and SUB

a score equal to 0 or 1 has been assigned depending on whether a paper has collected objective (OB) or subjective (SUB) parameters.

Concerning QC4, the number of citations per year c_i has been calculated as:

$$c_i = \frac{C_i}{Y},$$

where C is the total number of citations and Y represents the number of years since the date of publication. Then the maximum number of citations mc has been computed. Finally, a score ranging from 0 to 1 for each paper has been determined as:

$$QC4_i = \frac{c_i}{mc}.$$

Regarding QC5, papers have been manually analysed and it has been selected the paper with maximum number of references mr, equal to 67. Then the QC5 score has been computed as:

$$QC5_i = \frac{r_i}{mr},$$

where r_i is the number of references of the ith paper.

In Table 5, the final result of the QC process is presented.

Paper	**QC1**	**QC2**	**QC3**	**QC4**	**QC5**	**Quality**
[25]	1	1	0.25	0.79	0.49	3.53
[26]	1	1	0.75	0.24	0.51	3.50
[27]	1	1	0	0.71	0.66	3.37
[28]	1	1	0.25	0.07	1	3.32
[29]	1	1	0	1	0.31	3.31
[30]	1	1	0.25	0.33	0.67	3.25
[31]	1	1	0.58	0.07	0.4	3.05
[32]	1	1	0.25	0.27	0.48	3.00
[33]	1	1	0.25	0.29	0.4	2.94
[34]	1	1	0.25	0.07	0.45	2.77
[35]	1	1	0	0.05	0.63	2.68
[36]	1	1	0	0	0.64	2.64

[37]	0	1	0	0.71	0.72	2.43
[38]	0	1	0.55	0.18	0.69	2.42
[39]	1	1	0	0.12	0.24	2.36
[40]	0	1	0.53	0.5	0.31	2.34
[41]	0	1	0.56	0.5	0.25	2.31
[42]	0	1	0.67	0.29	0.24	2.20
[43]	0	1	0	0.91	0.28	2.19
[44]	0	1	0.79	0.14	0.25	2.18
[45]	0	1	0.57	0	0.61	2.18
[46]	0	1	0.62	0.04	0.39	2.05
[47]	0	1	0.57	0.07	0.39	2.03
[48]	0	1	0.53	0.21	0.25	1.99
[49]	0	1	0	0.39	0.54	1.93
[50]	0	1	0	0.18	0.75	1.93
[51]	0	1	0	0.14	0.78	1.92
[52]	0	1	0.55	0.14	0.19	1.88
[53]	0	1	0.25	0.23	0.39	1.87
[54]	0	1	0.33	0.14	0.36	1.83
[55]	0	1	0.29	0.41	0.1	1.80
[56]	0	1	0.53	0	0.22	1.75
[57]	0	1	0.28	0.06	0.31	1.65
[58]	0	1	0.3	0.07	0.28	1.65
[59]	0	1	0.25	0.09	0.3	1.64
[60]	0	1	0.5	0.03	0.09	1.62
[61]	0	1	0.25	0	0.33	1.58
[62]	0	1	0	0.21	0.36	1.57
[63]	0	1	0	0.2	0.36	1.56
[64]	0	1	0.25	0.18	0.13	1.56
[65]	0	1	0.27	0.07	0.21	1.55

[66]	0	1	0	0.21	0.34	1.55
[67]	0	1	0	0.18	0.36	1.54
[68]	0	1	0	0.06	0.48	1.54
[69]	0	1	0	0.37	0.15	1.52
[70]	0	1	0.25	0.12	0.12	1.49
[71]	0	1	0	0.25	0.24	1.49
[72]	0	1	0.25	0.08	0.16	1.49
[73]	0	1	0	0.15	0.3	1.45
[74]	0	1	0.25	0.01	0.16	1.42
[75]	0	1	0	0.17	0.21	1.38
[76]	0	1	0	0	0.3	1.30
[77]	0	1	0	0.04	0.25	1.29
[78]	0	1	0	0	0.25	1.25
[79]	0	1	0	0	0.19	1.19
[80]	0	1	0	0.04	0.15	1.19
[81]	0	0	0	0.27	0.07	0.34
[82]	0	0	0	0.24	0.07	0.31
[83]	0	0	0	0.14	0.03	0.17
[84]	0	0	0	0.07	0.09	0.16
[85]	0	0	0	0.04	0.1	0.14
[86]	0	0	0	0	0.12	0.12
[87]	0	0	0	0	0.04	0.04

Table 5: The result of the quality assessment procedure. Papers are ordered by quality decreasing score.

3.4. Step 4 - Synthesis and Analysis

The synthesis and analysis step involves the classification and the examination of the selected papers. In order to analyse and extrapolate data relevant for the research scope, the 63 selected papers have been divided according to the use of the AR contents. Three different macro-areas have been identified called Workspace, Control Feedback and Informative, respectively (Fig. 4).

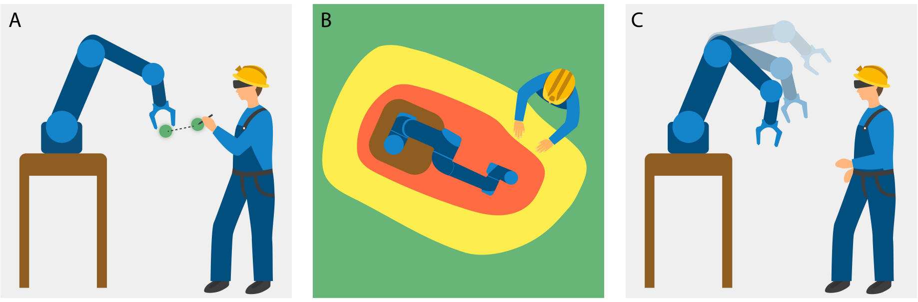


Figure 4: Image A: the Control Feedback category. A technician is designing a new path using AR technologies. Image B: the Workspace category. A technician can visualize several typologies of safety zones of the workspace. Image C: the Informative category. A technician can foresee the future motions of an industrial manipulator.

The Workspace category is composed by works that use AR contents to display the area occupied by the manipulator. The main objective consists in ensuring a safe working space, highlighting the possible collision areas with the robot. The Control Feedback category comprises works that utilize AR assets to give feedback to the users when they are actively interacting with the industrial manipulator. The primary role of these AR contents is to inform the user whether the robot or the system itself has clearly understood the user input. Lastly, the Informative category illustrates works that apply AR technologies to visualize general information regarding the industrial robot or the task itself.

Using the aforementioned classification, papers have been deeply analysed in order to find answers related to the research scope. Since this analysis involves a considerable amount of papers, it has been decided to not present it in this subsection but to introduce it in the following section.

4. Data Taxonomy

In the following sections, each macro-category is presented and analysed.

4.1. Workspace

The Workspace papers have been divided into two subcategories:

- AR systems for relatively small-size environments and manipulators;
- AR systems for large-size environments and manipulators.

In the following sections, these two subcategories are introduced and analysed.

4.1.1. Large Size Environments and Manipulators

Large Size					
Paper	**Tracking**	**Device**	**Category**	**Year**	**Quality**
[28]	Marker	Wearable	Large Size	2018	3.32
[29]	Marker	Wearable	Large Size	2016	3.31
[36]	Marker	Wearable	Large Size	2019	2.64
[43]	Marker	Wearable	Large Size	2016	2.19
[82]	Markerless	Projected	Large Size	2016	0.31
[83]	Markerless	Projected	Large Size	2017	0.17

Table 6: Papers of the Large Size Workspace category.

Table 6 shows the Large Size Workspace category. Works in [28, 29, 36] present a system in which a HO can collaborate with a high payload industrial robot in a fenceless environment.

In [28], a technician can cooperate with a manipulator by using a manual guidance system and a smart-watch interface. In addition, the 3D robot working areas can be visualized by using a wearable AR device. The working areas have been represented by using different colours (red and green) to highlight the robot working area and the user's safe working area, respectively [29]. The system has been tested in a human-robot collaborative automotive assembly scenario and the results show that the proposed AR system allows a considerable cycle time reduction, passing from a 92.15 seconds to 76.31 seconds. An extension of this work can be found in [36].

Although 3D virtual metaphors may be useful to represent some particular volumes, their effectiveness strictly depends on the characteristics of the hardware used to visualize them. Wearable devices are still affected by a limited Field-of-View (FoV) that prevents to clearly detect 3D assets in the real space. Thus, other approaches involve the use of 2D projected systems that do not force users to wear any particular device. Two interesting approaches are proposed in [82, 83].

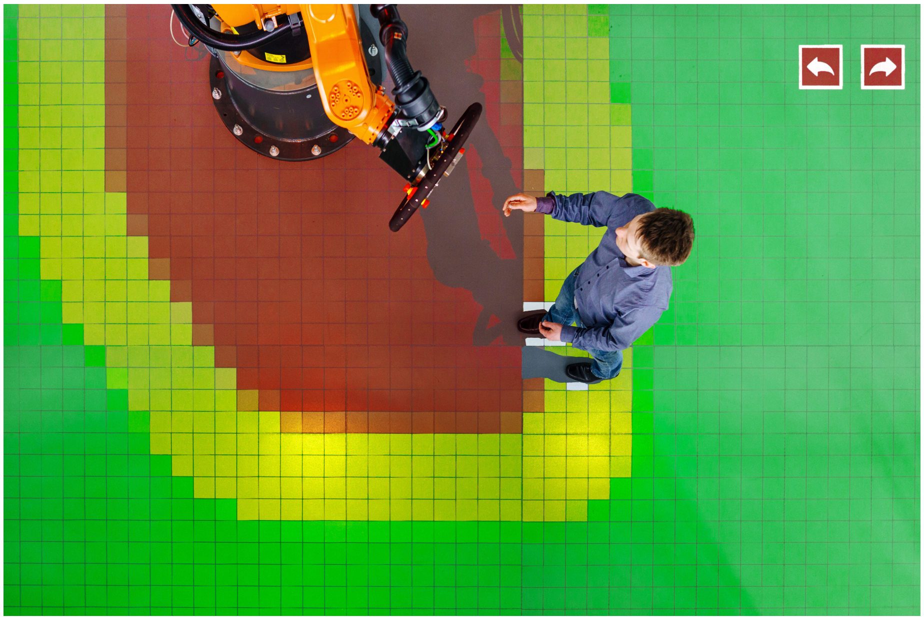


Figure 5: If the human operator enters the warn zone (yellow colour), the robot decreases its velocity to avoid any possible hazard. As the human operator gets in the critical zone, the robot movement is immediately stopped. Figure published in [83], credits to Stephan Deutsch / Fraunhofer IFF.

In [82], a projection system capable of displaying static safety zones in a large environment is proposed. The system is composed of a tactile floor connected to a projection system. The tactile floor has been divided in three static zones, called *free*, *warn* and *critical* zone, respectively. Since the tactile floor continuously monitors the movement of the HO, the system is capable of detecting in real-time in which zone the worker is entering. Four DLP projectors have been employed to display the three static zones on the tactile floor. Moreover, each zone is coloured differently, using green (free zone), yellow (warn zone) and red (critical zone) colours. In order to project dynamic zones that can change their shapes in real-time according to the motion of the industrial manipulator, the monitoring of the values of the robot joints has been added in [83]. Thanks to the data acquired by the tactile sensors and by the robot encoders, the projection system is able to modify the shape of the safety zones according to the movement of the manipulator (a video of the dynamic safety system is available at[9]). Moreover, the velocity of the robot movement changes according to the robot-HO distance until the HO enters the critical zone and the robot movements are immediately stopped. Figure 5 shows a top-view of the AR workspace system.

4.1.2. Small Size Environments and Manipulators

Small Size					
Paper	**Tracking**	**Device**	**Category**	**Year**	**Quality**
[64]	Markerless	Projected	Small Size	2013	1.56
[69]	Markerless	Projected	Small Size	2012	1.52
[71]	Markerless	Projected	Small Size	2017	1.49
[72]	Markerless	Projected	Small Size	2012	1.49
[81]	Markerless	Projected	Small Size	2013	0.34

Table 7: Papers of the Small Size Workspace category.

Table 7 shows the Small Size Workspace category. Regarding the visualization of small-size robot workspaces, Vogel et al. [69] developed a dynamic safe AR system based on projection and vision technologies. The system relies on the use of a projector that emits a beam of light towards a surface and on the adoption

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[9] `https://youtu.be/sykfaMuuVEI`

of a camera to acquire the reflected beam. The projector is capable of drawing a dynamic 2D cell that can modify its shape over the time.

The proposed system has been adopted in [72, 64, 71] to monitor and to visualize the volume occupied by a medium-size robotic arm. In [72], a projected system based on the principle of the light barriers is proposed. The pixels of the projector are used as barriers and when objects enter in their emitted light, a safety violation is raised in 125ms (in the worst case). In addition to using the light barriers, a safety area around the manipulator is dynamically determined by employing the robot joint positions and velocities in [64]. A 3D bounding-box that contains the robot is computed and then projected on the workspace area. Hence, human operators can visualize in real-time the 2D projected robot workspace directly in the real environment. Finally, in [71], the area that encloses the object that has to be manipulated during the collaborative task and the area that separates the robot from the human operator are considered in addition to the robot workspace (Fig. 6).

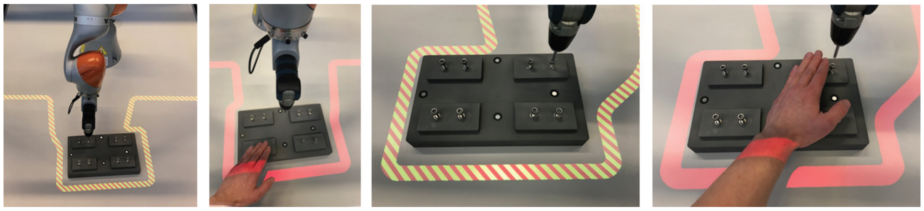

Figure 6: When the human operator violates the working area while the robot is operating, the robot movement is suddenly stopped and the colour of the projected safety zone is changed to red. Figure published in [71], licensed under CC BY-NC-ND 4.0.

4.2. Control Feedback

The Control Feedback category comprises papers regarding the use of AR assets as a feedback on an active input. In this work, an *active input* is defined as: “*the action exerted by the user with the purpose of interacting with the industrial manipulator placed in the same workspace*”.

From the aforementioned definition, it is straightforward that remote-telerobotic operations are not included in this analysis. Although it is possible to find several relevant works concerning the use of AR for the remote control of an industrial robot ([88, 89, 90, 91, 92, 93, 94, 95] or more recently [96, 97]), remote-telerobotic concerns the control of a robot from a distance. Hence, it is not suitable for operations that depend on sharing the same environment.

In the Control Feedback category, the AR assets are mainly employed to have a feedback on:

- path: it consists into a feedback on a set of connected points generated by the user;
- input recognition: it consists into a feedback on a generic user input.

In the following sections, the path and input recognition feedback are discussed.

4.2.1. Path

Table 8 shows the path Control Feedback papers. It can be noticed that the desktop and projected interfaces are the two most used visualization systems.

Concerning the desktop interfaces, several works employed a fixed camera and custom probes to define virtual paths [73, 25, 63, 33, 27, 59, 30, 38, 32]. In [73] the methodologies to control a robotic arm using a flat image-based probe with a desktop AR interfaces are introduced and evaluated in an emulated environment. Then a heuristic beam search algorithm is introduced in [25] to provide users the ability of easily create an AR path using virtual spheres. Moreover, a virtual asset of the industrial manipulator is rendered to allow users to figure out whether the manipulator is capable of reaching the generated path. If a point that is not reachable by the end-effector (EE) is generated, the virtual sphere colour is changed to red to warn the user. Fang et al. [63] showed that these types of AR interfaces may be largely affected by the employed tracking system's accuracy, bounded between 10 to 15mm. In [33], a Piecewise Linear Parameterization algorithm is introduced to parameterize the curve generated by the users. It allows to generate a smooth curve, not affected by the velocity with which users move the probe. In [27], the flat image target has been replaced

Path					
Paper	**Tracking**	**Device**	**Category**	**Year**	**Quality**
[25]	Marker	Desktop	Path	2009	3.53
[27]	Marker	Desktop	Path	2012	3.37
[30]	Marker	Desktop	Path	2014	3.25
[31]	Marker	Wearable	Path	2020	3.05
[32]	Marker	Desktop	Path	2015	3.00
[33]	Marker	Desktop	Path	2010	2.94
[38]	Marker	Desktop	Path	2015	2.42
[44]	Markerless	Wearable	Path	2018	2.18
[48]	Marker	Projected	Path	2014	1.99
[55]	Markerless	Projected	Path	2008	1.80
[57]	Markerless	Projected	Path	2013	1.65
[59]	Marker	Desktop	Path	2012	1.64
[63]	Marker	Desktop	Path	2010	1.56
[66]	Markerless	Projected	Path	2015	1.55
[70]	Markerless	Projected	Path	2007	1.49
[73]	Marker	Desktop	Path	2007	1.45
[76]	Not-Specified	Wearable	Path	2019	1.30
[77]	Marker	Wearable	Path	2018	1.29
[81]	Markerless	Projected	Path	2013	0.34

Table 8: Papers of the Path Control Feedback category.

with a cube composed by 6 different image targets. The use of multiple targets allows to track the probe even with large rotations, ensuring more flexibility in controlling the virtual robot. Then, a nodes modification mechanism has been added to the system. In fact, users can further manipulate the virtual path by adding or removing nodes between the start and the end nodes using the tracked probe. A similar system has been evaluated in [59] and [30], showing that it is possible to achieve an accuracy of 11mm with a camera positioned at 1.5m away from the workspace. The overall system has been tested with 12 unskilled users in [38]. They had to complete two different tasks to evaluate the node selection and the EE orientation definition mechanisms. Each task has been tested in limited (to emulate a teach-in method) or full (all AR interaction mechanisms were available) AR modality. The results show that in both tasks, the full AR modality has allowed the users to complete the procedures in almost half of the time, proving that even inexperienced users could intuitively interact with the virtual manipulator. Despite these promising results, some problems have been found related to the user interface used to visualize the AR assets. In fact, the desktop interface forced users to continuously switch their attention (the user had to alternatively focus on the real environment and the monitor), thus experiencing distractions, fatigues and a high cognitive load. Furthermore, users faced some problems to detect the real depth of the objects. Finally, Pai et al. [32] greatly improved the accuracy of the robot control, achieving a position error less than $\sim$ 4mm using a similar probe and a printed marker.

Feedback on a path generation can be also obtained using projected AR systems. In [55], an interactive programming AR system to control industrial robots is proposed. A tracked stylus is employed to define a virtual path projected on real surfaces. Once the projected path is defined, the motion of a virtual industrial robot is represented on a video see-through interface. The results show that the proposed user interface allows to program an industrial robot in less than one fifth of the time required by a classic teach-in method. Furthermore, the proposed projected metaphors have been deemed intuitive and suitable to control the robot. Concerning the precision of the AR system, the creation of new spatial points by using the stylus is bounded by a precision of $\sim$ 0.5mm. This accuracy declines when the tip of the stylus has to be positioned above a surface. In addition to the creation and modification of the projected path, Reinhart et al. [70] proposed to exploit the projected points to digitize the workpiece surfaces. Interpolating the positions of the projected points, a height map is projected on the real workpiece. Thus, users are able to generate 3D assets of the real workpieces that can be used for collisions checking in the simulation of motion of the industrial manipulator. Similarly to [55], in [57] a projected AR path planning system has been created to provide assistance during the grinding process of ceramic objects. Custom AR paths can be generated on the ceramic parts, even allowing to define trajectories on complex objects. The system has been compared to an offline mode (CAD based) and a teach pendant programming mode in six different grinding and fettling operations. The results show that the AR path system outperformed the other modalities in term of time required to successfully complete the tasks, going from 32 hours requested by the offline modality to 7 hours demanded by the AR system. Figure 7 shows the described AR path planning system.


(a) (b)

Figure 7: (a): a human operator is defining a projected AR path. (b): the result of the AR path generation. Images published in [57], licensed under CC BY 4.0

Demolition scenarios are also considered in [48]. A projected AR system allows users to display demolition path points on real surfaces. The positions of the projected AR contents can be controlled by the HOs by using a smartphone. Once the points are generated, a vision system is employed to determine the related coordinates that are used by an inverse kinematic solver to derive the final robot joints configuration. Although the robot starts moving as the vision system recognizes the AR contents, the user can still modify the position of the assets to improve the precision of the EE. The AR system has been compared with a teleoperation modality (*i.e.* the EE is directly controlled). The results show that by using the AR system, the users completed the tasks in half the time with respect to the teleoperation method. Finally, a projected interface for a collaborative stud welding process is proposed in [66]. Task welding information is dynamically projected on a ship wall by means of a projector mounted on the EE of an industrial manipulator. The augmented data locations (represented by red crosses) can be modified by using an Inertial Measurement Unit (IMU) device. In case the red crosses have been placed in wrong positions, the user can move them using the IMU device. The precision (the distance between the projected stud position and the real one) that the current system can reach is less than 1cm. However, no feedback mechanism has been added to the system to inform the user whether the stud positions have been projected in a location reachable by the robot arm.

Wearable devices have been also employed to generate AR robot paths. In [77], a first experiment in using the Microsoft HoloLens to control industrial robot arms and a discussion related to the underlying architecture can be found. In addition to visualize the AR path, the user interface provided in [76] allows users to detect the torques of each axis and to execute the robot task using virtual buttons positioned in the real environment. In [31], a handheld pointer is employed to define a virtual path, visualized by means of a modified Oculus Rift device. Two different typologies of path can be defined, namely *Cartesian* and *point-to-point* paths. The first type allows the robot to continuously track the input device, following its positions and orientations. On the other hand, in the point-to-point modality, only some key positions have to be defined and the robot motion is automatically calculated by a motion planning library. The virtual path is represented by a green virtual line and it can be executed by a virtual manipulator to evaluate its reliability. The authors stated that the proposed system allows to reduce the task time, passing from 347s to 63s for a welding task and from 117s to 34s for a pick-and-place task.

Finally, two different approaches for generating AR paths are proposed in [44]: the free space and the surface trajectories approaches. Users can interact with the trajectories by means of gesture and speech commands. In the free space approach, trajectories are generated automatically using start and end points created by the users. In the surface approach, users have to place all the virtual points required to create a path feasible for the robot. The points are constrained on a virtual surface, determined by using the HoloLens SLAM capability. The virtual paths are editable and users can dynamically add, modify or delete points. Moreover, the system allows to visualize the motion of a virtual manipulator along the path. The system has been tested by comparing it with a kinesthetic teaching modality for a pick-and-place task. The results shows that the users have been faster using the proposed user interface with respect to the kinesthetic modality. Nonetheless, since the users had to memorize a set of vocal commands to generate the virtual path, the proposed user interface required a greater mental load than the kinesthetic modality. Regarding physical workload, the proposed system was instead less demanding compared to the kinesthetic one. A video showing the system features is available at[10].

4.2.2. Input Recognition

Table 9 shows the input recognition Control Feedback papers.

In this work, an AR feedback has been classified as *implicit* or *explicit*. An AR feedback is defined as *implicit* when the user visualizes only a virtual manipulator performing the corresponding task without a representation of the correct input recognition. On the other hand, an AR feedback is defined as *explicit* when the user input itself is highlighted using some AR assets.

Four different works utilize the implicit AR feedback to represent the motion of a virtual manipulator [47, 78, 84, 85]. Krupke et al. [47] proposed a comparison between an AR gesture-based interface and an AR gaze-based one. Both user interfaces are combined with speech commands and they allow to select objects of interest that will be manipulated by a virtual manipulator. The results show that the gaze interface has been faster than the gesture one, providing

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[10] `https://youtu.be/amV6P72DwEQ`

Input Recognition					
Paper	**Tracking**	**Device**	**Category**	**Year**	**Quality**
[26]	Marker	Handheld	Input Recognition	2017	3.50
[37]	Markerless	Wearable	Input Recognition	2018	2.43
[42]	Marker	Handheld	Input Recognition	2016	2.20
[45]	Markerless	Projected	Input recognition	2019	2.18
[46]	Marker	Handheld	Input Recognition	2017	2.05
[47]	Marker	Wearable	Input Recognition	2018	2.03
[53]	Markerless	Handheld	Input Recognition	2013	1.87
[62]	Marker	Wearable	Input Recognition	2018	1.57
[78]	Markerless	Wearable	Input Recognition	2019	1.25
[79]	Marker	Wearable	Input Recognition	2017	1.19
[84]	Not-Specified	Wearable	Input Recognition	2017	0.16
[85]	Marker	Desktop	Input Recognition	2011	0.14

Table 9: Papers of the Input Recognition Control Feedback category.

also lower failure rates. Furthermore, the gaze interface required a significantly lower task load than the gesture one. In [85], a Wiimote is employed to control a virtual robotic arm. As the user moves the Wiimote controller, the controller's movement is translated into angular values that are received by the robot controller to update the joint positions of the virtual robot. A similar work is proposed in [84]. The main difference is the interaction paradigm: a mobile wearable device capable of gesture recognition has been employed instead of a motion device. A wearable device is also employed in [78] to visualize the motion of a robotic arm. The system supports hand gestures recognition and it can act in two different modalities: *Manual Control* and *Automatic Control*. In the first modality, as the virtual robot moves, the real one immediately follows its movements, whereas in the second modality the real robot waits for an additional user input before moving to the position of the virtual manipulator.

Explicit AR feedback can be obtained by highlighting the specific object that the user wants to manipulate or by directly emphasizing the user's interaction through AR contents. In [62], a wearable AR device is employed to control a real robotic arm. After an initial calibration phase, users can interact with several virtual objects exploiting the gesture recognition capabilities of the wearable device. Once the objects are selected, the user input is sent to the robot controller to assemble the virtual objects. Frank et al. [42] developed an AR mobile interface whereby users can control a 6-DOF robotic arm through a tablet. An image target is used to establish a mutual reference frame between the tablet and the robotic arm. Users can indicate to the robotic arm which real objects should be manipulated by using the mobile interface. If a real object is selected, a virtual representation of the object is superimposed to highlight the selection. The virtual assets can be moved by specifying starting and ending positions. Once the objects are selected, an inverse kinematic algorithm is applied to find the correct joints values and a path is planned between the starting and ending positions. Both objective and subjective parameters of the system have been tested. The results indicate that participants have been able to accurately control the manipulator. No differences between the calculated and the ideal poses of the real objects have been found. The system has been extended in [26] considering also egocentric and exocentric user interfaces. Despite users still visualize the augmented environment using an handheld device, with the egocentric user interface the visualization is provided from the perspective of a camera mounted on the robotic arm. Users can control the camera tilt and pan movements by exploiting the device accelerometer and gyroscope. On the other hand, a fixed camera has been mounted to the ceiling to provide a top-down overview of the workspace in the exocentric user interface. The two user interfaces and the previous one [42] have been compared in a pick-and-place scenario. Although the results do not show significantly differences in terms of success rate, statistically meaningful differences have been found between the egocentric and exocentric user interfaces in terms of task time. Since the camera did not have to be moved, the users have been faster with the exocentric user interface than with the egocentric one. Regarding subjective parameters, the users encountered more difficulties in using the egocentric user interface that has required high levels of mental and physical workload. Figure 8 shows an operator interacting with the AR environment using an handheld device.

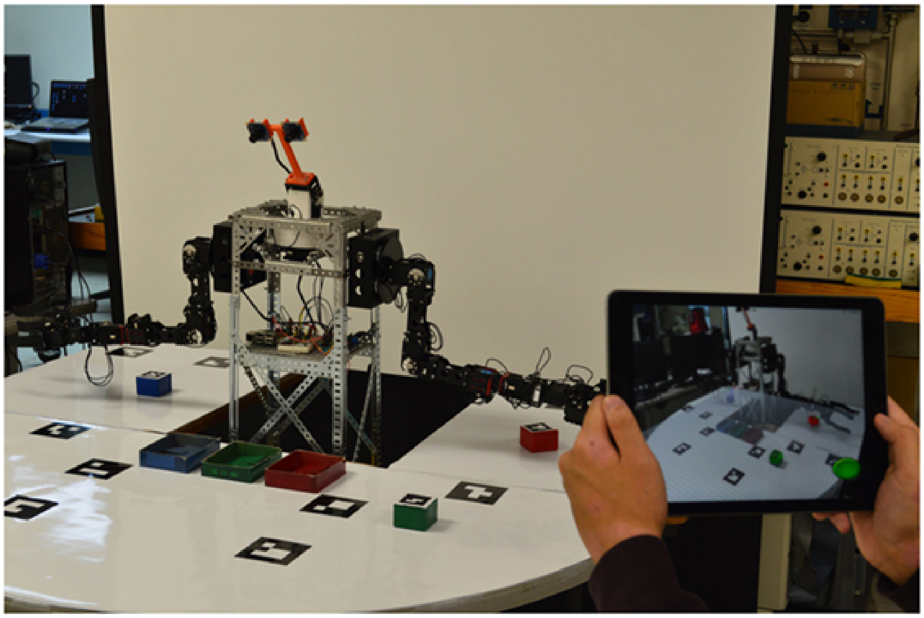

Figure 8: The selection of the objects is highlighted using virtual assets, superimposed on the real objects. Figure published in [26], licensed under CC BY 4.0.

Hand gestures can be also highlighted using AR. In [53], an AR spatial programming system is proposed. Users can define poses and trajectories by using pointing gestures. As the gestures are recognized by the system, feedback on the correct/incorrect gesture recognition is displayed on a handheld device by surrounding the real hand with yellow and green lines. Then, the corresponding trajectory is displayed using additional virtual blue lines. Finally, the desired path is transferred to the robot controller. The results show that, although the time required to program the robot is significantly reduced, the frame rate drastically drops at 5fps when the AR system is enabled. A similar approach is proposed in [46]. The AR gesture recognition procedure proposed in [53] has been improved by using a special particle filter called Condensation [98]. In addition to displaying gesture recognition feedback, the orientation of the EE is visualized by means of a virtual flag. Although the results show that the time required to program the robot has been significantly reduced, less programming errors have been made using the traditional offline programming methods. Gestures are also recognized in [45] combined with a tangible interface and a projection system to program a robotic arm. The system supports different types of gestures: pinch, zoom, rotate, pan and swipe. An object tracking module has been added to the system to recognize the interactable objects. Once a combination of gestures and fingertip movements (recognized by the tangible interface) is recognized, the system automatically translates the user input into a program executed by the robotic arm. Users select objects of interest that are dynamically highlighted using virtual metaphors. The AR system has been compared with a traditional Program-by-Demonstration (PbD) approach in a pick-and-place task. The results show that the proposed system required less time and it was prone to fewer errors than the traditional one. Furthermore, the AR system has been assessed as requiring less workload with respect to the PbD one.

Regarding the use of AR contents in collaborative human-robot 3D printing processes, an interesting approach is presented in [37]. Users are able to create 3D models using a custom wearable AR device. When the users are modelling virtual assets, the models' virtual coordinates are sent to a robotic arm to start the 3D printing process of the real objects.

Finally, an AR collaborative user interface for taping robots is presented in [79]. The HO is able to indicate to the industrial manipulator the area to be isolated using laser pointers. Giving the starting and final positions, the system can generate a reliable taping path directly on the real object. A vision system connected to the robot detects the laser positions and, in case of a correct recognition, a small red circle is superimposed on the starting and the ending path positions. Then, using the defined positions, a taped area is calculated and projected on the real object.

Task Information					
Paper	**Tracking**	**Device**	**Category**	**Year**	**Quality**
[28]	Marker	Wearable	Task Info	2018	4.32
[29]	Marker	Wearable	Task Info	2016	3.31
[34]	Markerless	Projected	Task Info	2019	2.77
[35]	Markerless	Projected	Task Info	2012	2.68
[43]	Marker	Wearable	Task Info	2016	2.19
[51]	Markerless	Projected	Task Info	2014	1.92
[52]	Marker	Handheld	Task Info	2017	1.88
[56]	Marker	Projected	Task Info	2018	1.75
[60]	Marker	Desktop	Task Info	2011	1.62
[67]	Markerless	Desktop	Task Info	2017	1.54
[74]	Markerless	Projected	Task Info	2014	1.42
[76]	Not-Specified	Wearable	Task Info	2019	1.30
[79]	Marker	Wearable	Task Info	2017	1.19
[86]	Marker	Projected	Task Info	2017	0.12
[87]	Marker	Wearable	Task Info	2019	0.04

Table 10: Papers of the Task Information category.

4.3. Informative

The Informative category comprises works related to the use of AR assets to display task or robot information. Task information works focus on using AR assets to display generic task data, such as the current step procedure or instructions. Robot information projects focus on the use of augmented metaphors to display robot data, such as joint values or robot intentions. In the following sections, the task and robot information categories are presented and discussed.

4.3.1. Task Information

Table 10 presents the Task Information papers along with the quality assessment obtained in Sec. 3.3.

In this work, AR instructions are classified as *static*/*dynamic* and *interactive*/*not-interactive*. An AR instruction is considered as *static* when its spatial position is context-independent. Once the AR instruction is generated, its position will no longer be modified. On the other hand, AR instructions are considered as *dynamic* when their spatial positions can change according to the context or to the user input. Both typologies of AR instructions can be also *interactive* or *not-interactive*, depending on whether the user can modify the information displayed by the AR assets or not.

In [28], static not-interactive information is displayed to support technicians in a collaborative assembly scenario (a more in depth description has been already given in 4.1). During the robot and collaborative human-robot operations, instructions and warning information are sent to HOs to inform them on the system status. The related Graphic-Unit-Interface (GUI) is similar to the one presented in [29, 43]. The assembly, warning and production information is displayed as a text in the top area of the GUI in order not to interfere with the FoV. Different colours have been used to highlight the different typologies of messages: green colour for the assembly instructions and the red one for the warning messages (see Fig. 9).

A similar user interface is proposed in [52]: here HOs can visualize on a GUI a set of text-based instructions that are regularly updated depending on the specific step of the assembly procedure.

Concerning the visualization of static interactive AR information, in [79] AR data are displayed by a wearable AR device (the system has been already introduced in 4.2) in the real workspace. The operator can visualize text-based task instructions close to the taping area and he/she can navigate through them using the custom handheld device. Similarly, in [87] the users can interact with a virtual menu positioned close to the real manipulator. Moreover, a wrist camera

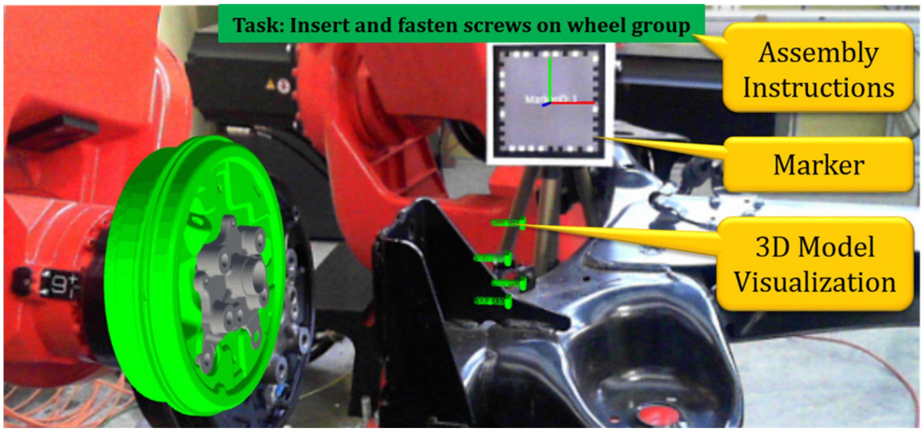

Figure 9: Task information is displayed on the top area of the GUI. The green colour indicates that it represents an assembly instruction. Figure published in [29], license courtesy provided by Elsevier N. 4817880214761, Apr. 28, 2020.

has been added to the robot itself to improve the precision of a pick-and-place task.

In [67], Liu H. et al. proposed an AR interface to display dynamic assembly information to assist HOs during a human-robot collaborative assembly procedure. The system uses a fixed camera to recognize the assembly tools placed in the workspace. Once the objects are recognized, the homography matrix is computed to display augmented names of the assembly tools close to the real objects. In addition to the augmented names, integer numbers are also superimposed on the real objects to inform the user in which order the objects should be assembled. A similar work is proposed in [60]. Once the objects to be assembled are tracked using a marker-based system, some 3D virtual shapes are superimposed on them to guide the users during the task.

Another *dynamic* projected interface for an assembly task can be found in [51]. The system is composed of a robotic arm surrounded by several Microsoft Kinects and one projector. The system can project task information or it can provide feedback about the system status. The HO can interact with the projected interface using several virtual buttons to both control the robot itself and to control the assembly process. The AR assets change their spatial positions and the task information according to the assembly procedure. A demonstrative video can be found at[11]. A similar work is proposed in [86] and in its updated version [56]. In [56], an interactive dynamic projected AR system is proposed. The system projects the list of available programs directly on the surface of the touch-enabled table. Depending on whether the program contains all the required parameters, the instructions are displayed with green (all parameters set) or red (some parameters have to be set) colours. The projected GUI provides interactive buttons and it can be moved at will, exploiting the touch capability of the table. To provide more information about the system status, objects recognized by the system are highlighted by green rectangles (a demonstrative video can be found at[12]). The system has been tested in a collaborative assembly procedure with six participants. The results indicated that users had difficulty in understanding the current state of the system and they have not always been able to clearly figure out which instruction should be carried out. Moreover, users did not always place the interface at the most appropriate position, making it difficult to read the current system status and thus slowing down the overall assembly procedure. Tavares et al. [34] proposed a projected AR system to assist operators in a welding task. The projection system indicates the area in which technicians should place and weld the metal parts. In this way, technicians do not need to employ objects for measurement (e.g. rules, squares, etc.) that can lead to undesired errors. The system has been compared with a traditional procedure and the authors stated that the AR system allowed to achieve a significant time reduction, passing from 18 minutes to 11 minutes. A demonstrative video can be found at[13]. Regarding the positioning of the GUI, works in [35, 74] present two different approaches. In [35], a tangible interface for transferring skills from a HO to

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[11] `http://www.youtube.com/watch?v=GpXkEd6y1LE`

[12] `https://www.youtube.com/watch?v=cQqNLy6mE8w&feature=youtu.be`

[13] `https://tinyurl.com/yyrnavw9`

a robot manipulator is proposed. A projection system is employed to use the workspace as a touchable interface where AR instructions are dynamically projected taking into account the HO's position and orientation. Hence, the GUI can be projected in such a position that it is always visible to the user.

In [74], an active dynamic AR interface to control a mobile industrial manipulator is proposed. The main objective of the system is to find a suitable planar surface to project an interactive AR interface. The projected interface has been tested to evaluate its robustness and applicability. More than one thousand user inputs have been evaluated to understand how the position of the projection system relative to the projection plane affects the gesture detection algorithm. The results show that if the projection angle is kept constant around 30°, the detection rate does not fall below 90%. On the other hand, it drops significantly if the angle exceeds 50°of inclination.

4.3.2. Robot Information

Table 11 presents the Robot Information papers along with the quality assessment obtained in 3.3.

AR contents can be used to display data relative to the industrial manipulator [40, 80]. In [80] a desktop interface is employed to visualize virtual information related to the industrial robot components. Malý et al. [40] developed an AR interface to highlight an industrial manipulator. The main objective of this work is to appraise the effectiveness of the AR interface when the user is freely moving around the environment. The AR application enables the users to visualize the robot in three different modalities: "*outline*", "*virtual robot*" and "*real robot*". Three different virtual metaphors have been added to the AR interface to indicate some specific parts of the robot: 3D arrows, virtual leading lines and virtual text. The AR interface has been evaluated by comparing a wearable and a handheld device. The results show that the limited FoV of the wearable device has forced the users to keep distance from the virtual objects, increasing chances of user accidents with the surroundings. Moreover, the handheld device has outperformed the wearable glasses in term of marker detection, recognizing

Robot Information					
Paper	**Tracking**	**Device**	**Category**	**Year**	**Quality**
[39]	Markerless	Projected	Robot Info	2001	2.36
[40]	Marker	Wearable	Robot Info	2016	2.34
[41]	Markerless	Projected	Robot Info	2016	2.31
[49]	Marker	Wearable	Robot Info	2018	1.93
[50]	Marker	Wearable	Robot Info	2018	1.93
[54]	Marker	Handheld	Robot Info	2018	1.83
[58]	Markerless	Projected	Robot Info	2019	1.65
[61]	Markerless	Projected	Robot Info	2019	1.58
[65]	Markerless	Projected	Robot Info	2016	1.55
[68]	Marker	Desktop	Robot Info	2010	1.54
[75]	Marker	Wearable	Robot Info	2016	1.38
[76]	Not-Specified	Wearable	Robot Info	2019	1.30
[78]	Markerless	Wearable	Robot Info	2019	1.25
[80]	Marker	Desktop	Robot Info	2017	1.19
[81]	Markerless	Projected	Robot Info	2013	0.34

Table 11: Papers of the Robot Information category.

the markers from a distance of 1m with respect to a distance of 0.6m for the wearable device. Regarding the visualization techniques, the outline or virtual reality modalities have been considered more effective to augment the real robot. Text and 3D arrows have deemed more suitable than the leading line to highlight some specific parts of the robot. Finally, outcomes show that the text visualized on the wearable device should not exceed 1 line with 30 characters. In addition to highlight some specific parts of a robot, joint torque is considered in [78] (the system has been already presented in Sec. 4.2.2). The motion plan of the robot is extracted in real-time and it is used by an inverse dynamics solver to determine the joint torques. Depending on the intensity of the torque, the virtual joints are coloured with cold or hot colours.

AR assets can be also used to visualize the intention of the industrial manipulators. In [41], an object-aware dynamic projection system is presented. The system is capable of tracking moving objects using a RGB camera. During the tracking procedure, a projected wireframe of the tracked object is overlapped on the real one using different colours to provide feedback of the tracking system. Once the object has been tracked, the projection system can display in real-time the future intentions of the manipulator, showing which specific parts of the object will be manipulated by the robot. The usability of the proposed user interface has been evaluated by comparing it with a desktop and a paper-text interface. The results indicate that the projected interface has been preferred in terms of effectiveness and efficiency. Despite these outcomes, the paper-text approach has been considered suitable to have an overview of the overall task. In the projected and desktop interfaces, the AR instructions were displayed and updated at each step of the procedure. Hence, users were not able to know what they were supposed to do after the current instruction.

Three other similar works have been proposed in [39, 58, 65]. Wakita et al. [39] presented a system to improve the cooperation between a HO and a robotic arm in a hand-to-hand delivery scenario. Besides displaying the future motion of the robotic arm, the person's expectation that the robot is intently looking at him/her has been added to the projection system. Hence, the HOs can realize *when* the robot is watching at their actions and *whether* their actions have been correctly understood by the robot. In [65], a projected AR system is employed to improve the safety of HOs in a collaborative assembly scenario. The system is capable of displaying three different typologies of information: the human intentions, the robot intentions and warnings of possible task failures. As the system identifies the position of the worker's hands, a small red circle is superimposed on the hand to let the user know that the system is correctly recognizing his/her movements. Furthermore, the recognition of the human intentions is used to plan in real-time the robot movements that are projected in advance on the working area. Weng et al. [58] analysed the features needed to optimally reference target objects. By mathematically determining the positions and orientations of the virtual metaphors, the robot is capable of expressing its intentions, highlighting with virtual projected arrows the objects of interest. The results show that relative angle and edge proximity features improve the accuracy of the system. The use of 3D virtual metaphors to display robot intentions has been also considered [54, 68]. In [54], a handheld AR system is proposed to visualize the future motion of a robotic arm in an assembly scenario (Fig. 10). The results show that safety is deemed as the most critical aspect of a human-robot collaborative system and users should be given context-awareness information to enhance its perception.

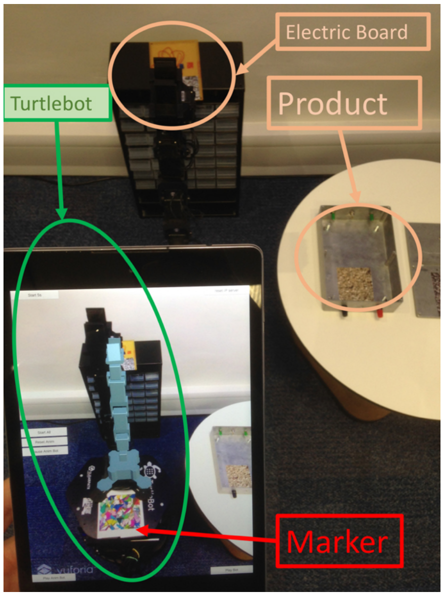

Figure 10: Human operators can understand robot intentions visualizing the AR representation of the manipulator. Figure published in [54], licensed under CC BY-NC-ND 3.0.

A similar work is proposed in [68]. In addition to visualizing the robot motion intention as a 3D virtual wireframe, the system provides the possibility to visualize the internal state of the robot. Thus, users can quickly realize whether robot sensors are affected by faults, lowering repairing time. Further examples of robot internal state visualization can be found in [49, 50]. Chakraborti et al.

[49] presented a system that allows humans and robots to collaborate in solving puzzles. The user can visualize which object will be manipulated by means of the Microsoft HoloLens device. Objects are highlighted using 3D virtual arrows (a demonstrative video can be found at[14]). In [50], a conceptually similar work is presented whereby users are capable of analysing the internal robot knowledge structure, thus understanding the reasons behind the robot's choices. Finally, work in [61] analysed which vision algorithm should be used to let the robot know where the human gaze is positioned. Feature descriptors are employed to project the gaze point from an image acquired from an eye tracking camera to the image acquired by the manipulator camera. Experiments have been carried out by comparing several descriptors in motion and no-motion conditions. The results show that all the considered descriptors optimally performed in no-motion condition. As motion is introduced, the accuracy drops for most of them, but for BRISK, AKAZE and SURF it seems to remain stable, although they cannot satisfy real-time requirements.

5. Results

This section reports the principal findings of this work. The aim of this SLR is to answer to questions Q1, Q2 and Q3 presented in Sec. 3.1. In the following, the three questions are reviewed separately.

5.1. What are the main uses of AR technologies in the HRC context?

In order to answer to this question, the user interfaces and their distribution over the time have been firstly analysed.

As can be depicted in Fig. 11a, the projected and wearable interfaces are the most used visualization systems, followed by the desktop and handheld interfaces. These results are not totally unexpected: due to their intrinsic capability of not forcing users to wear any particular device, it is reasonable to assume that the projected interfaces have greatly attracted the attention of

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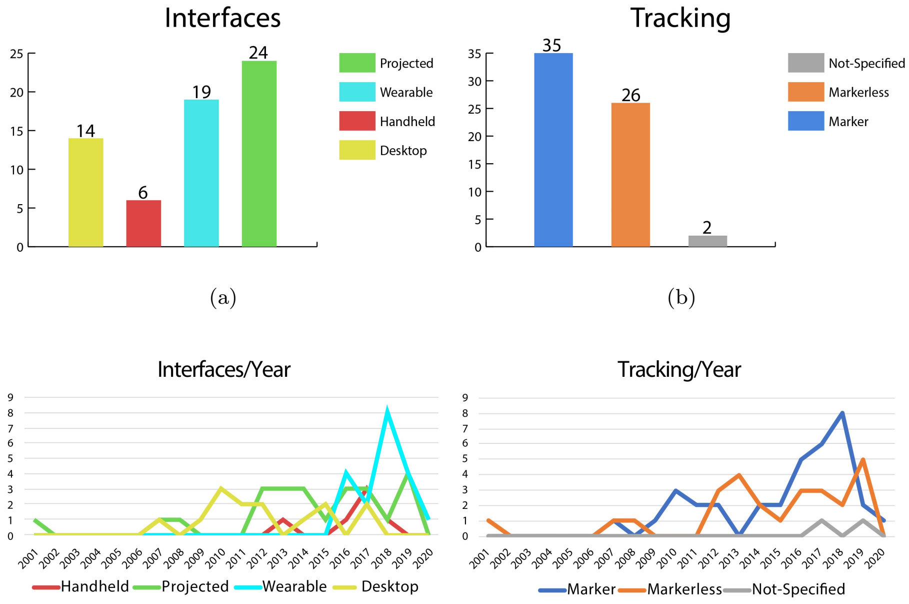
[14] `https://goo.gl/SLgCPE`



(a) (b)

(c) (d)

Figure 11: (a): the interface repartition. (b): the tracking repartition. (c) - (d): the interfaces and tracking distribution over the time, respectively.

researchers and thus they have been deeply analysed and evaluated. Considering the wearable interfaces, although they were the last to appear on the market and only recently they have begun to be employed for research purposes, they are increasingly becoming a hot research topic, not limited to the HRC area. The desktop interfaces are indeed the “oldest” visualization system and they are one of the most tested and adopted interfaces. Nonetheless, they force users to continuously switch the attention from the augmented environment to the real scene, negatively affecting the effectiveness of the AR system. Hence, they might have been considered less appealing for the HRC context. Finally, the handheld interfaces present some intrinsic restrictions (such as binding users to keep their hand occupied) that might have negatively influenced their use in the HRC context. These considerations seem supported by the user interfaces’ distribution over the time (Fig. 11c). Although desktop interfaces spread over a

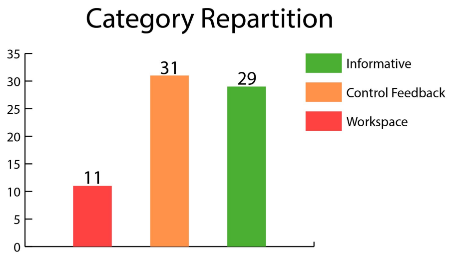
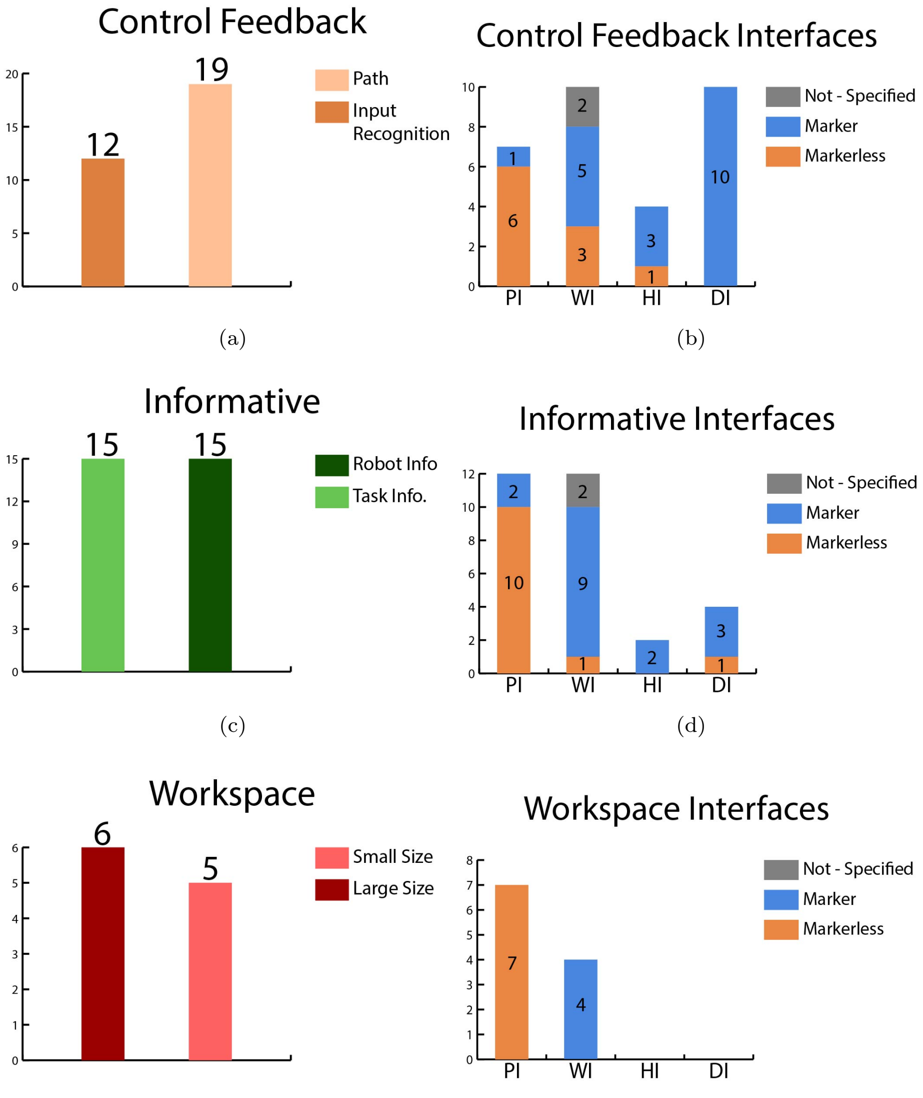


Figure 12: The interfaces' repartition over the three categories. Since some works belong to multiple categories, the total amount of the interfaces differs from the total amount of collected papers.

considerable time period, recently they seem to be less considered, whereas the fair amount of recent works that employ projected interfaces suggests that they are increasingly used in the HRC context. Wearable interfaces have started to be used only recently, specifically from 2016 to current days, whereas the handheld interfaces have been employed only in 2013 and 2017, suggesting that they might not be the most appropriate user interfaces for the HRC context. Tracking typology has also been considered (Fig. 11b): tracking based on the use of image targets or markers and markerless technology are employed almost at the same extent. Only two works do not specify the adopted tracking methodology. The spread of tracking technology over the time shows an interesting scenario (Fig. 11d): marker-based technologies seem to decline in favor of those markerless. In the works collected for this SLR, markerless technology has usually been employed by AR projected systems and since they are increasingly attracting the attention of researchers, consequently also the markerless tracking is progressively becoming more adopted and employed.

Referring to the classification proposed in this SLR, Fig. 12 shows the paper distribution over the three categories. The AR interfaces have been mostly employed to control or program robotic arms (Control Feedback category). The most assessed aspects were the interaction and visualization of AR paths (61%) followed by the visualization of a generic user input (39%, see Fig. 13a). With



(a) (b) (c) (d) (e) (f)

Figure 13: (a) - (b): the Control Feedback category repartition and the Control Feedback AR interfaces, respectively. (c) - (d): the Informative category repartition and the Informative AR interfaces, respectively. (e) - (f): the Workspace category repartition and the Workspace AR interfaces, respectively.

almost the same extent, AR technology has been used to visualize general tasks or robot information (Informative category). Informative papers are equally divided in works that employ AR visualization systems to display task and robot data (Fig. 13c). Finally, only the 15% of the collected works focused on the visualization of the robot workspace (Workspace category). Considering the small-large size repartition, since high-payload industrial robots occupy a considerable amount of space and they are more dangerous for HOs than the small-size robots, research focused more on large size robots or environments (55%, see Fig. 13e). These findings seem also confirmed by the number of different interface typologies used in each category. In both Control Feedback and Informative categories (Fig. 13b and 13d), all the distinct types of interfaces have been used and evaluated whereas only projected and wearable interfaces have been employed in the Workspace category (Fig. 13f). In the Control Feedback category, marker and markerless tracking technologies have been used almost with the same extent whereas the marker-based approach is predominant in the Informative category.

Summarizing, AR technologies are mainly used to:

- control and program a robotic arm;
- visualize general tasks or robot information;
- visualize the industrial robot workspace.

Moreover, regarding the different typologies of AR interfaces:

- projected interfaces seem to be the most promising ones;
- since the wearable interfaces are the newest ones, more research is needed to evaluate their effectiveness;
- handheld and desktop interfaces do not seem adequate for the HRC context;
- marker-based technology is still the most employed but markerless solutions are becoming increasingly popular.

5.2. What are the main strengths and weaknesses of the AR technologies in the HRC context?

Before answering to this question, it is necessary to make a premise related to the results' collection process. As depicted in Fig. 14a, only 51% of the collected papers have evaluated the proposed system.

Within this 51% of papers, 50% has evaluated only objective parameters, 6% only subjective parameters and 44% both objective and subjective parameters (Fig. 14b). Moreover, only 56% of the papers has performed tests involving unskilled users (Fig. 14c). It should be noticed that only the work proposed in [44] has assessed the system considering also expert users.

Regarding the proposed classification, the Control Feedback category is the most tested one, followed by the Informative and Workspace categories (see Fig. 15a, 15c and 15e). Objective data have been evaluated in all three categories whereas the subjective ones have been assessed only in the Control Feedback and Informative categories (see Fig. 15b, 15d and 15f). The most analysed objective data are the following:

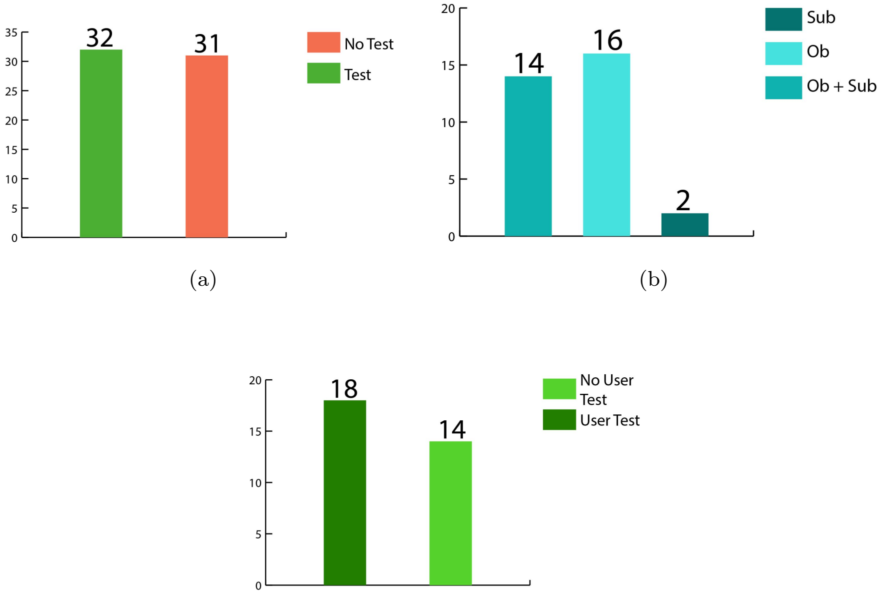
- time required to complete the task;
- number of user errors;
- tracking precision.

On the other hand, the most assessed subjective data are the following:

- usability;
- likability;
- workload.

Subjective data have been usually collected using custom or standard questionnaires. Concerning standard questionnaires, the most adopted are the following:

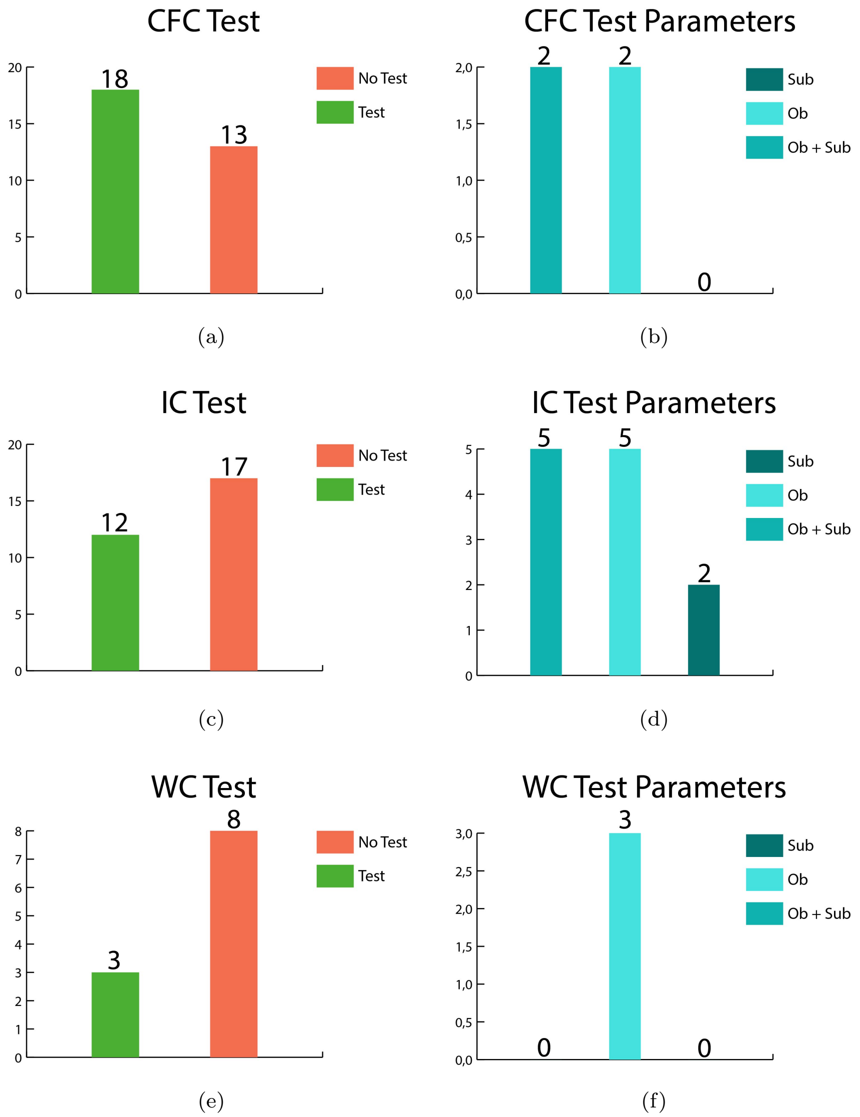
- System Usability Scale [99]: a 10-item questionnaire on a 5-likert scale used to evaluate the usability;
- AttrakDiff [100]: a questionnaire used to evaluate the perceived pragmatic and hedonic quality;



(a) (b)

(c)

Figure 14: (a): the 51% of the collected works have evaluated the proposed system. (b): the subjective (SUB), objective (OB) parameters analysed. (c): the 56% of the test papers have evaluated the system carrying out user tests.



(a) (b) (c) (d) (e) (f)

Figure 15: (a) - (c) - (e): the amount of works that have performed tests in each category. (b) - (d) - (f): the analysed parameters of each category. CFC stands for Control Feedback category, IC stands for Informative category and WC stands for Workspace category.

- NASA TLX [101]: a questionnaire used to evaluate the perceived workload.

Generally, the reduction of the time needed to complete a specific task is the main advantage. Analysing the subjective data, it turns out that users felt more comfortable and satisfied using AR systems than interacting with traditional approaches (such as kinesthetic teaching or joypad control). Outcomes that seem to be confirmed by the usability results that present higher scores for the AR systems than the traditional approaches. Finally, AR systems tend to reduce the physical workload whereas the mental one seems to depend on the interaction system (e.g. mental workload may increase using AR systems along with speech interfaces [47]). Concerning weaknesses, the main concerns are related to the tracking accuracy and to occlusion problems. Depending on the category, the required accuracy may vary, deeply affecting the performance of the system (e.g. an AR control system may require higher accuracy with respect to an AR informative system). Conversely, occlusions could lead to the loss of the tracking system, making the virtual assets disappear from the scene. Some concerns have been also found related to the narrow FoV of the wearable devices that do not allow to properly visualize the augmented environment. Summarizing, the AR main strengths are the following:

- AR systems are faster than traditional approaches;
- AR systems are more appreciated by users in terms of likeability and usability;
- AR seems to reduce physical workload whereas the mental one depends on the interaction interface.

The main weaknesses are the following:

- tracking accuracy;
- occlusion problems;
- FoVs of AR wearable devices.

5.3. What are the potential future developments of AR technologies in the HRC context?

The fair number of collected papers suggests that the use of AR technologies to improve the collaboration with industrial robots is in an early stage yet. Nonetheless, given the results presented in Sec. 5.1 and 5.2, it is possible to make some considerations.

Despite projected AR systems seeming to be the most effective and appreciated visualization systems, they have not been assessed with expert users yet. Wearable interfaces have not been properly evaluated neither by unskilled nor by expert users. Hence, it is till not clear how they can be employed to improve the HRC context. Researchers should improve their evaluation considering also that the wearable interfaces are still negatively affected by hardware limitations that reduce their usability (such as the narrow FoV). More research should be done also in the Workspace category and it is till not clear why it has not been widely considered so far. In a human-robot collaborative scenario, HOs and industrial robots work side by side and visualizing the robot workspace should increase the sense of safety.

It is worth noticing that, independently of the category, AR systems should be always tested involving a number of users sufficient to obtain statistically significant data. It is essential that researchers, academics and industrialists involve a greater number of people in evaluating the effectiveness of the AR in the HRC context. Since both AR and collaborative industrial robots are strongly increasing their presence in the Industry 4.0 domain, it can be expected that their combined use becomes increasingly analysed and studied. It is expected that collaborative robots will replace industrial robots, combining the efficiency of the robots with the flexibility of the human operators [102]. Hence innovative interfaces should be designed in order to truly exploit collaborative robot features. It is crucial that human-robot augmented interfaces are designed using a *human-centered approach.* HOs should be positioned at the center of the design process to correctly figure out which type of information is still missing, achieving a truly human-robot collaboration scenario.

Summarizing, the potential future developments of AR technologies in the HRC context are the following:

- all AR interfaces should be more evaluated from a user's point of view, considering also expert users;
- there is a huge research gap in the use of wearable interfaces with industrial robots;
- more tests should be performed for the Workspace category;
- a human-centered approach should be applied for the design step of AR interfaces.

6. Conclusion

This paper presents the current state of the art about the use of AR interfaces in human-robot collaborative scenarios. A SLR approach has been used to gather and analyse the selected papers. Specifically, the employed protocol is based on the SALSA framework, which ensures both the transferability and reproducibility of this study. Starting from 3734 initial papers, 63 papers have been deemed suitable to answer the three research questions: (Q1) What are the main uses of AR technologies in the HRC context? (Q2) What are the main strengths and weaknesses of the AR technologies in the HRC context? (Q3) What are the potential future developments of AR technologies in the HRC context? Three different main categories related to the use of AR in the HRC context have been identified: Workspace, Control Feedback and Informative. Overall, it seems that before AR technology is effectively used on the production lines, some efforts still need to be done to deeply investigate its strengths and weaknesses. Despite some results consistent with the current AR state of the art (task completion time reduction and user experience enhancement), too few works have evaluated the effectiveness of AR technology performing tests that involve users. Since facilities should start to effectively employ collaborative robots in a few years, original interfaces should be developed to improve the human-robot collaboration in order to truly exploit collaborative robot features. Besides improving the underlying technology, a human-centered design approach should be employed by involving a greater number of users, thus understanding the effective usability and acceptability of the AR interfaces.

7. Supplementary materials

The original list of the collected papers, along with the employed classification can be found at[15]. It consists of an Excel file. Sheet "1_3734" contains the papers list. Sheet "Sheet_1" contains the related legend.

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