What, How, and Why are Visual Assets Used in Industrial Augmented Reality? A Systematic Review and Classification in Maintenance, Assembly, and Training (From 1997 to 2019)

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Abstract—Industrial Augmented Reality (iAR) has demonstrated its advantages to communicate technical information in the fields of maintenance, assembly, and training. However, literature is scattered among different visual assets (i.e., AR visual user interface elements associated with a real scene). In this work, we present a systematic literature review of visual assets used in these industrial fields. We searched five databases, initially finding 1757 papers. Then, we selected 122 iAR papers from 1997 to 2019 and extracted 348 visual assets. We propose a classification for visual assets according to (i) what is displayed, (ii) how it conveys information (frame of reference, color coding, animation), and, (iii) why it is used. Our review shows that product models, text and auxiliary models are, in order, the most common, with each most often used to support operating, checking and locating tasks respectively. Other visual assets are scarcely used. Product and auxiliary models are commonly rendered world-fixed, color coding is not used as often as expected, while animations are limited to product and auxiliary model. This survey provides a snapshot of over 20 years of literature in iAR, useful to understand established practices to orientate in iAR interface design and to present future research directions.

Index Terms—Augmented reality, industry, reviews, user interfaces, visualization

1 Introduction

Maintenance, assembly, and training must strictly follow technical documentation and procedures to guarantee safe and reliable machines and systems. The form in which technical documentation is presented to workers has evolved in the course of the years starting with early paper-based documents, characterized by black and white text and 2D illustrations. In the past few decades, digital documentation, through the use of for example computer graphics, has ushered in new opportunities to convey information (e.g., via color and animation), as well as new ways to interact with the content (e.g., rotating 3D parts to alter viewing perspectives). Examples of digital content include CAD models and multimedia as image-based or video-based tutorials.

Augmented reality (AR) aims to convey information that is directly registered to the physical environment. In particular, in the industrial field, AR aspires to bridge real and virtual assets in support of complex maintenance and assembly procedures. According to the Separation of Concerns principle [1], an augmented scene is composed of three main components: (1) a real-world object (feature), (2) its projected location in the augmented scene (anchor), and, (3) a virtual model associated to the real-world object (visual asset, Fig. 1). Industrial Augmented Reality is particularly well-suited for technical communication since it affords spatial registration of information and instructions anchored with the real object. Thus, iAR introduces additional information otherwise not contained in the real world and thus is capable of reducing workers' cognitive load as compared to paper-based procedural approaches [2], [3], [4]. iAR has proven to be successful for personnel training in industrial settings [5]. The number of potential AR implementations in the industrial domain has continuously increased over the past few decades. Despite this growth, AR is still not broadly used in real industrial settings due to the complex requirements that iAR applications have to deal with, as argued by Lorenz *et al.* [6]. They can be of different origins: user, technical, environmental, regulative or economical.

Then, for an effective use of AR in industry, iAR implementations must be reliable, safe, helpful, accepted by operators, and, must adapt to strict rules. However, as argued by Rolim *et al.* [7], there is no agreement in the literature about the best way to present information and provide instructions for users via AR. Providing such design guidelines is challenging, because AR necessarily deals with open-ended real environments and each scenario may introduce new constraints. Existing standards such as the Augmented Reality Markup Language (ARML) [1] and the Keyhole Augmented

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Fig. 1. Three different visual assets that convey the same instruction in an iAR interface: An animated product model of a socket wrench (a), a static auxiliary model of an arrow (b), a text instruction (c).

Reality Markup Language (KARML) [8] while generalist, can be used as starting point for future implementations (e.g., to specify nomenclature). The IEEE Standards Associations is developing a family of standards for virtual and augmented reality that addresses aspects such as safety, how different technologies should be defined, and how virtual and real objects should work together.

Therefore, literature is scattered among several proposals of iAR interfaces. We found works using different visual assets based on specific studies [5], [9], [10]. Beside these, for many iAR applications described in the literature, but there are limited details or descriptions of the interfaces, nor motivations for the choices of visualization methods. We also found papers providing design recommendations [11], even for industrial AR interfaces [12]. However, these recommendations need to be integrated with specific insights on the interface, also considering different devices. In fact, the design of iAR interfaces may be further complicated by the nature of AR devices. For example, occlusive visual assets may limit the situation awareness and operator safety when viewed through head-worn displays as compared to those same visual assets presented via handheld iAR devices [13].

Then, a preliminary work to reach guidelines for authors of next-generation iAR technical documentation is that of reviewing how technical instructions were presented in the literature. To the best of our knowledge, there is a lack of literature that systematically studies technical visual assets that can be used in AR user interfaces for maintenance, assembly, and training procedures. Thus, in this work, we want to address the following research questions: "what are the most commonly used visual assets and how are they used in iAR interfaces for maintenance, assembly, and personnel training tasks?"

In this paper, we present results from our Systematic Literature Review (SLR) of visualization methods for technical instructions in industrial augmented reality prototypes and concepts for maintenance, assembly, and training procedures presented in the last decade (in italic are the keywords used in the searching phase). Based on this review, we further propose a classification of technical visualization methods, considering different aspects in their authoring in iAR interfaces, and defined as follows:

- What is displayed as a visual asset;
- How visual assets convey information; and;
- Why a certain visual asset is used.

This classification could serve to promote community discussion and ultimately go towards standardization.

This paper is organized into six sections. Section 2 reports the related work related to AR reviews. In Section 3, we describe the methodology used for the SLR process. In Section 4, we detail the classification method. Section 5 reports the main results, followed by discussion and conclusion.

2 Related Work

Azuma's works [14], [15] are a reliable starting point for all the following research in AR. They describe medical, manufacturing, visualization, path planning, entertainment and military applications that have been explored since then. It is interesting to note that most of the applications reviewed made use of 3D models. Other more recent surveys of AR technology, applications, and limitations are those made by Van Krevelen and Poelman [16], Carmigniani *et al.* [17], Billinghurst *et al.* [18]. Moreover, in 2008, Zhou *et al.* [19] provided a successful review of ten years of ISMAR; ten years later Kim *et al.* [20] updated this survey with a revisiting of ISMAR trends from 2008 to 2017.

These studies present interesting surveys about different fields of application of AR, as well as devices, tracking techniques and limitations. We also found targeted review papers that address specific AR topics or industrial applications of AR as described below.

2.1 Reviews on a Specific AR Topic

We selected papers that addressing topics about the interface design, such as those that describe perceptual issues related to the use of non-conventional visualization devices and user studies.

Kruijff *et al.*, [21] identified the main perceptual problems that affect the correct perception of augmentations on a range of AR platforms: head-worn displays (HWDs), handheld devices, and projector-camera systems. Rolland *et al.*, [22] reviewed optical architectures for see-through HWDs along with key factors and functions required of a successful see-through HWD. This review was made independent of a specific application domain.

Another field of research seen in the literature is that of user-based experimentation. As argued by Swan and Gabbard [23], there is a need to further develop AR interface and systems from user-centered perspectives. They surveyed and categorized the user-based studies that have been conducted in AR, finding that work is progressing along three complementary lines of effort: those that study low-level tasks, those that examine user task performance within specific AR applications or application domains, and those that examine user interaction and communication between collaborating users. Dey *et al.*, [24] present the broad landscape of user-based AR research, providing a high-level view of how that landscape has changed. They identify primary application areas for user research in AR, describe the methodologies and environments commonly used, and propose future research opportunities for making AR more user-friendly.

2.2 Reviews on Applications of AR in Industry

Ong *et al.*, [25] provide one of the first inclusive reviews of iAR research and development, including some of the relevant issues that are limiting the successful applications of AR in the manufacturing field. They summarize the requirements that a successful iAR application should ideally have in terms of hardware and software systems, such as an efficient and suitable user interface that can be conveniently used to interact with the augmented manufacturing environment.

Nee *et al.*, [26] presented some of the iAR applications that are relevant for the manufacturing filed. This work emphasizes the importance of the design phase of an AR application, such as the development of highly interactive and user-friendly interfaces and providing valuable insight in order to make AR an interesting tool in the manufacturing and engineering field.

Syberfeldt *et al.*, [27] focused on the industrial domain, aiming to take the manufacturing industry one step closer to the broad adoption of AR smart glasses. They present a step-by-step process for evaluating AR smart glasses, including concrete guidelines as to what parameters to consider and their recommended minimum values. They suggested an evaluation process for manufacturing companies to quickly make optimal decisions about what products to implement on their shop floors.

Rankohi and Waugh [28] present a statistical review of AR technology in the architecture, engineering, and construction (AEC) industry. They synthesize the current state-of-the-art and trends of augmented reality technologies for construction projects and identify key application areas that could significantly affect the AEC. It is interesting to note that most of the articles reviewed discuss non-immersive user experiences, i.e., desktop-based AR, rather than immersive ones. As seen in other reviews, their work reveals that most of the AR systems found in the literature are prototypes, one-offs, and demonstrations.

Dini and Dalle Mura [29] provide a comprehensive survey that reviews some recent applications in Through-life Engineering Services (TES), emphasizing potential advantages, limits and drawbacks, as well as open issues which could represent new challenges for the future. The main open issues found are usability and portability of AR hardware, small field of view of devices, the visual quality of overlaid images, system delays, and difficulties in the preparation, preparation, programming and setting up of these systems.

Fraga-Lamas *et al.*, [30] describe the basics of iAR and then carried out a thorough analysis of the latest iAR systems for industrial and shipbuilding applications. Different iAR shipyard use cases are described and a thorough review of the main iAR hardware and software solutions are presented. After such a review, it can be concluded that there are many options for developing iAR interface software, but iAR hardware, although it has progressed a great deal in the last few years, it is still not ready for widespread deployment.

Palmarini *et al.*, [31] performed a Systematic Literature Review to evaluate the current state of the art of AR in maintenance and the most relevant technical limitations. From their study, it is clear that there is high fragmentation among hardware, software and AR solutions which leads to high complexity for selecting and developing AR systems. Specifically, their review cites:

- *Hardware.* there is a similar percentage of use of HWDs (27 percent), Handheld Displays (HHDs) (27 percent), and desktop PC (30 percent), whereas projection (5 percent) is less used;
- *Visualization.* the most common method is based on dynamic 2D/3D contents (40 percent), including 2D and 3D animations which give more vivid instructions to technicians as compared to other methods; it is followed by static 2D/3D contents (26 percent) and text (26 percent); and;
- *Authoring Solutions.* a large portion of AR applications are manually generated (64 percent).

Bottani and Vignali [32] in a recent survey, classify the literature on iAR from 2006 to 2017 and identify the main manufacturing areas were iAR is deployed. The authors state that many technical studies were carried out only in laboratory settings without implementing the AR system in a real context scenario. Moreover, their results show that HHDs and HWDs are the most widely used display devices in iAR. Finally, one of the most important insights of the survey is that the results confirm the fact that AR shows great application potential in many industrial operations and, in particular, in the field of maintenance and assembly.

3 Methodology

This review paper was synthesized from the literature using a systematic literature review process [33]; a process used in other AR reviews such as [24], [31]. Our systematic review process was performed into two phases: paper selection followed by paper analysis.

3.1 Paper Selection

The paper selection process consists of 5 steps:

1. planning the search;
2. defining the research question;
3. defining keywords and search criteria;
4. searching the papers; and;
5. definition and application of exclusion criteria.

In the search planning, we used five bibliographic databases: Scopus (www.scopus.com), IEEE Explore Digital Library (www.ieeexplore.ieee.org), ACM Digital Library (www.dl.acm.org), Science Direct (www.sciencedirect.com), and Web of Science (www.webofknowledge.com). The search was carried out in April 2020. To answer our research question, we identified three sets of keywords. The first set refers to the technology. We used both “Augmented Reality and ”Mixed Reality“ because we found that many authors

TABLE 1
Outcome of the Searching Phase

Database	Search fields	Documents returned: Before refinement	After refinement
Scopus	Title-Abs-Key	880	689
IEEE Explore	All Metadata	280	265
ACM	Title-Abs-Key	170	164
Science Direct	Title-Abs-Key	90	76
Web of Science	Topic	337	282
Total:		**1757**	**1476**

use this more general term to refer to AR prototypes (e.g., [34], [35]). The second set of keywords intended to limit the search to only the industrial fields of maintenance, assembly, and personnel training for industrial activities. We chose these keywords because, as reported by Dey *et al.* in a recent review [24], the majority of the work in the "industry" category focused on maintenance and assembly tasks. Further, the use of AR in industrial training for assembly and maintenance activities is increasing as revealed by Werrlich *et al.* [36] then we added also "personnel training." We did not use just "training" to avoid paper in the education field. The third set of keywords intended to limit the research to papers that either presented a prototype (concept) or a framework where a visualization method to display instructions is discussed. Thus, the search terms used were:

("augmented reality" OR "mixed reality") **AND** ("maintenance" OR "assembly" OR "personnel training") **AND** ("prototype" OR "concept" OR "framework" OR "visualization" OR "instruction").

The search was carried out in the title, abstract, and keywords fields for the databases Scopus, ACM, and Science Direct, in all the metadata for IEEE Explore, and in the Topic for Web of Science. With a first search using only the keywords described above, we gathered 1757 papers overall (see Table 1). Half of them came from Scopus database. To refine the search, we decided to include only the scientific articles with the following additional selection criteria, where possible:

- written in the English language,
- published in journals or conferences,
- applied to the engineering or computer science field, and,
- published from 1997 to 2019.

We started the observation period in 1997 when Azuma published a survey on Augmented Reality [14], also providing a clear definition of it. We excluded papers published in 2020 that is the same year when the search was carried out. After the refinement, the number of remaining papers was 1476. Since this phase has been carried out for each database separately, this number of documents includes duplicates. Removing all the duplicates, the number of papers reduced to 949.

We considered the relevance of scientific impact of the papers using the citation number. For each paper, we retrieved the total number of citations, reported in the databases, and calculated the Average Citation Count (ACC), as suggested in [19]:

$$\mathrm{ACC} = total\,lifetime\,citations/lifetime(years). \quad (1)$$

We wanted to consider only the set of papers that (based on ACC) appear to have made more than a minimal impact, so we discarded papers with an ACC less than 1.5 resulting in a reduced set of 296 papers.

It is worth noting that up to this point neither the title nor the abstract of any paper had been read. Thus, we next shifted our attention to the contents of the remaining 296 papers, defining 2 sets of exclusion criteria: EC1 and

EC2. For each of the 296 papers, the title and the abstract were read in order to apply the first set of exclusion criteria (EC1):

- The paper does not talk about AR or AR is not applied to the industrial domain.
- The paper focuses on industrial augmented reality, but the prototype described is not used for maintenance, assembly, or training tasks.

The result of the application of the EC1 was a list of 171 papers. After this, it was necessary to read the papers in their entirety in order to apply the second set of exclusion criteria (EC2):

- In the paper neither an interface or a prototype is described.
- No useful information is provided in the document to describe the interface.
- The same interface is described in other included papers.

Applying the exclusion criteria resulted in a final set of 122 papers that we formally reviewed.

3.2 Paper Analysis

In the analysis phase, the 122 papers were randomly divided among the authors in order to carry out independent and parallel reviews. Furthermore, after brainstorming, we reached a common agreement on the data to be collected from each article. This iterative process of meeting and brainstorming among the authors leads to the proposed classification described in Section 4. For each article, we analyzed the AR user interface by disassembling the interface into different atomic elements (see Fig. 2). We considered as augmented elements all the pieces of information used by U.I. designers to convey instruction. Thus, we included not only information provided through annotations (i.e., a virtual information that describes in some way, and is registered to, an existing object, as defined by Wither *et al.* [38]), but also through elements attached to specific positions in the U.I.

These atomic elements were then added to a classification table created by the authors for the systematic collection of data. When analyzing an interface described in a paper, we looked for videos on the web that showed the interface features. When these videos were not available, we sought further insights from within the paper. First, we searched in the figures and their captions. If the information provided in the figures was incomplete, we consulted the body of the paper. In some cases, information about the interface was only present in the body of the paper.

During our reading of the papers, we also recorded which type of AR display device was used, distinguishing among head-worn displays, handheld displays, desktop monitors, and spatial AR (SAR)displays.

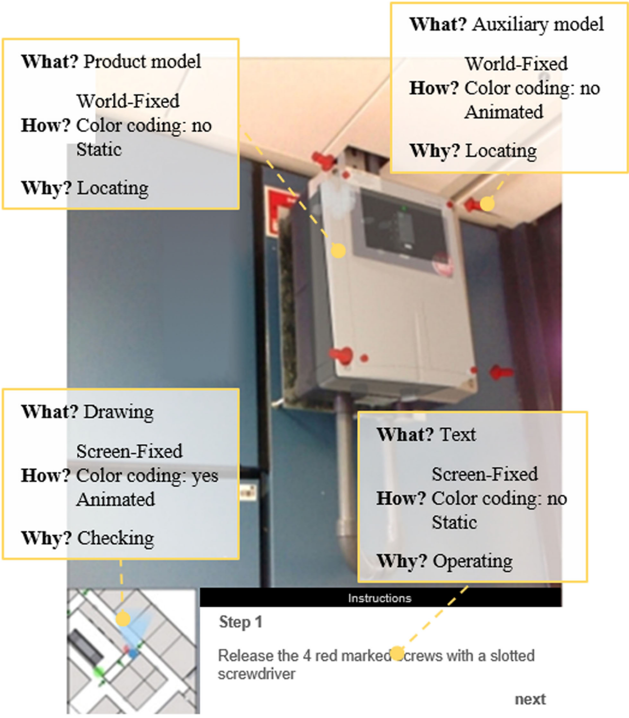

Fig. 2. Example analysis of an interface (inspired from [37]) according to our proposed classification. We added the yellow boxes, dashed leader lines, and filled circles to illustrate application of our proposed classification.

During paper analysis, we met regularly to discuss papers and user interfaces that were not clear, in order to reach an agreement. From Fig. 3, it is possible to note that the number of reviewed papers is higher in the last ten years of the observation period than in the rest of the period, with a peak in 2018. There were no papers that met our criteria in 1997, 2000, 2002, 2004, 2006 and 2010. In the last five years, after a peak of 11 papers in 2014, the proportion of papers in maintenance field is decreased respect to those in assembly. In fact, there is a strong increase of papers in the assembly field in the last five years (37 papers against 19 in the rest of the period). The papers in the training field were all published in the last decade. Overall, we found most of the papers in the field of assembly (56, or 46 percent), whereas papers in maintenance contain the highest mean number of visual assets (3.37), as observable in Table 2, where summary statistics for all 122 papers are reported.

Papers in the maintenance field have a higher mean number of authors and were published more in journal than to conference venues, contrary to papers on assembly and personnel training (Table 2).

In the set of work that we examined, there is a higher proportion of maintenance prototypes tested in real environments, whereas the majority of assembly prototypes where tested in the laboratory. For personnel training, there is almost the same number for each real and laboratory environment (Table 2). An explanation could be that maintenance requires a real scenario, whereas an assembly scenario it is easier to reproduce in a laboratory (and sometimes using a simplified form of the actual assembly). In fact, we found several papers using furniture or LEGO assembly applications to describe their research prototype.

Our review suggests that handheld displays are the most commonly used devices for maintenance; HWDs the most common for assembly and training (see Table 2). As observable in Fig. 4, handheld displays were used mostly in the last decade with a steady trend. This was expectable due to the availability of commercial smartphones and tablets in these years. HWDs were also used in the first years of observation, but there is a strong increase in the last years with a peak in 2018. This is mainly due to the availability of new more ergonomic HWDs as Microsoft HoloLens and Meta 2. As a consequence, the use of desktop monitors has decreased in the last years. Spatial AR displays were used only in the last decade with a steady trend.

4 Visual Assets Classification

Based on a preliminary analysis of the papers, we propose a classification for iAR user interface visual assets (Fig. 5). To create the classification, we followed the process recommended in [39] to first create an intentional classification that contained mutually exclusive and jointly exhaustive classes and extensions. We then applied a subsequent classing phase where visual assets were assigned to classes. Specifically, we first analyzed which visual assets are used in the literature, i.e., what visual assets are commonly used. We made the proposed classification following the authoring pipeline of an AR scene. We can divide it into two main stages: i) authoring

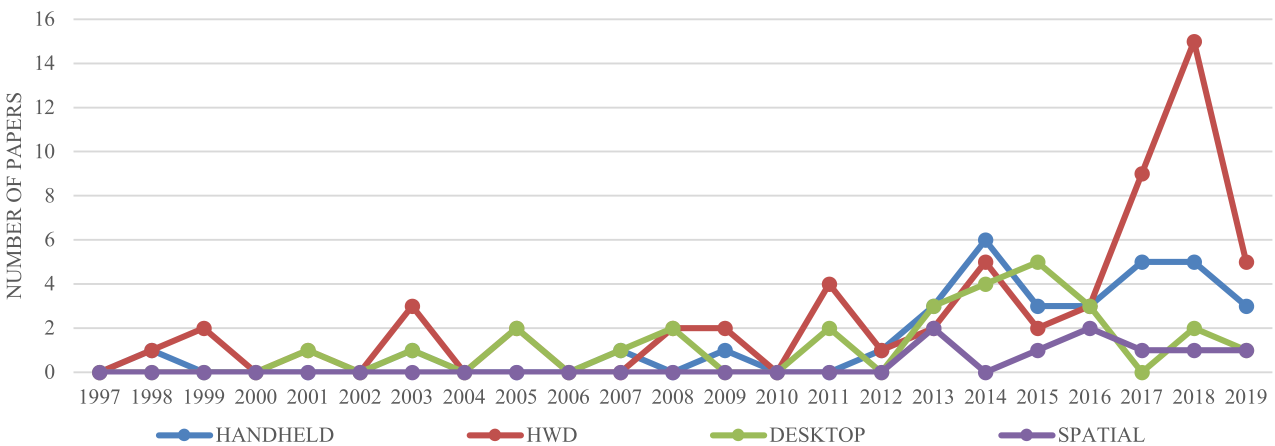

Fig. 3. Trend about the use of AR devices in the prototypes described in the analyzed papers.

TABLE 2
Summary of the 122 Reviewed Papers

Application Area	*Paper*	*Mean ACC*	*Mean Author Count*	*Publication*		*Display**				*Test scenario*		*Mean Visual Asset Count*
				Journal	*Conference*	*HWD*	*HHD*	*MON*	*SAR*	*Real environment*	*Laboratory*	
Maintenance	51	5,2	4,59	27	24	18	25	11	0	24	27	3,35
Assembly	56	5,4	3,90	26	30	31	6	14	7	11	45	2,30
Personnel Training	15	7,1	3,73	7	8	10	2	2	1	7	8	3,27
Overall	**122**	**4,2**	**5,53**	**60**	**62**	**59**	**33**	**27**	**8**	**42**	**80**	**2,86**

**HWD = Head Worn Display, HHD = Hand-Held Display, MON = Desktop Monitor, SAR = Spatial Augmented Reality*

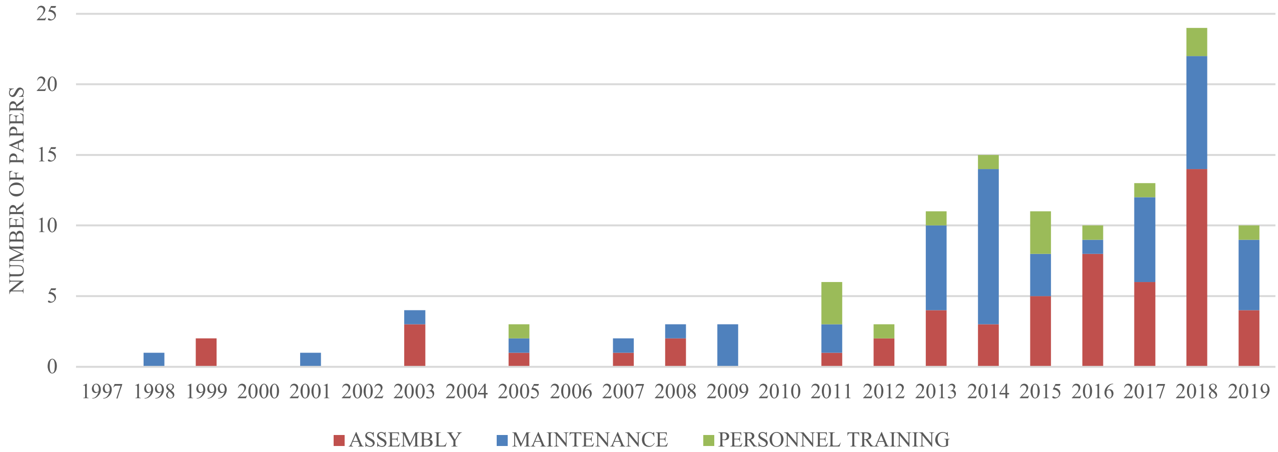

Fig. 4. The number of papers in our review per year where an iAR prototype is presented. 103 out of the 122 analyzed papers are in the last decade (2010-2019) when also "personnel training" topic is more addressed.

of the single visual assets, that changes according to the type: 3D modeling in CAD software, photograph acquisition, and so on; ii) creation of the AR scene, usually done with development platforms (e.g., Unity 3D or Unreal) where the visual assets are combined with the real scene and additional properties can be added to them.

Then, we made the first distinction, putting into different bins visual assets that needed different approaches in the authoring phase ("what"). This is the reason why, for example, we distinguished between photograph and video: even if both are created using a camera, a photograph is used as it is in the interface, whereas a video often needs postprocessing and then authoring is harder.

Then, we analyzed properties of the visual assets that can be added during the creation of the AR scene and that

could give additional information ("how"), as the location in the AR scene, a specific color, an animation. These properties of a visual, i.e., how visual assets are presented, represent the second level of our classification.

Finally, we wanted to study the relationship between the type of visual asset used in an iAR interface and the information conveyed, i.e., why are visual assets used in iAR interfaces.

To enforce mutually exclusive classes assignment, we counted the same types of visual assets (what) if they had different properties (how) or used for different scopes (why). For this reason, in a given paper we could have more than one text, auxiliary model, and so on. Whereas, if a type of visual asset with the same properties and scopes was used more than once in a paper (e.g., for disassembling and re-assembling a product), we counted it only one time. If an instruction was composed of more than one visual asset, we analyzed the two visual assets separately. In the following sections, we describe the classes contained in the proposed visual asset classification.

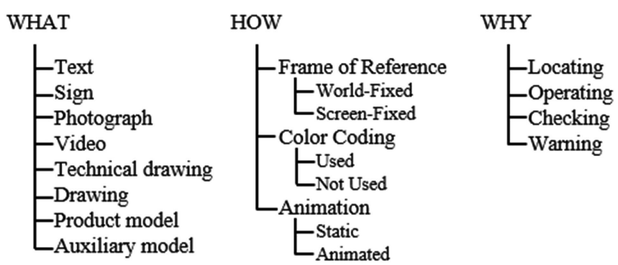

Fig. 5. Our proposed classification of visual assets commonly used in iAR user interfaces as presented in the literature from 1997 to 2019.

4.1 Class: What (is the Visual Asset)?

4.1.1 Text

Text is the traditional way to convey verbal information. Authoring text is very simple since it requires just the definition of text content.

We include in this category both 2D text and 3D text, as well as text both displayed within bounding boxes and without.

Examples of analyzed papers using text as visual asset are [40] and [41].

4.1.2 Photograph

In this class, we consider assets, whose content is generated through photographs of the real world as acquired by a camera. The use of photographs is very common in manuals, especially digital manuals and instructional websites such as iFixit.com [42].

Examples of analyzed papers using photograph as visual asset are [5] and [43].

4.1.3 Video

In this class, we consider assets whose content is generated through video recordings of the real world as acquired by a video camera or webcam.

Examples of analyzed papers using video as visual asset are [4] and [44].

4.1.4 Sign

We applied the definition of Peirce [45] whereby: "a sign is a thing which serves to convey knowledge of some other thing, which it is said to stand for or represent." Signs can be of three types: icons, indices, and symbols.

Signs are regulated by standards that could be either International Standards, such as ISO 3864 [46] for safety symbols, or internal practices. The information contained in signs is very focused, which is a key characteristic that distinguishes signs from photographs.

Examples of analyzed papers using sign as visual asset are [47] and [48].

4.1.5 Auxiliary Model

We used the definition provided by Wang *et al.* [49] that states: "auxiliary models are virtual models for auxiliary instructions". Then, in the proposed classification, auxiliary models are 2D and 3D annotations, used by technical authors for delivering hints to the operator (e.g., guiding operator's visual attention to a detail). Some examples include arrows, circles, and abstract sketches. We did not make a distinction between 2D and 3D elements since the same information can be conveyed by both the 2D and 3D version of auxiliary models.

Examples of analyzed papers using auxiliary model as visual asset are [50] and [51].

4.1.6 Drawings

In this class we consider all digitized 2D drawings that do not follow formal standards. Examples from the literature include freehand sketches, maps and charts. We also included in this group annotated photographs (i.e., a combination of a photograph and 2D auxiliary models and/or text) since, for the authoring, they require postprocessing of the photograph acquired from a camera (e.g., adding annotations).

Examples of analyzed papers using drawing as visual asset are [10] and [52].

4.1.7 Technical Drawing

For technical drawings, authoring is harder because the drawings must follow international standards to deliver constructive and functional information about products (ISO 128-1:2003 [53]). In this category, we include 2D representations in the form of technical drawings displayed as a static image on a canvas, but also 3D graphical annotations, according to ASME Y14.41 – 2003 [54].

Examples of analyzed papers using technical drawing as visual asset are [55] and [56].

4.1.8 Product Model

We again use the definition provided by Wang *et al.* [49] that states: "product models are 3D virtual models of product and parts". Product models are the digital representation of real objects (e.g., machinery parts, components, tools) and their authoring is typically made using 3D CAD and 3D modeling tools (e.g., Solidworks, CATIA, Blender).

Examples of analyzed papers using product model as visual asset are [57] and [58].

4.2 Class: How (Are Visual Assets Presented)?

4.2.1 Frame of Reference

The frame of reference for visual assets within an AR interface is an important classification criterion because it can influence the information provided. We used the definition provided by Gabbard *et al.* [59] initially presented within the context of automotive AR interfaces. They conceptualized the frame of reference from the user's point of view as follows:

- Screen-fixed AR graphics are rendered at a fixed location on the display and are generally not spatially anchored to any specific objects in the scene; and;
- World-fixed (or conformal) AR graphics are rendered such that they are perceived to exist at specific locations in the real world.

A world-fixed visual asset (i.e., an annotation [38]) often conveys a greater amount of information than the same visual asset presented in a screen-fixed fashion, because the former increases the spatial proximity between the information provided and its real-world referent.

4.2.2 Color Coding

In the industrial domain, the use of color is regulated by international standards and internal practices. For example, colors are used for the identification of material properties in pipes (ASME A13.1, 2007 [60]), for safety symbols (ISO 3864 [46]), and to identify product status in aerospace facilities. The 5S, a common workplace organization method, suggests the use of color in the workspace to enforce sorting, straightening, systematic cleaning, standardizing and sustaining [61]. Thus, we distinguished visual assets whose color is associated with a specific meaning (i.e., purposeful color semantics) from those whose color is arbitrary (or we perceive to be arbitrary based on the paper's figure and/or associated figure caption and text).

4.2.3 Animation

We distinguish animated visual assets from static ones since the use of animation can provide further directional or temporal information to the users. We consider animated visual assets to be those that change their position/rotation/scale

TABLE 3
Summary of the 348 Visual Assets Found in the iAR User Interfaces Reported by the 122 Reviewed Papers.

Application Area	*Visual Asset Count*	*WHAT*								*Information about VA extracted from*			
		Text	*Online Video*	*Online Video*	*Online Video*	*Online Video*	*Drawing*	*Product Model*	*Auxiliary Model*	*Video*	*Figure*	*Figure and body*	*Body*
Maintenance	170	51	4	5	8	3	12	48	39	39	57	48	26
Assembly	129	26	0	6	1	6	7	49	34	8	17	87	17
Personnel Training	49	14	1	1	2	0	3	12	16	7	11	21	10
Overall	**348**	**91**	**5**	**12**	**11**	**9**	**22**	**109**	**89**	**54**	**85**	**156**	**53**

in the interface over time, while keeping the point of view of the real world fixed. Examples of animated visual assets include: a product model of a screw that is animated to show unscrewing (change of position and rotation), virtual arrows that pulse (change of scale), and sliding text (change of position). Videos that occupy a fixed position in the interface are considered static even if the content changes over time.

4.3 Class: Why (Is the Visual Asset Being Used)?

4.3.1 Locating

We consider locating an important use of visual assets, since iAR elements can assist in identifying objects of interest within the scene. In iAR, users need to identify and locate parts both inside and outside their field of view (FOV). Locating is always a supporting task because it does not involve a change in the system status (no action); instead it is a prerequisite for some task action. A location task could be for instance: locate the screw to be unscrewed, locate the button to be pressed, or locate the tools to be used.

4.3.2 Operating

Operating tasks refer to all actions that are carried out by the user, with and without the aid of tools, that change the state of the scene/system. The operating task is generally performed after a locating task for the target. Representative examples could include unscrew the screw counterclockwise, press a button or raise a lever.

4.3.3 Checking

Checking tasks involve the examination of an object in order to make a decision (e.g., determine its condition, or to detect the presence of something wrong) but without performing the subsequent operation. Checking the oil level, discrepancy checks, checking the pressure on a pressure gauge or checking that a surface is clean are all examples of checking tasks.

4.3.4 Warning

In an industrial environment, safety is a priority. Therefore, even iAR interfaces must provide special warnings that indicate a potential hazard or condition that requires special attention, in order to prevent injury or avoid hazards that could threaten operator health and safety. Industrial hazards can be found in almost every work environment (e.g., radiation hazard, overhead hazard, machine safety) and each hazard requires a specific visual asset to reduce ambiguity.

5 Results

From our analysis, the 122 papers present 348 visual assets. Looking at the source for the collection of assets, 54 (16 percent) of visual assets were from videos, 85 (24 percent) from figures, 156 (45 percent) from both figures and the body of the paper, while 47 (15 percent) visual assets were identified using only information presented in the body of the paper.

Table 3 gives summary statistics for all identified visual assets. We distinguished among papers in the fields of maintenance, assembly and personnel training.

The product model is the most common in all application fields (109 occurrences of 348, 31 percent), followed by text (91, 26 percent), and auxiliary models (89, 26 percent), while all the other visual assets were used at lower counts (Fig. 6).

Analyzing the application field (Table 3), the number of visual assets in maintenance is much higher (170, or 49 percent) than in the other two fields (assembly 129 or 37 percent, personnel training 49 or 14 percent).

For the maintenance field (Fig. 7), the most-used visual asset was text (51 or 30 percent), for assembly the most-used was the product model (49 or 38 percent), and for personnel training field, the auxiliary model was most-used (16 or 33 percent). In assembly, the text was used less (20 percent) than the other fields (30 percent in maintenance and

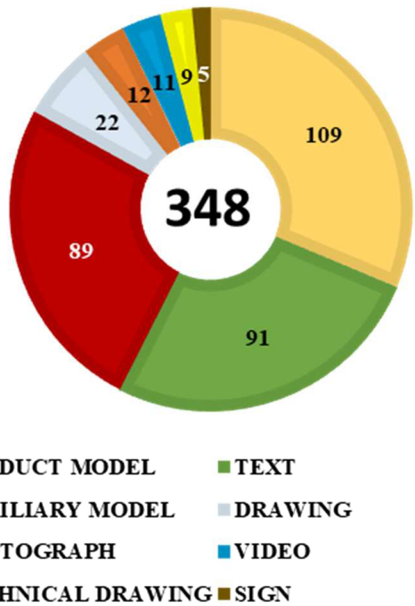

Fig. 6. The number of visual assets occurrences in various applications fields derived from our systematic review.

Fig. 7. Results about "what" and "how" classification. CAD models, both product and auxiliary ones, are almost always used as world-fixed and often animated. Visual assets that fill a rectangular area of the interface are mostly used as screen-fixed and static. Text is used equally screen- and world-fixed and is almost always static. Color coding is less used.

29 percent in training), while technical drawing was used more (5 percent).

Fig. 8 depicts results from the "what" and "how" classification. Regarding text, there is no evident preference between screen-fixed (48 or 53 percent) and world-fixed (43 or 47 percent). On the contrary, for product model, there is a great predominance of world-fixed assets (100 or 92 percent) as compared to screen-fixed (9 or 8 percent). Auxiliary models are almost all world-fixed (88 or 99 percent). For signs, there is a slight prevalence of world-fixed assets (3 or 60 percent). For technical drawing, photograph, drawing, and video there is a prevalence of screen-fixed assets. As regards the color coding, we were surprised to notice that it was rarely meaningful used (only 48 visual assets or 14 percent). Color coding is sometimes used for text, product and auxiliary model, sign and drawing.

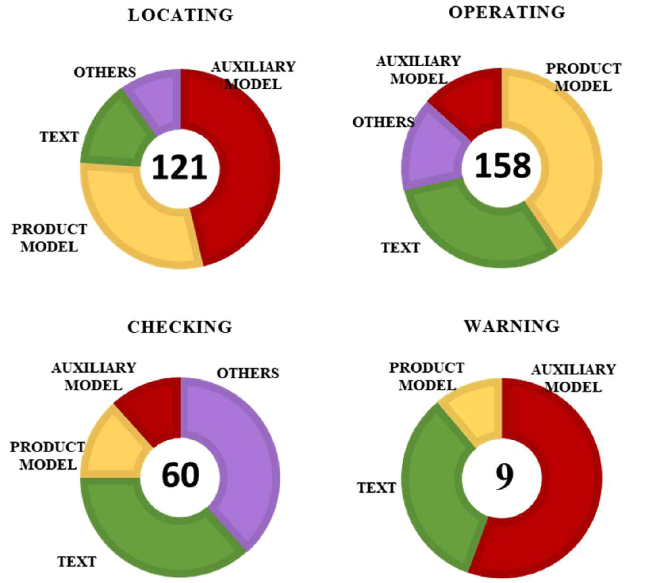

Fig. 9. Results about "what" and "why" classification. The most used visual assets for locating tasks are auxiliary and product models. The most used visual assets for operating tasks are product models and text. For checking tasks, text is far more used than all the other visual assets.

Finally, the animation in visual assets was scarcely used, but when used, were mostly found in product model (54 or 50 percent in Fig. 8), and auxiliary model (21 or 24 percent).

Fig. 9 shows an analysis of why visual assets are used for specific tasks. For locating, the most used was the auxiliary model (56 or 47 percent), for operating, the product model (64 or 40 percent), and for checking, the text (22 or 37 percent). It is worth to note that in checking tasks, the presence of technical drawings is comparable to other tasks (7 or 12 percent). As to warning tasks, there are very few instances (only nine visual assets), with a prevalence of auxiliary models (5 or 56 percent).

6 Discussion

The proposed visual asset classification and results of our SLR reveal the presence of some interesting patterns useful for answering our research questions: "which are the visual assets and how they are used in iAR interfaces for tasks in maintenance, assembly and personnel training?".

A useful summary of results is presented in Table 4, reporting each task type along with the three most commonly used

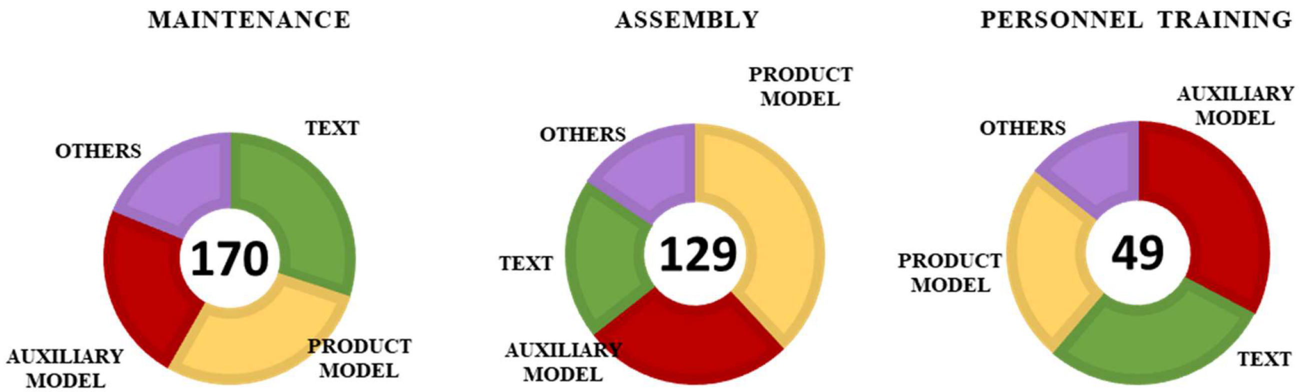

Fig. 8. The most used visual assets change depending on the industrial field.

TABLE 4
Synthesis of the Three Most Used Visualization Methods (What and How) for Different Tasks (Why)

WHY?		WHAT?	HOW?			USAGE*	OCCURENCES
			FRAME OF REFERENCE	*COLOR CODING*	*ANIMATION*		
Locating	1)	Auxiliary model	World-fixed	Not color coded	Static	36%	43
	2)	Product model	World-fixed	Not color coded	Static	23%	27
	3)	Text	World-fixed	Not color coded	Static	10%	12
Operating	1)	Product model	World-fixed	Not color coded	Animated	27%	42
	2)	Text	Screen-fixed	Not color coded	Static	20%	31
	3)	Text	World-fixed	Not color coded	Static	10%	16
Checking	1)	Text	World-fixed	Not color coded	Static	15%	9
	1)	Text	Screen-fixed	Not color coded	Static	15%	9
	3)	Technical drawing	Screen-fixed	Not color coded	Static	10%	6
Warning	1)	Auxiliary model	World-fixed	Color coded	Static	44%	4

**percentage of occurrences of visual assets found in the systematic literature review for each task.*

visualization methods. A technical author aiming to design a next-generation manual, exploiting both web and AR content, could start from these results that provide a snapshot of over 20 years of literature on the topic.

A first observation that we can draw from the results, is that locating tasks are often supported through world-fixed, static, either auxiliary or product models (59 percent overall). The use of CAD models helps operators to identify a real object either observing their virtual copy (product model) or highlighting the space region where it is located (auxiliary model). Thus, it is evident why CAD models are often world-fixed, but perhaps should not be animated since there is limited added value and an unjustifiably high authoring effort. The locating task is accomplished through the perception of visual assets, involving stimulus preprocessing, feature extraction, and stimulus identification. Among the methods for directing visual attention to specific spatial locations, Stork and Schubö [62] distinguished between exogenous (or peripheral) cueing (i.e., presenting salient spatial cues at the relevant position), and endogenous (or central) cueing (i.e., using symbolic cues in order to indicate the spatial position). Peripheral cues afford faster attentional shifts than central cues because the latter need additional time for the interpretation of the symbol. World-fixed assets can be considered peripheral cues since information is presented exactly on the part to be located. This is one of the greatest advantages of using AR as compared to static textbook manuals. Nevertheless, designers should evaluate if the use of a product model would provide more information than an auxiliary model, considering that the formers require a higher authoring effort, cannot be used with SAR, and require precise alignment with real products. Auxiliary models with salient attributes like animation, size, orientation, color and transient luminance changes can provide the needed information for locating single objects in an assembly or object details (e.g., a hole), as in [63]. To locate a group of objects in a large assembly instead, the use of auxiliary models can lead to ambiguous interpretations. In these cases, the use of a product model is justified to highlight the exact group of objects involved, as in [64], [65], and [56].

A second observation is that operating tasks were achieved mainly using world-fixed, animated product models (27 percent). This is an expected result because the main information conveyed in an operating task is the way to operate on objects (e.g., the way to assemble two parts), and the use of animations of product models provides a powerful preview of task steps to accomplish. Operators watch the animation and then have only to replicate what they have watched. The same result could be achieved through a video tutorial, but CAD models have the benefit of being registered to their real components to be handled. World-fixed product models are indeed peripheral cues whereas videos are central cues, thus in the former there is minimal demand to shift attention between the information and the object to handle. Nevertheless, operating tasks highly depend on task difficulty. Then, for low difficulty task, product models could provide too details that are not needed. For example, to instruct an unscrewing operating task, it is not necessary to have the animation of a virtual screwdriver and screw. Other visual assets can be explored in these cases such as auxiliary models and signs that require less authoring effort and provide operating task information without too many extraneous details.

As to checking tasks, there is a higher scattering among visual assets, with a predominant preference for text (30 percent). The range of checking tasks is so wide that the proper visual asset should be chosen case by case. The use of text is justified since it is the simplest method to describe the way the checking task should be carried out, e.g., through a visual inspection. Text is needed to fully describe the context and/or to provide quantitative values of physical properties (e.g., the pressure of a manometer). Thus, in most of the AR interfaces analyzed, authors tended to use the same text information that would be present in a traditional manual. Then, specific research could be done for checking tasks exploring the use of other visual assets, as static product models for discrepancy checks, as done in [66]. Furthermore, studies on text optimization in AR interfaces are of utmost importance, especially as regards visualization style, translation issues, summarization techniques.

Considering the overall results of this review, we found that the most used visual assets are product models, followed by text, and then auxiliary models. All the other visual assets are less common. Thus, there is still a high burden of authoring, caused by the use of product models, which can be the cause of the limitation in the scalability of the AR prototype applications. Furthermore, ongoing research is showing that effectiveness of product models in iAR is still to be proved, as argued by Radkowski *et al.*, who claim that "a user needs more time to understand complex 3D models, which is one reason why their usage is not recommended to display instructions [10]." A possible explanation for the scarce use of some 2D visual assets such as photograph, video, drawing, technical drawing and sign could be that many of the interfaces have been designed with the scope of demonstrating the effectiveness of novel tracking systems, as well as novel techniques for rendering virtual content in three dimensions. Therefore, demonstrating the effectiveness of these techniques through 2D contents would not have been possible. Moreover, in other cases, it could be just a design choice, in fact photograph, video, drawing and technical drawing occlude a large portion of the real world, hiding what is behind them, especially when they are used world-fixed. This issue concerns all visual assets that fill a rectangular area of the visual interface. The use of these visual assets, rendered transparently and in a small size, reduces occlusion, but the information comprehension could be compromised. Other visual assets, such as signs, are not widespread probably because they introduce the challenge of defining a standard 2D sign vocabulary to convey technical instruction [47]. However, signs are easier to recognize and comprehend than other complex 2D elements such as photographs, which are elaborated and full of detail, sometimes unnecessary. Moreover, signs cause a minor occlusion of the real scene and they could also be displayed screen-fixed on the interface.

Finally, the association of specific information to the color of a visual asset (color coding) has been rarely used in the analyzed interfaces. The scarce use of color coding may be due to the low consideration of this technique as a means of communicating specific information. Probably, iAR researchers have focused more on aspects such as tracking, visualization and interaction techniques, neglecting aspects that may seem secondary such as convey information with color coding.

To the best of our knowledge, this is the first review about the use of visual assets in iAR interfaces. Thus, our results are hard to compare to other works in the field. In [31], 2D/3D models are used more than text in maintenance. If considering product and auxiliary models together, our results are consistent with [31]. However, they found more animated than static models.

While the results presented herein are a useful starting point for classifying and discussing what, how and why iAR visual assets are used, we cannot directly generalize these findings to all existing AR interfaces in the literature (industrial or otherwise). This is just a snapshot of 122 selected iAR applications. Moreover, the visual assets analyzed herein are not necessarily the choice of an optimal iAR interface design. In fact, there are many factors to be taken into account to define an "optimal" iAR interface such as: cognitive effort (e.g., a 3D model is more complex than plain text [10]), effects of the interface on behavior and situational awareness, authoring [67], occlusion [68], and style [69] to name a few.

We are continuing this research and we started from a heuristic evaluation considering the advantages and disadvantages of the proposed visual assets [70]. From this initial research, it is possible to reveal some future directions for the research in this field. For example, the use of signs together with auxiliary models could be explored as an alternative to the most popular product models for operating instructions. Authoring of both signs and auxiliary models is done first defining a library. Then when a technical writer creates a new instruction document, a predetermined sign and auxiliary model can be easily recalled from this library. In this way, authoring involves less effort since a standard library of visual assets can be reused in many iAR applications. However, currently, there are no standards to follow, thus future research can be focused on the definition of standard libraries of visual assets.

Other future directions can arise from our review. One of these could be a study for a wider exploitation of color coding to convey information, also considering limitations due to color blindness [71]. Specific research on checking tasks is also needed since in the literature this type of instruction has been presented with various visual assets.

Finally, future studies are needed to find which are the optimal ways to provide a complete instruction - i.e., a combination of locating, operating, checking, and warning tasks - combining different visual assets, and supporting context-aware iAR interfaces that adapt to task difficulty and operator knowledge.

7 Conclusion

In this work, we present a systematic literature review of visualization methods for technical instructions in iAR prototypes and concepts for maintenance, assembly, and training procedures. The extensions of each class proposed in Section 4 proved to be mutually exclusive, and jointly exhaustive for all the 348 visual assets analyzed, extracted from 122 selected papers published between 1997 to 2019. We propose a novel classification for iAR technical visual assets according to: (i) what content is displayed via the visual asset, (ii) how the visual asset can convey information, and, (iii) why the visual asset is used.

The main findings can be summarized as follow:

- iAR has a positive trend in literature;
- HWDs are trending, spatial AR (to date) has few iAR implementations;
- the number of visual assets in maintenance is higher than assembly and personnel training;
- product model is the most common visual asset, followed by text and auxiliary model;
- the most-used visual asset in maintenance is text, in assembly product model, and for personnel training the auxiliary model;
- product model and auxiliary models are almost always world-fixed;
- technical drawing, drawings, photographs, and video are usually screen-fixed assets;
- color coding is uncommon;
- animation is uncommon and limited to product model and auxiliary model only; and;
- for locating, the most common visual asset is the auxiliary model, for operating the product model, and for checking, the text.

Even though we analyzed the literature specific to applications of AR in maintenance, assembly, and training, the classification proposed herein could be applied to other industrial fields such as manufacturing, construction, plant layout, and so on. Furthermore, it can be effective for other domains such as medical applications, cultural heritage, transportation, etc.

This work may further help the community (e.g., researchers, developers, standard technical committees) to better understand the practices and trends that, with further scientific support, may eventually lead to consolidated guidelines for iAR interface design.

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