Is there a Reality in Industrial Augmented Reality?

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ABSTRACT

In the spirit of the seminal article by Brooks [12] that surveys the field of Virtual Reality to evaluate its level of applicability, we study the readiness of Industrial Augmented Reality (IAR). We have been hearing about IAR since *Mizell* and *Caudell* [14] first gave a name to AR, but how many applications broke out of the lab to be used by non-developers? In reviewing the literature, we note the amazing progress made in display technology, rendering and tracking. Given these improvements, one might expect AR-based industrial products to flourish. Unfortunately, this is still not the case.

In this paper, we provide a comprehensive and up-to-date survey of industrial AR applications. We organize the different applications of IAR over the life-cycle of products, in order to draw some parallels between the different proposed concepts and offer a clear taxonomy for future applications. We also propose and apply a rubric to evaluate existing IAR systems in order to highlight reasons for success and offer guidelines in the hope that it will help IAR become "really real".

1 INTRODUCTION

For the AR community, industry has always been one of the steering forces for research. Researchers at *Boeing* [14] defined AR and pushed it forward. Since then many researchers, projects and companies followed this path. They each tried to apply the concept of aligning virtual information with the real context for the user's benefit [6, 7]. AR applications are everywhere: medical, military, manufacturing, robotics, architectural design, advertisement, etc., but few of the developed ideas have made it into products. The entertainment industry is using AR techniques for televised sports (e.g. the first down line in US football) [7] and for theme parks [66]. The printed media is toying around with AR [18]. In the medical field, several AR concepts are undergoing clinical trials: InnerOptic's InVision [65], Siemens' Camera Augmented C-Arm (CAM-C) [41], and SurgicEye's declipseSPECT [73]. Recently, an app, the *Atelier Pfister* [3], was released for mobile devices, which allows a user to position furniture from an on-line catalog onto a view of the real world displayed on the screen of his iPhone.

During the first *IWAR* in 1998 [9], a panel was formed to discuss possibilities, limitations and applications of AR. The members of the panel felt that AR had great potential in many areas (factories, airplanes, medicine) for trained and untrained users. They discussed the necessary steps to build a truly useful AR system. Both academic and industrial researchers emphasized the need to design applications in collaboration with end-users and to focus on applications where AR technologies can make a real difference. Moreover, AR should limit human errors and facilitate better performance of a given task. The panelists noted the technological challenges of the time, some of which are still actively researched in current scientific publications–mainly head-worn display (HWD), tracking, and connectivity (e.g. wireless network). They unfortunately could not yet define the "killer app" where AR would have a massive impact.

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Azuma [6] wrote the first state of the art survey of AR. He gave an overview of the different technologies needed to create an AR system and their shortcomings. He also defined some of the main areas of applications: *medical*, *manufacturing and repair*, *annotation and visualization*, *robot path planning*, *entertainment* and *military aircraft*. When updating this survey [7], newly explored areas were added to the list: *outdoor and mobile AR* and *collaborative AR*.

ARVIKA [72], a German project founded by the ministry of education and research, applied AR ideas to many application fields. It generated great excitement for the companies within this consortium, who each contributed problems suitable for the application of AR. Unfortunately, because of technological limitations with displays, tracking and registration algorithms, most of the demonstration applications did not make it to market. Only one prototype made it out the door: the *Intelligent Welding Gun* [17].

More recently, two surveys [47, 69] studied IAR applications by focusing on enabling technologies and describing some of the proposed applications. Our survey differs from these previous works by proposing a novel taxonomy based on the product life-cycle and presenting an original rubric for evaluating existing and proposed IAR solutions. We hope that these contributions will support researchers in defining realistic applications and transforming prototypes into reproducible AR systems that are placed in the hands of end-users.

The paper is structured as follows. First, in Sec. 2 we give a definition for AR and IAR, describe the life-cycle we use as a taxonomy, and convey the methodology used to select the papers in our survey. In Sec. 3, we review the selected papers and categorize them across the life-cycle of a product. In Sec. 4, we present our rubric and apply it to the papers in Sec. 5. This survey concludes in Sec. 6 by offering some guidelines and describing open questions.

2 DEFINITIONS AND METHODOLOGY

Augmented Reality (AR) : environment in which virtual components have been added to, or replace some aspects of, the reality.

Industrial Augmented Reality (IAR) : applying Augmented Reality to support an industrial process.

This definition is voluntarily broader than Azuma's [6], which tends to disregard photo-based augmentations, which have proven to be effective in an industrial context. Though we are only surveying visual augmentation, one could imagine applications where augmentation of the real world using sound would be practical and useful.

Methodology : when preparing this survey, we reviewed all scientific publications related to IAR. We reviewed all proceedings for IWAR (98,99), ISAR (00,01), ISMR (01) and ISMAR (02 to 10). We then performed a transitive closure on the references present in the relevant articles. We also searched for articles citing the selected papers in order to find other relevant works. In the original list, a paper was selected if the presented application could be applied to an industrial process. This included crude prototypes. We then pruned our list to only retain works describing the original concept of an application or works presenting a crucial advance towards real applicability. Because of the limited space in this paper, our citations focus on the latest publication of each project in the hope of covering most of the important aspects and original reference(s).

2.1 Product life-cycle

When we reviewed existing IAR applications, it was clear that each system tackled a particular problem for a particular industry. By trying to generalize their particular area of applications, the underlying life-cycle of an industrial product as described by Grieves [26] became visible. In the remaining part of this section, we define the five steps of life-cycle that we use throughout this paper as a taxonomy to group each system.

Product Design is focused on generating ideas to be conceptualized into a tangible object. It often requires communication between designer, manufacturer and final customers to evaluate ideas and prototypes. This stage of the life-cycle also integrates development of production processes and systems.

Manufacturing is the act of transforming goods (raw material or manufactured) into a more complex product that is ultimately delivered to an end-user. This process mainly focuses on assembling objects. This task can require the training of inexperienced workers.

Commissioning is the process of verifying that all systems and components of a product are installed and functioning as required by the client. This process includes verifications of the product against the plan, testing its functionality and document discrepancy when required.

Inspection and Maintenance is the action, sometimes regulated, of verifying the condition of a product. It often includes repairing or replacing faulty components required to return a product to proper functionality. Inspection and Maintenance operations usually involve workers carrying out codified and standardized procedure.

Decommissioning is the act of retiring a product when it reaches the end of its life. It can include dismantlement, decontamination and recycling.

3 IAR Survey

3.1 Product Design

One of AR's first area of application was architectural design [68], where virtual models are rendered onto photos to illustrate the visual impact of a proposed architectural project. Since then it has been used to ease the development of many other products such as cars and planes.

For example, in the automotive industry, Ohshima et al. [45] propose to evaluate a design while sitting in an actual car skeleton (seat, steering wheeling, on-board commands). The skeleton helps improve the evaluator's level of immersion and their understanding of the virtual world by enhancing the depth perception. The user can switch between various options and design versions to evaluate the best fit. Similarly, Klinker et al. [33] augment a car mock-up with different light optics to evaluate in-situ its appearance. This system includes the possibility of navigating around an augmented mock-up. They emphasize how integration of AR into the design process can reduce the industry's reliance on and use of expensive clay mock-ups. Regenbrecht et al. [53] also sought to bring realism into car design by integrating augmentations with physical mock-ups for use during meetings. Nölle and Klinker [44] developed a system to verify if manufactured objects matched their CAD data. This verification can be quite useful during the design period of a product, where design variations can lead to confusion among several versions of a manufactured piece and their 3D models.

AR is not only used for aesthetic evaluation. Regenbrecht et al. [52] use a trolley-type system to evaluate the functionality of a design. Their system uses AR to visualize the airflow within an airplane cabin resulting from a particular structural design. The application also supports a customer selecting and visualizing options for the airplane cabin. The authors also propose using the system to improve the functionality, ergonomics and safety of the cockpit design. In this instance, a designer can place virtual instruments and controls in a life-size cockpit to develop a more efficient layout. Nölle [43] proposes a system to validate crash test simulations using AR by comparing simulated crash results with real experiments. The ultimate goal is to replace some of the real crash tests by simulation to cope with the shorter life-cycle of cars.

Furthermore, AR can be used to optimize a design. For example, Webel et al. [70] push the in-situ design concept further by integrating it tightly in the design process. The design of submarine piping systems is complex, as many pipes have to go through a restricted space. By using AR, the engineers can verify that the current mock-up matches the design. Engineers can physically change the mock-up and integrate any modifications back into an underlying CAD model using vision-based reconstruction. This tight integration of AR in the design workflow shortens the loop between real and virtual mock-ups and creates a more efficient development process.

Most of the previously mentioned approaches are designed to work in prepared environments. Thomas [67] lifts this constraint by proposing the use of HWDs combined with wearable computers to visualize design data on-site by aligning CAD data to the real world. They present tools to modify the design and to model existing objects that are not yet represented in the virtual data.

Once the design of an object has been validated, AR can be used to plan its production. For example, Behzadan et al. [10] develop an AR system for outdoor construction sites where they emphasize the animation of 3D models. The authors propose using AR to verify simulation results on-site before implementing a project plan. They demonstrate their system to simulate a bridge construction and verify if their plan was realistic in the context of the real target site. This type of task has traditionally been done using VR, which helps to understand the subtleties of a plan but does not provide any contextual information. Additionally, VR requires a lot of overhead to model features not presents in the CAD data.

In the industrial process, a lot of care is given to factory setup, when a new item needs to be produced. This factory design activity can involve a new facility or an existing production line that needs careful evaluation to verify what (if any) modifications are required to support the new item. This process is called *factory planning*.

Rauterberg et al. [51] propose one of the first IAR factory planning systems. In this application, designers sit around a tabletop display depicting a virtual orthogonal view of a proposed plant design superimposed on real objects. A full perspective view of the virtual world is accessible on an additional display. The designers can select an object to change its position or to delete it. They can also manipulate the viewpoint of the perspective view. This offers a more immersive and collaborative experience than similar VR systems.

Gausemeier et al.[23] propose using AR not only to assemble 3D components, but also to consider semantic knowledge about the plant (e.g. water and electrical access) and to determine the minimum and maximum distance required between each factory component and its adjacent module . Components that need to be positioned are materialized by markers that the designers manipulate to create a proper design. The resultant plant design can be tested in a production simulation tool to verify its efficiency.

For the positioning of components and systems in a new factory, Siltanen et al. [64] propose using an iterative process where a plant operator requests a proposed alteration. This request is generated from the factory floor for the designer team. The operator using an augmented view of the current plant can evaluate the proposed alternation to the factory design. This can lead either to a validation of the proposed design and eventual implementation or to further design modifications in order to obtain an optimal plant design. This

Figure 1: **AR in Large Building Construction**: AR is often used to display up-to-date design information and to verify the correctness of the current construction in comparison to the planning data. (©[35])

method allows the plant operator to communicate from the place he feels the most confidant: the factory floor. He can directly explain his requests by showing the reality of the factory to the designer and clearly describe problems he finds on-site.

When new items need to be produced in an existing plant, the plant needs to be verified to know whether they can handle the new production line and if it needs alterations. METAIO [2] introduced methods to plan the upgrade of a factory not only in a VR system but also in an actual plant. They hope to reduce the time required to validate factory planning, improve data quality, and avoid collisions between new components and ones already installed. This should minimize re-planning activities. Pentenrieder et al. [48] propose reducing errors in factory planning by creating an up-to-date CAD model of the current plant. They realize that most of the available CAD data for plants is not correct when compared to the current plant state because it is an extremely complex task to synchronize the CAD model with the plant. They focus their work on the accurate alignment of the CAD model with reality to offer a precise augmentation to plant designers. After several iterations of their system, they settle for a photo-based augmentation because they found it to be the most accessible technique for the plant designers. In their system (ROIVIS), the authors offer precise (verified and bounded) measurement functionality and collision detection between a plant update and the current plant state. They offer comprehensive documentation by saving AR screen-shots of the plant images that can be used later to inform someone about design acceptance or rejection.

3.2 Manufacturing

When the design of a new product is finalized, its production can be launched. AR has not only been used to support workers in assembly tasks (Sec. 3.2.1) but also to train operators to produce new objects (Sec. 3.2.2).

3.2.1 Assembly Guidance

Caudell and Mizell [13], when developing one of the first IAR applications, contemplated offering support for an assembly task using a see-through HWD. Their system was originally proposed to reduce the storage requirements of formboards used as life-size maps to guide workers in preparing wire bundles. Each type of wire bundle requires a different formboard. The proposed AR system promised to replace the need for specific formboards by augmenting a generic formboard with bundle-specific information. Their proposed system not only promised to reduce the need to maintain dozens of bulky formboards, but also might allow workers to assemble each wire bundle assembly more quickly [14]. Regenbrecht et al. [52] also propose using AR to display a montage of highly customizable objects. They specifically examine the task of producing fuse box assemblies for trucks that are based on client-selected options. This makes each truck unique. Therefore, the authors propose a system that uses AR to present workers with model-specific instructions. This simplifies the workflow of the assembly since the worker is not required to refer to a generic paper-based instructions manual and can directly follow the model-specific instruction.

AR is also used to support the manufacturing of larger goods such as power-plants. Webster et al. [71] use an AR system to support construction. Their system uses AR to present an x-ray view to visualize hidden structures (e.g., pipes and wires) within walls that should be avoided during follow-on construction. A similar solution is proposed in [35] to display the most recent construction plan to the worker, as seen in Fig. 1. For unmanned construction sites, Fujiwara et al. [21] propose an AR system that displays virtual property lines on a video stream. This additional information helps the construction worker properly perform his task.

AR can also be used to render information traditionally delivered using paper-based assembly instruction manuals. The development overhead for such systems can be justified because product life-cycles are constantly getting reduced. Ever-changing product lines force workers to be more flexible in manufacturing new models. For example, during the CICC project, AR was deployed to support a car door assembly [54, 35]. This project sparked the interest of many European industrial entities in AR applications and inspired several similar projects. Raghavan et al. [50] studied the applicability of AR for assembly tasks. Their system offers step-by-step instructions to the worker. By sensing the current state of the assembly, the application offers the right information to the assembly worker. The construction process is modeled as a state graph, which represents evolution of the object being assembled. They use a multiple hypotheses verification method to determine the evolution of the assembly. By analyzing this graph, the application can determine when the worker performs a step that blocks him from finalizing the construction. Using this technique, they can evaluate instructions to find the optimal set. For the same task, Zauner et al. [74] propose an MR system, where instructions are displayed to explain each step of the assembly. They do not use an instruction graph but a more object-oriented approach. For each object, animations are available to describe its assembly. Each object can be detected by the system and when pieces are combined they form a new object with its own set of instructions. Barakonyi et al. [8] present a virtual agent to guide the user to build an object. The agent presents required pieces and displays an animation on the currently built object to explain the next step.

Fiorentino et al. [20] propose improving current industrial drawing by introducing a tangible digital master (TaDiMa). They link Product Lifecycle Management (PLM) with drawing using AR. The idea is not only to add typical assembly information to the drawing, but also to incorporate up-to-date information onto the drawing that is only available in PLM. This allows the user to quickly verify the validity of a drawing, and when necessary, offers correction to it.

AR has also been used to support logistic applications. This is investigated in FORLOG. When assembling complex systems, such as cars, specific pieces need to be available on production lines. These items are often picked up in a warehouse by a worker who follows an item picking list. This list is typically paper-based. In order to reduce errors that can produce delays on the production lines, Schwerdtfeger et al. [61] propose a new guidance system for order picking using augmentation displayed in a HWD. The augmentation points the user to a target location where an item needs to be picked up. This offers advantages in terms of reducing mistakes and automatically reporting since the system is linked to larger logistical IT infrastructure.

AR has not only be proposed to support unskilled workers but also considered to assist highly trained operators who use complex machinery. For example, Olwal et al. [46] support a lathe[1] operator. Their system displays sensor readings in-situ such as cutting forces, RPMs, and temperatures. This allows the workers to stay focused

[1] A spinning tool performing various tasks such as carving and drilling.

on the piece being manufactured and access readings that require constant monitoring.

Following a similar trend of supporting skilled workers, many AR welding projects have been developed [4]. Most manual welding procedures have been replaced by programmable robots, for example in the automotive industry. Unfortunately, for some complex and non-recurring tasks, manual operators cannot be replaced, for example in a shipyard. By leveraging AR, researchers hope to improve welding seam quality, decrease rejection rate, and therefore reduced cost. The typical AR setup integrates a HWD into a welding shield and includes a pair of High Dynamic Range (HDR) cameras. The direct view through the darkened lens is replaced by a view captured by the cameras. Instructions and sensor information are displayed on this video view. The AR display can inform the worker about electrical welding parameters (e.g. current and voltage). This constant monitoring of the worker's actions offers the possibility to automatically log the manufacturing process. This documentation can give hints about mistakes that could have happened and how to avoid them in the future.

On the other hand, Echtler et al. [17] were able to introduce a new product and related workflow, the *Intelligent Welding Gun* (IWG) that enjoyed the wide support and implementation of industry. The target application of the IWG is helping welders shoot high precision studs for experimental car designs (i.e. prototype), a task not normally performed by robots due to required programming time. Rather, these prototypes are mainly built by hand. In the IWG setup, a regular welding gun is tracked using external sensing devices and is augmented with a display that provides guidance for the worker to find designated stud's location. In the proposed application, the goal is to find the best placement for the studs. The produced prototype can be evaluated and a stud position can be validated or modified. This new workflow replaces a cumbersome procedure that requires one worker to manipulate a probe sensor to find a stud location as he reads from an instruction sheet, while a second worker marks the position and then studs. Clearly an AR setup is more effective as it only requires one operator. The IWG was found to be four times faster while sustaining the same precision. To our knowledge, this AR project is the only publicly known IAR project to be deployed and used by a car manufacturer (*BMW*). Note the use of IWG was recently discontinued as the process to develop prototypes at BMW changed and rendered the IWG obsolete. A picture of the final product is shown in Fig. 2. For the same application, Schwerdtfeger et al. recently proposed replacing the gun-mounted display by a projected laser that would reduce the gun size and make it more maneuverable [62]. This proposed system is currently becoming productized [1].

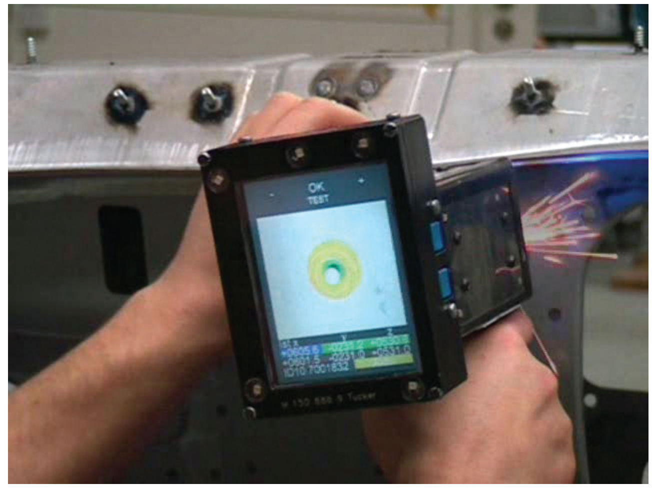


Figure 2: **The Intelligent Welding Gun** is the first AR based product to be used in the manufacturing industry. The welder has access to navigation information on a screen attached to his welding gun that helps find the next stud location. *Courtesy of Gudrun Klinker*.

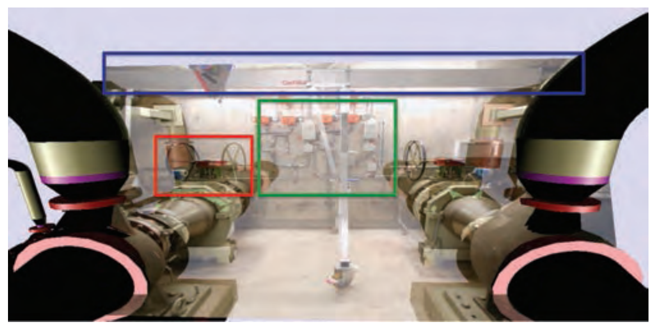


Figure 3: **AR based Discrepancy Check**. In the red box a discrepancy, a valve is switched. In green undocumented features, electrical installation are visible in the image but not present in the CAD. In blue plant alteration, metallic structure was added to the original design.

3.2.2 Training

In this section, we present AR applications that try to improve workers' training in the manufacture of new items.

For example, AR has not only been used to support welders but also used to train new welders. Welders need to be properly trained as the strength of a welded product depends on the operator's skills. However, this is a complex procedure to learn and the number of good teachers is limited. As a solution, Kobayashi et al. [36] propose an AR welding simulator that permits training in a safe and efficient environment. Their system uses a similar display setup as [4] and offers additional haptic and sound feedback.

Schwald et al. [60] propose using AR to reduce training time for a complex assembly task. The user obtains visual augmentation via a HWD, instructions via audio, and can request information via vocal input.

AR has also been used to design new types of instruction manuals to support worker training. Haringer et al. [27] look at the creation of an AR-ready manual to support car mechanics. A basic workflow of the repair is sketched as a set of 2D slides using PowerPoint. For each step (i.e. slide) a 3D layout of the instruction is constructed based on the set of 2D instructions. Then, the order and relationship between steps is finalized. Each instruction manual is then tested and modified until it reaches an acceptable quality.

3.3 Commissioning: Validation and Documentation

After its production and before its use, a manufactured item needs to be verified and documented during a process called commissioning. This quality control is done for small items (e.g. microprocessors and cell-phones) as well as for larger systems (e.g. ships and power-plants).

Klinker et al. [35] introduce an AR system for the construction business. By using their system, one can visualize design modification directly on the building site and verify their correctness. This verification can be conducted both during and after construction.

Navab et al. [40] propose creating an as-built documentation system that could offer new application to the industry. They develop a software platform (*Cylicon*) to register industrial drawing and perspective images. This new plant's document includes hyperlinks in images (inherited from the drawings) to meta-information (e.g. inventory status and past maintenance logs) to ease data access. They call this new type of document: *the transparent factory*. *Cylicon* was extended by Appel et al. [5] to support the creation of as-built 3D models based on the fusion of industrial drawing and perspective images. Such a solution has great financial advantages with respect to delivery payment and quality control.

Following the concept of the transparent plant, Georgel et al. [24] propose using AR to perform discrepancy checks following construction of a power-plant. The idea is to find differences between a 3D CAD model and the constructed plant. Such discrepancies can arise from outdated building instructions, design incompatibilities or human error. The proposed system aligns high resolution images from the plant with the CAD model. The system includes a set of interactions that allow a user to find and document discrepancies. This solution is encapsulated into CAD viewing software to facilitate its use by a civil engineer. By using such a system, the user not only verifies the construction but also directly builds a new, up-to-date set of documentation that includes the 3D CAD model, images and annotations. This new document more accurately represents the actual construction. Beyond presenting information on discrepancies, the system also informs the user about objects that are not part of the CAD model but that are visible in the photographs (e.g., electrical wires). An example of this useful tool is shown in Fig. 3. This concept is currently commercialized by Siemens CT and tested by Areva NP to follow the construction work on a power-plant.

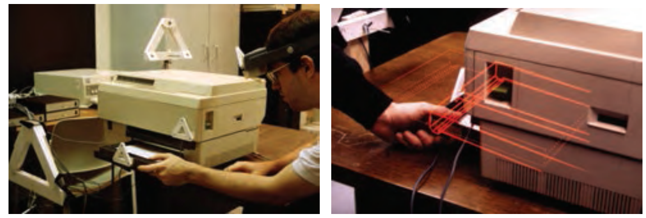
Schoenfelder and Schmalstieg [59] propose a system for Augmented Reality Building Acceptance (ARBA). This task is sometimes known as plant walk-down, where the plant engineers want to document discrepancy existing between the newly built plant and the planning documentation. The task is performed using *planar*, a tracked touch screen mounted on wheels that can be moved around the factory floor. Their system can superimpose in-situ CAD planning data on an image of the plant captured from a camera mounted on the *planar* system. They expect stakeholders to accept discrepancies more easily when viewed in-situ as their impact might be evaluated in context. Discrepancies are detected using similar interaction as [24]. The on-site generated report can be passed on to the contractors that have to deliver revised 3D data. This system offers a limited precision due to the use of a low resolution camera and can be only applied to some hotspots, as it requires an external tracking system to be installed before end.

In order to help construction workers, Klinker et al. [35] present the latest document to minimize mistakes generated from outdated or inaccurate planning data. This system informs workers during construction by augmenting the current construction state with virtual components that are yet to be built. It offers x-ray viewing to access invisible features documented in the model. Dodson et al. [16] develop a system to help field workers localize sub-terrestrial information such as pipes (gas and water), contaminated soils, geological structures, power-cables, communication hubs, etc. This system helps the worker as it is difficult to visualize the relation of 2D maps with the real world and a misinterpretation could lead to extra excavations. Their system uses virtual goggles that align digitally stored maps using GPS and gyroscopes This idea was extended by Schall et al. [58] to allow field workers to annotate the digital map.

On-site data access was demonstrated for non-industrial applications such as AR Vino [30], an application that superimposes viticulture GIS data onto vineyards to help viticulturists understand the effect of environmental parameters on the quality of grapes.

3.4 Inspection and Maintenance

If well-designed, an AR system can improve workflow. For example, Klinker et al. gather information available in CAD systems and instruction manuals to create an AR-ready document that could be used in many different scenarios [32]. They present a prototype to support the maintenance of a nuclear power-plant, driven by the idea that if the right information is given at the right time then the worker should be more efficient and therefore the downtime of the power-plant could be shortened or at least be on schedule. Many



(a) Setup (b) Display

Figure 4: **The KARMA Printer Repair Project**: an operator wearing a HWD in which is displayed animation to describe the step to follow to achieve the task of filling the paper tray. (©[19])

similar solutions have been developed to support the maintenance of manufactured systems, for example: radar control devices, nuclear power-plants, airplanes, streetcars, or cars. In this section we describe some of these projects that cover most of the applications and themes developed over the years.

Feiner et al. [19] describe the first maintenance and repair task supported by AR. The KARMA (Knowledge-based AR for Maintenance Assistance) system graphically guides the user through the repair of a printer. The system automates the design of augmentations that explain how to perform a 3D task with a set of methods (related to display) and evaluators (related to the accomplishment of a task). An action in the world is recognized by KARMA and interpreted to change the state of the system. For example, a new augmentation is displayed corresponding to the next step. Augmentations, displayed with a HWD, help the worker in localizing and identifying actions to be performed using highlights, labels, and animations as show in Fig. 4.

For mechanic training, Klinker et al. [31] propose displaying names and functions of the different parts of an engine. They present typical procedures to train workers by displaying visual augmentations. Using a tracked object, the trainee can query information about the real objects or by using a 2D mouse to select the virtual parts. The system can present a variety of information, such as meta data (e.g. repair logs). The authors emphasize the need for object interaction. For example, an AR system should understand the modification applied to the scene (e.g. when a piece is removed during the repair).

Reading paper-based documentation to perform a complex maintenance task is a long and accepted tradition in the industry even if it is not the most productive method. Neumann et al. [42] propose an IT system that would support a maintenance worker to test the circuitry of an aircraft by displaying augmentation. This AR system gives information on the task to perform and can sense the step of the process (e.g. a dust cap has been removed, which calls for the next step in the process). It can also show hidden objects (e.g. give a preview of what is under the dust cap). They test their system using an aircraft mock-up and demonstrate that AR is particularly attractive as an information technology.

For the inspection of a water distribution system, Goose et al. [25] develop a speech-enabled AR system. The worker interacts with the system using vocal commands. A technician, performing a servicing task, is supported by a PDA that can sense his location. This location triggers an augmentation of the current view with a virtual model and avails context aware speech interaction. For example he can "verbally" ask a valve for its pressure, which triggers a query in the plant-managing software to check on this specific status. The combination of a simple interaction and a tight integration to the IT structure is clearly beneficial for the worker, as he has information constantly and immediately available.

Some systems try to integrate measurement reading (e.g. oscilloscopes) with the augmentations in order to avoid task switching. For example, Sato et al. [57] present two prototypes. The first

Figure 5: **Remote Expert Using Augmented Reality**. The expert indicates the part of the computer to be repaired. The annotation is transferred to the field work and follows the user motion. (©[55])

is a desktop-based system that uses a half-tinted mirror to supervise the maintenance of a PCB. The PCB is tracked in real-time and each step is validated by the MR system, which is reading the measurement from the instrument's output. They also develop a second, backpack MR-based prototype to support electrical parts inspection in an industrial compound. Similarly, FixIT [34] uses the current pose of a robot being inspected and its sensor to indicate malfunction. The current state of the robot is overlaid to help find malfunctions.

Regenbrecht et al. [52] propose a maintenance system, which uses AR as a UI to guide astronauts in changing air filters for the international space station.

For military personnel, Henderson and Feiner [28] demonstrated using AR to support military repairs of a terrestrial vehicle. The mechanic is guided through tasks by visual augmentation presented in a HWD and can interact with the AR system using a wrist-worn controller. Their system has been shown to be very useful in a complex cramped environment even for trained repairmen by limiting the head movement and allowing quicker localization.

AR Maintenance systems can also close the gap between the diagnosis software and the malfunction documentation because, while supporting the worker in performing his task, the system can document the procedure, which is a clear benefit for the worker.

Remote expert systems are popular to deploy AR technologies for supporting field workers. For example when the worker in charge of the maintenance can take care of the repair by himself, but sometimes he is unable to find the problem and he would benefit from the knowledge of an expert. The interaction between the expert and the worker needs to be effective. The expert needs to understand the problem that the worker is facing and the worker needs to understand the instructions given by the expert. Toward this end, audio communication between the worker and the remote expert is often augmented with a video feed. The inclusion of video is the perfect scenario to demonstrate the benefit of AR. AR for remote expert systems was first sketched for tele-training [56] as a general purpose system. It has since been implemented to support specific tasks such as electronic switchboard repair, AC repair and electronic diagnosis. We describe here the most elaborated remote expert applications that feature AR.

To fight the constant increase in complexity of maintenance tasks, Lipson et al. [37] propose to use an on-line product maintenance system that would not require the field worker to be an expert. This would avoid the expert having to travel to an area to diagnose the problem and perform the repair. The expert could support several complex repairs using his advance knowledge in different remote locations at the same time. This is clearly beneficial for products which need constant maintenance, such as aircraft, medical equipment and production plants. The authors demonstrate their ideas on a hard-disk cabinet. Their system can help guide the field worker using augmentation, and additionally, it reports automatically back to the head-quarter using a log of the maintenance.

SLAM systems are very popular for remote expert applications.

(a) Original View (b) Dimished View (c) Augmented View

Figure 6: **Diminished Reality Used to Illustrate a Revamping Procedure**. The task planner can erase a pipe from a picture, using the information from neighboring views and superimpose the model of the replacement module (in red). (©[75])

For example, Davison et al. [15] use their SLAM system to map the real environment to allow simple interaction. The expert can indicate an area of interest in a stabilized 3D world, in comparison with a jittery video stream. Reitmayr et al. [55] push this idea further by allowing the expert to annotate the 3D world. They demonstrate their system to support the maintenance of a computer. The local geometry is estimated based on SLAM and the annotations sketched by the expert are snapped on the geometry. This allows to precisely describe the task to be performed as shown in Fig. 5.

Remote collaboration has also been proposed for training an ATM maintenance procedure. Boulanger [11] proposes using AR to teach multiple trainees how to repair an ATM. The trainers are all connected to the same expert located in a remote site. They all have access to live augmentation (remote or local) through an HWD and can communicate like in a regular conference call. This simultaneous experience not only cuts cost but also allows students to learn from each other's questions and mistakes.

3.5 Revamping and Decommissioning

When a product is reaching its retirement, it needs to be recycled or destroyed during a revamping or decommissioning procedure. For large systems, this process is planned in advance to minimize labor cost and limit exposure to hazardous materials (e.g. when dismantling a nuclear power-plant). In this section, we describe AR systems that support such procedures.

Siemens Corporate Research is extremely active in applying AR to support industrial processes. They play a major role in trying to change the workflow of traditional industry. For example, Zokai et al. [75] look at how AR could help to illustrate a revamping procedure. They allow maintenance planners to remove objects (e.g. a pipe) from the scene. This is made possible because they have access to images registered to a CAD system. The real pipe would then be replaced by a virtual new pipe that would be designed using a CAD system. This helps the planners to know whether this could create a clash with an object not represented in the CAD data. Fig. 6 demonstrates the possibility offered by such a diminished reality system for revamping.

Augmented reality is also used to support decommissioning of nuclear power plants. This task is heavily regulated for obvious security and safety reasons. It needs first to be planned and the feasibility of the process needs to be verified. Then, the actual dismantling occurs. Progress needs to be constantly documented. When the decommissioning is finished the work achievement is verified and the CAD model is annotated to reflect the current physical state of the plant. Finally, the area where the dismantling occurred is cleaned. Ishii et al. [29] demonstrate the benefit of AR for the dismantling of an ion tower. They introduce new technologies for safe and efficient decommissioning work of contaminated zones. Their system supports the work by ensuring that the cuts made to the surrounding pipes are properly localized. The proposed system also monitors the work and records progress. Finally, it gives the field worker direct access to the CAD data on site [63].

4 Evaluation Criteria

In this section, we describe the rubric we use to score the different presented papers, the final score formula and the procedure used to assign grades. This rubric is based on Navab's comments [39] about developing IAR solutions at Siemens, where he provides tips to develop a successful industrial application. For him, IAR applications should avoid "overkill". He emphasizes the need for IAR applications to provide financial benefits. Any IAR solutions should not try to solve something that is better addressed for less money with another technology. Finally, he presses on the necessity of scalable solutions, which work beyond the lab and are easily reproducible, to be accepted by the industry. Following the concept proposed by MacIntyre and Livingston [38], we evaluate the advancement from the laboratory toward "real-world use". As Brooks suggested [12] we also consider the fact that a system has completely left the developers' hands. In addition to these criteria, we consider for each system: its workflow integration, user evaluation, if it has reached full deployment, and the industry involvement.

Workflow integration: we rated each presented system with respect to its integration with a well-defined industrial procedure. We considered if the industrial problems were themselves well-defined and if associated input data and output results can easily be integrated into some global process. This integration is important because the closer a system is to the industrial process, the easier it will be to understand underlying problems and non-trivial solutions.

Scalability: we evaluated the selected systems depending on their re-usability and their applicability to a real-life full size scenario. This includes examining the technology used (i.e. tracking, display, etc) to include installation, maintenance, and removal costs. This is an important consideration as it has a direct impact on an AR system's broader applicability.

Cost Benefit: we rated the cost benefit aspect of each presented solution. This is not meant as a full scale analysis at it would fall outside the scope of this paper. Rather, it mainly evaluates the arguments (if any) given by the authors to justify the benefit of their system in comparison to current (non AR) systems used in practice.

Out of the lab: we evaluate the state of each proposed system at time of publication with respect to the idea that each system should ultimately leave the lab and be used in an actual industrial context. This assesses if the scenario used realistic data and is also used by a target application environment or in a lab setup. For us, this is a major criterion for the acceptance of an IAR system as it helps the end-user to evaluate the benefit offered by AR.

User tested: we consider the fact if each system was user tested. There are three possibilities: either the system was not user tested, it was informally user-tested or reviewed by an expert (which usually provides interesting input for improvement), or it was formally tested in a scientific setup to evaluate user acceptance and performance. Please note that a system does not have to be tested by professional to obtain the maximum score.

Out of developers' hands: this considers the fact that the system was deployed to the end-users and is being used without requiring constant presence of the developers. For us, this is considered to be the ultimate desired end state for an IAR system. This is a binary state.

Involvement of the industry: this criterion informs us whether the AR system was developed with significant input from industrial partners. This is an important fact as it usually introduces a level of reality to a prototype (constraints, data, expected output, etc).

We scored each paper over the dimensions of our rubric by looking at what was presented in the papers and by judging how well each proposed system achieved each criterion. The scores in each criteria ranged from 0 (lowest) to 4 (highest). For the cost benefit criteria, when the paper did not mention any benefit, we scored it as N/A (and assigned it a numerical score of 0). Fully user-tested prototypes received a 4, partial user-tested systems received a 2 and non-user–tested systems received a 0. The out of developer hands and industry involvement criterion were scored as either 4 (yes) or 0 (no).

The grades resulting from application of this rubric to the selected systems are visible as a parallel coordinates plot in Fig. 7. If the reader is interested about a specific grade for a specific paper, he is referred to Table 1. We created a final score that is a sum of single score criteria. A histogram of the resulting scores is visible in Fig. 8. The histogram was obtained using 5 bins.

5 Analysis

In this section, we analyze the statistics obtained from the taxonomy and rubric we developed in order to define trends and offer guidelines for IAR applications.

We observe that a small majority of the presented systems involve to some degree industrial partners. The percentage rises to 85% when only looking at advanced systems[2]. Only 44% of the analyzed systems have been user tested, to some degree. This percentage rises to 72% for the advanced systems. Usually the advanced systems use a series of tests to iterate their prototype. Such a process is formally known as User-Centered Design, which has been applied for the development of an AR battlefield application [22]. When these two criteria are combined, we can see that the application's score is, on average, 1 point higher[3]. This shows a strong correlation between the degree of success, industrial involvement, and user testing.

It appears that only a quarter of the discussed systems analyze in detail the cost benefit (rated strictly above medium) of their proposed solutions and a small majority for the advanced system. We understand the difficulty of such a task but it might be one of the justifications for the current limited number of IAR applications in use. Finally, our rubric shows that only 17% of systems are rated strictly above medium on the scalability metric, so this is an area of opportunity for further exploration.

We can see that, apart from the decommissioning applications, researchers have applied AR concepts uniformly across the lifecycle. Design and Inspection/Maintenance systems reviewed in this survey are less likely to be integrated into the workflow (scored 2.1 and 2.3 on average) or to be scalable (1.6 and 1.7). One of the reasons for such a behavior might be that these applications are easier to conceptualize compared to commissioning or decommissioning applications, which score higher on average across all criteria (2.2 and 2.5). We think that is because the development of a commissioning or decommissioning application requires deeper understanding of industrial product management.

6 Conclusions and Future Work

The original aim of this survey was a comprehensive review of the state of the art in IAR. The resulting article is a first attempt to find some reason for success, offer guidelines and describe some of the open questions. Currently the answer to the question which entitles this article, "is there a reality in Industrial AR", is still negative as only two applications have broke out of the laboratory to be regularly used by non-developers [17, 24], with only one still in use. However, we note that progress has been made, with more than a

[2] We classify as advanced systems every system that scores 9.75 or higher. This corresponds to anything beyond advanced prototypes.

[3] The mean of the first four criteria is 2.7 when a system was developed with the help of the industry and was at least partial tested compared to 1.8 for all reviewed systems.

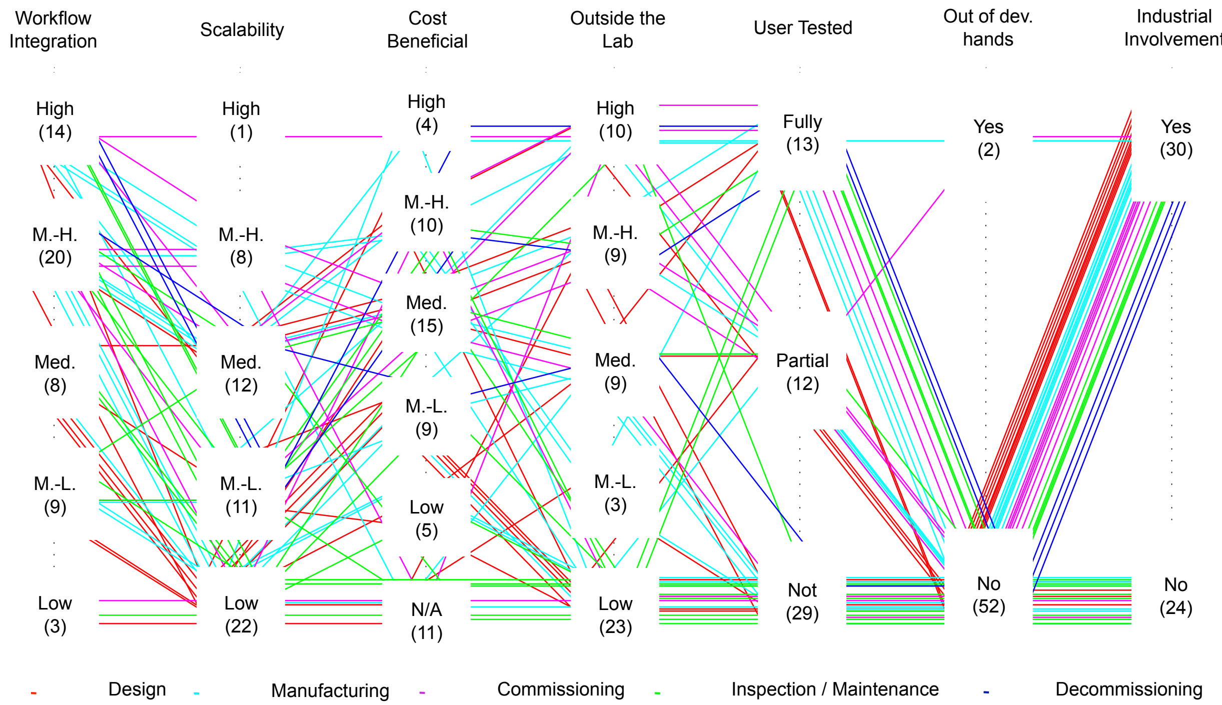


Figure 7: Multi-dimension plot of the selected applications. Each color (resp. number) refers to an application area (resp. total count).

dozen on the cusp of breaking out of the lab. Because of the continued industry interest, we remain hopeful and expect to see more AR systems used by the industry to support their workflow.

As with any emerging technology, AR needs to be cost beneficial, scalable and reproducible [72, 39, 34, 64] in order to go beyond a niche market. The presented articles generally make a good case to justify the benefit of an AR solution, but the problem of scalable solutions has been barely studied in existing systems. We believe that it would be an interesting area of future research. Industrial applications require proper integration of technology into existing workflows [39, 52]. This means that it is important to understand the reason for using a specific type of data, why the process is performed and the expected output (quality and data). For this reason it is necessary for the development of an IAR system to fully involve the whole company (i.e. decision makers, workers, engineers) to ease its acceptance [52].

As expected, our rubric reinforces the need to involve industry in the design of any proposed IAR system. This relationship tends to encourage tight collaboration with end-users during development to improve the chance for success. Therefore, as a general guideline, we encourage academic researchers to collaborate with industrial partners to improve their IAR prototypes in an iterative process of development that is based on user feedbacks and, when possible, formal studies.

The proposed taxonomy does not show a clear area of application where AR offers more applicability than others. Finding a “killer-app” for AR has been an open question since its early days. To this day there are still no signs of the existence of such an application, even if we have shown in this survey that AR has been applied in many different scenarios.

This survey was not focused on enabling technology. Since the technological limitations are often cited as the main reason to explain the failure of AR [14, 72, 34], it would be interesting to look at the technology used in existing IAR systems in a future survey. Following this path might be useful by reexamining the feasibility and acceptance of earlier IAR implementations given improved

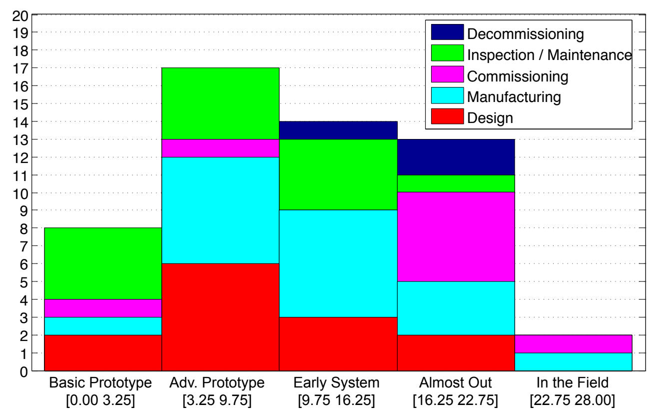


Figure 8: Bar plot showing the final scores based on our rubric. The number on the x-axis corresponds to score ranges for each bin.

technology.

At the time when we evaluated the selected systems against the “out of lab” metric, it was unclear if we had access to the latest information about a given system and if the system was still being developed. Therefore, we might be reporting incomplete scores. To correct this, it would be useful to interview the different project investigators to obtain this important piece of information. This process could also reveal some interesting open problems.

Finally, it is interesting to note that few of the IAR systems presented are making use of available measurements. We could think of recording: voltage values to evaluate weld quality, distance traveled for a picking task, or amount of head movements for a repairman. These measurements could support after action reviews [49] that would not only help improve the worker performances but also support the testing of new workflows.

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ref	WF Int.	Sca.	Cost Ben.	Out. Lab	User Test	Out Dev.	Ind. Inv.
Design							
[10]	0	0	0	3	N	N	N
[23]	1	1	0.8	2	F	N	Y
[33]	3	0	2.4	3	F	N	Y
[43]	1	0	1.6	0	N	N	Y
[44]	1	0	0.8	0	N	N	Y
[45]	2	0	0	1	N	N	N
[48]	4	2	3.2	4	P	N	Y
[51]	2	0	1.6	0	N	N	N
[53]	2	1	1.6	0	P	N	N
[52]	3	2	2.4	2	P	N	Y
[64]	2	0	1.6	0	N	N	Y
[67]	2	2	2.4	3	N	N	N
[70]	4	0	3.2	0	N	N	Y
Manufacturing							
[4]	4	3	2.4	2	N	N	N
[8]	1	1	1.6	0	N	N	N
[13]	4	3	3.2	4	F	N	Y
[17]	4	2	4	4	F	Y	Y
[20]	3	3	3.2	1	N	N	N
[21]	3	0	1.6	2	N	N	N
[27]	3	3	0	0	N	N	Y
[35]	2	0	0	2	N	N	Y
[36]	3	2	3.2	1	F	N	N
[46]	4	3	2.4	4	P	N	Y
[50]	3	2	2.4	0	P	N	N
[52]	3	2	2.4	2	P	N	Y
[54]	3	0	1.6	3	P	N	Y
[60]	1	0	4	0	N	N	N
[61]	4	1	2.4	3	F	N	Y
[71]	1	0	0.8	0	N	N	N
[74]	3	0	0.8	0	N	N	N
Commissioning							
[5]	3	3	2.4	3	P	N	Y
[16]	3	1	2.4	2	N	N	N
[24]	4	4	4	4	P	Y	Y
[30]	3	3	0	4	F	N	Y
[31]	0	0	0	0	N	N	N
[40]	3	2	2.4	3	P	N	Y
[58]	4	3	2.4	4	P	N	Y
[59]	4	2	3.2	4	F	N	Y
Inspection / Maintenance							
[11]	3	1	3.2	0	N	N	N
[15]	1	1	0	0	N	N	N
[19]	0	0	0	0	N	N	N
[25]	4	1	2.4	4	N	N	Y
[28]	4	1	3.2	3	F	N	Y
[32]	3	0	3.2	0	N	N	Y
[34]	2	0	0.8	0	F	N	Y
[37]	3	0	1.6	0	N	N	N
[42]	2	0	2.4	0	N	N	N
[52]	3	2	2.4	2	P	N	Y
[55]	1	2	0	0	N	N	N
[56]	1	0	0	0	N	N	N
[57]	3	0	0	0	F	N	N
Decommissioning							
[29]	4	1	3.2	3	F	N	Y
[63]	4	1	4	4	F	N	Y
[75]	3	2	1.6	2	N	N	Y

Table 1: This table includes the score of each systems reviewed in this survey. Y stands for Yes, N for No, F for Fully and P for Partial.

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