Is there a Reality in Industrial Augmented Reality?

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ABSTRACT

In the spirit of the seminal article from Brooks [13] that survey 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* gave a name to AR. But how many applications broke out of the lab to be used by non-developers? By gazing at the literature, we see the amazing progress made in display technology, rendering and tracking. From these improvements, we could expect AR based industrial products to flourish. Unfortunately this is still not the case.

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

1 INTRODUCTION

For the AR community, the industry was always one of the steering forces for research. *Boeing* is the company that defined AR and pushed it forward [14]. Since then many researchers, projects and companies followed this path. They all tried to apply the concept of aligning virtual information with the real context for the user's benefit [4, 5]. AR applications are everywhere: medical, military, manufacturing, robotics, design, advertisement, etc. But only few of the developed ideas made it into products. The entertainment industry is using AR techniques for televised sports (e.g. the first down line in US football) [5] and for theme parks [71]. The printed media are toying around with AR [18]. In the medical field, some concepts are finally in a tryout phase: the Camera Augmented C-Arm (CAM-C) [45] and the Navigated Beta-Probe [78]. In the car industry, the intelligent welding gun was one of the only ideas that was fully put into a product.

The first digital augmentation of real pictures, to the best of our knowledge, was proposed by Uno et al. [73] who present a CAD software that can use real photographs called A-IDAS (advanced integrated designer's activity supports). Digitalized photographs can be displayed as background images. Their software includes a set of routine to distort perspectively the image. The obtained image could then be used for image composition that is "superimposing of one image onto another". In photo-montage, most of the work was based on manual interactions. Images are scanned and their textures is used to obtain realistic views [19]. This can be seen as a pure VR compositing where everything is a virtual object rendered by the computer [53]. Photo-montage is useful in architectural simulation to evaluate the visual impact of a new construction [42]. A typical result of a photo-montage system is visible in Fig. 1. Kaneda et al. extend static 2D montage by allowing some images navigation by generating near view images [30]. This is achieved by using a 3D model of the real world generated from cartographic images, which is textured using aerial images.

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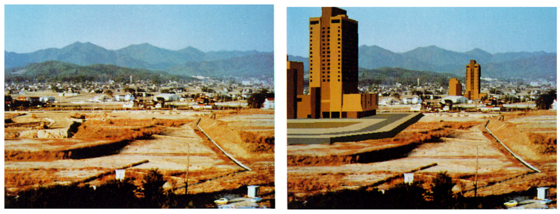

(a) Original Photograph (b) Photo-montage

Figure 1: **Photo-montage for an Architecture Project**: Early work in graphic rendering was used to illustrate the visual impact of architectural project by rendering a virtual model onto a photo. (©[42])

All these systems are all based on a manual alignment, which limits their applicability. This limitation is first tackled by integrating an automatic method to align image with their relative 3D Model [10]. This alignment is used to evaluate different illumination projects for architectural landmark (e.g. bridges). This allows to visualize architectural projects in their existing urban environment and to show the impact of different projects to decision makers directly on-site.

AR was used to improve collaboration for example for interior design application as studied in [39, 65]. A customer is supported using an AR system to design and evaluate new interior arrangements. The customer is in contact with an interior architect that helps him decide for new furniture. They both can manipulated the furniture in the mixed world. The customer can contact friends or colleagues to request opinions. This allows him to create a design that can be validated in-situ and that he is confident with. The software client has the appearance of an regular CAD software with a Mixed view and it can be used to order new furniture directly.

To improve collaboration, the MIT developed table top augmentation system: URP (Urban Planning and Design) [9] and the Luminous table [28]. Their system integrates 2D drawings, 3D physical models and digital simulations. The user can re-arrange the building around this unique plateform. They propose complex simulation to evaluate their design based on sun exposure, cast shadows, wind pattern and traffic congestion. To interact, the user can create mixed views using a handheld tracked camera to share his "point of view" with his collaborators. The round table setting encourages social interactions and forms a creative space. In order to offer a more immersive experience, the ARTHUR (Augmented Round Table for Architecture and Urban Planning) project replaces projection based display by personal displays [12]. Each user is equipped with a HMD, which allows to examine the site by walking around. They use their system in different architectural evaluation scenarii: positioning of a high-rise within a city, or exit routes layout using crowd simulation software. They emphasize on the need to be tightly integrated with a real CAD system to allow constant design discussion and update. If a modification is proposed, it can be directly implemented and visualize. This direct feedback mechanism offers better collaborations. Kato et al. [31] use AR as a tangible interface for city planning where everyone can modify the virtual world being modeled. Designers can layout objects (buildings, trees, etc) to quickly evaluate the visual impact of different setups.

All these methods are designed for off-site collaborations. They restrict their use to labs or in meeting rooms. This limitation is tackled in [41], where they visualize the environmental impact of the project in the early stage of the design. For this, they use strollAR a mobile platform that they bring on-site to evaluate their design. They handle realistic lighting for the virtual model to offer convincing augmentation. This has shown to be a good evaluation tool before meeting the stakeholder.

Recently, an app was made publicly available for mobile device developed in colaboration with METAIO. *Atelier Pfister*[1] allows the user to position furniture from an on-line catalog onto a view of the real world display on the screen of his Iphone. To our knowledge this is the first fully immersive and publicly available AR system for architectural design. We can see that from the development of the first photo-montage system to this app, many years have past and many iterations have been made to refine the concept. The improvements are not only focus on better technologies (e.g. tracking or displays) but also: better automation, user expectations and realistic scenario. This different aspects are integrated in the rubric we propose to evaluate IAR systems. We hope that it will help the community to bring their ideas from the lab into the hand of the end-user.

The paper is structured as followed first in Sec. 2 we give a definition for AR and IAR, describe the step life-cycle used as taxonomy, as well as the methodology used to select the papers, then we discuss related work in Sec. 3. In Sec. 4, we review the selected papers categorized across the life-cycle of a product. In Sec. 5, we present our rubric and we analyze the obtained scores in Sec. 6. This survey concludes, in Sec. 7 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 replaced some aspects of, the reality.

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

This definition is voluntarily broader than the Azuma's [4], which tends to disregard photo-based augmentations that have proved to be effective in an industrial context. Though we are only surveying visual augmentation one could imagine application where sound augmentation would be practical and useful.

Methodology : when preparing this survey, during the summer of 2009, we tried to find all scientific publications related to IAR. For this we reviewed all proceedings for IWAR (98,99), ISAR (00,01), ISMR(01) and ISMAR (03 to 08). We then performed a transitive closure on the references present in the relevant articles. We also searched for article citing the selected papers in order to find other relevant works. In the original list, a paper was selected, if the application presented could be applied to an industrial process. This included crude prototypes. This list was then pruned to include original concept of an application or clear progress towards real applicability. Because of the limited space we selected the latest publication related to a project that usually covered most of the aspect presented here or at least included original reference. Finally prior to publication we included more recent publications that cover 2009 and 2010.

2.1 Product life-cycle

Product Design is focused on generating ideas to be conceptualized to 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.

[1]http://www.atelierpfister.ch/atelier-pfister/iphone-app/

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, to verify the condition of the product and if required the repair or replacement of faulty components in order for the product to function properly. Inspection and Maintenance correspond usually to codified and standardized procedure.

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

3 Related Work

During the first *IWAR* in 1998 [7], a panel was formed to discuss possibilities, limitations and applications of AR. They felt that AR had a 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 that they should design properly their applications in collaboration with end-users and that the focus should only be given to applications where AR technologies can make a real difference. AR should limit human errors and create a mean to perform a task better. They point out the technological problems of the time, some of which are still addressed issues in current scientific publications, mainly HMDs and connectivity. They unfortunately could not yet define the “killer app” where AR would have a massive impact.

Azuma wrote the first state of the art on AR[4]. He gave an overview of the different technologies needed to create an AR system and their short comings. He also defined some of the area of applications: *medical*, *manufacturing and repair*, *annotation and visualization*, *robot path planing*, *entertainment* and *military aircraft*. When updating this survey[5], newly explored areas were added to the list: *outdoor and mobile AR* and *Collaborative AR*.

ARVIKA , a German project founded by the ministry of education and research, applied AR ideas to many application fields. It created a great excitement for the companies within this consortium. They all came with problems that could be solved using AR [77]. Unfortunately, because of technological limitations with display, tracking and registration algorithms most of the demonstrations did not make it to the market. Only one prototype made it out of the door: the *Intelligent Welding Gun* [17].

Navab reports on his work on IAR at Siemens and gives tips to develop an industrial application [43]. For him, it should not be an overkill. He emphasizes on the necessity to be financially beneficial. The AR solution should not try to solve something that is solved better and for less with other technology. Finally, he presses on the necessity of scalable solution, which should not only work out of the lab but in a complete setup and need to be easily reproducible to be accepted by the industry.

More recently two surveys [51, 74] studied IAR applications by focusing on enabling technologies and describing some of the proposed applications. In our survey, we not only propose a taxonomy based on a product life-cycle but we also present a rubric to evaluate existing solutions. We hope that together this will support researchers defining realistic application and refining prototype into usable AR system in the hand of end-users.

4 IAR SURVEY

4.1 Product Design

AR is not only used for architectural design but also to ease the development of other products such as cars and planes. For example for the car industry, Ohshima et al. propose to evaluate the design while sitting in an actual car skeleton (seat, steering wheeling, on-board commands) [49]. The skeleton helps improving the immersion and the understanding of the virtual world by enhancing the depth perception. The user can switch between option and version to evaluate the best fit. Similarly, Klinker et al.[35] augment a car mock-up with different light optics to evaluate in-situ its appearance. This offers the possibility to navigate around an augmented mock-up. They emphasize on the need to integrate AR into the designing process. As a goal they hope to reduce the need (or at least the numbers) of expensive clay mock-ups. Regenbrecht et al. also try to bring realism into car design by integrating augmentations to physical mock-ups during meetings[58]. Nolle and Klinker develop a system to verify that manufactured object matched the CAD data, which can be useful during the design period of a product, where multiple designs exist and can lead to confusion between version of a manufactured piece and its 3D model[48].

AR is not only use for ecstatic evaluation. Regenbrecht et al. [57] use trolley type system to evaluate the functionality of a design. They interpret air flow data in an airplane cabin resulting from a particular design via visualizing an augmentation. They also support a customer when selecting option for an airplane cabin. They also propose to improve functionality, ergonomy and safety of the cockpit design. The designer gets to place virtual instruments and commands in a real size cockpit to develop a more efficient layout. Nolle [47] proposes to validate crash tests simulation using AR by comparing them 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. [75] push this concept further by integrating it tightly in the design process. The design of submarines piping system is complex, as a lot of pipes have to go through a restricted space. Therefore the designers are forced to use mock-ups to optimize the pipe layout for it to take the smallest amount space possible. By using AR, the engineers can verify that the current mock-up matches the design. The engineers can physically change the mock-up and integrate to the CAD model this modification using vision based reconstruction. This tight integration of AR in the design workflow allows to close the loop between the real and the virtual mock-up to create a more efficient development process.

Most of the previously mentioned approaches are designed to work in a prepared environment. Thomas et al.[72] lift this constraint by proposing to use a HMD combined with a wearable computer 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 object 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. [8] develop an AR system for outdoor construction sites where they emphasize on the animation of 3D models. They want to verify simulation results on-site before implementing them. VR helps to understand the subtleties of such plan but does not give any contextual information. Additionally VR has a lot of overhead in order to model features not presents in the CAD data. They demonstrate their system to simulate a bridge construction and verify if their plan was realistic in the context of the real target site.

4.1.1 Factory Planning

In the industrial process, a lot of care is given to factory setup, when a new item needs to be produced. This factory design can happen in new compound or in already existing production line that needs to be evaluated to verify if they can produce a new item or if eventually they require revamping. This process is called *factory planning*.

The first demonstrator for planing activity for plant design is proposed in [56]. The designers sit around a table with a virtual orthogonal view of the plant currently being designed 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 a VR system.

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

For the positioning of components and system in new factory, Siltanen et al. propose to use an iterative process where a plant operator requests an alteration that he believes is best suited [70]. This request is generated from the factory floor for the designer team. Using an augmented view of the current plant and the proposed design alteration, the operator can evaluate them. This can lead either to a validation of the proposed design and to its implementation or to further design modifications in order to obtain an optimal plant. This method allows the plant operator to communicate from the place he feels the most confident: 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 introduce methods to plan the upgrade of a factory not only in a VR system but in an actual plant. They hope to validate the planning faster, to improve the data quality, and to avoid collision between new components and the once installed. This should minimize re-planning activities. Pentenrieder et al. propose to reduce errors in factory planing by creating an up-to-date CAD model of the current plant[52]. They realize that most of the available CAD data for plants are not correct 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 the reality to offer a precise augmentation to plant designers. After several iterations of their system, they settle for photo-based augmentation because they found it to be the most accessible technique for the plant designers. In their system (ROIVIS), they 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 later used to inform someone about design acceptance or rejection.

4.2 Manufacturing

When the design of a new product is finalized, its production can be launched. AR is not only used to support worker for an assembly task (Sec. 4.2.1) and to train an operator to produce a new object (Sec. 4.2.2).

4.2.1 Assembly Guidance

Caudell and Mizell, when developing the first AR application, try to offer support for an assembly task using a see through display [14]. Their system was originally proposed to reduce storage requirements of foam boards. These foam boards are used as real size map to guide the assembly worker when preparing wire bundle.

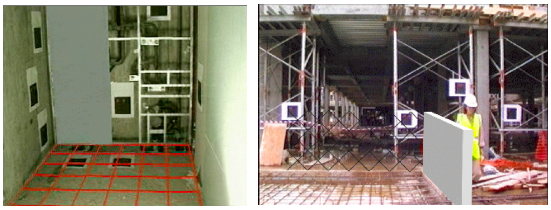

Figure 2: **AR in Large Building Construction**: AR is often used to display up-to-date design information and to verify the correctness of the current construction in comparaison to the planing data. (©[37])

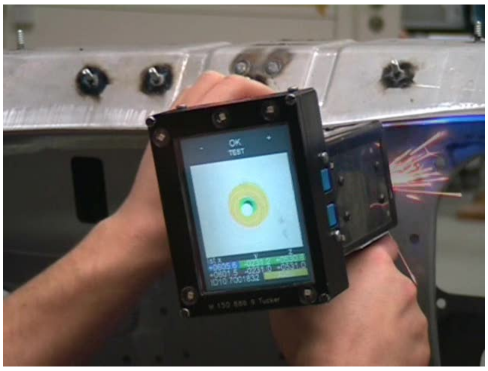

Figure 3: **The Intelligent Welding Gun** is the first AR based product to be used in the manufacturing industry. The welder has access to navigation information on a screen attached to his welding gun to find the next stud location. *Courtesy of Kudrun Klinker.*

Each type of wire bundle requires a different foam board. Using AR they can replace the need for specific foam boards by augmenting with wire bundle specific information a generic foam board. Their system does not only remove the need for specific foam board storage space but it helps the work to perform their task faster [14] Regenbrecht et al. [57] also propose to use AR for montage of highly customizable objects. They specifically look at fuse boxes assembly for trucks that are based on the options selected by the client. This makes each truck unique. Therefore they present to the worker model-specific instruction using AR. This simplifies the workflow of the assembly as 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. use an AR system to support construction [76]. Using AR they offer an x-ray view to visualize hidden structures such as pipes installed in between walls that should not be damaged. A similar solution is proposed in [37] to display the most recent construction plan to the worker, as seen in Fig. 2. For unmanned construction sites, Fujiwara et al. [22] propose an AR system that displays virtual property lines on a video stream. This additional information helps the construction worker to properly performs his task. The need for remote operation can be justified when the construction site is hazardous, in their case an active volcano.

AR can be used as a replacement for paper based assembly instruction manual. The development overhead for such new manual can be justified because products' life-cycle is constantly getting reduced. Ever changing product lines constantly force workers to be more flexible in manufacturing new models. For example, during the CICC project AR is deployed to support a car door assemblage[59, 37]. This project sparked the interest of the European industry for AR. Raghavan et al. study the applicability of AR for assembly tasks[55]. They offer step by step instructions to the worker. By sensing the current state of the assembly, they offer 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 multiple hypotheses verification method to determine the evolution of the assembly. By studying this graph, they can determine when the worker performs a step that blocks him to finalize the construction. Using this technique, they can evaluate a set of instructions to find the optimal set. For the same task, Zauner et al. propose an MR system, where instructions are displayed to explain each step of the assembly[79]. 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. present a virtual agent to guide the user to build an object[6]. The agent presents required pieces and display an animation on the current built object to explain the next step.

Fiorentino et al. [21] propose to improve current industrial drawing by introducing tangible digital master (TaDiMa). They link Product Lifecycle Management (PLM) with drawing using AR. The idea is not only to add information to the drawing such as assembly instructions. This bring up-to-date information onto the drawing, information 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 is also used to support logistic application. This is investigated in FORLOG.When assembling complex systems, such as cars, specific pieces need to be available on the production lines. These items are picked up in a warehouse by a worker that follows an item picking list often paper based. In order to reduce errors that can have a certain impact such as delays on the production lines, Schwerdtfeger et al.[67] propose a new guidance system for order picking using augmentation displayed in a HMD. The augmentation points the user to a target location where an item needs to be picked up. This offers advantages in terms of lowering mistakes and automatic reporting as the system is linked to the IT infrastructure.

AR can not only be used to support unskilled workers but it can also considered for highly trained operators who use complex machinery. For example, Olwal et al. support a lathe[2]operator [50]. Their system displays sensor readings in-situ such as cutting forces, RPMs, temperatures. This allows the workers to stay focus 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 [2]. Most manual welding procedures have been replaced by programmable robots, for example in the car industry. Unfortunately, for some complex and not recurring tasks, manual operators cannot be replaced, for example on shipyard. By using AR, researchers want to improve welding seam quality, decrease rejection rate and therefore reduced cost. The usual setup integrates in a welding shield a HMD and 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 sensors information are displayed on this video view. It can inform the worker about electrical welding parameters (e.g. current and voltage). This constant monitoring of the worker 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. Both these projects stayed at the prototypical level.

On the other hand Echtler et al. [17] with their *Intelligent Welding Gun* (IWG) introduce a new product and a related workflow for the industry benefit. The target is to help welders shoot studs with high precision for experimental car (i.e. prototype) where robot cannot be programmed for, as it would require too much time.

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

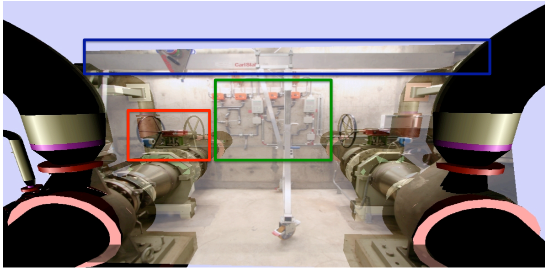

Figure 4: **AR based Discrepancy Check**. In the red box a discrepancy, a valve is switched. In green undocumented features, electrical installation are visible in the image but not present in the CAD. In blue plant alteration, metallic structure was added to the original design.

These prototypes are mainly hand built. 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 studs location. In their application they are trying to find the best stud's placements. 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. They have demonstrate that using their setup they can be four times faster while sustaining the same precision. This AR project is one of the only publicly known ones, which has been deployed and used by a car manufacturer (*BMW*). The use of IWG was recently discontinued as the process to develop prototype at BMW changed and rendered the IWG obsolete. A picture of the final product is visible in Fig. 3. For the same application, Schwerdtfeger et al. recently propose to replace the gun mounted display by a laser projected that would reduced the gun size and to be more manoeuvrable[68], this is currently becoming a product[1].

4.2.2 Training

Here we present applications of AR that try to improve workers training to manufacture new items.

For example, AR is not only used to support welders but also to train new welders, which is a complex procedure to learn [38]. Welders need to be properly trained as the strength of a welded product depends on the operator's skills. This project proposes an AR simulator in a safe and efficient environment because welders learning is a complex process that can be harmful. Additionally, the number of good teachers is limited. Their system uses a similar display setup as [2] and offers additional haptic and sound feedback.

Schwald et al. propose to support training for a complex assembly task[66]. They hope to save on training time by using AR. The user obtains visual augmentation via a HMD and instruction via audio and can request information via vocal input.

AR is also used to design new type of instructions manual for workers training[26], where they look at the creation of an AR ready manuals for car mechanic support. 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 elaborated based based on the set of 2D instructions. Then the order and relations between steps is finalized. Each instructions manual is then tested and modified until it reaches an acceptable quality.

4.3 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. micro-processors and cell-phones) as well as for larger systems (e.g. ships and power-plants).

Klinker et al. introduce an AR system for the construction business [37]. During and after construction using their system one can visualize design modification directly on the building site and verify its correctness.

Navab et al. [44] propose to create an as-built documentation that could offer new application to the industry. For example, it could simplify the maintenance planning and execution, where a precise 3D model is required for the plan to be realistic. They develop a software platform (*Cylicon*) to register industrial drawing and perspective images. A decade ago drawings were the only documents used during the complete plant life-cycle from design to decommissioning. They create a better documentation of the plant, where images have hyperlinks (inherited from the drawings) to meta-information (e.g. inventory status and past maintenance logs). They call this new type of document: *the transparent factory*. Their solution does not only focus on floor maps but also wiring schematic and factory layout. Using *Cylicon* one can create an as-built 3D model based on the fusion of industrial drawing and perspective images [3]. 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. propose to use AR to perform discrepancy check to follow up of the construction of power-plant[24]. The idea is to find difference between the 3D CAD model and its built plant. This discrepancy can arise from outdated building instructions, plan incompatibility or human error. They propose to align high resolution images from the plant on to the CAD model. They offer a set of interactions to a user to find and documents discrepancies. This solution is encapsulated into an CAD viewing software, to facilitate its use for civil engineer. By using such a system the user does not only verify the construction but directly build a new up-to-date documentation that includes 3D CAD, images and annotations. This new document represents more accurately the actual construction as it does not only include information on discrepancy but also informs about systems that are not included in the CAD such as electrical wires as they are visible in the photographs, as shown in Fig. 4. 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 develop a system for Augmented Reality Building Acceptance (ARBA) [64]. This task is sometimes known as plant walk-down, where the plant engineers want to document discrepancy existing between the new built plant and the planning documentation. For this they use *planar* a tracked touchscreen mounted on wheels that can be moved around the factory floor. They tested their system on a multistory factory floor where they compared the built plant against planning documents. They justify the need of such a system not only for guaranteeing the usability of the new plant's documentation, but also because discrepancies might lower the value of the building in terms of re-usability. A discrepancy might not affect its current operability but it could have an impact when the plant is re-factored. Their system can in situ superimpose CAD planning data to an image of the plant captured from a camera mounted on *planar*. They expect stack-holders to accept discrepancy more easily when viewed in-situ as their impact might be evaluated in context. Discrepancies are detected using similar interaction as [24]. Documentation of the discrepancies is done using a stylus to annotate the augmentations after the inspection. The documentation data is gathered to assemble a report. This report can be passed on to the contractors that have to deliver revised 3D data. If necessary they can use *planar* to change the position of CAD components to obtain an as-built. This system offers a limited precision due to the use low resolution camera and can be only applied to some hotspot as it requires a external tracking system to be installed before end.

(a) Setup (b) Display

Figure 5: **The KARMA Printer Repair Project**: an operator wearing a HMD in which is displayed animation to describe the step to follow to achieve the task of filling the paper tray. (©[20])

4.3.1 AR Ready and Accessible Documentation

In this section, we discuss how existing documentation created with the help of an AR system can be accessed on-site.

In order to help construction workers, Klinker et al. present the latest document to minimize mistakes generated from outdated or inaccurate planning data. This system informs worker during the erection by augmenting the current construction state with virtual components that are left to be built [37]. It offers x-ray view to access invisible features documented in the model. Dodson et al. develop a system to help field works to localize sub-terrestrial information such as pipes (gas and water), contaminated soils, geological structures, power-cables, communication hubs, etc [16]. This system should help the worker as it is difficult to apprehend the relation of 2D maps with the real world and a misinterpretation could lead to extra excavations. Their system uses virtual goggles that aligns digitally stored maps using GPS and gyroscopes This idea was extended to allow field worker to annotate the digital map[63].

On-site data access was demonstrated was developed for AR Vino to superimpose viticulture GIS data on to vineyards to help viticulturists understanding the effect of environmental parameters on the quality of grapes[32].

An AR system if well designed 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 scenarii [34]. 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.

The applications of AR as the ultimate interface for a maintenance task are plethoric and is the focus of the next section.

4.4 Inspection and Maintenance

Many solutions have been developed to support the maintenance of manufactured system, for example, for: 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. describe the first maintenance and repair task supported by AR[20]. The KARMA (Knowledge-based AR for Maintenance Assistance) system guides graphically 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 HMD, help the worker in localizing and identifying action to be performed using highlights, labels, and animations as show in Fig. 5.

For mechanics training, Rose et al. propose to display names and function of the different part of an engine[33]. 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 using a 2D mouse for the virtual parts. The system can present a variety of information, such as meta data (e.g. repair logs). They emphasize on 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. propose an IT system that would support a maintenance worker to test the circuitry of an aircraft by displaying augmentation [46] . 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 speech enabled AR system. The worker interact with the system using vocal command. 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 ”vocally” 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 measurements reading (e.g. oscilloscopes) to the augmentations. This is to avoid task switching. For example, Sato et al. [62] present two prototypes. They develop a desktop-based system that uses a half tainted mirror to supervise the maintenance of a on a PCB. The PCB is tracked in real-time and each steps is validated by the MR system, which is reading the measurement from instruments output. They also develop a backpack MR based system to support electrical parts inspection in a industrial compound. Similarly FixIT [36] 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. [57] propose a maintenance system which uses AR as UI to guide astronaut in changing air filter for the international space station filter. This was only an earth-located demo because of the constraints that are related to performing a demo in outer-of-space.

For military personnel, Henderson and Feiner [27] propose to support military repair of a terrestrial vehicle. The repair-main is guided through is task by visual augmentation visible an HMD and can interact with the AR system using a wrist-worn controller. Their system have been shown to be very useful in a complex cramped environment even for trained repair man by limiting the head movement and quicker repair.

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

4.4.1 Maintenance with Remote Experts

In the previous section, we focused our attention on AR systems that directly support the users. Another popular approach is to support the user by giving him access to an expert. In this case, 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

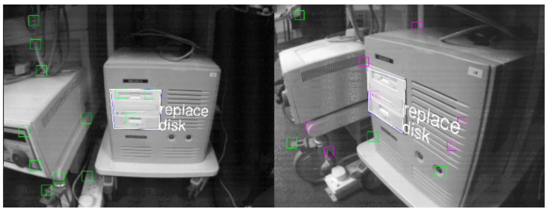

Figure 6: **Remote Export Using Augmented Reality**. The expert indicates the part of the computer to be repaired. The annotation is transferred to the field work and follows the user motion. (©[60])


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

Figure 7: **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). (©[80])

expert. It is why the audio communication between them is often augmented with a video feed. The access to a video is the perfect scenario to demonstrate the benefit of AR. AR for remote expert system is first sketched for tele-training [61] as a general purpose system. It has been implemented for support specific task such as electronic switchboard repair, AC repair and electronic diagnosis. We describe, here, the most elaborated remote expert applications that use AR.

To fight the constant increase in complexity of maintenance tasks. Lipson et al. [40] propose to use an on-line product maintenance system that would not require the field worker to be an expert. This would avoid for the expert to be flown for diagnosing the problem or performing 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 aircrafts, medical equipment and production plants. They demonstrate their ideas on a hard-disk cabinet. Their system can help to guide the field worker using augmentation, additionally it reports automatically back to the head-quarter using a log of the maintenance.

SLAM system are very popular for remote expert application. 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. [60] 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 allow to precisely describe the task to be performed as shown in Fig. 6.

Remote collaboration has also been proposed for training of ATM maintenance procedure. Boulanger [11] propose to use AR to teach multiple trainees how to repair an ATM. The trainers are all connected to the same expert located in a remote sites. They all have access to live augmentation (remote or local) through an HMD and can communication like in a regular conference call. This simultaneous experience allows not only to cut cost but they can learn from each others questions and mistakes.

4.5 Redesign and Decommissionning

When a product is reaching its retirement, it needs to be recycled or destroyed during a revamping or decommissioning procedure. This process for large system are planned in advance not only to minimize the labor cost but also to limit the exposure to hazardous materials, for example when dismantling a nuclear power-plant. In this section, we describe AR systems that support this procedure.

Siemens Corporate Research is extremely active in trying AR to support industrial processes. They play a major role in trying to change the workflow of traditional industry[80]. For example, they 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. 7 demonstrates the possibility offered by such a diminished reality system for revamping.

Augmented reality is also used to support decommissioning of nuclear power plant. This task is heavily regulated for obvious security and safety reasons. It needs first to be planned and the feasibility of the process need 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. demonstrate the benefit of AR for the dismantling of an ion tower [29]. They introduce new technologies for safe and efficient decommissionning work of contaminated zones. Their system supports the work by ensuring that the cuts made to the surrounding pipes are localized where they are supposed to. It also monitors the work and record the progress made. Finally it gives the field worker a direct access to the CAD data on site [69].

5 Evaluation Criteria

In this section, we describe the rubric we use to score the different presented papers, final score formula and the procedure used to assign grade.

Workflow integration: we rated each presented system with respect to integration to a well defined industrial procedure. We consider the fact that the industrial problems are well defined and that the input data and output result can easily be integrated in a global process. This is important as the closer to the industrial process the system is the easier it will be to understand underlying problem and non trivial solutions.

Scalability: we judged the selected systems depending on their re-usability and their applicability to the real-life full size scenario. This considers the technology used (i.e. tracking, display...), not only the raw cost but also the installation, maintenance, removal cost. This is an important aspect as it has a direct impact on AR broader applicability.

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

Out of the lab: we evaluate the state in which the current system was with respect to the idea that they should ultimately leave the lab and be used in the real industrial context. This assesses if the scenario used realistic data and is used the target application environment or in a lab setup. For us, this is a major quality for a system to have as it allows an end-user to properly evaluate it.

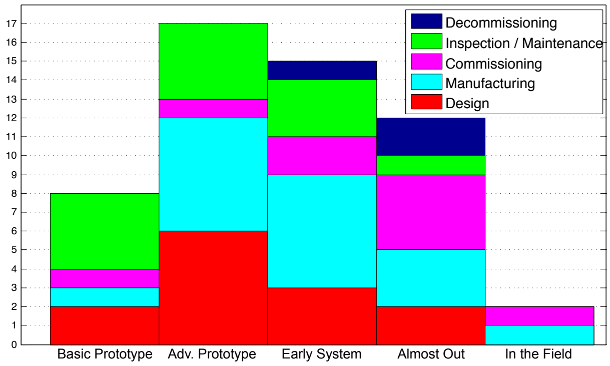

Figure 9: Bar plot showing the final scores based on our rubric.

User tested: we consider the fact if a system was user tested. There are basically three possibilities either the system was not user tested, or it was informally tested by end-user or expert which usually give interesting input for improvement, or it was formally tested in an "scientific" setup to evaluate user acceptance and performance.

Out off 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 state for an IAR system that prove its usability. This is a binary state.

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

The resulting scores of the selected systems using this rubric is visible in Fig. 8. We scored each paper over each criteria by looking at what was presented in the papers and by judging how well it achieved this implementation aspect. For the cost benefit criteria when the paper did not mention any benefit we score it as N/A. We created a final score that is a sum of single score criteria. Each single score are scale to vary from 0 to 4. An histogram of the resulting scores is visible in Fig. 9. The histogram was obtained using 5 bins.

6 Analysis

In this section, we analyze the statistic 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 involves to some degree industrial partners. The percentage raises to 85% when only looking to advanced systems[3]. This shows some correlation between the degree of success and the industrial involvement. Only 44% of the analyzed systems have been at some degree user-tested and 72% for the advanced systems. Usually the advanced systems have used a series of tests to iterate their prototype, which seems to be an healthy process. 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 justification for the current limited number of IAR applications in use. Finally, our rubric shows that the scalability aspect has hardly been studied.

We can see that apart from the decommissioning applications researchers have applied AR concepts uniformly across the life-cycle. The degree of advancement of each system seems to be balanced across domain of applications with a slight advantage for commissioning, which might be justified by its specific and clearly defined workflow and its important needs for industry support to develop such a system. It seems more difficult to create a basic lab prototype for commissioning than for a repair task.

[3]We classify as advanced systems every systems that score 9.75 or higher. This corresponds to anything beyond advanced prototypes.

7 Conclusion 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 attempts 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 still negative as only two applications have broke out of the laboratory to be regularly used by non-developers[17, 24] but only one is still in use. But we note that progress are being made with more than a dozen of systems at the door, we can expect to see more AR systems used by the industry to support their workflow.

The articles discussed in this survey present an overview of the potential benefit of an AR system: performance enhancement (support the worker's task), saving material and resources (by replacing some real resource by simulated ones or offering remote access to experts), and improving service (automatize some less rewarding but important task).

As many emerging technology AR need to be cost beneficial, scalable and reproducible[77, 43, 36, 70] 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 solution has been barely studied in existing systems. We believe that it would be an interesting area of future research. Industrial applications requires a proper integration to existing workflows[43, 57]. 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 involve the whole company to ease its acceptance[57].

As expected our rubric shows that the development of IAR system should involves the industry. It tends to encourage for the tight collaboration with end-users during the development to improve the chance for success. Therefore as a general guideline we encourage academic researcher to collaborate with industrial partners to improve their prototype in an iterative process of development 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 sign of the existence of such an application. Generally it would be interesting to see if it is an necessity for AR to be deployed by the industry. In this survey, we have shown that the use of AR was ubiquitous as it been applied it many different scenarii. Therefore we tend to think that there are no killer-app but many useful ones.

This survey was not focused on enabling technology. Since the technological limitations have often been stated as the main reason to justify the failure of AR [14, 77, 36], in a next iteration it would be interesting to look at the technology used in existing systems. Following this path it might be useful to revisit some existing systems using different technology that may be more adequate.

Finally it is interesting to note that few of the IAR systems presented are making use of the available measurement. An AR system has access to all sort of measurements that could offer after action review [54] that would not only support the worker to perform his everyday task but could allow for testing new workflows.

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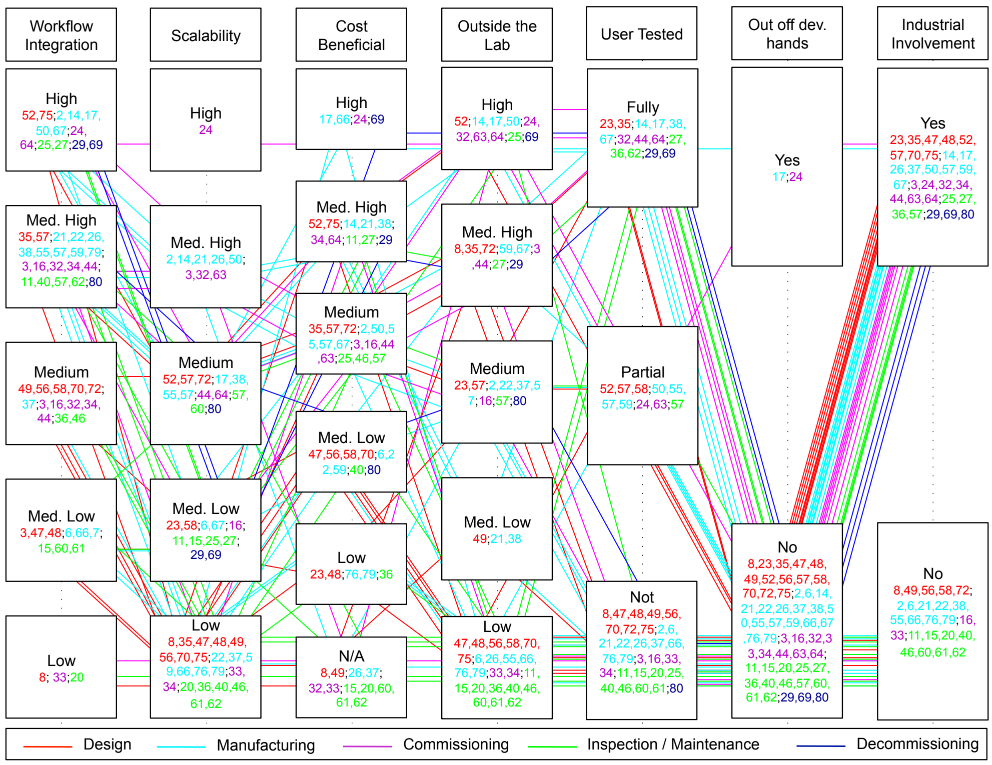

Figure 8: Multi-dimension plot of the selected applications. Each color (resp. number) refers to an application (resp. citation).

discuss the final manuscript. Finally I would like the ISMAR PC members for their time and amazing input that helped transform a purely scholar essay into the document you have in front of you.

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