The Design Space of Augmented and Virtual Reality Applications for Assistive Environments in Manufacturing: A Visual Approach

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ABSTRACT

Research on how to take advantage of Augmented Reality and Virtual Reality applications and technologies in the domain of manufacturing has brought forward a great number of concepts, prototypes, and working systems. Although comprehensive surveys have taken account of the state of the art, the design space of industrial augmented and virtual reality keeps diversifying. We propose a visual approach towards assessing this space and present an interactive, community-driven tool which supports interested researchers and practitioners in gaining an overview of the aforementioned design space. Using such a framework we collected and classified relevant publications in terms of application areas and technology platforms. This tool shall facilitate initial research activities as well as the identification of research opportunities. Thus, we lay the groundwork, forthcoming workshops and discussions shall address the refinement.

CCS Concepts

•Human-centered computing → Mixed / augmented reality; Virtual reality; •Applied computing → Industry and manufacturing;

Keywords

Assistive Environments; Mixed Reality; Augmented Reality; Virtual Reality; Manufacturing;

PETRA '17, June 21-23, 2017, Island of Rhodes, Greece

DOI: http://dx.doi.org/10.1145/3056540.3076193

1. INTRODUCTION

Exploiting the potentials of Augmented Reality (AR) and Virtual Reality (VR) concepts and technologies has been a research topic for decades. Among other topics, a huge body of research dealt with the question of how to support humans in manufacturing environments with these technologies. Along the way, Navab [39] and Fite-Georgel [17] contributed to coining the term Industrial Augmented Reality (IAR) which we will refer to throughout the paper. A number of surveys, e.g. [40, 48], indicate that IAR can potentially innovate many aspects of manufacturing by improving processes and reducing physical and cognitive strain for workers. With technologies becoming increasingly robust and economical, novel use cases and applications are being explored. Additionally, empirical data on the real-world usage is increasingly available and gives well-founded insights into the actual employment efficiency of such systems.

On the other hand, manufacturing environments itself are also transformed. The digitalization of industrial production, often referred to as "Industrie 4.0" (I4.0), "Industrial Internet" or "Digital Factory", makes way for more flexible and efficient ways of producing goods. This new approach is often highly complex yielding new requirements for the design of such systems [27]. Hence, new interface concepts and technologies are required for the future of industrial manufacturing that allow users an intuitive and natural interaction with industrial manufacturing environments. The progress in research on AR and VR concepts and technologies promise to offer significant benefits in terms of assisting the human user in managing the complexity of I4.0 scenarios.

However, the research landscape is very diverse and thus the design space for AR and VR applications is huge. Therefore, we take account of the current state of the art by describing and visualizing the design space for industrial AR and VR technologies and applications. To this end, we first present previous overview works and surveys that have been done in this research field. We use this work as an input for a taxonomy of relevant research projects concerned with the development of industrial AR/VR applications. Second, we describe the aforementioned design space by proposing an interactive, community-driven tool for visualizing this space. Finally, we derive opportunities and challenges resulting from the previous steps.

The goal of this paper is to provide an overview of research done in the area of using new AR and VR concepts for facilitating and supporting industrial applications and use-cases. By presenting our proposed interactive, community-driven tool for the visualization of the design space we aim on creating an active community that further discusses the future development of assistive environments in manufacturing in the context of I4.0.

2. RELATED WORK

As already mentioned, the topic of using AR and VR applications for the support of processes in industrial manufacturing has been the focus of multiple decades of research. Therefore, it is not surprising that a number of overview works have been published. In this section, we describe other overview papers with a focus related to our work. We focus on very broad work with multiple industrial application areas or multiple technologies. More specific work is presented in section 3.3, where we use our visualization framework to classify the more specific research publications.

Fite-Georgel [17] presents an comprehensive overview on the topic of IAR by structuring work with different AR technologies regarding the application domain in the product life-cycle. He also evaluates the reviewed systems and assesses the maturity level of the IAR applications presented. One finding of his work is, that there were only two out of 54 reviewed IAR applications in use at the time of publication. However, the author found 13 systems that had a high maturity, where he expected at least some of them to be in the field soon.

Another comprehensive elaboration on AR and VR in industry is given by Nee et al. [40] who consider applications in design and manufacturing. They describe the current state-of-art by presenting different AR and VR technologies including input devices and software frameworks. They name various projects in the context of design, robotics, factory planning, maintenance, computerized numerical control (CNC) machine simulation, assembly and operations planning. Furthermore, they address technical challenges to be solved by future research.

A more technical-driven overview on AR is given by Papagiannakis et al. [45]. Focusing on mobile AR systems, they provide a very informed overview over different enabling, tracking and display technologies. Furthermore they review software architectures in the context of mobile AR. However, they also provide a list on different application areas of future AR systems, where they also list multiple industrial application areas.

Based on his early survey on AR [4], Azuma published a complementary paper [3] that also explicitly names industrial application domains for AR, such as supporting the assembly of wire bundles in aircrafts or using AR for factory floor or pipeline planning. Not an overview work but a project dealing with a broad perspective on IAR has been carried out by a consortium consisting of multiple universities, research institutes and industrial partners. In the ARVIKA project, a software framework for the development of IAR applications was developed and multiple IAR use-cases and concepts have been developed and implemented. A large number of use-cases is covered, ranging from product development over production to service and maintenance. Particularly the automotive and aircraft domain is addressed [18, 59, 61].

When it comes to VR, Brooks [10] reports findings of an analysis of use-cases and applications. Finally there is another very broad overview presented by Van Krevelen and Poelman [57], who also investigate the topic of industrial application.

3. VISUALIZING THE DESIGN SPACE

We understand a design space as a room of possibilities in terms of applicability and feasibility. It comprises application areas with potential for AR/VR support on the one hand and technology platforms for which feasibility has been demonstrated on the other hand. We constituted the design space by investigating the current state of the art concerning AR and VR applications for assistive environments in manufacturing. Unlike many other initiatives, we chose a visual approach in the form of an interactive diagramm to satisfy a more designerly and hands-on demand for assesment and navigation of the realm. In this section we describe the concept of our visualization, its web-based implementation and give an excerpt of previous research classified within our visualization framework.

3.1 Concept

The visualization shown in Figure 1 classifies previous publications into two dimensions: application area and technology.

Dimension one describes the application area. Grounded in the related work part, we derived four main domains one typically finds in smart factory environments. First, there is manufacturing. This area comprises systems supporting manual assembly work, operating machinery, supervising, and similar tasks. Second, there is logistics which addresses manual tasks such as picking, navigation or data management. Third, there is maintenance comprising systems which e.g. enable remote support scenarios via AR or VR technology. Finally, we included training as an application area consisting of systems specifically designed to facilitate learning scenarios.

The second dimension distinguishes between the four relevant technology platforms in terms of AR and VR. First, there are AR mobile devices such as tablets and smartphones. Second, there are AR projections made possible by combining a depth camera and a video projector for instance. Third, there are AR head-mounted displays (HMD) such as the Microsoft Hololens, Google Glass, and the like. Fourth and finally, there are VR HMDs including devices such as HTC Vive, Oculus Rift, Google Cardboard, and the like.

The final dimension is constituted by the number of publications which address one combination of the former two dimensions. For example, Hakkarainen et al. [31] falls within the two dimensions of manufacturing and AR mobile devices because it describes an AR system which enables displaying complex computer-aided design (CAD) models on mobile phones to support assembly tasks.

By integrating more and more publications into this framework, especially in collaboration e.g. through a crowd-sourcing

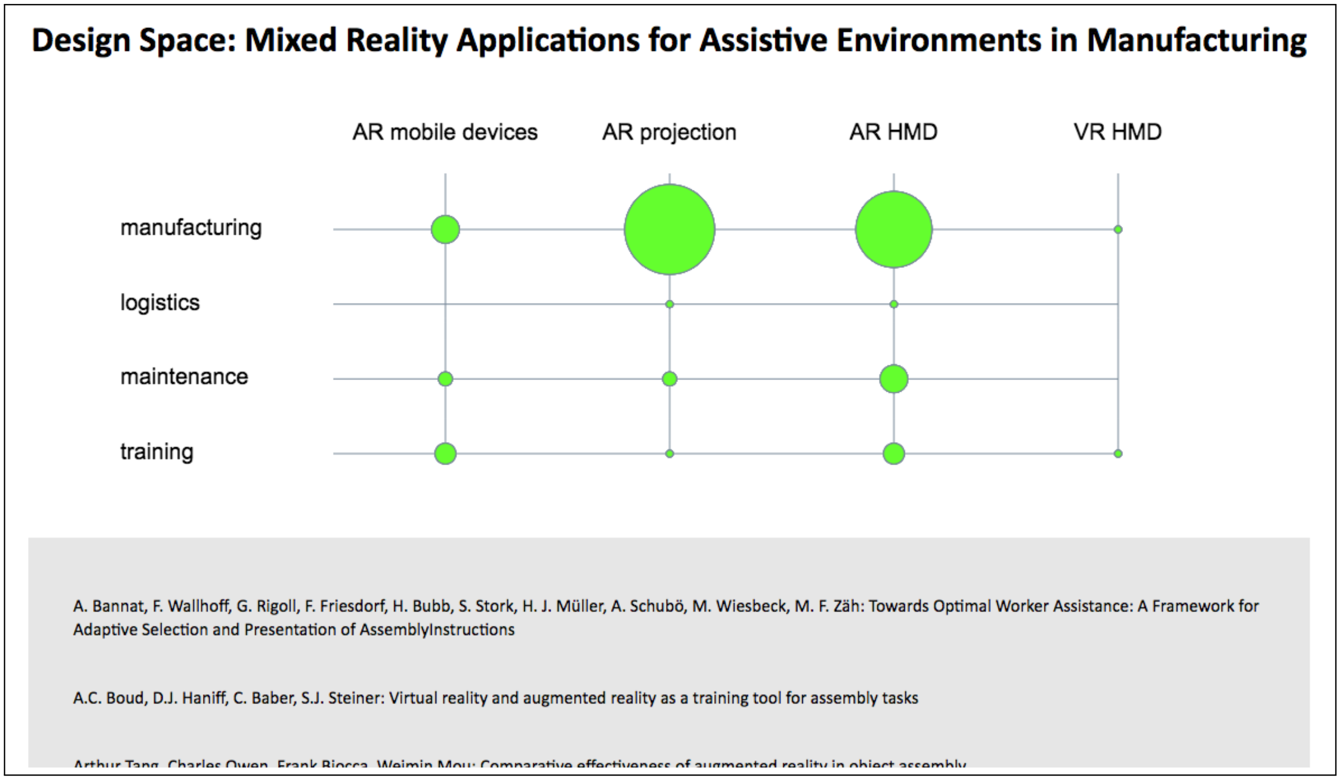

Figure 1: Screenshot of the web-based, interactive visualization tool showing the number of publications for the combination of a given application area and technology platform. The tool shall inform researchers and practitioners through a visualization of the design space.

approach, it bears the potential to serve different purposes. First and foremost, it visualizes the state of research activities. Henceforth, the diagram can contribute to the formulation of research questions. On the one hand, if a combination has significantly less contributions than the others it may offer research opportunities or gaps. On the other hand, if a combination convenes a great number of publications it may be an indicator for the general success of this combination.

3.2 Web-based Visualization

Apart from the classification, our contribution is to visualize the design space and thus make it more accessible for researchers and practitioners in the field. To this end, we built an interactive (web-based) visualization tool which is shown in Figure 1 and published on our website: http://www.smartfactory-owl.de/designspace/designspace.html. The diagram visualizes the number of papers addressing each combination of the two relevant dimensions "application area" and "technology" and provides the corresponding full references.

The tool is implemented in HTML5 including JavaScript frameworks, such as jQuery and AngularJS, which makes it compatible to all modern web browsers and devices.

The framework is intentionally designed to be modular, i.e. application areas, technology platforms that are unheard of by now as well as future publications can be easily added. The graph is meant to be a living tool accompanying our own research activities.

3.3 Classification of Previous Research

Bringing the framework to life and establishing it as a living research tool will happen by taking one step at a time. This paper is meant to be the starting point. Future steps will be taken in research workshops and online community work. However, here we take the opportunity to initiate this process. By efforts of research, review and classification we were able to produce a first version of the framework comprising about 30 publications across all domains. In this section we are presenting a selection of the latter underlining the relevance of the four application area domains.

3.3.1 Manufacturing

Most notably AR technology has been used for supporting manual manufacturing processes. The technology that has been proposed can be divided into three categories: projections, head-mounted displays, or mobile devices.

Considering projection-based AR systems, the first system combining an RGB camera and a projector was Wellner's DigitalDesk [60]. A camera detects objects, such as paper and user interaction, to highlight information on a desk. Bannat et al. [6] created an augmented workbench for workers, capable of displaying in-situ assembly instructions into the field of view of workers. Similar systems were developed by Funk et al. [24] and Büttner et al. [12, 13, 51]. Using a depth sensor, correct or incorrect working steps are recognized and communicated via projections with workers. In evaluations with cognitive impaired people working at sheltered work organizations, in-situ projections showed less cognitive effort and lower error rates during assembly [5, 19, 21]. Kosch et al. [35] compared different error feedback modalities at manual assembly work places for cognitively impaired workers. Comprising projections, auditory feedback, and tactile feedback integrated into a work glove, projections have shown best performance regarding subjective rating, error rate, and task completion time. Augmented workbenches have also presented by using HMDs. Paelke et al. [44] present an augmented manual assembly station that gives picking and assembly instructions to users with an HMD. Büttner et al. [11] compare HMDs with projection-based AR and a paper baseline. They show that the use of projection-based AR is more efficient than HMDs in the context of manufacturing assistance.

Besides providing in-situ projections or using HMDs, Gupta et al. [29] use an external display to provide assembly instructions. Correct and incorrect working steps were detected using a depth sensor. Korn et al. [33] compared assembly efficiency between in situ and display-based instructions. Displaying in-situ instructions into the field of view of workers leads to a higher working efficiency in terms of error rate and task completion time compared to displaying assembly instructions on an external display [37]. Additional work about how to help and motivate workers during manual assembly tasks using gamification has been done in the context of smart factories [32, 34]. Integrating gamification into assistive technologies enhances working experiences, especially for elderly or cognitively impaired persons.

Other research projects utilize AR [14, 43, 56] or VR [9] to support manual manufacturing processes. In order to evaluate different assembly instruction modalities, Funk et al. [22] compared the efficiency of displaying instructions on paper, tablets, HMDs, and projections. Results show improved assembly performances regarding error rate and task completion time. Since each manual assembly working step consists of multiple strides, the general assembly task model [20] has been proposed to make working steps comparable among each other for different assembly instruction modalities.

In Fehling et al. [15] the opportunities of AR were explored in close combination with a pedagogical perspective on improving the vocational training in manufacturing environments. They could identify the impact of learning with AR in comparison to traditional vocational training approaches.

3.3.2 Logistics

Early work on using AR in industry has been presented in the logistics area, especially for the support of warehouse-picking tasks with HMDs, e.g. by Schwerdtfeger et al. [54] and Günther [28]. Both works present HMD-based systems that guide users through warehouses and highlight the objects that need to be picked. In this context, the attention funnel presented by Biocca et al. [7] can help to guide users' attention to the specific object. Other warehouse picking approaches include a cart-mounted projector [25], or a head-mounted projector [23]. Recent trends also include a weight checking system to prevent the users from making errors [62]. Beyond warehouse picking Sarupuri et al. [52] investigate the use of AR to assist humans in forklift operations. Furthermore, AR can be used to support planning processes in logistics: Pentenrieder et al. [46] present AR support for factory planning. By using AR based on HMDs and mobile devices, virtual objects representing future parts of the production systems can be shown in the physical space of a factory. By this, (re-)building of industrial facilities is supported. For similar planning purposes, Otto et al. [42] have used AR projections to augment floor surfaces to visualize layouts of assembly stations. Additional to an overview of AR technologies in logistics, Reif et al. [49] also present the use of VR technologies for the planning of logistic systems. They state that the systems are planned in CAD tools anyway, which is an enabler for the use of VR environments to allow intuitive planning and visualization.

3.3.3 Maintenance

The ability to provide real-time and context-related information is destined to be used for maintenance scenarios were users have to be guided through complex processes by e.g. other human experts. Therefore, many research initiatives have worked on the question of assistance in (industrial) maintenance. Early approaches focused on technical solutions e.g. [16, 41, 53] while more contemporary ones concentrated more on applicability in real-life situations e.g. [47, 50, 58]. Zheng et al. [63] compared the efficiency of using HMDs to provide instructions in machine maintenance scenarios. During their investigations, the efficiency of paper, mobile device-based, and head-mounted instructions were compared to enable hands-free interaction. Gurevich et al. [30] propose a system which supports remote assistance tasks using in-situ projections. Notably, the projector and a camera are mounted on top of a robotic arm allowing the remote expert to adjust the point of view and projecting visual clues and text into the worker's field of view. Kritzler et al. [36] were proposing to use a telepresence robot to provide maintenance instructions on an iPad. Moreover, Speicher et al. [55] describe a system which seeks to automate the creation of instructions in the form of AR content.

3.3.4 Training

Even though training is often a cross-cutting concern of the aforementioned application areas, we want to investigate work on AR/VR applications for training separately, since multiple applications focus specifically on this aspect. In the context of mobile worker assistance in manufacturing, researchers used smartphones [31] or tablets [15, 26] to train assembly processes. Aehnelt and Bader [1] use external displays to provide assembly instructions. They include contextual background knowledge in raising awareness, guiding, and monitoring assembly workers. In the domain of training, Aehnelt and Wegner [2] focus on combining the work with a learning experience in order to improve the cognitive understanding and processing of work tasks which helps to align and plan own activities in a smart manufacturing environment. Boud et al. [8] compare the use of different AR and VR techniques for the training of assembly processes. They measured the completion time of the assembly process after the participants were trained with either VR headsets, VR on a display, HMD-based AR or a paper manual as a baseline. According to their results, the HMD-based AR training resulted in the fastest completion time, followed by the various VR techniques and the paper baseline. Schwald et al. [53] present an HMD-based AR system for maintenance training for machines and industrial equipment.

4. OPPORTUNITIES AND CHALLENGES

While developing the design space taxonomy, we were inevitably led towards deriving both opportunities and challenges. It seems worth looking into these in more detail and, unlike the norm, we like to start with considering the opportunities:

- **Inclusion**: Assistive environments allow for the integration of the untrained, impaired or less skilled worker in partly high complex manufacturing processes of the primary labor market. Here it is the strength of visual assistance to guide workers through complicated work tasks by reducing the complexity and providing visual anchors and help in real work environments [2, 24].

- **Cognitive support**: The production of small lot sizes in high variabilities requires cognitive flexibility from the worker, e.g. for a fast anticipation of current work situations and the cognitive switching between single tasks. Thus, assistive environments which specifically focus on supporting the cognitive understanding and interpretation of manufacturing work can improve both cognitive processes of the worker as well as his work performance [2, 38]. This also includes aspects like sensemaking, learning, and decision making.

- **Quality assurance**: AR/VR applications need to gather and interpret information on the current work situation in order to provide an adequate assistance experience. This information in parallel allows the automated enhancement of already existing quality assurance processes at the workplace. A visual documentation of single work activities as well as the information based control and feedback improves the quality of work and reduces failure rates and extra work [21, 22].

- **Training**: Often manufacturing work conditions do not allow on the job training of specific work tasks and situations, e.g. when too expensive, dangerous or when it would influence the overall production performance. Here, assistive environments which use AR or VR as methodology for visualizing complex work tasks or even invisible processes improve the training experience and outcomes for the individual worker [15].

However, we could also find bottlenecks and challenges for the usage of AR/VR applications in smart manufacturing environments which call for further research into this direction.

- **Hardware**: The form factor of most assistive technologies is still a major show stopper when using wearable solutions for augmenting and assisting in real work processes. With heavy HMDs or limited battery capacities, hand-held or body worn devices still challenge the worker using assistive technologies eight hours a day.

- **Content**: The growing flexibility and complexity of manual work processes result in increasing efforts and limited time frames for producing the digital content to be used in AR/VR applications. An automation is here required but in many cases not yet established or even possible.

- **Acceptance**: The hardware limitations on one hand, and limited trust into automated assistance on the other one, do not necessarily lead to growing acceptance rates. Here, the workers need to learn trusting on technology without giving away their own competencies and cognitive power.

- **Ethics**: Assistive environments in manufacturing require a high degree of modeling and observing the user behavior under real work conditions in order to align manual work tasks with the automated parts of smart factories. This provokes the fear of over controlling the workforce or treating them as human robots. Here, worker participation in designing processes is required and important.

Both opportunities and challenges will provide the baseline for further research and discussion.

5. CONCLUSION AND FUTURE WORK

We have seen that AR and VR applications have been in the center of interest for many researchers from various fields. With the advances in hardware and software capabilities more and more opportunities arise. Likewise, researches are facing new challenges and have to overcome bottlenecks in order to make AR/VR applications truly usable and enjoyable. The context of use, i.e. manufacturing and industrial scenarios, impose additional requirements for future systems. Having said this, it becomes apparent that the design space researchers, designers, and developers have to navigate keeps expanding. This fact calls for tools to tackle the complexity. Therefore, this paper is intended to be a first step towards establishing a research tool which supports keeping track of the continuously expanding design space of industrial AR and VR applications and systems. It is designed to be fostered by the community, hence its modular architecture. We hope to contribute a simple tool which supports interested researchers and practitioners in gaining an overview, identifying relevant publications, and spotting research opportunities. This paper lays the groundwork, forthcoming workshops and discussions shall address the refinement.

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