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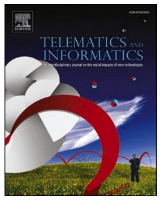

Extended reality applications in industry 4.0. – A systematic literature review

Leonor Adriana Cárdenas-Robledo [a], Óscar Hernández-Uribe [b,*], Carolina Reta [c], Jose Antonio Cantoral-Ceballos [d]

[a] Department of IT, Control, and Electronics, CIATEQ A. C., Av. 23 de Agosto #213, Jesús García, Villahermosa, Tabasco 86040, Mexico
[b] Department of IT, Control, and Electronics, CIATEQ A.C., Av. Manantiales #23-A, Parque Industrial Bernardo Quintana, El Marques, Queretaro 76246, Mexico
[c] Department of IT, Control, and Electronics, CONACYT-CIATEQ A. C., Gaza 30 Lote 1 Distrito de Educación, Salud, Ciencia, Tecnología e Innovación, San Agustín Tlaxiaca, Hidalgo 42163, Mexico
[d] Tecnologico de Monterrey, School of Engineering and Sciences, Mexico

A R T I C L E I N F O

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A B S T R A C T

Extended reality technologies such as virtual reality, augmented reality, and mixed reality represents a paradigm that enhances and supports industry 4.0 in diverse settings. To spread such a revolutionary environment, this systematic review focuses on analyzing extendend reality essence and application and reporting the assessment of 287 approaches gathered from 2011 to 2022, classified and characterized in the proposed taxonomy. Based on the sample of analyzed works, the results indicate that industry 4.0 has embraced the use of these technologies.

Heterogeneous solution proposals in various fields of application and activities were found. Notwithstanding, the research articles report similar advantages and benefits (e.g., high performance on human tasks or robot collaboration, high-quality rates for specific products, among others). In addition, we present the most widespread equipment and devices that are currently preferred to develop extended reality applications, which allows us to identify hardware patterns commonly shared in a variety of fields. Whilst, with the aid of association rules, we reveal further insights among the items of the proposed taxonomy. Furthermore, we also present a thorough analysis of trends and research directions in the extended reality field for industry 4.0. Finally, from our results, we show that the accessibility and accelerated progress in technological devices, incorporating advanced algorithms, ergonomic features, built-in cameras, and sensors, have encouraged a massive adoption and extensive application development in a wide spectrum of industry 4.0 domains.

1. Introduction

Industry 4.0 aims at transforming traditional industries into smart ones by the integration of technologies, such as the internet of things (IoT), big data, machine learning, cloud computing, cyber-security, robotics, simulation, additive manufacturing, extended reality (XR), among others (Fernández-Caramés et al., 2018). Indeed, industry 4.0 incorporates novel practices in computer science,

* Corresponding author.
E-mail addresses: leonor.cardenas@ciateq.mx (L. Adriana Cárdenas-Robledo), oscar.hernandez@ciateq.mx (Ó. Hernández-Uribe), carolina.reta@ciateq.mx (C. Reta), joseantonio.cantoral@tec.mx (J. Antonio Cantoral-Ceballos).

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electronics, manufacturing, and engineering, for example, XR technologies, widely used in education and entertainment (Hammady et al., 2020), offer novel alternatives to the traditional industry. This way, it allows merging the physical and digital world, creating new knowledge in real-time, decision making, and product and process innovation (Slavkovic et al., 2019). Industry 4.0 also provides further flexibility in manufacturing, where the conditions change rapidly, increasing quality and productivity (Frank et al., 2019), whilst providing maximum efficiency according to the customer demands (Aydin, 2018). Here, the virtual representation of complex environments allows for faster and easier adoption of newer practices, which, in turn, may lead to more value creation.

The combination of such technologies reduces the gap between the physical and digital world, allowing the direct interaction of remote physical locations, where the work of the Operator 4.0, "a smart and skilled operator who may perform not only cooperative work with robots but also work aided by machines and if needed by means of human cyber-physical systems, advanced human–machine interaction technologies and adaptive automation towards achieving human-automation symbiosis work systems" (Romero et al., 2016a), leads to faster real-time decision making (Berg and Vance, 2017) and new knowledge generation (Romero et al., 2016b; Romero et al., 2016a; Romero et al., 2017).

Therefore, this paper presents a comprehensive review to describe how different modalities of virtuality within the scope of industry 4.0, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), have been successfully used in different industries (de Souza Cardoso et al., 2020a), for example, construction (Sidani et al., 2019), education and training (Jou and Wang, 2013), (Gao et al., 2019), automotive (Merenda et al., 2018), energy (Francisco and Taylor, 2019), and manufacturing (Gimeno et al., 2013), just to name a few.

In the context of industry 4.0, Digital Twins (DT), Cyber-physical systems (CPS), and XR represent fundamental supporting technologies. DT and CPS are based on the principle of making physical objects interact with their digital counterparts. In contrast, XR technologies focus on enhancing the user experience in terms of digital content visualization, interaction, and remote or collaborative operation. In order to provide an initial framework for the remaining sections, we start by defining some key concepts which are inspired by distinguished researchers.

- *Cyber-physical system (CPS)* refers to computational intensive system's connectivity where the changes in the physical-system are reflected in the cyber-system (i.e., human-made environments by using software, embedded processors, networks, and sensors), using data feedback to take a suitable decision (Liu and Wang, 2020; Khaitan and McCalley, 2015).
- *Digital twin (DT)* relates to the effortless integration of data between a physical machine and its digital replica in the virtual world, either online (real-time) or offline (using history data). This can use 3D computer models, multiphysics simulation, or anything that represents the virtual world's whole physical behavior. The technological goal is to gain knowledge and foster a data-driven smart environment of the physical machine, physical or chemical process, even a manufacturing process (Lu et al., 2020; Fuller et al., 2020).
- *VR* deals with virtual worlds built using 3D computer models with physics and simulation features, where the human's real sense perceptions are linked through sensors and actuators to give users a fully immersive and presence sensation. Individuals with almost no awareness of being in a virtual world are able to recreate physical endeavors closely as if they were in the real-world (Slater et al., 2020; LaValle, 2019).
- *AR* aims to enrich a real-world space by seamlessly integrating digital visual data (e.g., text, graphics, images, videos, and 3D virtual objects), audio content, and other external stimuli in real-time. This technology provides an immersive and realistic feeling to the user (Kim and Kim, 2018) since reality and additional material coexist in the same space (Azuma et al., 2001; Jetter, et al., 2018).
- *MR* is "a particular subset of VR-related technologies that involve the merging of real and virtual worlds somewhere along the virtuality continuum" (Milgram and Kishino, 1994). "The virtuality continuum connects completely real environments to completely virtual ones", placing AR and augmented virtuality (AV) between them. In contrast to AR, which brings virtual content or digital material to reality, AV blends digitalized or emulated real content to virtual environments (Milgram and Kishino, 1994).

The remaining sections of this paper present our systematic survey of diverse industrial applications of the different reality experiences (modalities). Not only do we focus on the type of experience, but also on the amount of user interaction, equipment, devices, interconnectivity, and sensors. For this, a detailed search from Web of Science and Scopus is carried out, limited to 119 journals and pruned to include 287 publications leading to a taxonomy that includes 10 categories and 68 sub-categories. The complete methodology used to select the most relevant papers is described in detail in Section 2. The remaining sections of the paper include our review of relevant related works in Section 3. Results are shown in Section 4, which proposes a novel taxonomy and the analysis of applications. Discussion and Conclusions appear in Section 5 and Section 6, respectively.

2. Material and methods

This section describes the process followed to elaborate the current systematic review. For this, the Preferred Reporting Items for Systematic Review and meta-Analysis Protocols (PRISMA-P) (Page et al., 2021; Moher et al., 2015) is used to identify and narrow down the relevant studies and previous surveys on XR and industry 4.0, as outlined in the proposed taxonomy.

Research questions. The motivation for pursuing the present systematic literature review is centered on the following core research questions.

RQ1. What is the practical use or implementation of XR technology in industrial settings?

RQ2. What are the fields or areas in industry 4.0 that use XR technology?

RQ3. Which are the main activities or processes that apply XR technology in industry 4.0?
RQ4. What type of reality experience (e.g., virtual, augmented, and mixed) is being adopted in industry 4.0?
RQ5. What kind of gadgets, devices, and equipment are currently used to experience XR?
RQ6. What are the main XR research topics?
RQ7. What are the essential highlights of XR technology in the context of industry 4.0?

Eligibility criteria. In order to identify and select the sample of research papers relevant to this systematic review, the *inclusion criteria* are as follows:

- Research articles that focus on VR, AR, and MR in the context of explicit practical application in any field of industry 4.0.
- Full-text journal papers in English published from 2011[1] up to the first quarter of 2022.

The following criteria are used to excluded non-pertinent studies:

- Review articles, conceptual studies, theories, methodologies, models, and incipient works
- Studies that apply XR to other fields different from industry 4.0.

Information sources. The present work uses Web of Science (Clarivate Analytics®) and Scopus (Elsevier®) as information sources. The lists of records obtained from each database were merged and filtered, removing duplicated records. Consequently, a list of 119 journals was realized, with an impact factor greater than or equal to 1.0 according to Clarivate Analytics® Journal Citation Reports (JCR 2020), included in the Science Citation Index Expanded, the Social Sciences Citation Index, or both. Table 1 shows the 15 journals with the highest frequencies of published papers across time concerning XR applications in industry 4.0.

Search strategy. The literature search was performed on the 28th of March 2022 to identify the papers focusing on XR, VR, AR, and MR applied to industry 4.0. The search queries for both databases are presented in Table 2 and were executed as an advanced search. In addition to the main terms of the search (e.g., *virtual reality, augmented reality, mixed reality, cross reality, extended reality, virtual environment, head mounted display (HMD), cave automatic virtual environment (CAVE), virtual world*), other relevant constraints are indicated in the search parameters, such as the period ranging from *2011* up the current date, the type of document (limited to *articles),* and the language of publication (*English)*.

Study records. The data management is executed using Zotero (Zotero, 2020) (i.e., to collect, organize, and cite the sample of papers). On the other hand, the selection process started with a screening phase where the titles and abstracts of the retrieved list from the database searches were examined. The list was then screened independently by two authors (L.A.C.R. and O.H.U.) and using the inclusion criteria produced a unified list; then, the full-text articles were perused by all authors.

The second phase analyzed the eligibility and inclusion of the articles, where the four authors (L.A.C.R., O.H.U., C.R., and J.A.C.C) applied eligibility criteria to the retrieved set of research papers. In case of disagreement, it was resolved through discussion until a consensus was reached. The selection process is illustrated in Fig. 1, showing a total of 287 articles to include in this review.

Based on an initial reading of a simple random sample of 24 articles, two standardized templates with common attributes were designed to keep a homogeneous data extraction. The first one contains information related to general features of the study and the second one includes features related to the practical application of XR technologies in industry 4.0, clustered in ten categories.

Therefore, the above sample was used as a calibration exercise before starting the review, with additional categories or sub-categories added as data extraction continued, developing the second template further. The data extraction for each article in the review was carried out by one author and validated independently by another. Consequently, the two templates lay the foundation of the proposed taxonomy, explained in Section 4.1.

Data items. Concerning the data items considered in this review and according to the research questions stated, the information is identified and organized in categories and subcategories, as extracted from the articles. Therefore, the data items are used to fill the two designed templates:

- The first one contains general characteristics such as *title, abstract, domain knowledge, research topic, key findings, implications, and trends*, in concordance with RQ6 and RQ7.
- The second template includes characteristics such as *field of application, activity, type of reality* (e.g., *virtual, augmented, and mixed*), *environment perception* (e.g., *synthetic, captured, and hybrid*), *devices* and *equipment*, in correspondence with *RQ1, RQ2, RQ3, RQ4,* and *RQ5*.

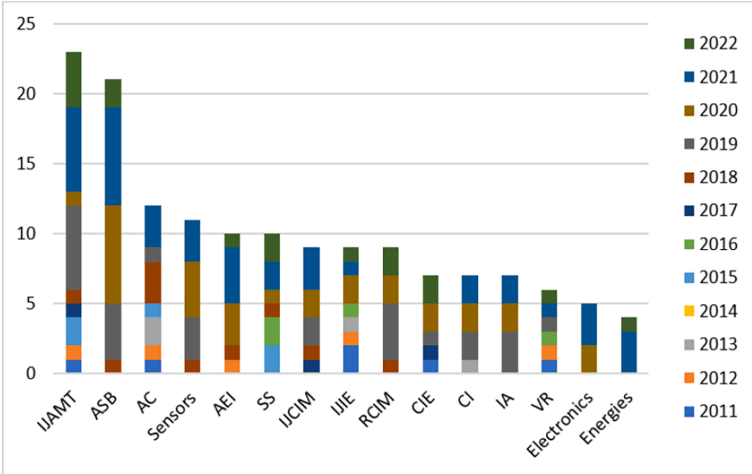
Outcomes and prioritization. The primary outcomes of this review consist of a taxonomy shaped by the profile of the examined studies (integrated by their general and thematic characteristics) and the description of such taxonomy through the view of the studies classified in Table A of the Appendix. Secondary outcomes include the elaboration of statistical analyses and data mining on the collected information, and analysis of our results on XR in industry 4.0.

Risk of bias. With the aim of limiting bias, two major bibliometric databases are used, Web of Science and Scopus, considering that

[1] The term industry 4.0, originated in Germany in 2011, referring to changes directly linked to automation fields and information technology (Carvalho and Cazarini, 2020; Tay et al. 2018). For this reason, in the present study, the articles published dating from 2011 are taken into consideration.

Table 1
Journals with the highest frequencies of the reviewed papers.

Journal	Impact factor	Sum	Behavior over time 2011–2022
Int. J. Adv. Manuf. Technol. (IJAMT)	3.226	23	
Appl. Sci. -Basel (ASB)	2.679	21	
Autom. Constr. (AC)	7.7	12	
Sensors	3.576	11	
Adv. Eng. Inform. (AEI)	5.603	10	
Saf. Sci. (SS)	4.877	10	
Int. J. Comput. Integr. Manuf. (IJCIM)	3.205	9	
Int. J. Ind. Ergon. (IJIE)	2.656	9	
Robot. Comput.-Integr. Manuf. (RCIM)	5.666	9	
Comput. Ind. Eng. (CIE)	5.431	7	
Comput. Ind. (CI)	7.635	7	
IEEE Access (IA)	3.367	7	
Virtual Real. (VR)	5.095	6	
Electronics	2.397	5	
Energies	3.004	4	



Notes. The journals are shown using ISO abbreviation and the impact factor corresponds to the year 2020, both obtained from the website InCites Journal Citation Reports (Clarivate Analytics®). The acronym of the journal used as an identifier is formed utilizing the first letter of each word of the journal name.

Table 2
Search query string executed in the database platforms.

Database	Search query string
Web of Science	((TS=((“virtual reality” OR “augmented reality” OR “mixed reality” OR “cross reality” OR “extended reality” OR “virtual environment” OR “HMD” OR “CAVE” OR “virtual world” OR (“virtual” AND “perception”)) AND ((“smart industry” OR “intelligent manufacturing” OR “cyber physical system” OR “industry 4.0″ OR ”manufacturing 4.0″ OR (“digital twin” AND (“industry” OR “manufacturing”))) OR ((“industry” OR “manufacturing”) AND (“experiments” OR “results”))))))
Scopus	TITLE-ABS-KEY (“virtual reality” OR “augmented reality” OR “mixed reality” OR “cross reality” OR “extended reality” OR “virtual environment” OR “HMD” OR “CAVE” OR “virtual world” OR (“virtual” AND “perception”) AND (“smart industry” OR “intelligent manufacturing” OR “cyber physical system” OR “industry 4.0″ OR ”manufacturing 4.0″ OR (“digital twin” AND (“industry” OR “manufacturing”))) OR (“industry” OR “manufacturing”) AND (“experiments” OR “results”))

the journals’ coverage of both databases in terms of the field of study is wide. In this context, the sample of articles used in this review pertains to journals that appear in the JCR 2020 by Clarivate Analytics®, classified in the Science Citation Index Expanded or the Social Sciences Citation Index, or both. The selected journals have an impact factor greater than or equal to 1.0. Regarding the analysis of the studies across the development of this review, at least two of the four authors participated independently during each stage of the review in a rotational manner. For each research work, the attributes identified using the proposed taxonomy are presented in the Appendix.

Data synthesis. In this review, the data synthesis is presented through the proposed taxonomy, which incorporates a classification of the research papers summarized in Table A (Appendix). In this context, categories and subcategories from the taxonomy are exemplified by describing at least one related approach and several supplementary studies’ citations. Another form to illustrate the data consists of descriptive statistical analysis and data mining findings using tables and figures. Moreover, to complement the discussion of the XR technologies in the context of industry 4.0, outcomes and interpretation analysis are included.

3. Related works

This section presents previous endeavors to describe the state of the art of virtual technologies (VR, AR, MR) among different industries related to industry 4.0. For example, Choi et al. (2015) present a comprehensive survey on the relevance of VR technology on manufacturing industries, identifying past and present trends. By analyzing a total of 154 articles from 1992 to 2014, researchers found a correlation between VR and new product development (NPD). In addition, they develop an analysis map on a VR technology classification and NPD process, as well as a bibliometric analysis.

In an effort to point out the benefits and costs associated with VR and 3D modeling in a systematic way, Akpan and Shanker (2017)

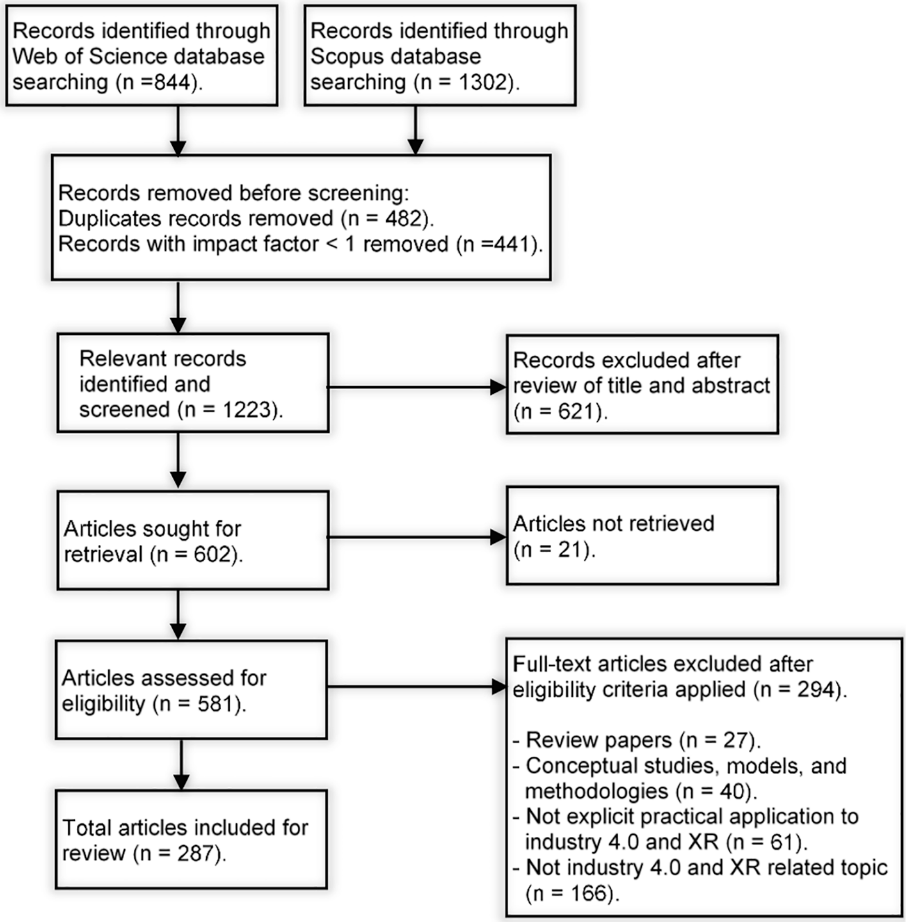


Fig. 1. Selection process of the study records.

assess 67 articles from 2000 to 2016 and use the PRISMA methodology to present a review of research and practical applications, clearly differentiating between unsubstantiated claims and proven benefits. The research concludes that VR does not show any benefit in initial stages of problem definition. However, for model development, it was concluded that 3D visualization and VR offer several advantages over its relatively higher cost, whilst also improving model understanding, validation, and verification. Additional benefits were observed for experimentation and analysis of simulation results, showing enhanced performance, including significant time-saving. This study also shows that the main drawback of creating 3D or VR models is related to development time. These models take longer to develop than 2D models, although reasons for this difference were not addressed.

Regarding the construction industry, Sidani et al. (2019) study how VR technologies are incorporated to facilitate the deployment and application of building information modeling (BIM). The authors review 16 articles from 2013 to 2018 and report that most of them focused on enhancing teamwork, communication layer, and database to exchange non-geometric information. In the context of the research stage of the projects' life cycle, they found that the stage of design is the most researched (12 occurrences), followed by pre-construction, construction, operation, and management (9 occurrences).

Further, de Souza Cardoso et al. (2020a) conduct a study to evaluate the impact of AR applicability and usefulness on industrial processes. This systematic review covers a collection of 120 articles and 16 patents. They identify some disruptive innovations of AR (e.g., eliminating the need for on-site experts, using remote assistance, or robot programming by identifying user movements). They find the need for some technological improvements to enhance the user's comfort while wearing HMD in a production environment. The authors also highlight the relevance of user mobility, time to set up and interact with the system, and an ergonomic device selection. In the context of AR challenges in industry 4.0, Masood and Egger (2021) present a comprehensive survey that makes emphasis on the relevance of photonic components as one of the main challenges to overcome for AR success, including those areas related to ergonomics, usability of user interface, visibility of information, and hardware robustness.

Human-Robot collaborations are also studied by Blaga et al. (2021) with a focus on the impact of AR in assembly manufacturing execution systems. In this work, the authors present current challenges of AR integration in different scenarios, showing that AR approaches must match the user's application, both in hardware and software/firmware.

In order to evaluate decision making, Berg and Vance (2017) present an exhaustive survey that describes the use of VR as a tool for product design in engineering. It is relevant to notice that VR application data was collected from on-site visits to 18 companies that use VR in their design processes; likewise, 62 people were interviewed to collect case studies on successes and challenges. It is concluded that VR is mature, stable and actively used in decision making. In addition, this survey identifies the state of some canonical research challenges for VR to work, as originally presented by Brooks (1999). In this context, it was shown that the advances in technology system latency have improved to a level that makes systems usable, with some opportunities in improving communication time among different technologies used in VR systems such as haptic interaction.

Further exploration of the impact of AR on the fourth industrial revolution is reported by Masood and Egger (2019). They identify that the estimated aggregated market value of industrial AR may reach $76 billion by 2025. This is supported by quantitative and qualitative methodologies to identify critical factors for the successful implementation of AR in industrial projects, highlighting the suitability of the task and the workers' level of expertise, as well as technology acceptance.

Supplementary systematic studies have shown that there is an important opportunity for profiting of VR, AR, and MR strengths. For instance, the coherent integration of technologies such as smart sensors, actuators, the IoT, big data, and data science, as well as machine learning (ML) is enabling the development of industry 4.0, where such technologies play a fundamental role (Ruppert et al, 2018). Moreover, the potential benefits associated with industry 4.0 outweigh its implementation costs. It is emphasized that information technology governance is of paramount importance to ensure the harmonious and agile integration of the different technologies in the smart factory, which in turn allow for reliable interoperability (Ghobakhloo, 2018). Following this trend, immersive technologies allow the interconnection of the physical with the cyber-world. Both VR and AR will be commercially successful given benefits allowing a portal to physical experiences through the distance for a wide spectrum of applications, for example: training applications in the aviation industry (Govindarajan et al., 2018), vocational training (Chiang et al., 2022), model visualization and comprehension (science community), structure modeling (construction industry), and virtual tours (entertainment and education) just to name a few. These technologies, in combination with the IoT, will lead to the development of the internet of presence (IoP) or the internet of experiences (IoE) (Govindarajan et al., 2018).

In the meantime, one of the most successful areas for XR technologies is education and training; such technologies have a positive impact on areas that emulate actual possible scenarios that involve machine operation, process parameter selection, and planning (Jou and Wang, 2013). For example, Papanastasiou et al. (2019) review related literature addressing the benefits for learning outcomes due to enhanced student experiences, engagement, self-learning, multi-sensory learning, cognitive load decrease, and general enjoyment, that together demonstrable benefits such as recall of lists, knowledge assimilation and retrieval, showing that possible entrance barriers (e.g., intellectual property) and challenges are worth overcoming. A more recent study (Chiang et al., 2022) shows that AR is relevant invocational training applications, in a variety of fields, with a total 80 papers from 2000 to 2021. This study shows that within the context of industry 4.0, AR improved spatial cognition and visualization skills, assembly skills, task and decision making abilities, reduction of cognitive load, shortening training time and reducing operational errors.

Additionally, Gao et al. (2019) carry out a systematic review that evaluates the effectiveness of training using traditional tools (TT) and computer-aided technologies (CAT) on the well-being of individuals. The literature search was not limited to any language and time span constraints. The selected sample encompassed 49 articles in the field of traditional training, serious games, computer-generated simulations, VR, AR, and MR in relation to the domain of health and safety training in the construction sector. According to the authors, results show a learning gain in trainees' knowledge acquisition, behavior alteration, and injury rate reduction with the use of TT techniques. The authors express that: "The systematic review also revealed that the overall performance of CAT is superior in several technical aspects compared to TT, namely, representing the actual workplace situations, providing text-free interfaces, and having better user engagement".

The current review covers in-depth studies that highlight the importance of XR technologies for the development of industry, particularly with the advent of industry 4.0. However, other relevant applications outside the industrial scope are identified and studied. For instance, Kim et al. (2018) expose trends in AR, VR, and MR from 2008 to 2017 in the context of the International Symposium on Mixed and Augmented Reality (ISMAR). They identify 439 classification topics, focusing on 15 areas of research. This way, the survey reports that the five most frequent research topics are tracking, interaction, calibration, applications, and display with newly identified categories such as perception, collaboration, reconstruction, and modeling.

4. Results

The XR applications in industry 4.0 presented in this work are consistent with the review of the collected sample that includes 287 research articles. This section is organized according to the proposed taxonomy introduced in Section 4.1 and showed in Fig. 2. Hence, it is divided into subsections (4.2–4.11) to outline the ten categories. The subsections exhibit the subcategories by means of an item relation, percentages, or by a table to give some clues about the most relevant XR research paths. Regarding the content, the subcategory is depicted using at least one related approach and supplementary citations. Furthermore, the complete set of works characterized according to the taxonomy is illustrated in the Appendix section.

4.1. A taxonomy for XR approaches in industry 4.0

XR approaches can be intricated due to the requirements to be considered in order to develop applications. Thus, diverse issues need to be addressed, such as activity target, purpose, domain knowledge, applied technologies, and user experience. Consequently, a multidimensional perspective is useful for organizing and classifying the approaches, as well as describing them to depict the state of the art. For this reason, the present work contributes to outline a taxonomy for XR approaches in industry 4.0, as shown in Fig. 2. The taxonomy contains ten categories that offer particular views to illustrate the approaches; they are split into 68 subcategories that define a construct of such views and describe the nature of our approach.

4.2. Field of application

4.2.1. Automotive

Atici-Ulusu et al. (2021) study the effect of AR glasses on the cognitive loads of the employees on an automobile assembly line. They use electroencephalography (EEG) and NASA Task Load Index (NASA-TLX) to measure cognitive load. In addition, Konstantinidis et al. (2020) propose a user-centered methodology that encompasses AR and computer vision to aid novice operators in maintenance procedures on an automotive shop floor. On the other hand, Merenda et al. (2018) analyze two ways to communicate real-world

Fig. 2. Taxonomy for XR approaches.

hazards to drivers; they use a head-up display inside the car to show fixed and animated AR text and images to examine the driver's performance and the visual attention.

4.2.2. Construction

Safety in construction is a relevant issue addressed by Placencio-Hidalgo et al. (2022), and Eiris et al. (2020), who focus on injury prevention. The former uses AR to teach safety elements on scaffolding to avoid falls, and the latter implements VR storytelling with 360-degree panorama technology of the construction job site. Moreover, Chalhoub and Ayer (2018) propose MR to design information delivery for electrical conduit assemblies with performance benefits to reduce construction errors and time on assembly tasks. Lastly, Lu and Davis (2016) use a virtual construction simulator to investigate the effect of sound and how to reduce unsafe behaviors in a physical environment.

4.2.3. Energy

Francisco and Taylor (2019) explore and evaluate open urban energy data to improve citizen decision-making where AR visualization elements are integrated to enable links between physical infrastructure and smart meter data. Whilst, de Barreto Junior et al. (2021) develop and assess an authoring system methodology based on CAD floor plans to create VR scenarios applied to the electric power field.

In this context, tablets and smartphones are some of the most used devices since they provide a cost-effective solution; such as an energy application showing a virtual world for home energy saving while reducing human intervention (Lu, 2018) or for electrical risk mitigation and establishing a safety culture (Zhao et al., 2016).

4.2.4. Recreational

Tourism has always been a hot topic in XR applications. For instance, AR is used to support cultural heritage management tasks (Kovachev et al., 2014). Indeed, it has been shown that *navigation* is useful in AR applications to enhance people's willingness to participate in cultural activities (Chiu and Lee, 2018).

Hammady et al. (2020) develop a novel museum guidance system where they examine the influence of interactivity, spatial mobility, and perceptual awareness of individuals within MR environments. Chiu et al. (2019) show an AR application with image-based recognition where cultural bearers can stimulate visitors' willingness to learn about cultural history. Likewise, McLean and Barhorst (2021) and Martínez-Molés et al. (2022) study the influence of VR technology on tourism consumers' attitudes and purchase intentions, applied to hotel bookings and cruise vacation packages, respectively.

4.2.5. Manufacturing

Gimeno et al. (2013) propose an AR authoring tool that enables non-programming users to build low-cost AR applications oriented to assembly and maintenance tasks by placing the 3D virtual objects in a real scenario template. Masood and Egger (2020) use an AR framework for assembly tasks and identify factors (e.g., user acceptance, visibility of information, ergonomics, and usability) to succeed in adopting AR. They found user acceptance organizational issues are more relevant to the industry than technological aspects. Another example is an integrated MR system for safety-aware human-robot collaboration using deep learning and a digital twin to assist the human operator in task execution more effectively and safely (Choi et al., 2022).

4.2.6. Maritime

Jang and Nam (2020) apply VR to verify the pipe installation process (installed or disassembled in the order calculated by an algorithm) by visualizing each installation step in three-dimensional space for cramped spaces of ships and offshore structures. In this context, an MR collaborative application is developed to assist and guide shipyard operators in training and assembly tasks. This enables the interaction and visualization in a synchronized manner in the same virtual content (Vidal-Balea et al., 2020). Additional works within the domain knowledge of physics and engineering in the maritime field employ an AR architecture based on cloudlets for shipbuilding operators and remote collaboration in a shipyard's pipe workshop in maintenance procedures (Fernández-Caramés et al., 2018) and an AR/VR framework for ship construction and offshore structures (Han et al., 2019).

4.2.7. Education and research

VR technology supports the educational process to meet the need of industry 4.0. Paszkiewicz et al. (2021) proposed a methodology and the design, creation, implementation, and evaluation of courses in a VR environment in safety training. Later, using this methodology, they developed a digital circuit course based on games to promote knowledge acquisition and skills (Paszkiewicz et al., 2022).

Ma et al. (2019) apply VR technology to measure effectiveness in a manufacturing system design course for queuing theory. Whereas Nykänen et al. (2020b) evaluate training and human factors on the safe usage of a table saw and work at height. Similarly, Doolani et al. (2020) and Lee (2020) focus on vocational training. The first one teaches how to use a mechanical micrometer by employing a story embedded inside a virtual manufacturing plant. The second one applies VR for learning woodworking for batch furniture production.

4.2.8. Health and safety

The inclusion of AR technology enables inspection to assist the inspector's workflow and increase awareness in conducting infrastructure inspections (Maharjan et al., 2021). In addition, VR provides insight into the design process and model heat maps depicting risk for patient rooms (Piatkowski et al., 2021). Additional examples employ MR to enhance safety risk communication and managerial operations on construction sites (Dai et al., 2021) and for designing, building and publishing experiences related to occupational safety and health learning (Lopez et al., 2021). Concerning *safety*, Longo et al. (2019) propose a framework and an industry 4.0 architecture for emergency staff training to enhance preparedness skills for key roles in an emergency response system. Furthermore, the design of VR training simulators for safety procedures for electric overhead crane operators (Dhalmahapatra et al., 2021) and crisis management emergency drills (Kwok et al., 2019) are built.

4.2.9. Aerospace

Aerospace is one active industry that invests in XR research, development, and innovation. For instance, Osterlund and Lawrence (2012) use VR, a motion capture system, haptic interfaces, and 3D software to train the personnel operators, using a controlled environment, and to evaluate a spacecraft flight. In addition, Ottogalli et al. (2021) study the ergonomics of the human worker inside the narrow space of the fuselage in an aircraft while assembling the parts and coexisting with robots without compromising the worker's safety. The VR simulator executes multiple process scenarios and performs a productivity and ergonomics evaluation to support assembly line activities. Moreover, an AR application that addresses the requirements of the structural assemblies used in aeronautical industries is analyzed by de Souza Cardoso et al. (2020b).

4.2.10. Petrochemical

Manca et al. (2013) developed a VR and AR training solution tailored for the chemical process industry. It integrates a dynamic process simulator with a dynamic accident simulator to effectively train operators to respond in abnormal situations. In the same way, Corallo et al. (2020) explore applicative cases focusing on Oil and Gas products, such as multistage centrifugal pumps and ball valves. They integrate CAD tools with VR full-scale simulations to design and verify assembly procedures before the implementation. Lastly, a couple of works that address inspection and maintenance activities using MR and AR are presented by Koteleva et al. (2022) and Marino et al. (2021), respectively.

4.2.11. Bussiness

Companies seek the potential advertising tactics and effects on customers using XR technology, such as brand and purchase intention. Rhee and Lee (2021) examine the relationship between virtual fitting experience satisfaction and the customer's purchase journey. On the other hand, Wu et al. (2022) investigate the influence of 3D animated agents on video ads in a VR context (e.g., brand/product recall and ad-skipping behavior). In addition, a study by Leung et al. (2020) shows that VR commercials have more immediate advertising effects than their classic counterpart.

Furthermore, online shops use interactive technology to simulate an immersive product experience. For instance, Kinzinger et al. (2022) developed a virtual room with a table and kitchenette, creating a realistic, typical application scenario for a kitchen appliance. Lastly, Waterlander et al. (2011) explored a virtual supermarket tool to gain insights into food purchasing behavior.

4.2.12. Others

Regarding the *mining* industry, Grabowski and Jankowski (2015) developed a blasting scenario for VR training to practice the correct behavior of the miners in a controlled and safe environment. Pedram et al. (2020) examine co-presence in an interactive VR training in rescue operations, so that trainees work together to search for a missing miner.

In *agriculture,* an AR educational resource grounded on the theory of situated learning is developed to promote eco-agritourism while encouraging tourists to be environmentally responsible (Garzón et al., 2020). For *livestock,* computational fluid dynamics models combined with VR is used to create a simulator where diverse parameters (e.g., internal airflow, air temperature, humidity, and gas) are applied to a VR simulator for a piglet house (Kim et al., 2019). As for *aquaculture*, Rahman et al. (2021) present a framework for a prawn farm management using MR, sensing, and monitoring the water quality with machine learning algorithms. For *water* sector, Lian et al. (2022) develop a DT to remotely monitor and control a water plant to verify the water quality and to reduce the risk of failure. Whereas, for *biotechnology*, Baceviciute et al. (2022) use a VR application to teach particular molecular structures and to perform a hydrolysis experiment.

4.3. Activity

XR technologies have been helpful in construction, engineering, and architectural *design* activities. For instance, Osorto Carrasco and Chen (2021) employ MR to enhance comprehension of the aesthetic characteristics of materials and evaluate their effect during the design stage. In the same context, Birt and Vasilevski (2021) develop a BIM *visualization* experience for a 24-hour transition simulation (the day-night lighting change), using visual avatars and voice communication capabilities for single and multiuser modes.

A relevant issue addressed in this sector is the workers' *training*. For example, Mora-Serrano et al. (2021) develop a VR application to support the safe use of tools, machinery, and materials to avoid risk and occupational incidents.

A relevant issue addressed in this sector is the workers' training. For example, Mora-Serrano et al. (2021) develop a VR application to support the safe use of tools, machinery, and materials to avoid risk and occupational incidents. Other pertinent research issues within the scope of training are those related to the evaluation of the Operator's tacit knowledge. An essential aspect is promoting the articulation to allow such knowledge to become explicit and manifest in practice (Garzón et al., 2020; Hoffmann et al., 2019).

Similarly, *assembly* is a core activity in manufacturing processes. Židek et al. (2021) create a methodology and an assembly work cell using a collaborative robot, MR, and neural networks to build a digital twin representation and assist the assembly process of a cam switch. Also, in the manufacturing cells, Yang et al. (2019) employ computer vision algorithms to *track* the target and achieve data fusion to guide the worker in the correct wiring connection in the assembly of a wiring harness equipment. Besides, *simulation* is essential in manufacturing processes, Ottogalli et al. (2019) describe a framework to model industry 4.0 processes in AR and VR simulations. They developed scenarios involving the assembly and disassembly of components (e.g., aircraft assembly, high-voltage cell security, and training in machine-tool usage).

As for *content authoring*, Fernández del Amo et al. (2020) designed a framework based on structured messages. It enables data capture and sharing to create AR content to support remote collaboration. For *maintenance* activity, Mourtzis et al. (2021) implement an AR application pursuing the integration of machine monitoring, maintenance, and scheduling with the potential of detecting the available timeslots on a machine schedule to plan maintenance tasks. In addition, AR has been used to promote *operations* and remote collaboration in the industry. For example, Calandra et al. (2021) develop a remote operation system to support the communication and assistance of field operators during the assembly of a robotic gripper.

Rapid prototyping is an activity that assists the personalization of products. Aheleroff et al. (2021a) propose an AR architecture for additive manufacturing for personalized protective equipment (e.g., face masks). XR technology is compatible with large-scale resolution displays to visualize and *navigate* through scenarios, as shown by Otto et al. (2020). They studied how the users perceive true-size dimensions of models and enhance spatial perception in the automotive sector. In *logistics*, Barata and da Cunha (2021) provide an example of AR for traceability of the lifecycle of glass windows in the supply chain. This application supports electronic product labeling and emerging regulations to achieve transparency for product information.

Kačerová et al. (2022) explore the combination of VR and *motion capture* to moderate the need to build physical prototypes. They describe a method to design and optimize a workplace tested on an assembly line for door parts in the automotive industry. Another activity where XR is applied concerns *measurement*. For instance, Lalik and Flaga (2021) use MR to measure real and virtual distances to locate a robot arm in the workplace and operate it remotely. Regarding the activity of *location*, Sidiropoulos et al. (2021) develop an AR application to provide indoor guidance in a warehouse for logistics activities. Lastly, *analytics and decision-making* have become relevant issues addressed with XR technology. For example, Tadeja et al. (2021) use VR technology to identify patterns in high-dimensional engineering data sets to improve decision support applied to the aerodynamic design of turbomachinery components.

4.4. Domain knowledge

XR applications have proven beneficial in different domains, helping users' in daily activities and work tasks. Regarding *physics and engineering*, Ceruti et al. (2019) combine AR and additive manufacturing to identify failed parts of commercial aircraft. They use finite element models and a topological optimization of brackets to reduce the spare parts warehouses of non-structural parts. As for *pattern recognition*, industry 4.0 has taken advantage of this field in combination with XR technology. For example, Lai et al. (2020) use two cameras (AR tracking and object detection) and deep learning prediction for tool detection, superimposing the assembly instructions. Likewise, speech recognition is combined with deep learning to interact with MR content in aircraft maintenance training (Siyaev and Jo 2021a; Siyaev and Jo 2021b).

Dhiman and Röcker (2021) develop and test a middleware to support cross-device (tablet, smartphone, and AR glasses) for assembly and calibration tasks in a virtual manufacturing context. Another work creates a VR simulation to assess the mental workload of

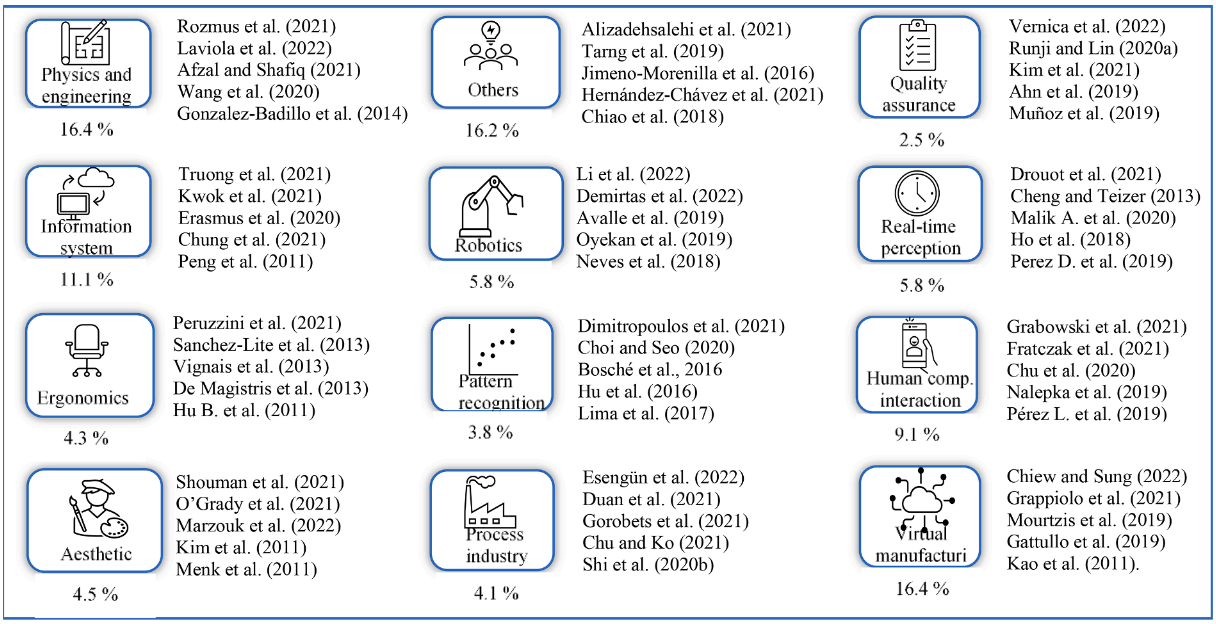


Fig. 3. Domain knowledge category.

overhead crane operators using eye movement metrics (Das et al., 2020). As for ergonomics in the industry, Simonetto et al. (2022) propose a methodological framework and use a mocap system with VR to evaluate workplace design procedures and layouts. In order to improve the worker ergonomics and safety, Muñoz et al., 2020 deploy an MR interface for camera 3D positioning tasks in inspection systems of car body quality assurance.

Finally, Fig. 3 depicts additional works belonging to the twelve domain knowledge subcategories identified in the review. Below each subcategory icon we show a percentage of the global distribution of the research works.

4.5. Reality experience

In addition to the field of application, activity, and domain knowledge, the design of an XR approach considers the nature of the reality experience to recreate. In this regard, three kinds of realities are utilized: *virtual*, *augmented*, and *mixed*. Moreover, a sample of the approaches illustrates such reality experiences, as shown in Table 3.

4.6. Environment perception

The wide range of XR applications offers different views of environment perception. The *synthetic* way builds a colorful computer graphics environment mainly used in VR applications. Regarding the *captured* environment, the use of cameras allows mixing virtual and real objects (e.g., AR applications). Finally, the *hybrid* environment uses MR devices or the integration of devices and sensors to HMD or AR equipment where the user is fully aware of the interaction of real and virtual objects from the perspective of both worlds. It should be noted that in all these environment variations, human–machine interactions are carried out within an Intelligent Space (iSpace) for the support of people and mobile robots, allowing them to complete their work with high efficiency, and success rate, whilst maintaining a low burden. Examples of such environment perception are presented in Table 4.

4.7. User interaction

This section highlights a sample of works organized into two subcategories: individual (Izard et al., 2017), (Taha et al., 2014) and collaborative Ferraguti et al. (2019). Regarding individual interaction, Checa et al. (2021) designed a framework and a VR experience where a worker controls a bridge crane to detect occupational hazards and carries out the corresponding corrective measures. Concerning the real estate market, Juan et al. (2018) developed a VR-based navigation system for pre-sale housing. They studied the understanding of the project (perceived usefulness) and clients' intention to purchase.

As for *collaborative*, Wang et al. (2019a) develop a gesture-based remote collaborative platform using MR; they study the effects of sharing the remote expert's gestures in collaboration with local workers on physical tasks (e.g., assembly) using a VR HMD, a Leap Motion, and a projector. An example of a real-time synchronization system is introduced by Du et al. (2018b). It allows users to update BIM models and coordinate reviews of design changes using VR headsets (e.g., Oculus Rift DK2) automatically and simultaneously. It supports multi-player and animations of avatars. In addition, Shi et al. (2019) simulate a high-rise walking scenario and investigate the effects of reinforced learning. They employ a multi-user VR system integrated with motion sensors, where users can interact and see other avatars' motions. Moreover, social interaction is also addressed by means of role-playing collaboration for construction safety (Le

Table 3
Types of reality experience.

Virtual reality	Augmented reality	Mixed reality
Assembly is an important activity in the manufacturing process. An *immersive* VR system is built using HTC Vive Pro device for industrial plug assembly to support the teaching process of digital factory module at the industrial engineering (Gabajová et al., 2019). In addition, another example is found in Abidi et al. (2019), where a *semi-immersive* VR system based on a 3D projector and active glasses is employed as an effective and efficient means for evaluating assembly operations and training personnel. As for a *non-immersive* experience, an example is provided by Phoon et al. (2017) that uses an interactive platform for layout planning and simulation to allocate machinery (e.g., conveyor) and support loop layout decisions.	Concerning the AR experience, Pardo-Vicente et al. (2019) propose a haptic hybrid prototyping solution that employs an AR marker system (QR codes) using textures and reliefs of a product to help product design teams evaluate and select semantic information conveyed between product and user. In contrast, Mirshokraei et al. (2019) develop an AR markerless application for acquiring inspection data, processing the results, and facilitating collaboration among the actors involved in quality management. This system uses depth-sensing as the tracking system to overlay the building model to the reality on site. In addition, Han et al. (2019) develop a framework with a piping component file parser and a 3D model generator that works as a bridge for CAD systems and AR/VR applications.	MR is integrated into learning and training programs to create authentic learning experiences and to facilitate knowledge acquisition and workplace expertise, as shown by Wu et al. (2019). They explore VR and MR interventions in construction education and workforce development in novice and experts through the lens of accessibility design review assessments in the building domain, employing HTC Vive and HoloLens devices. Another example is the proposed by Deshpande and Kim (2018), which supports gesture-based interaction to perform furniture assembly tasks; the system provides visual instruction in a sequence, which differs in the level of assembly complexity.
VR is the most used reality experience in health and safety and construction fields.	AR is the most used reality experience in automotive and petrochemical fields.	MR is the most used reality experience in aerospace field.

et al., 2015) and Richard et al. (2021) model AR and VR interactions to author training situations or procedural guidance applied to collaborative robotic workstations and workshop layout design.

4.8. Equipment

Fig. 4 presents seven classes of technological gadgets employed to support XR in industry 4.0 and cites some selected works revised in our study that uses them.

As examples of this category, in the construction industry, Hasanzadeh et al. (2020) explore behavioral adaptations of roofing workers to provide more safety interventions. Their MR experimental environment used a CAVE that incorporates eight projectors and four projection screens to get a high-resolution panoramic view in a darker 3 m × 3 m × 3 m cubic room, in addition to head and ankle tracker sensors mounted over the worker. In the education field, Shin et al. (2020) propose a method for evaluating users' perceptions of virtual objects and the effects of scale and color perception. For this, they use an optical see-through HMD (i.e., HoloLens glasses) and a video see-through HMD (i.e., Oculus Rift HMD with an OVRVision stereo camera attached). As for the simulator subcategory, Grandi et al. (2020) propose an MR set-up to support a human-centered product (a tractor cabin) and a process (assembly and maintenance tasks) design. They use motion capture to quantify human activity and allow real-time physical, ergonomics, and workload measures.

4.9. Devices

Different kind of devices (e. g., cameras, displays, projectors, controllers, and haptic devices) have been adopted in XR, which have diverse functionalities and characteristics depending on the specific application. For example, to enhance user experience in digital content visualization, Eiris et al. (2018) use fisheye cameras to capture 360-degree panoramas with low computational cost to be integrated into MR sceneries. Bordegoni et al. (2011) use a DLP projector with 3D glasses and a set of mirrors to explore cross-modal illusions to see the aesthetic features of a product.

In terms of interaction, Liang et al. (2019) and Jeong et al. (2016) use an RGB-D camera to identify hand gestures that allow human–machine interaction in VR systems, whilst Jayasekera and Xu (2019) use a Leap Motion device to track the user's hands in assembly tasks in VR. Similarly, Heydarian et al. (2015) use a wand tracker to navigate through an immersive VR environment, whilst Gorecky et al. (2015) and Li et al. (2012a) have used Nintendo Wii-mote for game-based user interaction. Moreover, there are haptic controllers with feedback force used for motor skill training to achieve comparable levels of motor performance among operators (Ma et al., 2020) or gloves with vibrotactile sensors used in assembly and disassembly tasks with physics constraints (Aleotti and Caselli, 2011).

4.10. Interconnectivity

4.10.1. Digital twin

Cai et al. (2020) design and implement a method for mechatronics systems connected to an IoT network and use AR to build a link between a simulation program (cyber domain) and the robotic arms (physical domain) for tool path planning. Similarly, Fang et al. (2019) propose a job shop scheduling method based on a digital twin to achieve real-time and precise scheduling. VR is used to establish a bridge between virtual and real space; it uses RFID, wireless sensor networks, intelligent instruments, and various sensors to collect data and monitor production processing workshops.

In addition, Nikolakis et al. (2019) use simulation-based approaches to optimize the planning and commissioning of human-based production processes in logistics operations for the white goods industry. The study involves a pick and place process of warehouse components. Moreover, a VR digital twin uses an RGB-D camera (Kinect motion system) and robotics to learn from human reactions and robot motions (Oyekan et al., 2019). Lastly, Yang and Miang Goh (2022) propose a customized design method for developing new board-type furniture production lines based on a DT model, which can parallelize the design process and reduce the design cycle.

4.10.2. Cyber-physical systems

Cyber-physical systems (CPS) play a key role in industrial processes and smart factories to optimize performance and efficiency. For instance, Hoffmann et al. (2019) study the support of CPS for exchanging and acquiring knowledge expertise in the context of manual set-up processes on modern production machines. They use HoloLens for recording and reproducing the set-up steps through contextualized AR visualizations and as a sensor for recording the logistical processes in assembly manufacturing contexts. In the mining industry, Xie et al. (2022) developed a CPS based on VR/AR information system. It integrates intelligent equipment using real-time sensing information and workers who collaborate with experts in mining operations (e.g., maintenance of an electrohydraulic controller) to support decision-making. In addition, Naqvi et al. (2019) use content analysis to optimize simulation training and improve human factors in drilling activities. A driller's cyber chair allows users to participate as assistant drillers and communicate with a driller as they usually do in a real-world setting to deal with a drilling problem.

4.10.3. Context-aware systems

del Amo et al. (2022) propose a method to provide context-aware and ontology-based AR recommendations to reduce the selection lists in diagnosis reporting tasks. For the method validation, they develop an AR system using electronic and electrical case studies. Nazir et al. (2015) show a 3D VR immersive environment for training methods on distributed situation awareness. The operators (field

Table 4
Environment perception.

Synthetic	Captured	Hybrid
Ng et al. (2012) study the human perception of hazard and risk in real and virtual environments. Participants observed robotic arms movements in both scenarios to train workers about robot motions and robot hazards; they found time is transferable from the virtual to the real-world. Also related to robotics, Matsas et al. (2018) implement a Human-Robot collaborative framework that integrates proactive and adaptive techniques for safe collaboration (for example, the user is provided with several cognitive aids and alarms, and robots use adaptive motion techniques). One of the study objectives is not to interrupt the flow of collaboration due to false safety alarms mainly triggered to safeguarded human integrity.	Wang (2015) shows an adaptive and collaborative manufacturing process where the workspace of a robot arm and a human operator is captured using cameras and sensor data to enhance safety collaboration due to an active robot control approach for collision avoidance. Simões et al. (2019) propose an MR system to support human safety and human–machine interaction; the system supports workers on assembly tasks delivering visual highlighting content of the items to be assembled. The MR system reduces the high costs of authoring assembly manuals and facilitates the acquisition of skills needed for specific tasks.	Wang et al. (2019b) use a virtual reality application as an interface for a collaborative human-robot welding system. The welding torch is connected to the robot and automatic seam tracking is performed. The human operator uses an HMD where a virtual welding environment is shown with augmented data about the robot welding performance so that the human operator can control the robot remotely along the weld seam. Malik et al. (2020a) present a framework where a VR device, haptic controllers, and RGB-D cameras are used to integrate a human-robot collaboration. With one hand, the operator can visualize simulations, and with the other hand, the operator can interact with the simulation, both using a HMD.

and control room) are immersed in an industrial plant environment to deal with uncertainties in normal and abnormal operating conditions. In the same way, Colombo and Golzio (2016) follow a similar approach. In addition, Irizarry et al. (2013) use an AR mobile application with a tracking system to add information to managers for their everyday tasks using the concept of Situation Awareness. 3D Models are used with low geometry and create 360° panoramas so the facility managers can see the objects' information with augmented data.

4.10.4. Cloud computing

Cloud computing facilitates the use of on-demand services, as depicted by Mourtzis et al. (2020): a real-time maintenance AR system as a cloud-based platform to enable data storage and communication of shop-floor technicians (augmented operator) and expert engineers. Besides, Xiao et al. (2018) present a mobile AR framework for assembly processes where the cloud computing layer tracks the natural features in the assembly scene, registers the assembly order of the product, and renders the mixture of virtual and real objects. This information is sent to the operator's workstation to improve the assembly process. Du et al. (2018a) show a cloud-based multiuser VR headset system where an imported model, and diverse remote users with distinct HMDs play different roles, such as owner, architect, and structural engineer. The users can interact, communicate, and inspect a building with real data through the system.

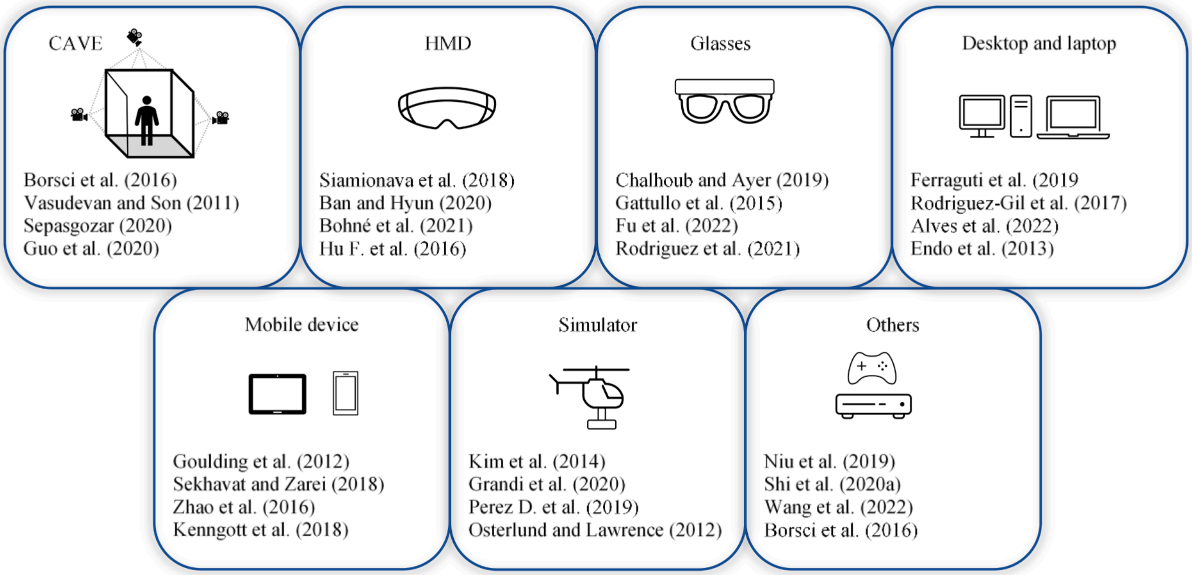


Fig. 4. Equipment category.

4.10.5. Internet of things

IoT devices require connecting wirelessly to a network, displaying data output, or accessing real-time configuration. In this context, Fuentes et al. (2021) propose an architecture that uses AR to visualize information in real-time from IoT devices without adding specific hardware. The architecture has a security layer to block access to unauthorized users. Likewise, Lu (2018) develops an adaptive, context-aware, and CPS for energy savings. The system allows bidirectionally interactive information visualization along with IoT-enabled technologies. The users can control remote appliances anywhere and anytime. In addition, Dong et al. (2018) implement a system for real-time location and sensors used for safety performance in construction workers.

4.11. Sensors

4.11.1. Physiological

In the health and safety field, Bu et al. (2021) propose a user-centric framework for smart product-service system. As validation, they use a VR rowing machine and functional near-infrared spectroscopy for detection of the hemodynamic activity of the cerebral cortex in real-time to evaluate the relationship between the task and brain function. Regarding assembly tasks, Ariansyah et al. (2022) study the impact of different AR modalities in terms of information (i.e., video vs 3D animation) and interaction (i.e., hand-gesture vs voice command) on the user (i.e., performance, workload, eye gaze behaviors, and usability), through a wristband sensor to capture continuous physiological measures of electrodermal activity (EDA) and interbeat interval (IBI) to measure levels of autonomic arousal.

Pontonnier et al. (2014) compare simulated assembly tasks on the design workstation in real, virtual, and virtual with force feedback environments. They track the motion of the upper body using infra-red cameras and an electromyographic (EMG) amplifier to record muscle activities. Stone et al. (2011) include EMG feedback for the deltoid, trapezius, extensor digitorum, and flexor carpi ulnaris muscles to examine the interactions between these muscles during the performance of welding tasks, whilst evaluating the process in VR versus traditional training.

4.11.2. Activity

Rezazadeh et al. (2011) show a prototype to control two virtual cranes through commands extracted from facial bioelectric signals via electrooculography (EOG) and electroencephalography (EEG) sensors. They use a fuzzy inference system to classify different gestures as commands (e.g., moving forward, right, lifting, or releasing the crane load). In a similar work, Postelnicu et al. (2012) propose a visual navigation interface with EOG electrodes to acquire signals near the user's eye, so the user can be evaluated and move in the environment using its eyes. Both works are alternative solutions for disabled people who cannot use traditional controllers.

Furthermore, Angrisani et al. (2020) integrate AR glasses with a noninvasive single-channel brain-computer interface as an input interface for a hands-free inspection task for electrical machines in a complex industrial plant.

4.11.3. Environment

Chen et al. (2019) show an application where a 3D geographic information system (GIS) based tool works with a virtual environment to manage an urban major hazard installation, such as a petrochemical enterprise. The system monitors several sensors in real-time (e.g., temperature, gas concentration, wind speed, and pressure) to evaluate accidents and detect early risks. Managers can supervise and find weaknesses at the facilities. In addition, Stark et al. (2020) develop an AR application to control and monitor a mechatronic system with environment sensors such as temperature and moisture.

5. Discussion

The present review examines the aforementioned works and offers a multidimensional view of the XR applications in the context of industry 4.0. This section describes outcomes, findings, and the analysis of XR in the industry 4.0 context.

For this purpose, the baseline data corresponds to the characteristics depicted by the selected sample of 287 articles from which we defined the 68 subcategories of the proposed taxonomy. It is worth mentioning that, each approach is expected to have the ten attributes to represent all categories of the taxonomy. However, in some cases, an approach could be outlined by more than ten attributes in view of its essence or less than ten attributes due to the lack of information in the source paper. Therefore, the attributes that describe the subcategories of each category are not exclusive.

5.1. Principal keywords and HMDs

Fig. 5 was developed using a visualization of similarities software VOSviewer (van Eck and Waltman, 2010). It illustrates the co-occurrences of the keywords through a network visualization, corresponding to 215 records from the Scopus database. 738 author keywords shape four main clusters: red (VR), green (AR), orange (industry 4.0), and violet (MR). The relevance of the circles and text in each node represents the strength of the co-occurrence with the other keywords, while the distance of the items shows the relatedness and the linkages of the keywords. Based on the closer network visualization, industry 4.0 development is strongly interlinked with five keywords: VR, AR, MR, training, and DT.

Thanks in part to the massive adoption of XR devices in the last decade, the XR applications have been growing at a faster pace than in prior years. It is also seen that regardless of the success of the CAVEs for industrial applications (with a higher price tag), the fierce competition in wearable XR devices such as the HoloLens and the Oculus has led to a price reduction and wider support around the world, making them the devices of choice to develop any XR application. In this research, the proportion between CAVE versus HMD is

1 to 8, showing a clear preference for HMDs, mainly due to cost and a higher sense of immersion and presence. Fig. 6 shows the HMDs and glasses found in this research where HTC Vive was the most employed, followed by the Oculus with a higher frequency than the rest. As for glasses, HoloLens is the most used.

5.2. Findings

In this research, some findings are identified by discovering knowledge in the baseline data. The Weka data mining tool (Eibe et al., 2016) is employed to produce association rules using the *apriori* algorithm. These rules have two parts, an antecedent (an item found within the data) and a consequent (an item found in combination with the antecedent) that are relied by a confidence value (CV) which indicates how often the rules are found to be true.

According to the baseline data, the following rules represent more relevance or interest to the study. For instance, the first rule indicates that 32 works include in the category field of application, *health and safety*, as well as for category activity, *training*; 30 also contain the category reality experience related to *virtual reality* with a CV of 0.94. Meaning that 94 % of the time involves the attribute of *health and safety* besides *training*, while another of its characteristics depicts a *virtual reality* experience. Likewise, the second rule shows that concerning the category field of application, *manufacturing*, also involves the category activity, *assembly*; both are contained in 45 works and 36 include the category user interaction in an *individual* manner with a CV of 0.8. Meaning that while 80 % of the time an approach involves the attributes of *manufacturing* and *assembly*, another of its attributes represents an *individual* user interaction.

1. health_safety = TRUE training = TRUE 32 ==> VR = TRUE 30 conf:(0.94).
2. manufacturing = TRUE assembly = TRUE 45 ==> individual = TRUE 36 conf:(0.8).
3. captured = TRUE mobile = TRUE 38 ==> AR = TRUE 36 conf:(0.95).
4. visualization = TRUE VR = TRUE hmd = TRUE 33 ==> individual = TRUE 30 conf:(0.91).
5. training = TRUE 67 ==> VR = TRUE 56 conf:(0.84).
6. education_research = TRUE VR = TRUE 53 ==> individual = TRUE 44 conf:(0.83).

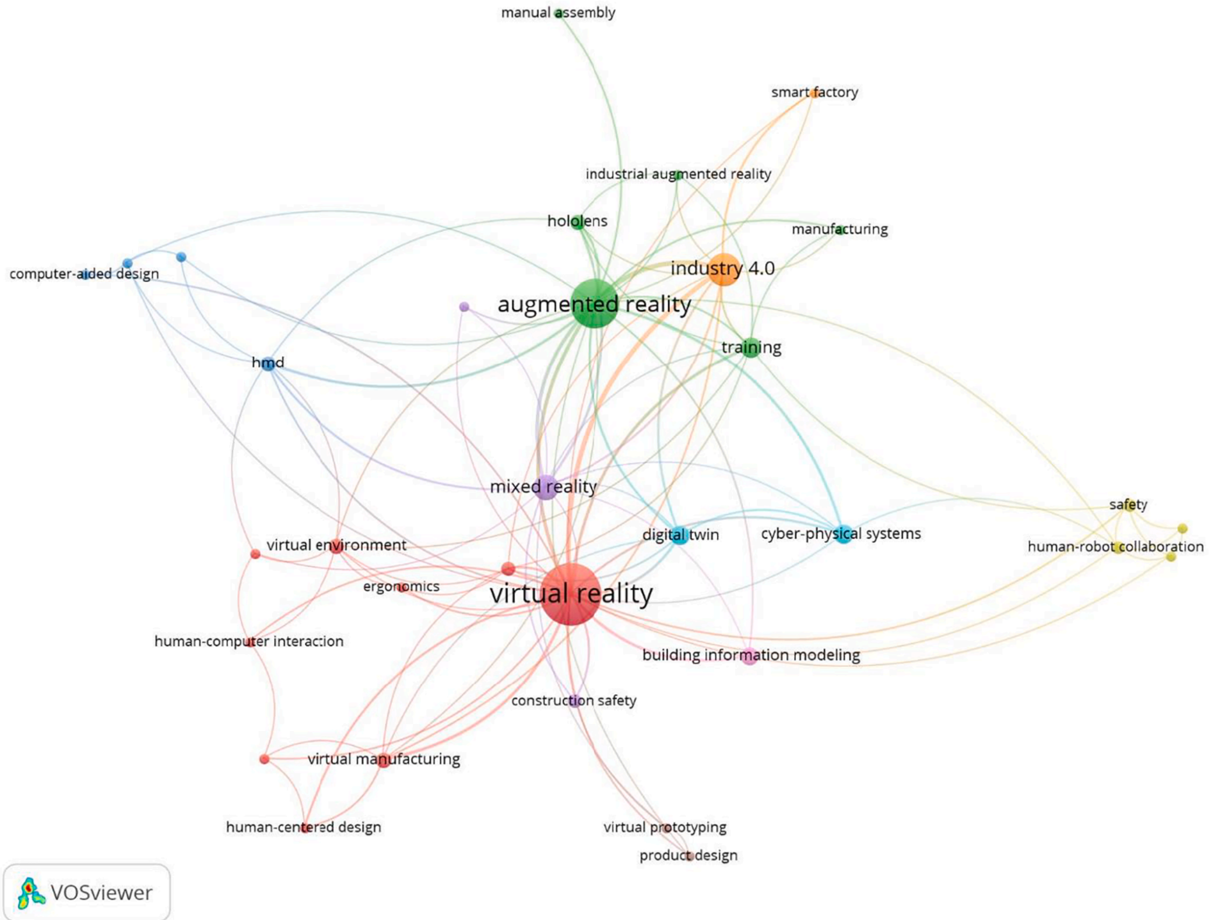


Fig. 5. Co-occurrence map of the author keywords.

7. manufacturing = TRUE glasses = TRUE 45 ==> individual = TRUE 37 conf:(0.82).
8. simulation = TRUE VR = TRUE 45 ==> synthetic = TRUE 37 conf:(0.82).
9. visualization = TRUE AR = TRUE 36 ==> individual = TRUE 29 conf:(0.81).
10. MR = TRUE hybrid = TRUE 36 ==> glasses = TRUE 29 conf:(0.81).

5.3. Outcomes and interpretation

While the use of Weka analysis software discovers relevant association rules, this section points out some insights related to *strengths*, *weaknesses*, and *opportunities* using XR technology in industry 4.0.

One of the most relevant *strengths* found in the XR applications for industry 4.0 addresses that the learning curve to use these technologies fluently is relatively short and fast. Moreover, the sense of immersion and presence in the virtual reality applications enable an approach to study the user behavior in different virtual scenarios before work in the physical environment. Such technologies foster learning and teaching by supporting spatial abilities, where real-world first-hand experience is not possible. They also promote user autonomy and performance in terms of time and productivity. Additionally, they provide safe and low-cost training, which would be difficult, expensive, or dangerous to reproduce in physical settings constrained to conditions, restrictions, or uncontrolled variables. Furthermore, users with devices such as HoloLens or Oculus Quest 2 do not need a computer, breaking the physical restrictions of wires and sensors.

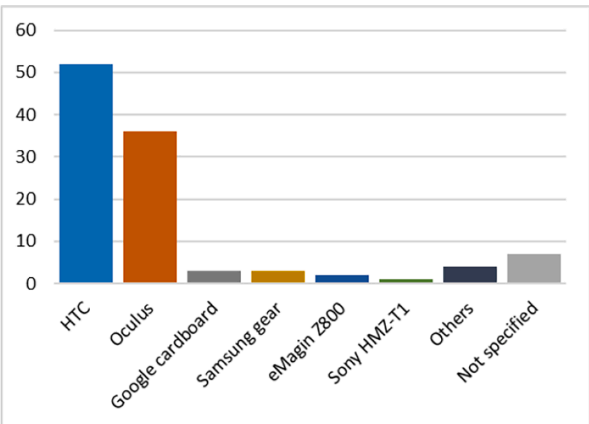
Regarding *weaknesses*, the approaches in VR experimentation lack important issues to be considered, such as the multi-regionality and heterogeneity of the participants (e.g., age, gender, degree of study, and group size). Therefore, the results require careful interpretation, and more studies are needed. Related to tracking devices, they present some difficulties in tracking fine user movements, which might cause atypical behavior in the interpretation of user gestures.

Furthermore, the use of XR applications increases cognitive workload. Other opportunities areas are the low resolution and the constrained field of view of the devices, the high computational cost in some applications (e.g., physics-based modeling), and the need for manual file conversions from certain areas to build a VR application (e.g., a BIM model). Additionally, the reduced variety of wearable sensors (e.g., touch, smell, taste, and proprioception) diminishes the immersion, whereas the low interaction and gesture expression between users reduces the communication level. On the other hand, the training time is constrained by the discomfort or simulation sickness of the user.

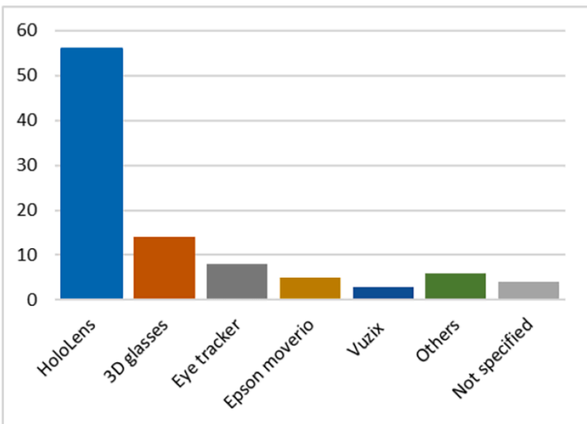
Moreover, some industries require the workforce to wear personal safety equipment (e.g., helmets or glasses), where using an extra XR device is difficult. Besides the physical restrictions due to wires and fixed sensors (e.g., The CAVE, Oculus Rift S, or HTC Vive), the visibility in these devices (e.g., HoloLens overshadows the light) tends to be limited. For the aforesaid, it is complex to expand this kind of XR application to a broad number of users.

The XR applications for industry 4.0 will continue to grow with an impact across all processes, encompassing the context of training and the complex skill domain. The reviewed papers highlighted *opportunities* to improve human-robot collaboration to support safety in operations and the application of artificial intelligence algorithms to build richer training environments. Furthermore, the use of pervasive sensors, haptic devices, force actuators, and high-resolution displays helps improving user immersion and user motor skills. There is also a need to propose industry standards among the main players for information exchange and device interconnectivity. Moreover, the use of high technology cameras and state of the art of computer vision algorithms to capture fine user movements (e.g., face expression and finger gestures) are required for the development of fully immersive and interactive applications. Similarly, devices such as a 3D scanner or RGB-D cameras enable the addition of new objects and capabilities to the XR application on the fly.

Since industry 4.0 enables new types of interaction between humans and machines (Ruppert et al, 2018). It is relevant to consider



(a) HMD



(b) glasses

Fig. 6. The most employed HMD and glasses.

the study of the Operator 4.0 paradigm (i.e., in the context of XR, the augmented, virtual, and collaborative operators become essential) as well as the evaluation of the operator's tacit knowledge (e.g., training, assembly, maintenance, operation, etc.) in XR based systems. However, this is a challenge that is out of the scope of this review.

Finally, due to the COVID-19 pandemic declared by World Health Organization, the XR applications related to recreation, entertainment, tourism, monitoring, and control of remote processes have been growing during the last months. Also, distance learning applications in collaborative environments foster the capabilities of future engineers.

6. Conclusions

XR applications are becoming pervasive in our professional lives. Especially with the advent of industry 4.0, these disruptive applications solve specific needs, such as training workers on a welder machine with no risks of injuries and designing a new product with interactive and immersive tools; even, reducing time and costs. Section 4.2 addresses RQ1 and RQ2 by describing practical implementations in different fields and section 4.3 addresses RQ3 by identifying the main activities in industry 4.0 that use XR technology and their impact. Most of the research works deal with experiments related to user training, remote lab and machine operation, assembly process, performance benefits, decision making, spatial mobility, perceptual and situational awareness, visualization, and ergonomic design, among others. Moreover, the deployment of authoring tools to facilitate developing low-cost XR applications, in combination with the rich integration with motion capture cameras, body sensors, and haptic devices allow analyzing and executing complex human tasks.

Regarding the experience of reality adopted in industry 4.0, sections 4.5, 4.6, and 4.7 address RQ4. XR technologies have been embraced positively where the capabilities of these devices are remarkable, whether for virtual, augmented, or mixed reality. Moreover, the deployment of applications enriched by sensors reduces the gap among them. Notwithstanding, MR would seem to be the dominant technology in the next decade. Industry 4.0 has chosen to adopt mainly HMD for VR (e.g., Oculus and HTC Vive); tablets, smartphones, and glasses (e.g., HoloLens) for AR. Since MR lies between AR and VR, it is possible to use any of these devices with additional sensors (e.g., physiological, activity, and environmental) as described in sections 4.7, 4.8, 4.9, 4.10, and 4.11 that tackles RQ5.

This XR survey explored the main XR research topics identified in sections 4.3 and 4.4 that address RQ6. Topics such as training and assembly are widely used in almost any area or process. In Section 5, RQ7 is addressed by presenting the essential highlights of XR technology for industry 4.0 related to the massive adoption due to the low cost of XR devices and the potential solutions for almost all processes with robot collaboration and without human risks.

We also presented a novel taxonomy based on our extensive review that characterizes XR applications into 10 categories and 68 subcategories that allows for fine and coarse granularity, which, in turn, provides a handy framework for future research works. Furthermore, as new technologies and applications emerge, this taxonomy could be extended further into additional subcategories and possibly classes.

Finally, this research shows the equipment and the main devices used in XR applications, summarizes the main fields of application, and focuses on various activities. In addition, it gives clues about the potential development of future applications, which will have a huge impact not only in industry 4.0 but also on a wide range of human activities at home and work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

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Appendix

Table A shows 287 works described according to the ten categories of the taxonomy to characterize extended reality approaches. The following abbreviations represent the topic name given in the taxonomy:

Table A
Description of the sample of works according to the extended reality taxonomy.

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Abidi et al. (2019)	mfg.	assem.	virtual mfg.	VR	synthetic	individual	3D g.	display, projector, amx ctrl	–	–
Afzal and Shafiq (2021)	HS	trng., simul., design	phys. eng.	VR	synthetic	individual	oculus	projector	–	–
Aheleroff et al. (2021a)	mfg.	RP, design	inf. syst.	AR	captured	individual	mobile	–	cloud c., IoT	–
Aheleroff et al. (2021b)	mfg.	operation, maint.	inf. syst.	AR	captured	individual	mobile	–	cloud c., DT	–
Ahn et al. (2019)	constr.	assem., visualiz.	QA, virtual mfg.	AR	captured	collaborative	computer	camera, projector	–	–
Aleotti and Caselli (2011)	mfg.	assem., simul.	virtual mfg., phys. eng.	VR	synthetic	individual	computer	gloves	–	–
Alizadehsalehi et al. (2021)	edu. res.	design, visualiz.	hci, aesthetic, learn. proc.	VR	synthetic	individual	hmd, htc, oculus	–	–	–
Alves et al. (2022)	mfg.	visualiz., assem.	virtual mfg.	AR	captured	individual	computer, mobile, meta 2 glasses	–	–	–
Angrisani et al. (2020)	mfg.	visualiz.	phys. eng.	AR	captured	individual	e. moverio	–	–	EEG
Ariansyah et al. (2022)	mfg.	assem., maint.	phys. eng.	MR	hybrid	individual	hololens	–	–	wps
Atici-Ulusu et al. (2021)	automot.	assem.	process ind.	AR	hybrid	individual	s. AR	–	–	EEG
Avalle et al. (2019)	mfg.	visualiz.	robotics, hci	MR	hybrid	collaborative	hololens	robot	–	–
Baceviciute et al. (2022)	biotechnology	trng.	learn. proc.	VR	synthetic	individual	l. mirage	–	–	–
Ban and Hyun (2020)	automot.	design, visualiz.	aesthetic	VR	synthetic	individual	oculus	pen tablet, interactive display	–	
Barata & da Cunha (2021)	mfg., constr.	logistics	QA	AR	hybrid	individual	mobile	camera	cloud c.	–
de Barreto Junior et al. (2021)	energy	cont. auth.	inf. syst.	VR	synthetic	individual	computer	display	–	–
Birt and Vasilevski (2021)	constr.	visualiz.	aesthetic, learn. proc.	VR	synthetic	individual, collaborative	s. gear	–	–	–
Bohné et al. (2021)	mfg., edu. res.	trng., assem.	phys. eng.	VR	synthetic	individual	htc	–	–	–
Bordegoni et al. (2011)	mfg.	design, visualiz.	aesthetic, hci	MR	hybrid	individual	computer, 3D g.	mocap c., projector, haptic strip	–	prox.
Borsci et al. (2016)	automot., edu. res.	assem., visualiz.	virtual mfg.	VR	synthetic	individual	cave, oculus, 3D table, 3D g.	–	–	–
Bosché et al. (2016)	constr., HS	trng.	PR	MR	captured	individual	oculus	monocular c.	–	–
Bruno et al. (2019)	petrochemical	design, maint.	phys. eng.	AR	captured	individual	mobile	–	–	–
Bu et al. (2021)	HS, edu. res.	simul.	RT perc.	VR	synthetic	Individual	hmd, simulator	–	–	FNIRS
Buń et al. (2021)	mfg.	maint., operation	learn. proc., phys. eng.	MR	hybrid	collaborative	hololens	–	–	–
Cai et al. (2020)	mfg.	simul.	process ind.	AR	captured	individual	computer	camera, robot	DT	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Calandra et al. (2021)	mfg.	operation., track	learn. proc.	AR	hybrid	collaborative	mobile	camera	cloud c.	–
Carulli et al. (2013)	mfg.	design, RP	virtual mfg.	VR	synthetic	individual	3D g.	mocap c., projector, virtuouse h.	–	–
Ceruti et al. (2019)	aero.	maint.	QA	AR	hybrid	individual	hololens	–	–	–
Chalhoub and Ayer (2018)	constr.	trng., visualiz.	inf. syst.	MR	hybrid	individual	hololens	–	–	–
Chalhoub and Ayer (2019)	constr., edu. res.	design	inf. syst.	AR	captured	individual	hololens	–	–	–
Checa et al. (2021)	HS	trng., simul.	phys. eng.	VR	synthetic	individual	htc	–	–	–
Chen et al. (2019)	petrochemical, HS	simul., operation	phys. eng.	VR	captured	individual	computer	display	–	press., temp., speed, gas conc., flow
Cheng and Teizer (2013)	constr., HS	location, visualiz.	RT perc.	VR	captured	individual	computer	–	ctx-awr	GPS, RFID
Chiao et al. (2018)	recreat., edu. res.	visualiz., nav.	tourism	VR	synthetic	individual	computer	–	–	–
Chiew and Sung (2022)	mfg.	assem.	virtual mfg.	AR	Hybrid	individual	computer	display	–	–
Chiu and Lee (2018)	recreat., edu. res.	nav., visualiz.	tourism	AR	captured	individual	mobile	–	ctx-awr, cloud c.	GPS
Chiu et al. (2019)	recreat.	visualiz., nav.	tourism	AR	captured	individual	mobile	–	–	–
Choi S. et al. (2022)	mfg., HS	location, operation	robotics, hci	MR	captured	individual	computer, hololens	robot, kinect	DT, CPS	–
Choi and Seo (2020)	mfg.	meas., visualiz.	PR	AR	captured	individual	computer	monocular c.	IoT	–
Chu and Ko (2021)	mfg.	assem.	process ind.	AR	hybrid	individual	hololens	leap motion	–	–
Chu et al. (2020)	mfg.	assem.	hci	AR	synthetic	individual	computer	kinect	–	–
Chung et al. (2021)	constr.	operation	inf. syst.	AR	hybrid	individual	mobile	–	ctx-awr	–
Colombo & Golzio (2016)	HS	trng.	process ind.	VR	synthetic	collaborative	3D g.	projector	ctx-awr	–
Corallo et al. (2020)	petrochemical, edu. res.	operation, visualiz.	process ind.	VR	synthetic	individual	computer, cave	art smarttrack, projector	–	–
Dai et al. (2021)	edu. res., HS, constr.	visualiz.	inf. syst.	MR	hybrid	individual	computer, hololens	–	–	–
Das et al. (2020)	HS	simul.	virtual mfg., process ind.	VR	synthetic	individual	oculus, tobii et.	joystick	–	–
De Magistris et al. (2013)	HS, edu. res.	simul., mocap	ergon.	VR	captured	individual	computer	mocap c.	–	force pltf.
de Souza Cardoso et al. (2020b)	aero.	visualiz., assem.	virtual mfg.	AR	hybrid	individual	mobile	–	–	–
del Amo et al. (2022)	edu. res.	cont. auth., maint.	inf. syst.	AR	captured	individual	computer, mobile, hololens	camera, display	ctx-awr, cloud c.	–
Demirtas et al. (2022)	edu. res., HS	location, operation	robotics, hci	AR	captured	individual	computer, hololens	robot, projector	–	safety laser
Deshpande and Kim (2018)	edu. res.	assem.	virtual mfg., learn. proc.	AR	captured	individual	hololens, smi g.	–	–	–
Dhalmahapatra et al. (2021)	edu. res., HS	simul., trng.	learn. proc., virtual mfg.	VR	synthetic	individual	computer, oculus	3D pro j.	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Dhiman and Röcker (2021)	mfg.	assem.	virtual mfg.	AR	synthetic	individual	glasses, mobile	camera, projector, RGB-D c.	ctx-awr	–
Dimitropoulos et al. (2021)	mfg.	assem.	PR	MR	hybrid	collaborative	hololens	kinect	–	–
Dong et al. (2021)	mfg.	assem.	PR	MR	hybrid	individual	hololens	–	–	–
Dong et al. (2018)	constr., HS	track, visualiz.	inf. syst.	VR	captured	individual	computer	–	IoT	mot. gest. track., RFID, press.
Doolani et al. (2020)	edu. res.	trng.	learn. proc.	VR	synthetic	individual	htc, mobile	–	–	–
Drouot et al. (2021)	educ. res.	assem., visualiz.	RT perc.	AR	hybrid	individual	hololens	projector	–	–
Du et al. (2018a)	constr.	design, visualiz.	inf. syst., phys. eng.	VR	synthetic	collaborative	oculus, htc	–	cloud c.	–
Du et al. (2018b)	constr.	design, visualiz.	inf. syst.	VR	synthetic	collaborative	mobile, oculus, s. gear, g.c.	game ctrl	cloud c.	–
Duan et al. (2021)	mfg.	simul.	process ind.	VR	synthetic	individual	computer	–	–	–
Eiris et al. (2018)	HS, constr.	trng., visualiz.	phys. eng.	VR	hybrid	individual	computer, mobile	panoramic c.	–	–
Eiris et al. (2020)	HS, constr.	trng., visualiz.	phys. eng.	VR	hybrid	individual	computer, mobile, g.c.	panoramic c.	–	–
Endo et al. (2013)	edu. res., HS	trng.	phys. eng., robotics	VR	synthetic	individual	computer	robot	–	force
Erasmus et al. (2020)	mfg.	assem.	inf. syst.	AR	hybrid	collaborative	mobile	projector	–	–
Esengün et al. (2022)	petrochemical	cont. auth., maint.	process ind.	AR	hybrid	individual	hololens, e. moverio, t. x2, vuzix g.	–	–	–
Fang et al. (2019)	mfg.	simul.	virtual mfg.	VR	synthetic	individual	computer	–	DT, ctx-awr	RFID
Fernández del Amo et al. (2020)	aero.	cont. auth., maint.	phys. eng	MR	hybrid	collaborative	hololens	–	cloud c.	–
Fernández-Caramés et al. (2018)	maritime	visualiz., maint.	phys. eng., RT perc.	AR	captured, hybrid	collaborative	hololens, computer, mobile	–	cloud c., IoT	–
Ferraguti et al. (2019)	mfg.	visualiz., operation	aesthetic, virtual mfg.	AR	captured	collaborative	hololens, computer	robot	–	–
Francisco and Taylor (2019)	energy, edu. res.	operation, analyt. dm	inf. syst.	AR	captured	collaborative	mobile	–	CPS	energy
Fratczak et al. (2021)	HS, edu. res.	simul.	hci, robotics	VR	synthetic	collaborative	htc	–	–	–
Fu et al. (2022)	mfg.	assem.	virtual mfg.	AR	hybrid	individual	e. moverio	–	cloud c.	–
Fuentes et al. (2021)	edu. res.	visualiz.	RT perc.	AR	hybrid	individual	mobile	–	IoT	–
Gabajová et al. (2019)	mfg., edu. res.	assem.	virtual mfg., learn. proc.	VR, AR	synthetic	individual	htc, mobile	–	–	–
Gall & Rinderle-Ma (2020)	educ. res.	visualiz., trng.	learn. proc.	VR	synthetic	individual	htc	–	–	–
Garzón et al. (2020)	agricultural, recreat.	visualiz.	tourism, learn. proc.	AR	captured	individual	mobile	–	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Gattullo et al. (2015)	mfg., edu. res.	design, visualiz.	aesthetic, phys. eng.	AR	captured	individual	liteye g., vuzix g.	camera	–	–
Gattullo et al. (2019)	mfg., edu. res.	cont. auth., maint.	virtual mfg.	AR	captured	individual	mobile	–	–	–
Gimeno et al. (2013)	mfg.	cont. auth., maint.	phys. eng.	AR	captured	individual	computer, mobile	camera, RGB-D c.	–	–
Gonzalez-Badillo et al. (2014)	mfg.	simul., assem.	phys. eng.	VR	hybrid	individual	computer	phantom h.	–	–
Gorecky et al. (2015)	automot.	assem.	virtual mfg.	VR	synthetic	individual	computer	display, projector, RGB-D c., wii remote	–	–
Gorobets et al. (2021)	mfg.	simul., meas.	process ind.; virtual mfg.	VR	synthetic	Individual	htc	–	–	–
Goulding et al. (2012)	constr., edu. res.	trng., simul.	phys. eng., learn. proc.	VR	synthetic	individual	mobile	–	–	–
Grabowski and Jankowski (2015)	HS, mining	trng.	process ind.	VR	synthetic	individual	oculus, s. VR	razer ctrl, gloves	ctx-awr	–
Grabowski et al. (2021)	mfg.	simul.	hci	VR	synthetic	individual	htc	robot, vive tr.	–	–
Grandi et al. (2020)	mfg., edu. res.	design, simul.	virtual mfg., hci	MR	hybrid	individual	cave, tobii et., computer, simulator	camera, mocap c.	CPS	wps, press.
Grappiolo et al. (2021)	mfg.	assem.	virtual mfg.	VR	synthetic	individual	computer	display, camera	–	–
Guo et al. (2020)	mfg.	maint., simul.	virtual mfg.	VR	synthetic	collaborative	cave, computer, 3D g.	wand, gloves	CPS	–
Hammady et al. (2020)	recreat.	nav., visualiz.	tourism	MR	hybrid	individual	hololens	–	–	–
Han et al. (2019)	maritime	design, visualiz.	phys. eng., inf. syst.	AR, VR	hybrid	collaborative	mobile	–	cloud c., IoT	–
Hanson et al. (2017)	mfg.	logistics	inf. syst.	AR	hybrid	individual	hololens	camera	–	–
Hasanzadeh et al. (2020)	constr.	simul.	process ind.	MR	hybrid	individual	cave, 3D g.	camera	–	mot. gest. track.
Havard et al. (2021)	mfg.	maint.	virtual mfg.	AR	captured	individual	mobile	–	–	–
Hernández-Chávez et al. (2021)	automot.	assem., trng.	learn. proc., phys. eng.	VR	synthetic	individual	oculus	leap motion	–	–
Heydarian et al. (2015)	edu. res., constr.	design, visualiz.	ergon.	VR	synthetic	individual	oculus	kinect, wand	–	–
Ho et al. (2018)	HS, edu. res.	assem., operation	RT perc.	VR	captured	individual	oculus, computer, mobile	leap motion, gloves	ctx-awr	mot. gest. track.
Ho et al. (2021)	HS	assem., visualiz.	RT perc.	AR	hybrid	individual	e. moverio, mobile	camera	CPS	force
Hoffmann et al. (2019)	mfg.	assem., operation	phys. eng., learn. proc.	AR	captured	individual	hololens, tobii et., mobile	RGB-D c.	CPS	–
Hoover et al. (2020)	mfg.	assem.	learn. proc.	AR	hybrid	individual	hololens, mobile	ctrl	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Hoppenstedt et al. (2019a)	edu. res.	analyt. dm, visualiz.	RT perc., inf. syst.	MR	synthetic	individual	hololens, computer	–	–	–
Hoppenstedt et al. (2019b)	mfg.	analyt. dm, visualiz.	inf. syst.	MR	captured	individual	hololens	–	–	–
Hu et al. (2011)	edu. res.	track, meas.	ergon.	VR	synthetic	individual	5DT hmd	–	–	mot. gest. track.
Hu et al. (2016)	HS, edu. res.	trng., mocap	inf. syst., PR	VR	hybrid	individual	eMagin, computer	kinect, wii remote, gloves	ctx-awr	ECG, EMG, SpO2, pyroelectric, mot. gest. track.
Huerta-Torruco et al. (2022)	mfg.	simul., visualiz.	virtual mfg.	VR	synthetic	individual	oculus	–	–	–
Irizarry et al. (2013)	constr.	visualiz., operation	inf. syst.	AR	captured	individual	mobile	–	ctx-awr	–
Izard et al. (2017)	edu. res., HS	trng.	learn. proc., health science	VR	synthetic	individual	powis cardboard, mobile	–	–	–
Jang and Nam (2020)	maritime	visualiz., simul.	phys. eng.	VR	synthetic	individual	mobile	camera	–	–
Jayasekera and Xu (2019)	mfg.	assem.	phys. eng., virtual mfg.	VR	synthetic	individual	oculus	leap motion	–	–
Jeon and Cai (2021)	HS	trng.	RT perc.	VR	synthetic	individual	oculus	display	–	EEG
Jeong et al. (2016)	edu. res.	visualiz.	ergon., hci	VR	synthetic	individual	cave, 3D g.	kinect, i-station ctrl	–	–
Jimeno-Morenilla et al. (2016)	edu. res.	design, visualiz.	phys. eng., learn. proc.	VR	synthetic	individual	g.c., mobile	–	–	–
Juan et al. (2018)	constr.	visualiz., nav.	phys. eng.	VR	synthetic	individual	s. gear, mobile	ctrl	–	–
Kačerová et al. (2022)	mfg.	mocap	ergon.	VR	synthetic	individual	oculus	mocap c.	–	–
Kalkan et al. (2021)	mfg.	trng.,assem.	learn. proc.	VR	synthetic	individual	htc	projector	–	–
Kao et al. (2011)	mfg.	trng., simul.	virtual mfg.	VR	synthetic	individual	computer	–	–	–
Kim et al. (2011)	automot.	design, visualiz.	aesthetic, ergon.	VR	synthetic	individual	cave, computer	projector	–	–
Kim et al. (2014)	maritime	trng., simul.	phys. eng.	VR	synthetic	individual	eMagin	simulator, vibrating d., kinect, BC jacket	–	press., airflow, temp.
Kim et al. (2019)	livestock	simul.	phys. eng.	VR	synthetic	individual	htc	gloves, vive tr.	–	mot. gest. track.
Kim et al. (2021)	constr.	simul.	QA	VR	synthetic	collaborative	hmd	–	–	–
Kinzinger et al. (2022)	business	visualiz.	inf. syst.	VR	synthetic	individual	computer, htc	–	–	–
Konstantinidis et al. (2020)	mfg., automot.	maint.	virtual mfg.	AR	captured	individual	mobile	–	–	–
Koteleva et al. (2022)	petrochemical	maint.	hci, RT perc.	AR	hybrid	individual	hololens	–	–	–
Kovachev et al. (2014)	recreat., edu. res.	cont. auth., visualiz.	inf. syst., tourism	AR	captured	collaborative	mobile	–	–	GPS
Krishnamurthy and Cecil (2018)	mfg.	assem., visualiz.	virtual mfg.	VR	captured	individual	htc	camera, geomagic h.	cloud c., IoT	speed
Kurien et al. (2018)	HS, constr.	track, simul.	phys. eng.	MR	captured	individual	computer	kinect	–	–
Kuts et al. (2019)	mfg.	visualiz., operation	virtual mfg., robotics	VR	synthetic	collaborative	oculus, htc	–	DT, IoT	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Kwok et al. (2019)	edu. res., HS	simul., trng.	inf. syst., process ind.	VR	synthetic	collaborative	cave, htc	–	–	–
Kwok et al. (2021)	HS	trng., simul.	inf. syst.	VR	synthetic	collaborative	hmd	projector, tablet	–	–
Lai et al. (2020)	mfg.	assem.	learn. proc., PR	AR	synthetic	individual	computer	camera	–	–
Lalik and Flaga (2021)	mfg.	location, meas.	phys. eng.	MR	hybrid	individual	hololens, computer	robot	CPS, cloud c., DT	–
Laviola et al. (2022)	mfg., edu. res.	cont. auth.	phys. eng.	AR	hybrid	individual	computer, mobile	–	–	–
Le et al. (2015)	HS, edu. res.	trng.	learn. proc.	VR	synthetic	collaborative	computer	–	–	–
Lee and Shin (2021)	recreat.	design, visualiz.	hci, aesthetic	VR	synthetic	individual	htc, oculus	–	–	–
Lee (2019)	mfg.	simul., analyt. dm	phys. eng., virtual mfg.	AR	hybrid	collaborative	computer	kinect	CPS	–
Lee (2020)	mfg., edu. res.	trng.	phys. eng., learn. proc.	VR	synthetic	individual	htc	–	–	–
Leung et al. (2020)	business, recreat.	visualiz.	tourism	VR	synthetic	individual	htc	–	–	–
Li et al. (2012a)	constr., HS	trng.	phys. eng.	VR	synthetic	collaborative	computer	wii remote, wii nunchuk	–	–
Li et al. (2012b)	constr., HS	trng.	learn. proc., phys. eng.	VR	captured	individual	computer	–	–	–
Li et al. (2022)	mfg.	assem., operation	robotics, hci	AR	captured	collaborative	hololens	camera, robot	DT, CPS, cloud c.	force
Lian et al. (2022)	water	trng., operation	hci	VR	synthetic	individual	hmd	–	DT	press., flowrate, conductivity
Liang et al. (2019)	edu. res.	track, visualiz.	hci	VR, AR	synthetic, captured	individual	computer	RGB-D c.	–	–
Liccardo et al. (2021)	edu. res.	meas.	phys. eng., learn. proc.	AR	captured	individual	computer, mobile	–	–	–
Lima et al. (2017)	automot.	track	PR	AR	captured	individual	computer, mobile	kinect	–	–
Liu and Zhang (2015)	mfg.	trng., simul.	virtual mfg., RT perc.	AR	captured	individual	computer	camera, projector, leap motion	–	–
Liu et al. (2020)	constr.	visualiz.	QA	AR	synthetic	individual	mobile	thermal c., camera	–	–
Longo et al. (2019)	HS, edu. res.	trng., simul.	learn. proc.	VR	synthetic	collaborative	htc	–	–	–
Lopez et al (2021)	HS, edu. res.	cont. auth., simul.	virtual mfg.	MR	hybrid	individual	hololens	–	cloud c.	–
Lu (2018)	energy	operation, simul.	inf. syst.	VR	captured	individual	mobile	–	IoT, ctx-awr	press., temp., prox., current, hum.
Lu and Davis (2016)	constr., HS	simul., visualiz.	phys. eng.	VR	synthetic	individual	computer	camera	–	–
Ma et al. (2019)	edu. res., mfg.	visualiz., trng.	virtual mfg., learn. proc.	VR	synthetic	individual	oculus	–	–	–
Ma et al. (2020)	mfg., edu. res.	trng., assem.	ergon., learn. proc.	VR	synthetic	individual	computer, nvidia g.	phantom h.	–	–
Maharjan et al. (2021)	edu. res.	visualiz.	QA	AR	captured	individual	hololens	–	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Malik et al. (2020a)	mfg.	trng., simul.	phys. eng., robotics	VR, MR	hybrid	collaborative	htc	kinect	CPS	–
Malik et al. (2020b)	mfg.	design, visualiz.	phys. eng., RT perc.	MR	hybrid	individual	hololens	dexmo h., vive tr.	–	–
Manca et al. (2013)	HS, petrochemical	trng., simul.	process ind.	VR, AR	synthetic, captured	collaborative	3D g.	display, projector	ctx-awr	–
Marino et al. (2021)	petrochemical	visualiz.	PR	AR	hybrid	individual	mobile	–	–	–
Martín-Barrio et al. (2020)	edu. res., mfg.	operation	robotics, phys. eng.	MR	hybrid	individual	htc, computer	leap motion, thermal c., camera, kinect	–	–
Martínez-Molés et al. (2022)	recreat.	visualiz.	hci	VR	synthetic	individual	htc	–	–	–
Marzouk et al. (2022)	constr.	design, visualiz.	aesthetic	VR	synthetic	individual	htc	–	–	–
Masood and Egger (2020)	mfg., edu. res.	assem.	phys. eng.	AR	hybrid	individual	hololens	–	–	–
Matsas et al. (2018)	edu. res., mfg.	simul., operation	robotics, hci	VR	captured	collaborative	oculus	camera, kinect, projector	ctx-awr	–
Mayor et al. (2019)	edu. res.	nav., visualiz.	hci	VR	synthetic	individual	htc	xbox ctrl	–	–
McLean and Barhorst (2021)	recreat., edu. res.	visualiz.	tourism	VR	synthetic	individual	oculus	–	–	–
Menk et al. (2011)	automot.	visualiz.	aesthetic, phys. eng.	AR	captured	individual	computer	camera, projector	–	–
Merenda et al. (2018)	automot., edu. res.	visualiz., nav.	phys. eng.	AR	captured	individual	smi g.	head-up display	ctx-awr	GPS
Minhas et al. (2022)	automot.	simul.	RT perc., hci	VR	synthetic	individual	computer	camera	–	–
Mirshokraei et al. (2019)	constr.	visualiz.	phys. eng., QA	AR	captured	collaborative	mobile	–	–	–
Moghaddam et al. (2021)	mfg.	assem., trng.	phys. eng., learn. proc.	AR	hybrid	individual	hololens	–	–	–
Mora-Serrano et al. (2021)	HS	trng., simul.	learn. proc.	VR	synthetic	individual, collaborative	htc	–	–	–
Morillo et al. (2020)	edu. res.	assem.	learn. proc.	AR	captured	individual	mobile	–	–	–
Mourtzis et al. (2019)	automot.	assem.	virtual mfg., phys. eng.	AR	captured	individual	mobile, glasses	camera	ctx-awr	–
Mourtzis et al. (2020)	mfg.	maint.	RT perc., hci	AR	hybrid	collaborative	hololens	–	cloud c.	–
Mourtzis et al. (2021)	mfg.	maint.	inf. syst.	AR	hybrid	collaborative	mobile	–	cloud c.	–
Muñoz et al. (2019)	automot.	visualiz.	ergon., QA	MR	hybrid	individual	hololens, mobile	camera	–	–
Muñoz et al. (2020)	automot.	operation, visualiz.	PR, RT perc.	MR	hybrid	individual	hololens	camera	–	–
Nalepka et al. (2019)	edu. res.	simul.	hci	VR	synthetic	collaborative	oculus	–	–	mot. gest. track.
Naqvi et al. (2019)	HS, petrochemical	trng., simul.	hci, learn. proc.	VR	synthetic	individual	simulator, glasses	display, projector	CPS	–
Nazir et al. (2015)	HS, edu. res.	trng.	process ind.	VR	synthetic	collaborative	3D g.	projector	ctx-awr	–
Neves et al. (2018)	mfg.	operation, visualiz.	robotics, virtual mfg.	MR	captured	individual	hololens	robot	ctx-awr	–
Ng et al. (2012)	HS, edu. res.	simul.	robotics	VR	synthetic	individual	computer	robot	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Nikolakis et al. (2019)	mfg.	simul., mocap	virtual mfg., ergon.	MR	hybrid	individual	computer	kinect, gloves	DT, CPS	mot. gest. track., press.
Niu et al. (2019)	mfg., edu. res.	meas., track	phys. eng.	AR	captured	individual	AR helmet	mocap c., projector	–	–
Nykänen et al. (2020a)	constr., edu. res.	trng.	phys. eng.	VR	synthetic	individual	htc	–	–	–
Nykänen et al. (2020b)	edu. res., HS	trng.	phys. eng.	VR	synthetic	individual	htc	–	–	–
O'Grady et al. (2021)	constr.	visualiz., design	aesthetic	VR	synthetic	individual	hmd	–	–	–
Omidshafiei et al. (2016)	automot., aero.	simul., RP, nav.	robotics, phys. eng., RT perc.	AR	hybrid	collaborative	computer	mocap c., projector	ctx-awr, CPS	mot. gest. track.
Ortega et al. (2021)	mfg.	maint.	PR	AR	hybrid	individual	mobile	RGB-D c., thermal c.	–	–
Osorto Carrasco and Chen (2021)	constr.	design	aesthetic	MR	hybrid	individual	hololens	–	–	–
Osterlund and Lawrence (2012)	aero.	trng., mocap	phys. eng., hci	MR	hybrid	collaborative	VR helmet, computer, simulator	mocap c., gloves	–	–
Otto et al. (2020)	mfg.	visualiz., nav.	virtual mfg.	AR, VR	synthetic	individual	cave	–	–	–
Ottogalli et al. (2019)	mfg.	assem., trng. simul.	virtual mfg.	AR, VR	hybrid	collaborative	htc, oculus	–	–	–
Ottogalli et al. (2021)	aero.	assem.	hci, process ind.	VR	synthetic	collaborative	htc	mocap c.	–	mot. gest. track.
Oyekan et al. (2019)	HS, edu. res.	operation	robotics	VR	hybrid	individual	htc	kinect	DT	–
Paes et al. (2021)	constr.	visualiz.	RT perc.	VR	synthetic	individual	htc	–	–	–
Pardo-Vicente et al. (2019)	mfg., edu. res.	RP, design	virtual mfg., phys. eng.	AR	hybrid	individual	mobile	–	ctx-awr	–
Park et al. (2020)	mfg.	visualiz., maint.	PR, virtual mfg.	AR	captured	individual	computer, hololens	–	–	–
Paszkiewicz et al. (2021)	edu. res., HS	trng.	learn. proc.	VR	synthetic	individual	oculus	–	–	–
Paszkiewicz et al. (2022)	edu. res.	design, visualiz.	phys. eng., learn. proc.	VR	synthetic	individual	htc, oculus	–	–	–
Pedram et al. (2020)	HS, mining	trng. visualiz.	learn. proc.	VR	synthetic	collaborative	cave	projector	–	–
Pedro et al. (2020)	constr., HS	trng.	learn. proc.	VR	synthetic	individual	computer	–	–	–
Peng et al. (2011)	mfg.	design	inf. syst., virtual mfg.	VR	synthetic	individual	computer	–	–	–
Peng et al. (2012)	mfg.	design, simul.	virtual mfg., inf. syst.	VR	synthetic	collaborative	computer	–	–	–
Perez et al. (2019)	HS	simul., nav.	RT perc.	AR, VR, MR	synthetic, captured	collaborative	hololens, computer, simulator	projector	–	mot. gest. track.
Pérez et al. (2020)	mfg.	assem., simul.	robotics, RT perc.	VR	synthetic	collaborative	htc	robot	DT	prox., speed
Pérez et al. (2019)	edu. res.	trng., simul.	robotics, hci	VR	captured	individual	oculus, htc	–	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Peruzzini et al. (2021)	mfg.	assem., mocap	ergon., virtual mfg.	VR	synthetic	individual	htc	leap motion	–	–
Phoon et al. (2017)	mfg.	simul., visualiz.	virtual mfg.	VR	synthetic	individual	computer	–	–	–
Piardi et al. (2019)	mfg.	logistics, nav.	inf. syst., virtual mfg.	AR	captured	collaborative	computer	RGB-D c., camera, robot	CPS	prox.
Piatkowski et al. (2021)	constr.	design, visualiz.	hci, ergon.	VR	synthetic	individual	htc	display	–	–
Pirvu et al. (2016)	mfg.	assem.	virtual mfg.	VR, AR	synthetic, captured	individual	mobile	kinect, display	–	RFID
Placencio-Hidalgo et al. (2022)	HS, constr.	visualiz., trng.	inf. syst.	AR	captured	individual	mobile	–	–	–
Pontonnier et al. (2014)	mfg., edu. res.	assem., RP	ergon., virtual mfg.	VR	captured	individual	cave, 3D g.	mocap c., flystick2 ctrl, virtuouse h.	ctx-awr	EMG, force
Postelnicu et al. (2012)	edu. res.	nav.	hci, inf. syst.	VR	captured	individual	computer	–	–	mot. gest. track.
Psarakis et al. (2022)	mfg.	simul.	hci	VR	synthetic	individual	oculus	camera, mocap c.	–	–
Rahman et al. (2021)	aquaculture	analyt. dm, visualiz.	inf. syst.	MR	hybrid	collaborative	hololens, mobile, g.g.	–	cloud c.	temp., pH, oxygen, spectrometer, RI
Rezazadeh et al. (2011)	constr.	operation, trng.	hci	VR	hybrid	individual	computer	–	–	EEG, mot. gest. track.
Rhee and Lee (2021)	business	visualiz.	aesthetic, inf. syst.	AR	captured	individual	mobile	–	–	–
Richard et al. (2021)	mfg., HS	cont. auth., trng.	robotics, ergon.	VR, AR	synthetic	collaborative, individual	computer	display	–	–
Rocca et al. (2020)	mfg.	assem.	virtual mfg.	VR	synthetic	individual	mobile	robot	DT, IoT, CPS	position, prox., RFID, temp.
Rodriguez et al. (2021)	business, edu. res.	assem.	learn. proc.	AR	synthetic	individual	g.g.	–	–	–
Rodriguez-Gil et al. (2017)	edu. res.	design, operation	phys. eng., learn. proc.	MR	hybrid	individual	computer, mobile	–	–	water level
Roldán et al. (2019)	edu. res.	assem.	virtual mfg., learn. proc.	VR	synthetic	individual	htc, computer	–	–	–
Rozmus et al. (2021)	mining	visualiz., design	phys. eng.	VR	hybrid	individual	mobile	–	–	–
Runji and Lin (2020a)	mfg.	visualiz.	QA, PR	AR	captured	individual	computer, hololens	kinect	cloud c.	–
Runji and Lin (2020b)	edu. res.	visualiz.	RT perc., hci	AR	captured	collaborative	computer, mobile	projector, kinect	–	–
Saghafian et al (2020)	HS	trng.	learn. proc.	VR	synthetic	individual	htc	vive tr.	–	–
Salah et al. (2019)	edu. res.	assem.	learn. proc., virtual mfg.	VR	hybrid	collaborative	3D g., computer	projector, amx ctrl	–	–
Sanchez-Lite et al. (2013)	mfg., HS	design, mocap	ergon.	VR	synthetic, captured	individual	computer	mocap c., projector	–	–
Schall et al. (2013)	constr.	location, meas.	phys. eng.	AR	captured	individual	mobile	camera	ctx-awr	mot. gest. track., GPS, prox.

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Sekhavat and Zarei (2018)	recreat.	visualiz.	hci	AR, VR	synthetic, captured	individual	phoenix, mobile	–	–	–
Sepasgozar (2020)	edu. res.	trng., operation	inf. syst.	AR, VR	hybrid	collaborative	cave, htc, oculus, mobile	projector	ctx-awr	–
Serras et al. (2020)	mfg.	trng. maint.	inf. syst., hci	AR, MR	hybrid	individual	hololens	projector	ctx-awr	–
Shi et al. (2019)	constr., HS	trng.	learn. proc.	VR	synthetic	collaborative	oculus	kinect	ctx-awr	–
Shi et al. (2020a)	constr.	visualiz.	learn. proc., aesthetic	VR	synthetic	individual	computer, oculus, tobii et.	–	–	–
Shi et al. (2020b)	mfg.	maint., operation	learn. proc., process ind.	VR	synthetic	individual	computer, htc, tobii et.	–	–	–
Shin et al. (2020)	educ. res.	visualiz.	RT perc.	VR, AR	hybrid	individual	hololens, oculus	RGB-D c.	–	–
Shouman et al. (2021)	constr.	design, visualiz.	aesthetic	AR	captured	individual	mobile	–	–	–
Siamionava et al. (2018)	recreat., edu. res.	visualiz.	aesthetic	VR	synthetic	individual	oculus	–	–	–
Sidiropoulos et al. (2021)	mfg.	logistics, location	hci	AR	captured	individual	mobile	–	–	–
Simões et al. (2019)	edu. res., mfg.	cont. auth., assem.	learn. proc., virtual mfg.	AR, MR	captured	individual	hololens, mobile	RGB-D c., projector	DT, IoT	barometer, compass, GPS
Simonetto et al. (2022)	edu. res., mfg.	assem.	ergon.	VR	synthetic	individual	computer, htc.	mocap c.	–	–
Siyaev and Jo (2021a)	aero., edu. res.	trng., maint.	phys. eng., learn. proc.	MR	hybrid	collaborative	hololens	–	cloud c.	–
Siyaev and Jo (2021b)	edu. res., aero.	maint.	PR, virtual mfg.	MR	hybrid	individual	hololens	–	–	–
Solanes et al. (2020)	mfg.	assem.	virtual mfg., robotics	AR	hybrid	individual	hololens	game ctrl, camera, robot	IoT	force
Stark et al. (2020)	educ. res.	operation, visualiz.	inf. syst.	AR	hybrid	individual	mobile	camera	IoT	temp., moisture, prox.
Stone et al. (2011)	edu. res., mfg.	trng.	learn. proc., virtual mfg.	VR	synthetic	individual	simulator	–	–	EMG
Sun et al. (2021)	mfg.	cont. auth., assem.	learn. proc.	AR	synthetic	collaborative	mobile	–	–	–
Sung et al. (2012)	mfg.	trng.	inf. syst.	VR	synthetic	individual	v8	gloves	–	–
Szajna et al. (2020)	mfg.	assem.	hci, inf. syst	AR	captured	individual	hololens, mobile	–	cloud c.,	–
Tadeja et al. (2021)	edu. res.	visualiz., analyt. dm	PR, phys. eng.	VR	synthetic	individual	computer	leap motion, oculus ctrl	–	–
Taha et al. (2014)	edu. res., mfg.	design	ergon.	VR	synthetic	individual	computer	–	–	–
Tahriri et al. (2015)	edu. res., mfg.	trng., operation	robotics, learn. proc.	VR	synthetic	individual	3D g.	gloves, robot	–	–
Tarng et al. (2019)	edu. res.	trng.	phys. eng., learn. proc.	VR	synthetic	individual	htc, mobile	–	–	–
Truong et al. (2021)	constr.	design, maint.	inf. syst.	VR	synthetic	collaborative	oculus, htc, hmd	camera	cloud c.	–
Tyagi and Vadrevu (2015)	mfg.	simul., visualiz.	virtual mfg.	VR	synthetic	individual	computer	–	–	–
van Lopik et al. (2020)	edu. res.	cont. auth., trng.	inf. syst.	MR	hybrid	collaborative	hololens	camera	cloud c.	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Vasudevan and Son (2011)	HS, mfg.	simul., analyt. dm	virtual mfg.	VR	synthetic	individual	cave, 3D g.	wand	–	–
Vernica et al. (2022)	mfg.	assem.	QA	AR	hybrid	individual	mobile	–	–	–
Vidal-Balea et al. (2020)	maritime	assem., trng.	virtual mfg.	MR	hybrid	collaborative	hololens	–	cloud c.	–
Vignais et al. (2013)	mfg.	maint.	ergon., virtual mfg.	AR	captured, hybrid	individual	glasses, computer	–	–	goniometer, IMU
Vitali and Rizzi (2018)	business	meas., mocap	aesthetic	VR	captured, synthetic	individual	oculus	leap motion, kinect	–	–
Wang et al. (2022)	mfg.	assem., trng.	phys. eng.	AR, VR	captured, synthetic	collaborative	computer, mobile, htc, aGlass et.	camera, projector, leap motion	–	–
Wang (2015)	HS, mfg.	operation, assem.	hci, robotics	VR, AR	synthetic, captured	collaborative	computer	kinect	–	–
Wang et al. (2019a)	edu. res., mfg.	assem.	virtual mfg., RT perc.	MR	hybrid	collaborative	htc, computer	camera, projector, leap motion	–	–
Wang et al. (2019b)	mfg.	operation	robotics, virtual mfg.	MR	hybrid	collaborative	htc, computer	camera	CPS	arc w.
Wang et al. (2020)	mfg.	trng., operation	robotics, phys. eng.	VR	synthetic	individual	htc	–	CPS	–
Waterlander et al. (2011)	business	visualiz.	inf. syst.	VR	synthetic	individual	computer	–	–	–
Wolf et al. (2022)	constr., HS	trng.	learn. proc.	VR	synthetic	individual	htc	vive tr.	–	–
Wu et al. (2019)	constr., edu. res.	design, visualiz.	phys. eng., learn. proc.	VR, MR	synthetic, hybrid	individual	htc, hololens	–	–	–
Wu et al. (2020)	constr.	trng.	learn. proc.	MR	hybrid	collaborative	hololens	camera	–	–
Wu et al. (2022)	business	visualiz.	advertising	VR	synthetic	individual	htc	–	–	–
Xiao et al. (2018)	mfg.	assem.	virtual mfg.	AR	captured	individual	mobile	–	cloud c.	–
Xie et al. (2022)	mining	operation, simul.	phys. eng., hci	MR	hybrid	collaborative	hololens	RGB-D c.	CPS, cloud c.	acq. ctrl
Yan et al. (2021)	mfg.	visualiz.	virtual mfg.	VR	synthetic	individual	computer	display	DT	–
Yang and Miang Goh (2022)	HS, edu. res.	cont. auth.	inf. syst., learn. proc	MR	synthetic	individual	computer	–	–	–
Yang et al. (2019)	mfg.	track, assem.	RT perc., learn. proc.	MR	hybrid	individual	hololens	–	–	–
Yavuz Erkek et al. (2021)	mfg.	visualiz., simul.	phys. eng.	AR	hybrid	individual	mobile	–	–	–
Yildiz et al. (2021)	mfg.	simul.	virtual mfg.	VR	Synthetic	collaborative	computer	display	DT	–
Ying and Bo (2021)	constr.	visualiz., nav.	aesthetic	VR	captured, synthetic	individual	computer	display	–	–
Yoo et al. (2016)	mfg.	RP, design	virtual mfg.	AR	captured	collaborative	mobile	RGB-D c.	cloud c.	–
Yousfi et al. (2018)	business	location, visualiz.	inf. syst.	AR	captured	individual	mobile	–	ctx-awr	GPS
Zawadzki et al. (2020)	mfg.	assem., trng.	virtual mfg., learn. proc.	VR	synthetic	individual	oculus	–	–	–
Zhang et al. (2021)	mfg.	design, visualiz.	inf. syst.	VR	synthetic	individual	htc	–	–	–

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Table A (*continued*)

Work	Field of application	Activity	Domain knowledge	Reality experience	Environment perception	User interaction	Equipment	Devices	Inter-connectivity	Sensors
Zhao et al. (2016)	energy, HS	trng.	phys. eng., learn. proc.	VR	synthetic	individual	mobile	–	–	–
Židek et al. (2021)	mfg.	assem.	PR, robotics	MR	hybrid	individual	hololens	–	–	–
Żywicki and Buń (2021)	mfg., edu. res.	logistics	inf. syst.	AR	hybrid	individual	e. moverio, vuzix g.	–	–	–

Field of application: **aero.** = aerospace, aeronautics; **automot**. = automotive; **constr**. = construction; **edu. res.** = education and research; **HS** = health and safety; **mfg.** = manufacturing; **recreat.** = recreational.

Activity: **analyt. dm** = analytics and decision making; **assem.** = assembly; **cont. auth.** = content authoring; **maint.** = maintenance; **meas.** = measurement; **mocap** = motion capture; **nav.** = navigation; **RP** = rapid prototyping; **simul.** = simulation; **track** = tracking; **trng.** = training; **visualiz.** = visualization.

Domain knowledge: **ergon.** = ergonomics; **hci** = human–computer interaction; **inf. syst.** = information system; **learn. proc.** = learning process; **phys. eng.** = physics and engineering; **PR** = pattern recognition; **process ind.** = process industry; **QA** = quality assurance; **RT perc.** = real time perception; **virtual mfg.** = virtual manufacturing.

Reality experience: **AR** = augmented reality; **MR** = mixed reality; **VR** = virtual reality.

Equipment: **3D g.** = 3D glasses; **3D table** = zSpace holographic 3D table; **aGlass et.** = aGlass eye tracker; **BC jacket** = buoyancy compensator jacket; **cave** = cave automatic virtual environment; **computer** = desktop or laptop computer; **eMagin** = eMagin z800 3d visor; **e. moverio** = Epson Moverio BT-200o BT-300; **g.c.** = google cardboard; **g.g.** = google glass; **glasses** = not specified glasses; **hmd** = not specified hmd;

hololens = hololens glasses; **htc** = htc vive hmd; **l. mirage** = lenovo mirage hmd; **liteye g.** = liteye LE 750A glasses; **mobile** = tablet, smartphone, or PDA; **nvidia g.** = nvidia 3D vision glasses; **oculus** = oculus dk, go, rift, quest hmd; **phoenix** = phoenix hmd; **s. AR** = sony smart eyeglass; **s. gear** = samsung gear hmd; **s. VR** = sony HMZ-T1 hmd; **simulator** = simulator vehicle or cabin; **smi g.** = smi eye tracking glasses;

t. x2 = thirdeye X2 glasses; **tobii et.** = Tobii eye tracker; **v8** = v8 hmd; **vuzix g.** = vuzix 920, M400, MT300 glasses.

Devices: **3D pro j.** = 3D pro joystick; **amx ctrl** = amx controller; **camera** = video, web or ip camera; **ctrl** = not specified controller; **dexmo h.** = dexmo haptic force feedback; **display** = monitor, tv, or display screen; **flystick2 ctrl** = flystick2 controller; **game ctrl** = game controller o gamepad; **geomagic h.** = geomagic touch, haptic device;: **i-station ctrl** = i-station wing controller; **kinect** = kinect camera or controller; **leap motion** = leap motion, controller; **mocap c.** = motion capture camera; **oculus ctrl** = oculus controller; **panoramic c.** = panoramic camera; **phantom h.** = phantom omni haptic device; **razer ctrl** = razer hydra controller; **RGB-D c.** = RGB-D camera; **robot** = robot arm and hand; **vibrating d.** = vibrating device; **virtuouse h.** = virtouse haptic device; **vive tr.** = vive tracker; **wii nunchuk** = nintendo wii nunchuk controller;

wii remote = nintendo wii remote; **xbox ctrl** = xbox controller.

Interconnectivity: **cloud c.** = cloud or fog computing.; **ctx-awr** = context-aware; **CPS** = cyber physical system; **DT** = digital twin; **IoT** = internet of things.

Sensors: **acq. ctrl** = acquisition and control; **arc w.** = arc welding; **ECG** = electrocardiography ECG; **EEG** = electroencephalogram EEG; **EMG** = electromyography EMG; **FNIRS** = Functional Near Infrared Spectroscopy; **force pltf.** = force platform; **gas conc.** = gas concentration; **GPS** = global positioning system; **hum.** = humidity; **IMU** = inertial measurement unit IMU; **mot. gest. track**. = motion or gestures tracking.; **press.** = pressure; **prox.** = proximity; **RFID** = radio frequency identification.; **RI** = refractive index; **SpO2** = oxygen saturation Sp02; **temp.** = temperature; **wps** = wearable physiological sensors.

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