LICENTIATE DISSERTATION

AUGMENTED REALITY
SMART GLASSES AS
ASSEMBLY OPERATOR
SUPPORT
Towards a framework for enabling industrial integration

OSCAR DANIELSSON
Informatics
AUGMENTED REALITY SMART
GLASSES AS ASSEMBLY
OPERATOR SUPPORT
Towards a framework for enabling industrial integration
LICENTIATE DISSERTATION

AUGMENTED REALITY SMART GLASSES AS ASSEMBLY OPERATOR SUPPORT

Towards a framework for enabling industrial integration

OSCAR DANIELSSON
Informatics

UNIVERSITY OF SKÖVDE
Oscar Danielsson, 2020

*Title:* Augmented reality smart glasses as assembly operator support
Towards a framework for enabling industrial integration

University of Skövde 2020, Sweden
www.his.se

*Printer:* Stema Specialtryck AB, Borås

Dissertation Series, No. 37 (2020)
ABSTRACT

Operators are likely to continue to play an integral part in industrial assembly for the foreseeable future. This is in part because increasingly shorter life-cycles and increased variety of products makes automation harder to achieve. As technological advancements enables greater digitalization, the demands for increased individual designs of products increases. These changes, combined with a global competition, does put an increasing strain on operators to handle large quantities of information in a short timeframe. Augmented reality (AR) has been identified as a technology that can present assembly information to operators in an efficient manner. AR smart glasses (ARSG) is an implementation of AR suitable for operators since they are hands-free and can provide individual instructions in the correct context directly in their real work environment. There are currently early adopters of ARSG in production within industry and there are many predictions that ARSG usage will continue to grow. However, to fully integrate ARSG as a tool among others in a modern and complex factory there are several perspectives that a company need to take into consideration. This thesis investigates both the operator perspective and the manufacturing engineering perspective to support industry in how to make the correct investment decisions as regards to ARSG.

The aim of this licentiate thesis is to provide a basis for a framework to enable industry to choose and integrate ARSG in production as a value adding operator support. This is achieved by investigating the theoretical basis of ARSG related technology and its maturity as well as the needs operators have in ARSG for their usage in assembly. The philosophical paradigm that is followed is that of pragmatism. The methodology used is design science, set in the research paradigm of mixed methods. Data has been collected through experiments with demonstrators, interviews, observations, and literature reviews. This thesis provides partial answers to the overall research aim.

The thesis shows that the topic is feasible, relevant to industry, and a novel scientific contribution. Observations, interviews, and a literature review gave an overview of the operator perspective. Some highlights from the results are that operators are willing to work with ARSG, that operators need help in unlearning old tasks as well as learning new ones, and that optimal weight distribution of ARSG is dependent on the operators’ head-positioning. Highlights from the preliminary findings for the manufacturing engineering perspective include a general lack of standards for AR as regards vertical industrial application, improved tools for faster instruction generation, and large variations in specifications of available ARSG.
Future work includes a complete answer to the manufacturing engineering perspective as well as combining all the results to create a framework for ARSG integration in industry.
SAMMANFATTNING


Avhandlingen visar att ämnet är möjligt att genomföra, relevant för industrin och ett originellt vetenskapligt bidrag. Observationer, intervjuer och en litteraturstudie gav en översikt av operatörsperspektivet. Några exempel från resultaten att lyfta fram är att operatörer är villiga att arbeta med ARSG, att operatörer behöver hjälp med att avläsa sig gamla uppgifter såväl som att lära sig nya och att den optimala viktspridningen av ARSG beror på operatörernas huvudpositionering. Bland de preliminära resultaten från beredningsperspektivet inkluderar en generell avsaknad av standarder...
för AR gällande vertikala industriella tillämpningar, förbättrade verktyg för instruktionsskapande som stödjer snabbare instruktionsgenerering och stora variationer gällande specifikationer i tillgängliga ARSG.
Framtida arbete inkluderar ett komplett svar till beredningsperspektivet samt att kombinera alla resultaten för att skapa ett ramverk för ARSG integration i industrin.
ACKNOWLEDGEMENTS

And so, here is my opportunity to formally express my eternal gratitude to all the wonderful individuals around me that gave me the strength to persevere through this challenging enterprise.

My first thank you goes to my supervisors. First I want to thank Magnus Holm. You have had multiple roles. You have been my supervisor, boss, project director, and travel company. But throughout all of them one thing has been constant: your support and belief in me, thank you! I also want to thank Lihui Wang. Your experience and insightful advice has helped me see a clearer path forward on more than one occasion. Further I want to thank Peter Thorvald. Your methodological feedback has helped to temper my work to achieve an academic rigor. Lastly, but in no sense the least, I would like to express my gratitude to Anna Syberfeldt. You were the one that set all this in motion by luring an unsuspecting research assistant further down the path of academia, and now forever it dominates my path. Throughout my studies you have found the perfect balance of both pushing and supporting me to achieve new heights.

Thank you to all my colleagues at the University of Skövde for your company and support. And a special thank you to fellow PhD-student Patrik Gustavsson, I enjoyed the support, laughs, and of course the templates! I also want to thank everyone at Volvo Car Corporation for your time and support in this endeavor. Of course I also want to especially thank my industrial mentor Rodney Lindgren Brewster. Thank you for all your advice and guidance throughout this project. You put the focus on reality in augmented reality!

I also want to express my gratitude to my family. Thank you to my mother, Ulrika Björnberg, for your love, food, and prayers. And to my father, Håkan Danielsson, for your love and help with all kind of things. Also I want to thank my sister, Rebecka Danielsson, for your love and memes. Without you all I would not have grown up to be who I am today. And thank you too, Violet Zand. I see us as family now and your love and ghorme sabzi has given me so much joy.

And for the final acknowledgement I of course want to thank my love in life, Melina Ettehad! When we first met I had just started this journey, and now we have endured this project together. With your love and support I have found NRG+++ to continue to improve myself to finish these studies and built a life together with you and PPPH. In a sense, this thesis is the first chapter in the book of our life together.
PUBLICATIONS

This section first lists the publications that directly contributed to this thesis and then publications that are less directly relevant.

PUBLICATIONS WITH HIGH RELEVANCE


PUBLICATIONS WITH LOWER RELEVANCE


CONTENTS

1. INTRODUCTION .............................................................................................................................................. 1
  1.1 Background .............................................................................................................................................. 1
  1.2 Problem description ................................................................................................................................. 2
  1.3 Research aims .......................................................................................................................................... 3
    1.3.1 Research objectives ......................................................................................................................... 4
    1.3.2 Motivations for research objectives ............................................................................................... 4
  1.4 Industrial collaboration ............................................................................................................................. 5
  1.5 Summary of appended papers .................................................................................................................. 5
    1.5.1 Paper 1: Assessing instructions in augmented reality for human-robot collaborative assembly by using demonstrators .......................................................... 6
    1.5.2 Paper 2: Operators perspective on augmented reality as a support tool in engine assembly ........................................................................................................... 6
    1.5.3 Paper 3: Augmented reality smart glasses for industrial assembly operators: a meta-analysis and categorization ........................................................................ 7
    1.5.4 Paper 4: Augmented reality smart glasses for operators in production: Survey of relevant categories for supporting operators ........................................... 7
    1.5.5 Paper 5: Augmented reality smart glasses in industrial assembly: current status and future challenges ......................................................................................... 7
  1.6 Structure of the thesis .................................................................................................................................. 7

2. THEORETICAL BACKGROUND ....................................................................................................................... 11
  2.1 Industrial shift – Industry 4.0 .................................................................................................................... 11
    2.1.1 Operators in Industry 4.0 .................................................................................................................. 12
  2.2 Manufacturing engineering ......................................................................................................................... 13
  2.3 Assembly .................................................................................................................................................... 13
  2.4 Augmented reality ..................................................................................................................................... 14

3. RESEARCH METHODOLOGY .......................................................................................................................... 19
  3.1 Philosophical paradigm – pragmatism ...................................................................................................... 19
  3.2 Mixed methods .......................................................................................................................................... 20
    3.2.1 Summary of methodology for research aim ..................................................................................... 21
    3.2.2 Motivation for using mixed methods ............................................................................................... 21
  3.3 Design science .......................................................................................................................................... 22
    3.3.1 Applicability To the thesis ................................................................................................................. 22
    3.3.2 Applicability to prerequisite ............................................................................................................. 24
3.3.3 Applicability to RQ1 ........................................................................................................ 25
3.3.4 Applicability to RQ2 ........................................................................................................ 26

4. RESULTS .................................................................................................................................. 31
4.1 Key findings in each publication ............................................................................................ 31
  4.1.1 Paper 1: Assessing instructions in augmented reality for human-robot collaborative assembly by using demonstrators ................................................................. 31
  4.1.2 Paper 2: Operators perspective on augmented reality ...................................................... 32
  4.1.3 Paper 3: Augmented reality smart glasses for Industrial assembly operators: a meta-analysis and categorization .............................................................. 33
  4.1.4 Paper 4: Augmented reality smart glasses for operators in production: survey of relevant categories for supporting operators ........................ 33
  4.1.5 Paper 5: Augmented reality smart glasses in industrial assembly: current status and future challenges ................................................................. 33
4.2 Answers to RQs ...................................................................................................................... 34
  4.2.1 Prerequisite: Industrial relevance .................................................................................... 34
  4.2.2 RQ1: Operator perspective .............................................................................................. 35
  4.2.3 RQ2: Manufacturing engineering perspective ................................................................. 36
4.3 Summarized results ............................................................................................................... 38

5. SUMMARY AND FUTURE WORK .......................................................................................... 41
5.1 Summary ................................................................................................................................ 41
5.2 Future work ............................................................................................................................. 41
  5.2.1 Paper 6: Framework creation and evaluation ................................................................. 42
  5.2.2 Paper 7: Framework refinement and evaluation ............................................................. 42

6. REFERENCES ............................................................................................................................ 45

7. PUBLICATIONS ....................................................................................................................... 55
LIST OF FIGURES

Figure 1.1: Estimation (for 2020) and forecast (for 2021-2026) of the global production volume of ARSG (Inside Market Reports, 2020)......................................................... 3
Figure 3.1: Three common mixed methods, adapted from (Creswell, 2014) ....................... 20
Figure 3.2: Flowchart showing objective dependencies .................................................. 27
Figure 4.1: Step four, where test person and robot collaborate with interface instructions on the right ................................................................. 32
LIST OF TABLES

Table 2.1 Four clusters of key enabling technologies, adapted from (Culot et al., 2020) .......................................................................................................................... 12
Table 3.1 Graphical overview of the research objectives, the methods, data, type, and (if mixed method) sequence of qualitative and quantitative methods................................. 21
Table 4.1 Frequency of reasons that operators look at instructions ........................................ 32
ABBREVIATIONS

AGV  Automated guided vehicle
AR   Augmented reality
ARSG Augmented reality smart glasses
BLE  Bluetooth low energy
CAD  Computer aided design
CSF  Connected smart factory
FOV  Field of view
HRC  Human-robot collaboration
IoT  Internet of Things
Mbps Megabits per second
ms   milliseconds
NED  Near-to-the-eye display
RFID Radio Frequency IDentification
RQ   Research question
SAR  Spatial augmented reality
SG   Smart glasses
SIP  Single inspection point
SUS  System usability scale
TCP  Transmission control protocol
TRL  Technological readiness level
UR3  Universal Robots model 3
VCC  Volvo Car Corporation
INTRODUCTION
CHAPTER 1
INTRODUCTION

“I genuinely and truly believe we will all use AR and that it will alter forever our lives…” (Peddie, 2017 (p. ix)).

This chapter gives a brief background and description of the problem to be solved. This is followed by the aim of the thesis and the research questions to be answered. A summary of the relevant publications of the thesis are also presented as well as an outline of the thesis.

1.1 BACKGROUND
The term Industry 4.0 (Industrie 4.0) was first coined by the German government and publicly introduced at the Hannover Fair in 2011 (Drath and Horch, 2014). The name refers to the prediction of a fourth industrial revolution (Drath and Horch, 2014). Culot et al. (2020) show that there have been many other initiatives similar to Industry 4.0, such as the Advanced Manufacturing Partnership in the United States and Factories of the Future in the European Union. Industry 4.0 was, however, the first initiative. This thesis will use the term Industry 4.0 to refer to this paradigm shift as a whole.\footnote{See details in Chapter 2.}

There is currently some ambiguity in how Industry 4.0 is defined and possible outcomes from it, but improvements in productivity and flexibility leading to mass customization is the most common expectations (Culot et al., 2020). Some of the technologies generally connected to Industry 4.0 are associated with a risk of increased unemployment in society, such as Internet of Things (IoT), robotics and artificial intelligence (AI) (Sanchez, 2019).

The number of industrial robots in manufacturing has been steadily increasing worldwide. Between 2011 and 2016 there was an annual average increase in industrial robots of 12 % (International Federation of Robotics, 2017). While the electrical/electronics industry is increasing its robotization, the automotive industry was still the leading buyer of industrial robots in 2016, accounting for 31 % of the total supply.
(International Federation of Robotics, 2017). These numbers might seem to suggest that assembly workers are rapidly becoming redundant. There are concerns that the long term effects of Industry 4.0 will have a negative effect on employment, resulting in what is known as technological unemployment (Hungerland et al., 2015). However, similar fears have been expressed previously in the three earlier industrial revolutions but has not yet come to prediction (Hungerland et al., 2015, Rainnie and Dean, 2020). Not all assembly work is so routine that operators are easily replaceable; they will still have an important role to play in the future (Pfeiffer, 2016). As previous attempts to create fully automated factories have not been successful, Industry 4.0 instead focuses on human-centered (semi-)automation (Nelles et al., 2016). So, while there are concerns that the number of assembly workers needed will decline, humans are likely to continue to be an integral part of production in the near future, although their role is probably going to change. Three scenarios of how Industry 4.0 could change the work situation is presented by Kotynkova (2017): the automation, hybrid, and specialization scenarios. She describes the automation scenario as systems directing humans, where operators mostly respond to real-time information, devaluing lesser skilled workers. In the hybrid scenario there is a considerable pressure to increase operator flexibility since the monitoring and control of tasks are performed through cooperative and interactive technologies, networked objects, and people. Finally she describes the specialization scenario as the continuing domination of qualified workers who use cyber-physical systems as a tool in decision-making. What is common in all three scenarios is the increased complexity. The increasingly complex work environment for operators will lead them to needing to be highly flexible to be able to adapt to the new dynamic work environment (Longo et al., 2017).

1.2 PROBLEM DESCRIPTION

As described above, the current paradigm shift in the manufacturing industry will likely change the role of operators and the demands put on them (Rauch et al., 2020). Hierarchies will need to be reduced to enable faster decisions, and production will need to become more flexible (Lasi et al., 2014). Operators will need access to more assembly information and this information will need to be updated more often so that operators can keep up with more frequent updates to tasks and be able to handle more simultaneous tasks, thus increasing their flexibility. Augmented reality (AR) has been proposed as a way to digitalize information for operators and increase their efficiency (Wang et al., 2016).

There are three main ways in which AR can be realized: the technology can be worn on your head, held in your hands, or placed in the environment (Peddie, 2017, Bimber and Raskar, 2006). This thesis investigates only head-worn solutions, specifically augmented reality smart glasses (ARSG). In this thesis, ARSG is defined as:

“A wearable device with one or two screens in front of the user’s eyes that can merge virtual information with physical information in the user’s field of view (FOV).” (Danielsson et al., 2020a (p. 1299))

See Chapter 2 for a fuller explanation.
Using AR, operators can move around in their environment and manipulate digital objects naturally. They can see digital information dynamically in the real world in their FOV and in the correct context. This has made AR one of the most promising approaches to facilitating mechanical assembly processes (Wang et al., 2016).

For a long time AR has struggled to find a place in factories (Syberfeldt et al., 2017, Syberfeldt et al., 2016). This was mainly due to industrial constraints related to ergonomics, color coding, training of operators, and the reliability of the proposed solutions (Uva et al., 2018). Things have started to change recently, and there are currently examples of AR implementations for operators in manufacturing, and more manufacturing companies that plan to transition to AR in 2020-2021 (Campbell et al., 2019). The field of AR is predicted to grow with a compound annual growth rate (CAGR) of around 74 % until the year 2025 (BIS Research, 2018). More specifically ARSG is estimated to have a CAGR of 33.7 % until 2026 (Inside Market Reports, 2020). Figure 1.1 presents this forecast data broken down per year.

![Global ARSG Production Volume, Forecast Analysis 2020-2026](image)

**Figure 1.1:** Estimation (for 2020) and forecast (for 2021-2026) of the global production volume of ARSG (Inside Market Reports, 2020).

As more and more companies integrate AR into their production systems, they will be faced with issues that arise from the integration process. Masood and Egger (2020) identified a lack of a global industry-based perspective as regards the broader context of AR implementation in industry. Thus one area that needs to be researched is how to integrate AR solutions into production systems. Therefore it is important to consider not only the operator perspective, the end user of ARSG as a support tool, but also the manufacturing engineers and technicians who enables the integration of ARSG onto the industrial shop floor. It is this gap this thesis is aiming to partially fill.

### 1.3 RESEARCH AIMS

The aim of this thesis is to work towards the design of a framework that enables the manufacturing industry to integrate ARSG for assembly operators in order to guide their work. Two research questions (RQs) were formulated to achieve this goal.
**RQ 1:** What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?

This question focuses on the perspective of the end users of ARSG, namely the operators. Answering it will clarify what functionality operators need to be able to work efficiently. This information can be used to shape the specifications for ARSG to meet the needs of the operators and to determine what functionality the ARSG interface should support.

**RQ 2:** What do manufacturing engineers and technicians need in ARSG so the technology can be integrated into, maintained, and updated in a production system?

This question focuses on the perspective of the integrators of the technology. How can information be sent to and from ARSG, and from there to and from other parts of the production system? What safety standards must be met? The answer to this question indicated the limits to and possibilities of integrating ARSG in surrounding systems, and thus sets the boundaries for what capabilities of ARSG can be used for assembly on an industrial shop floor.

**1.3.1 RESEARCH OBJECTIVES**

The RQs have been divided into the following objectives to ensure that they are answered in a satisfactory manner and the aims of the thesis are achieved:

**Prerequisite:** Is the thesis relevant to industrial partners and novel for the scientific community?

1. Ensure relevance and feasibility for industrial partners at management level.
2. Conduct a literature review on ARSG in manufacturing.

**RQ 1:** What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?

1. Conduct a literature review on ARSG in manufacturing from an operator perspective.
2. Ascertaining that operators are willing to work with ARSG.
3. Identify operators’ needs in information systems.

**RQ 2:** What do manufacturing engineers and technicians need in ARSG so the technology can be integrated into, maintained, and updated in a production system?

1. Conduct a literature review on ARSG in manufacturing from an integrator and technical perspective.
2. Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.

**1.3.2 MOTIVATIONS FOR RESEARCH OBJECTIVES**

A concise motivation is given for each research objective in this section. Each objective is a partial step toward covering the respective research question.

**Prerequisite, O1:** This objective is a prerequisite to ensure that the thesis is feasible and to ensure that the results will be relevant to the industrial partner.

**Prerequisite, O2:** This objective sets a theoretical foundation from which to ensure scientific novelty and a solid understanding of the research area.

**RQ 1, O1:** A better understanding of current feasibility and challenges can be gained by performing a literature review on the operator perspective on ARSG, laying a theoretical foundation for further endeavors.
RQ 1, O2: If operators are not willing to work with ARSG, this technology will not be well accepted and operators’ performance will be negatively affected. This question must be resolved to ensure that ARSG can be accepted and thus validate the premise of the thesis.

RQ 1, O3: The purpose of ARSG is to present information to operators. This objective provides a baseline for how operators currently interact with information and will serve as a starting point for which information interactions are suitable for transfer to ARSG.

RQ 2, O1: To understand the perspective of those who are to integrate and maintain ARSG in a production system, it is important to gain a theoretical understanding of the technological maturity as well as the manufacturing engineering process related to integrating, updating, and maintaining production tools. The literature study will provide this background.

RQ 2, O2: This objective is to gather experience from manufacturing engineers and technicians regarding challenges that can occur when introducing new technology in a production system so that this can be taken into account in the framework.

1.4 INDUSTRIAL COLLABORATION
This thesis presents a research project done in collaboration with Volvo Car Corporation (VCC) which regards research as of paramount importance if VCC is to stay competitive.

Volvo Car Corporation (VCC) is the industrial partner for this thesis. VCC has recognized that this thesis may lead to a more attractive and ergonomic workplace that is more capable of dealing with varying volumes and tasks. To stay competitive, VCC investigates how different technologies can improve their products and AR is one technology that has shown potential for VCC in different areas (Volvo Cars Media Relations, 2019). This thesis may promote flexible collaborative automation that can support operators, reduce the adaptation time when introducing new products or variants, and increase the ability to handle rejects. ARSG has been assessed to have the potential to greatly enhance worker efficiency, and is aligned with VCC’s core values of technological advancement and a focus on human well-being.

1.5 SUMMARY OF APPENDED PAPERS
This section summarizes the publications that are of high relevance to this thesis. The papers are presented in chronological order.

1. Assessing instructions in augmented reality for human-robot collaborative assembly by using demonstrators: A demonstrator developed and evaluated through user tests was presented at the 50th CIRP Conference on Manufacturing Systems and published as part of the conference proceedings (Danielsson et al., 2017).

2. Operators perspective on augmented reality as a support tool in engine assembly: A survey and observation study presented at the 51st CIRP Conference on Manufacturing Systems and published as part of the conference proceedings (Danielsson et al., 2018).

3. Augmented reality smart glasses for industrial assembly operators: A meta-analysis and categorization: A structured literature review on literature reviews related to ARSG in manufacturing presented at the 17th International
Conference on Manufacturing Research and published as part of the conference proceedings (Danielsson et al., 2019).

4. *Augmented reality smart glasses for operators in production: Survey of relevant categories for supporting operators:* A literature review of the assembly operators’ perspective of ARSG presented at the 53rd CIRP Conference on Manufacturing Systems and published as part of the conference proceedings (Danielsson et al., 2020a).

5. *Augmented reality smart glasses in industrial assembly: Current status and future challenges:* A literature review of the manufacturing engineering and technical perspective of ARSG in manufacturing, submitted to the Journal of Industrial Information Integration. At the time of writing, it was under review (Danielsson et al., 2020b).

1.5.1 PAPER 1: ASSESSING INSTRUCTIONS IN AUGMENTED REALITY FOR HUMAN-ROBOT COLLABORATIVE ASSEMBLY BY USING DEMONSTRATORS

The first paper in this thesis describes a demonstrator created to determine whether demonstrators can be used as a testbed for assembly instructions. It asked whether demonstrators can simulate human–robot collaboration, and whether AR-based interfaces can guide test persons through assembly. The tests verified that this could be done, but that instructions needed to be clearer and that future tests should be done in a more controlled environment. This paper relates to RQ1 and the first objective in that it shows that demonstrator prototypes are a viable testing method.

I am the main author of this paper and wrote the paper. The practical work consisted of designing and creating the demonstrator and experiments and performing the experiments. This was a joint effort between myself and another PhD student, Patrik Gustavsson. We each contributed half the work. My part was mainly developing the AR interface and co-developing and performing the experiments. My co-authors were involved throughout the process and provided invaluable guidance and support.

1.5.2 PAPER 2: OPERATORS PERSPECTIVE ON AUGMENTED REALITY AS A SUPPORT TOOL IN ENGINE ASSEMBLY

The second paper focused fully on the operators’ perspective on assembly instructions. It reports on interviews with operators and observations of their interactions with instructions in assembly tasks. The operators were interviewed and observed to determine how they currently interact with instructions and their views on how operations could be improved. The observations helped to identify the most common instructions operators looked at during assembly. The interviews gave some insight into how operators would like to work and interact compared to current procedures. During the interviews ARSG was described to the operators, and 21 out of 28 operators clearly expressed a positive view of using ARSG, showing high initial acceptance of the technology. This relates to the RQ1 and the second and third objectives.

I am the main author of this paper and wrote the paper. I chose the method, performed all interviews and observations, and did the analysis. My co-authors were involved throughout the process and provided invaluable guidance and support.
1.5.3 PAPER 3: AUGMENTED REALITY SMART GLASSES FOR INDUSTRIAL ASSEMBLY OPERATORS: A META-ANALYSIS AND CATEGORIZATION

The third paper was a structured review of literature reviews in the area of AR in the manufacturing industry in the last five years. The keywords, thematic fields, and similar categorizations of the seven identified papers were analyzed to identify those which related to operators, assembly support, and ARSG. This resulted in a total of thirteen subcategories with three perspectives: operators, manufacturing engineering, and technological maturity.

I am the main author of this paper and wrote the paper. I chose the method, performed the literature review, and analyzed the papers. My co-authors were involved throughout the process and provided invaluable guidance and support.

1.5.4 PAPER 4: AUGMENTED REALITY SMART GLASSES FOR OPERATORS IN PRODUCTION: SURVEY OF RELEVANT CATEGORIES FOR SUPPORTING OPERATORS

The fourth paper was a literature review that presented a deeper analysis of the operator perspective on ARSG and related categories that were identified in the third paper. It summarizes the findings in the form of a table showing the current status and future challenges for each of the categories.

I am the main author of this paper and wrote the paper. I performed the literature review and analyzed the papers. My co-authors were involved throughout the process and provided invaluable guidance and support.

1.5.5 PAPER 5: AUGMENTED REALITY SMART GLASSES IN INDUSTRIAL ASSEMBLY: CURRENT STATUS AND FUTURE CHALLENGES

The fifth paper was a literature review that presented a deeper analysis of the two perspectives that paper four did not cover: manufacturing engineering and technological maturity. It summarizes the findings in the form of a table showing the current status and future challenges for each of the categories.

I am the main author of this paper and wrote the paper. I performed the literature review and analyzed the papers. My co-authors were involved throughout the process and provided invaluable guidance and support.

1.6 STRUCTURE OF THE THESIS

Chapter 2 presents the theoretical background to the field and the state of current research. Chapter 3 presents the philosophical paradigm on which this research is based and the methodology used. Chapter 4 shows the results of this thesis. Chapter 5 summarizes the thesis, shows the conclusions drawn, and identifies possible future work.
THEORETICAL BACKGROUND
CHAPTER 2
THEORETICAL BACKGROUND

This chapter presents the theoretical background to this thesis. It explains the definitions of the different theoretical areas and the current state of research. It begins by focusing on the industrial shift that is now taking place, called Industry 4.0 by many. This is followed by a closer look at perspectives in manufacturing engineering that are relevant to this thesis. Then it presents information on assembly instructions, which are relevant as these are the value-adding content that should be distributed to operators through ARSG. The final area is AR, with a focus on ARSG, which is the medium through which assembly instructions can be distributed.

2.1 INDUSTRIAL SHIFT – INDUSTRY 4.0

Rojko (2017) gives a summary explanation of four industrial revolutions. The first industrial revolution was marked by mechanization and mechanical power generation in the 19th century. It was followed at the start of the 20th century by the second revolution in the form of industrialization and mass production through electrification. In the 1960s, automation was enabled through microelectronics, which is seen as the third revolution. The fourth industrial revolution is predicted to lead to reorganization of classical hierarchical automation systems to become self-organizing cyber-physical production systems. Cyber-physical systems are coupled hybrid systems, that are characterized by interconnected heterogeneous subsystems, and they organize computing, networking, and physical processes (Legatiuk et al., 2017). This will facilitate flexible production that is customizable both in design and quantity (Rojko, 2017). Connected to the fourth industrial revolution the German government initiated the Industry 4.0 strategic initiative (Rojko, 2017).

The basic concept of Industry 4.0 was publicly introduced at the Hannover Fair in 2011 (Rojko, 2017). It has since spread around the world. Globally there are similar initiatives that were created after Industry 4.0, including “Industrial Internet” in North America (Anunziata and Evans, 2012, Rojko, 2017), “Industrie du future” in France (French Government, 2015, Rojko, 2017), “Made in China 2025” in China (Rojko, 2017, Wübbeke et al., 2016), and “Made in Sweden 2030” in Sweden (Teknikföretagen, 2015). It is therefore reasonable to assume that the coming decade will introduce radically different approaches to how products will be manufactured. The term Industry
4.0 is the most prevalent one according to Culot et al. (2020) and is the term used in this thesis.

According to Culot et al. (2020), Industry 4.0 has since its first conceptualization evolved significantly, leading to several ambiguities. To remedy this, they performed a structured literature review of Industry 4.0 to map out and analyze how to define Industry 4.0. In summary, their findings show that Industry 4.0 has evolved over time from only describing the impact of emerging technologies within manufacturing to now encompass several other economic sectors such as consumers and society at large. The key enabling technologies within Industry 4.0 that they identified from the current literature were categorized into four main clusters: physical/digital interface technologies, network technologies, data processing technologies, and digital physical process technologies, as seen in Table 2.1. Within the physical-digital interface technologies cluster lies Visualization technologies of which AR is a part of. Another similar term related to visualization is visual computing, which has been identified as relevant for Industry 4.0 (Posada et al., 2015). Visual computing are technologies that process or generate visual content or visual information and includes AR (Segura et al., 2020).

Table 2.1 Four clusters of key enabling technologies, adapted from (Culot et al., 2020).

<table>
<thead>
<tr>
<th>Physical/digital interface</th>
<th>Network</th>
<th>Data processing</th>
<th>Digital/physical process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet of things</td>
<td>Cloud computing</td>
<td>Simulation and modelling</td>
<td>3D printing</td>
</tr>
<tr>
<td>Cyber-physical systems</td>
<td>Interoperability and cybersecurity solutions</td>
<td>Machine learning and artificial intelligence</td>
<td>Advanced robotics</td>
</tr>
<tr>
<td>Visualization technologies</td>
<td>Blockchain technology</td>
<td>Big data analytics</td>
<td>New materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Energy management solutions</td>
</tr>
</tbody>
</table>

Culot et al. (2020) also identified three important implications that they believed research should align towards. Firstly, they identified that Industry 4.0 requires a context-specific approach, that what to focus on depends on the context of the specific country, industry, or company. Secondly, Industry 4.0 needs a multi-disciplinary approach due in part to the broad impact it will have. And thirdly, they identified that the technological landscape of Industry 4.0 is still in a state of flux. The fast development means that lists of key enabling technologies often lack more recent developments. In regards to the first implication, this thesis primarily has the context of the automotive industry in Sweden. It is not limited to this scope in that the industrial partner, VCC, also are active in other countries and markets such as China, USA, and Belgium. But the data collection has been done within the scope of automotive manufacturing in Sweden.

2.1.1 OPERATORS IN INDUSTRY 4.0

Industry 4.0 will affect operators and their work environment, with new interactions both between humans and machines, but also between digital and physical worlds (Romero et al., 2020). While it is still unclear in exactly what way the role of operators will develop in industry 4.0, it is currently clear that they will be central part of future production systems due to their cognitive abilities (Rauch et al., 2020). The changes in the role of operators is reflected in the term Operator 4.0, which refers to a smart
and skilled operator who works closely integrated with technology (Romero et al., 2016).

The role of the future Operator 4.0 will be more and more knowledge-based and include decentralized decision making and participation in engineering activities (Peruzzini et al., 2020). This will naturally lead to a higher cognitive load on operators. One technology suitable to help the Operator 4.0 to handle the increased cognitive load is AR (Zolotová et al., 2020). The ability to both perform traditional tasks and the possibility to define new tasks and scenarios for Operator 4.0 can be greatly improved through visual computing technologies such as AR (Segura et al., 2020).

2.2 MANUFACTURING ENGINEERING

To manufacture means “to make (a product, goods, etc.) from, of, or out of raw material; to produce (goods) by physical labour, machinery, etc., now esp. on a large scale” (Oxford English Dictionary). The manufacturing engineering branch of engineering relates to manufacturing and production processes for industrial products (Matisoff, 1986). It entails the research and development of tools, processes, machines, and equipment; and further the integration of facilities and systems to optimize quality and expenses when creating products (Matisoff, 1986).

Matisoff (1986) divides manufacturing engineering into four basic functional areas: manufacturing planning, manufacturing operations, manufacturing research, and manufacturing control. Of these four areas, this thesis relates mainly to manufacturing research and manufacturing operations. It relates to manufacturing research in that it is a pursuit of new and better tools and procedures to improve manufacturing processes and reduce costs. It relates to manufacturing operations in that the goal is the improvement of existing procedures.

ARSG is a technology that has the potential to improve operator efficiency by improving operator access to updated information, thereby enabling more efficient procedures for the way operators work. However, this technology is still only used to a limited extent (Campbell et al., 2019). While some assembly stations have digital instructions, paper-based instructions are still the norm in manufacturing. If the instructions could instead be digitalized and displayed in a set of ARSG, this would mean a significant improvement compared to the current procedure of printing out and distributing paper-based instructions at each station.

2.3 ASSEMBLY

Assembly can be described as the aggregation of those processes were different parts and subassemblies are combined to form a complete and geometrically designed assembly or a product, either through an individual, batch or continuous process (Nof et al., 1997). In turn, assembly consists of assembly tasks which Nof et al. (1997) divides into two categories: parts mating and parts joining. They describe parts mating as two or more parts being brought into alignment or contact with each other. Four types of mating tasks are described: peg in hole, hole on peg, multiple peg in holes, and stacking. Further, they describe parts joining as a step done after parts mating, where fastening is applied so that the parts are kept together. Eight types of joining are described: fastening screws, retainers, press fits, snap fits, welding and related metal-based joining methods, adhesives, crimpings, and riveting (Nof et al., 1997).
The above definitions describe all types of assembly. This thesis addresses only industrial assembly that requires high efficiency. It is important to be able to assess assembly complexity to allow comparison of different assembly setups. Falck et al. (2016) describe criteria to assess the complexity, high or low, of basic manual assembly steps.

### 2.4 AUGMENTED REALITY

The concept of merging information into our vision was described in fiction in 1901, in the form of the “Character Marker”: “It consists of this pair of spectacles. While you wear them every one you meet will be marked upon the forehead with a letter indicating his or her character” (Baum, 1901 (p. 94)). Six decades later a head-mounted display that could show computer-generated line drawings in a person’s FOV was realized (Sutherland, 1968). In 1992 it was possible to superimpose and stabilize computer graphics at a specific position on a real-world object in a person’s FOV (Caudell and Mizell, 1992). The authors described this technology as follows:

> “This technology is used to ‘augment’ the visual field of the user with information necessary in the performance of the current task, and therefore we refer to the technology as ‘augmented reality’ (AR)” (Caudell and Mizell, 1992 (p. 660)).

Later, AR was defined as having the following three characteristics: To combine real and virtual objects, to do so in real time and interactively, and that this combination is registered in 3D (Azuma, 1997). The definition was not limited to specific technological implementations of AR, and in a follow-up study the definition was widened to include more senses than the visual, such as hearing, touch, and smell (Azuma et al., 2001). However, in this thesis AR is limited to visual augmentation, which is by far the most common form of AR. Even though this definition of the three-characteristics of AR is more than 20 years old, it is still widely adopted and cited in the field of AR.

Wang et al. (2016) made a comprehensive survey of AR assembly research and found, among other things, that AR has the potential to improve the performance of users. However, limitations occur in complex assembly processes, time-consuming authoring processes, integration with enterprise data, and intuitive interfaces.

There are many ways in which AR can be implemented, and there have been several taxonomies on the forms of technology. Bimber and Raskar (2006) define three main implementations: head-attached, handheld, and spatial. Peddie (2017) divides AR into two main categories: wearable and non-wearable. The non-wearable category is divided into mobile devices (such as smartphones and tablets), stationary devices (such as televisions and personal computers), and head-up displays. The wearable category consists of different forms of “near-to-the-eye displays, or NEDs” (Peddie, 2017 (p. 29)), divided into headsets, helmets and contact lenses. In both definitions there are three main divisions that can be made: the technology to create and display AR can be placed on the head in front of the eyes, in a lighter device that can be carried in one or both hands, or placed in the environment. Elements from both taxonomies have been combined in Figure 2.1 for this thesis.
Different forms of AR implementations have different advantages and disadvantages. A handheld implementation, for instance, can be a very fast and cost-efficient way to create an AR experience since it can be developed as an app for a phone or tablet, platforms that are widely available and well supported by development tools. Tablets and phones are also widely used and easily understood by an average person. However, there is a large drawback in that they require at least one of the user’s hands, which is a severe limitation for operators in general. They also require operators to place the device between themselves and the physical object(s) they want to augment, which can further limit their efficiency. For these reasons handheld implementations are not considered in this thesis.

Most of the technology to display AR is integrated into the environment in a spatial solution (Bimber and Raskar, 2006). This has the advantage of removing the need for an operator to wear technology, thus reducing the ergonomic strain that a wearable or handheld solution naturally creates through its weight. One drawback of a spatial solution is that its use is limited to augmenting objects that are close to where the technology is mounted. This can be a major restriction for operators who work over large areas or move between many different work areas/cells. However, it may not be a problem for operators who work in a single cell or similarly limited work area. Another drawback is that spatial augmented reality (SAR) is limited in depth, as it cannot project digital information in mid-air but needs a surface to project on (Uva et al., 2018). This requirement can be compensated for to some extent by using visual techniques such as color coding to indicate distance (Schmidt et al., 2016). When operators share a workspace, they cannot see a different set of instructions at the same place with SAR, since the AR is implemented into the environment rather than onto equipment for each individual operator. SAR shares its main advantage of being hands-free with wearable AR, but is not considered in this thesis due to the above limitations.

The wearable, head-attached solution has the advantage of always being in an operator’s FOV while still keeping their hands free. The technology is mobile and can follow the operator wherever he or she goes. This category is therefore seen as the most suitable for operators. To the author’s knowledge, there are currently no implementations of working AR contact lenses. Thus the only options for AR are headsets and helmets in the head-attached category (Peddie, 2017), as seen in Figure 2.1. In this thesis they are both seen as part of the category of Augmented Reality Smart Glasses (ARSG) since the main difference is that of size. This factor is only due to the relevant technologies not being more compact yet, rather than to any inherent advantage of size. Over time, helmets are likely to disappear as a category and be replaced by ARSG once technical

![Figure 2.1 Taxonomy of AR, adapted from (Peddie, 2017, Bimber and Raskar, 2006)](image)
advancements have made it possible to reduce the size enough. Besides the term ARSG there is also the term smart glasses (SG). How they are used differs in the literature. Sometimes the term SG are used for glasses with AR capability (Sedarati and Baktash, 2017, Kulak et al., 2020). Sometimes the term ARSG are used (Han et al., 2019). And, finally, sometimes ARSG and SG are used interchangeably (Ro et al., 2018, Kim et al., 2019). In this thesis the terms are considered distinct, with ARSG being a subset of SG, that ARSG are SG with the capability of displaying AR. The broader term SG refers to a device worn with one or two semi-transparent screens in front of the user’s eyes, with the screens allowing the user to see the real world and digital information.
RESEARCH METHODOLOGY
CHAPTER 3
RESEARCH METHODOLOGY

“The ethos of engineering is necessarily one of practical action”
(Nair and Bulleit, 2020 (p. 66)).

This chapter presents the overall research approach used for this thesis and explains these choices. It also describes what types of data have been collected and how. The overall research approach for this thesis has been to combine the methodology of design science with a mixed methods approach.

3.1 PHILOSOPHICAL PARADIGM – PRAGMATISM
This research was conducted in the field of industrial informatics and is an engineering project. Engineering can be described as a method to use heuristics to create the best possible change in situations where not all information is available and resources are limited (Koen, 1985). All useful tools, regardless of discipline, are considered in the engineering way of thinking (Nair and Bulleit, 2020). The available tools are constantly evolving and thus driving the evolution of engineering (Bulleit, 2015). The focus of this thesis is to find ways to improve current practice through a better understanding of operator support using ARSG, which is an emerging field.

The philosophical paradigm that this thesis follows is pragmatism. One common view of the pragmatic worldview is that it arises from actions, situations, and consequences, in contrast to the antecedent conditions of postpositivism (Creswell, 2014). The focus lies on applications, what works, and solutions to problems (Patton, 1990). The problem that the research should solve is focused on, rather than specific methods, and all available approaches are used to understand the problem (Rossman and Wilson, 1985).

Engineering and pragmatism have similarities. Pragmatism answers questions through iterative, corrective responses based on experience, which fits well into how engineering works with incomplete and changing knowledge (Nair and Bulleit, 2020). Since the topic to be researched is complex and still emerging, it is not possible to know
the optimal methods to use beforehand. Pragmatism allows a wide choice of methods that can contribute to a broader understanding of the subject.

3.2 MIXED METHODS

There are three main research paradigms: qualitative, quantitative, and mixed methods (Creswell, 2014). Qualitative research is inductive, building from particulars to general themes, with the data typically collected in the test person’s setting. Quantitative research, in contrast, focuses on examining the relationships among variables that can be measured and analyzed using statistical procedures. Mixed methods research collects both qualitative and quantitative data and integrates them (Creswell, 2014).

Mixed methods research uses both qualitative and quantitative methods, either concurrently or sequentially (Venkatesh et al., 2013). Often, a synthesis of both the quantitative and qualitative perspectives provides the most informative, complete, balanced, and useful research results (Johnson et al., 2007). Since neither the qualitative nor the quantitative perspective encompasses the whole of research, they are both needed for a holistic understanding (Newman and Benz, 1998).

Creswell (2014) describes three types of mixed methods: convergent parallel mixed methods, explanatory sequential mixed methods, and exploratory sequential mixed methods, as shown in Figure 3.1. A convergent parallel design consists of collecting qualitative and quantitative data at roughly the same time, and then comparing or relating the results to each other and interpreting the results. An explanatory sequential design first gathers and analyses quantitative data and then follows this up by gathering qualitative data to get a deeper understanding of the quantitative data. An exploratory sequential design first gathers and analyses qualitative data, and then follows this up by gathering quantitative data to validate the initial qualitative findings. Table 3.1 gives an overview of how the different types have been used in this thesis.

---

Figure 3.1: Three common mixed methods, adapted from (Creswell, 2014)
3.2.1 SUMMARY OF METHODOLOGY FOR RESEARCH AIM
This section gives an overview of the methodology for the thesis as a whole. Table 3.1 shows the research objectives, the methods used, the data collected, the sequence in which the data were analyzed, and the paradigm used. The table is color-coded for an improved overview. Qualitative entries are red, quantitative are blue, and mixed methods are green. If an objective is purely qualitative (like 1.1) or purely quantitative (like 1.2) then the “Summary” column is red or blue, respectively. If an objective contains both qualitative and quantitative data collection the “Summary” column is green.

Table 3.1 Graphical overview of the research objectives, the methods, data, type, and (if mixed method) sequence of qualitative and quantitative methods.

<table>
<thead>
<tr>
<th>Prerequisite</th>
<th>Qualitative</th>
<th>Quantitative</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Group discussion</td>
<td>Improvement</td>
<td>Survey</td>
</tr>
<tr>
<td>0.2</td>
<td>Meta-analysis</td>
<td>Relation-hierarchies</td>
<td>Scoping review</td>
</tr>
<tr>
<td>RQ1</td>
<td>Rapid review</td>
<td>Research papers</td>
<td>Qualitative</td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td>Survey</td>
<td>Experiment</td>
</tr>
<tr>
<td>1.2</td>
<td>Interview</td>
<td>Patterns</td>
<td>Observation</td>
</tr>
<tr>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQ2</td>
<td>Rapid review</td>
<td>Research papers</td>
<td>Qualitative</td>
</tr>
<tr>
<td>2.1</td>
<td>Interview</td>
<td>Expert knowledge</td>
<td>Expert knowledge</td>
</tr>
<tr>
<td>2.2</td>
<td>Focus group</td>
<td>Expert knowledge</td>
<td>Expert knowledge</td>
</tr>
</tbody>
</table>

3.2.2 MOTIVATION FOR USING MIXED METHODS
It is important to note that while mixed methods research may seem to combine the best of two extremes, it is not to be seen as a panacea or cure-all solution, but should serve certain purposes (Venkatesh et al., 2013). Venkatesh et al. (2013) summarized seven purposes for mixed methods research: complementarity, completeness, developmental, expansion, corroborations/confirmation, compensation, and diversity. This thesis has followed a developmental purpose, which can be described as a form of iterative design where new questions are derived from previous research (Venkatesh et al., 2013). The RQs investigate the perspectives of two groups that have different agendas and thus different views. The methods adopted are mainly qualitative, to gain a better understanding of these groups’ realities and needs.

Hathcoat and Meixner (2017) identified some inherent risks when using mixed methods research from a pragmatist perspective which they formulated as a conditional incompatibility thesis. What they mean with this is that there is a risk in mixed methods research that actions are taken within a single study that have inconsistent philosophical prescriptions and, if left unaddressed, can challenge the what-works maxim in a mixed methods approach. The problem they identify relates to the many pragmatists in mixed methods research who de-emphasize philosophical aspects in favor of the what-works maxim. They concluded that the perceived incompatibility is a result of
researcher’s actions, such as methodological decisions asking questions ripe with philosophical assumptions and approaches to the interpretation of data, and is not due to an inherent incompatibility between qualitative and quantitative data (Hathcoat and Meixner, 2017). These risks will therefore be accounted for in the data collection and analysis. It is also important to consider the underlying philosophical worldview to be aware of what biases exist.

3.3 DESIGN SCIENCE
The methodology used for this thesis is design science. There are two basic activities that design science consists of: to build and to evaluate (March and Smith, 1995). In the building activity an artifact is created for a specific purpose and in the evaluation it is determined how well the artifact performs (March and Smith, 1995).

While the aim of natural science is to understand and explain phenomena, the aim of design science is to develop ways to achieve human goals (March and Smith, 1995). Design science can therefore be seen as a more pragmatic methodology, and focuses on the creation of artifacts to help further knowledge. It uses practical implementation to find more effective ways of doing things. Because of this, a common critique against design science is that design takes place all the time without it being called science. Therefore it is important that design choices are well motivated and evaluated before and after they are made (Oates, 2005). The artifacts and the process of creating them is science, since this process generates new knowledge.

According to March and Smith (1995), the products of design science can be one of the following: constructs, models, methods, and implementations. They define constructs as the basic concepts needed to characterize phenomena. Models use a combination of constructs to describe tasks, situations, or artifacts. Methods are the ways to perform activities which can be used to create specific implementations to achieve the goals.

3.3.1 APPLICABILITY TO THE THESIS
Hevner et al. (2004) established seven guidelines for effective design science research. They do not advocate strict adherence to the guidelines, but rather that the guidelines should form a basis for determining whether something is good design science research. This section gives a short description of these guidelines based on Hevner et al. (2004), and accounts for how they apply to this thesis.

Guideline 1: Design as an artifact. Design science creates artifacts to address relevant problems. The design process is shown to be feasible through the artifact. The creation serves as proof that it can be done and provides a way to change how tasks and problems are conceived.

One part of evaluating the results of this thesis is to create AR demonstrators to provide research participants with a better understanding of how different aspects of the research could turn out in a real implementation. It will also result in the creation of a framework that can be used for evaluation. Therefore this thesis follows guideline 1.

Guideline 2: Problem relevance. If a problem is not relevant, that is, if solving the problem does not lead to a better situation in any real application, solving the problem has no value.

This thesis aims to enable integration of ARSG into current production systems, an area that, as described in Chapter 1, needs more research. The involvement of Volvo Car Corporation, a global manufacturer, in this thesis is based on their interest in developing a better understanding of how AR can be integrated into their production. Therefore this thesis follows guideline 2.
Guideline 3: Design evaluation. Since design science focuses on practical improvements to real problems, the design must be evaluated to show that there has been an actual improvement. How this is measured varies with what is relevant in each application field, but it should be both relevant and comparable.

The research participants will be operators and integrators of production systems. The results that are gathered can be compared to current production and thus evaluated. It is unlikely in the scope of this thesis that the framework will be tested in a running production system, so there will not be a full empirical evaluation of the framework. The plan is, however, to use other relevant forms of evaluation such as simulations and comparison to a running production system. Therefore this thesis follows guideline 3.

Guideline 4: Research contributions. This boils down to the fact that all research must create new knowledge. Design science can contribute through the design artifact if it solves unsolved problems or solves old problems in new ways. It can also contribute by developing new constructs, models, or instantiations. It can also contribute by creating new evaluation methods and new evaluation metrics.

To the best of the author’s knowledge, there is no current framework for how to integrate, update, and maintain ARSG for assembly operator support from the perspectives of operators and manufacturing engineers. Therefore this thesis follows guideline 4.

Guideline 5: Research rigor. This addresses how the research is done, such as the replicability of the process and the assumptions made. Design science should balance the need for simplifications to make quantifiable measurements/calculations with the need for relevance.

This research has been done in close collaboration with Volvo Car Corporation. There has been a continual dialog with industrial managers and experts to ensure the relevance of the results. Thorough literature reviews has been done to link the thesis to current knowledge. Section 3.4 provides a thorough review of the data collection methods. Based on this the author concludes that this thesis follows guideline 5.

Guideline 6: Design as a search process. Real business problems are usually too complex to allow an exhaustive search of solutions. Therefore the goal of design science is not to find the best solution but to find a better solution than currently available.

A framework for integrating ARSG as assembly operator support from an operator and manufacturing engineering perspective is too complex a problem to search for all possible solutions. Thus in this thesis the focus was limited to the perspectives of operators and manufacturing engineering, and an iterative approach was used to continually improve the framework. Based on this, the author concludes that this thesis follows guideline 6.

Guideline 7: Communication of research. This guideline addresses presenting information about the research in a format that the target audience can understand. Those who focus on technology should be able to implement the results, and those who focus on management should be able to decide on the strategic value of implementing the results.

Since the goal of the thesis is to create a framework for integration, it should be understandable for someone with a focus on technology. Some of the results have also been communicated through fairs and similar events for industrial managers, who have expressed interest in and understanding of the topics, and have engaged in discussions regarding implementation. Chapter 1 also lists scientific publications and conferences.
where the research results have been communicated. Based on this, the author concludes that this thesis follows guideline 7.

To summarize, this thesis has been assessed and judged to follow all seven guidelines laid out by Hevner et al. (2004). Therefore, it is concluded that design science is a suitable methodology.

Ethical considerations

The ethical considerations for this thesis are based on the recommendations of the Swedish Research Council (Röcklinsberg et al., 2011). For the many user tests and observations during the research done for this thesis, it was important to ensure informed, and preferably written, consent from all research participants. Information provided to research participants has included information about the purpose of the research, their role, the expected results, and how the results are to be used. In some cases what was said before the experiments was limited so as to not affect the results. In such cases, participants were informed afterwards. Some experiments included human-robot collaboration (HRC) and care was taken to ensure the safety of all humans involved. The potential risks to research participants were estimated to be small enough to not warrant evaluation in accordance with Swedish legislation (SFS, 2003).

Data collection and analysis

As mixed methods were used, this section presents information on how both qualitative and quantitative data were collected and analyzed. Each section is presented separately with its own analysis in accordance with the recommendations of Venkatesh et al. (2013). This is followed by connecting the methods to the RQs and their objectives to show the practical application used in this thesis.

3.3.2 APPLICABILITY TO PREREQUISITE

Prerequisite: Is the thesis relevant to industrial partners and novel for the scientific community?

This question was posed to ensure that this thesis was a valuable contribution to both theory and practice. For a practical contribution the thesis needs to be relevant to the manufacturing industry, and for a theoretical contribution there needs to be a knowledge gap this thesis helps to fill. This is addressed in the two objectives described below.

Prerequisite, O1 Ensure relevance and feasibility for industrial partners at management level.

The initial relevance comes from the initiation of the thesis by the industrial partner. VCC initiated the thesis, gave it the initial direction of operator support, and has been an active partner throughout the thesis. An industrial mentor, Rodney Lindgren Brewster, provided practical support as well as industrial input when alternative research directions were considered to ensure industrial relevance.

This objective was also met by using design science to create an experimental platform. The platform was then used to perform tests to assess whether test persons can perform assembly by following AR instructions. The user tests were quantifiably evaluated through surveys and qualitatively through unstructured interviews and group discussions. The relevance of the platform was assessed by discussions with industrial representatives.

Prerequisite, O2 Conduct a literature review on ARSG in manufacturing.

This objective was met by performing a structured scoping review of AR in manufacturing. The method used was based on (Booth et al., 2016). All literature reviews related to AR and manufacturing that were found using specified search phrases were
included to ensure wide coverage. Aspects related to operators and ARSG were extracted to map out the current understanding of the field and to spot knowledge gaps. The extraction was done by first extracting quantitative data from the reviews in the form of identified keywords, topics, and themes. The data was arranged in tables and analyzed qualitatively by sorting out data relevant to ARSG in manufacturing into three perspectives (operators, manufacturing engineering, and technological maturity) and arranging their corresponding sub-categories into a hierarchy.

3.3.3 APPLICABILITY TO RQ1

**RQ1: What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?**

This RQ has two aspects. One aspect is identifying how operators view instructions in order to gain better insight into how they think about interfaces and information and their need to feel safe with an interface. The other aspect is to identify central aspects that need to be conveyed to operators to ensure that work is done correctly. The objectives described below address these two perspectives to create a holistic answer to how they can both be addressed.

**RQ 1, O1 Conduct a literature review on ARSG in manufacturing from an operator perspective.**

The literature review was a rapid review. According to Tricco et al. (2015) there is no formal definition of rapid reviews. They instead based their definition from (Khangura et al., 2012), that rapid reviews simplify some of the steps in a systematic literature review to produce results in a shorter time frame. The steps that were simplified varied in their findings.

For the literature review related to this objective, data collection was done iteratively based on keywords from the previous literature review in paper 3 (Danielsson et al., 2019), together with keywords, citations, and relevant keywords identified in the papers. The survey ended for each topic when sufficient coverage of the topic had been gained. Analysis of the topics was an iterative per-paper process with a qualitative analysis. Each paper was, read, interpreted, and the synthesized results added to the findings to gain an overview of the different topics.

**RQ 1, O2. Ascertain that operators are willing to work with ARSG.**

To get a preliminary answer, operators were asked about their views on using ARSG after they said that they understood what the technology is. This was also in part addressed in RQ 1.1 when assessing other existing cases of real-time usage. Since the start of this research, there are now also real-world examples of operators working with ARSG (Campbell et al., 2019).

Interviews were performed and recorded, which allowed for both quantitative and qualitative data extraction. However, for this objective quantitative data was obtained through survey questions asked during interviews. The findings in the literature provided empirical examples that affirm the objective and are quantitative in nature.

**RQ 1, O3 Identify operators’ needs in information systems.**

Observations of operators in their working environment yielded quantifiable data on how they currently interact with information. The observations provided a way to quantify the interaction, and also identified phenomena that operators might not have been aware of themselves. Interviews gave deeper explanations of how and why they interacted with different information. Findings in the literature review in objective 1.1 also provided insights from theory.
Analysis of observations allowed for quantifying information interaction by type. Interviews and debriefings after observations allowed for qualitative insights from the operators, and their views on how they interact with and want to interact with information systems.

3.3.4 APPLICABILITY TO RQ2

RQ2: What do manufacturing engineers and technicians need in ARSG so the technology can be integrated into, maintained, and updated in a production system?

This RQ has two aspects. The first is to identify previous findings of relevance for integrating, updating, and maintaining ARSG in a production system. Both theoretical findings and technological maturity are relevant. The other aspect is to gather the perspectives of manufacturing engineers and technicians who work with integration, maintenance, and updates of production systems.

RQ 2, O1 Conduct a literature review on ARSG in manufacturing from an integrator and technical perspective.

As with the literature review of objective 1.1, this was a rapid review with iterative data collection based on the results from the literature review in objective 0.2. As before, the survey ended when sufficient coverage of the topic had been gained. The topics were analyzed iteratively paper-by-paper using qualitative analysis. Each paper was also read, interpreted, and then the synthesized results were added to the findings to gain an overview of the different topics.

RQ 2, O2. Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.

This is done through focus groups and interviews and has a qualitative focus. The motivation for this approach is that engineers and technicians mostly work in teams where work tasks are discussed and solved in groups. It is therefore assumed that this will be the most natural forum for them to cooperate in, and the easiest way for them to provide their insights. Recordings allow for in-depth analysis.

 Dependencies and flowchart for research aim

This section shows how the research objectives depend on each other. Figure 3.2 gives an overview of what could be done in parallel and of what needed to be completed before something else could be achieved. The same color coding as in Table 3.1 is used: Qualitative entries are red, quantitative are blue, and mixed methods are green.
The prerequisite for the thesis is at the top of Figure 3.2. The two corresponding objectives are independent of each other and can be run in parallel. Both objectives need to be met before the thesis moves on to RQ1 and RQ2, both of which are independent of each other and can be run in parallel. They each have a literature review (1.1 and 2.1 respectively) which are separate extensions of the literature review in 0.2, and they thus depend on 0.2. RQ1 has two more objectives, 1.2 and 1.3, which are independent of each other and provide data to objective 3.1. RQ2 has one more objective, 2.2, which also provides data to objective 3.1. RQ3 has three objectives which are all dependent on each other in a sequential order from 3.1 to 3.3. Objectives 3.2 and 3.3 are planned to allow an iterative process if the evaluation in objective 3.3 does not meet the requirements. In this case the process will return to 3.2 for further improvements.
RESULTS
CHAPTER 4
RESULTS

This chapter presents the results to date. It starts with an overview of the key findings in all publications, and then summarizes the answers to the RQs.

4.1 KEY FINDINGS IN EACH PUBLICATION
The following section presents the key findings relevant to the thesis from each of the five publications included in this thesis. It also presents which objective(s) have been met and to what extent.

4.1.1 PAPER 1: ASSESSING INSTRUCTIONS IN AUGMENTED REALITY FOR HUMAN-ROBOT COLLABORATIVE ASSEMBLY BY USING DEMONSTRATORS
The first paper reports on the development of an AR interface that was integrated into a demonstrator simulating an assembly process (Figure 4.1). The design was based from a previous demonstrator but adjusted to fit the top-down view (Syberfeldt et al., 2015). The demonstrator served as a proof of concept of key technologies in operator support: AR, speech recognition, and human-robot collaboration (HRC). It was tested by four test groups of high school students using the System Usability Scale (SUS). SUS has been shown to be a simple and reliable tool for usability evaluations (Brooke, 2013). The demonstrator was developed in collaboration with Patrik Gustavsson, another PhD student working in collaboration with VCC on a parallel thesis. Initially, both of the theses were interested in AR and HRC. Testing showed the technologies were feasible and promising. The demonstrator served as a platform to disseminate the concepts to both the public and industrial representatives, particularly in VCC. The response from VCC managers was positive and the hands-on experience of working with the demonstrator was an effective way to explain the technology. Based on the findings of the paper and after strategic meetings, it was decided to focus this thesis on ARSG rather than more general AR, and to remove aspects of HRC from the thesis. This paper fulfilled research objective 0.1.
4.1.2 PAPER 2: OPERATORS PERSPECTIVE ON AUGMENTED REALITY

The second paper reports on how operators interact with information today. It also shows their views on how interactions can be improved and on ARSG as a medium for presenting information. The operators were observed during assembly to identify at which types of work-steps they interacted with the current interface. Table 4.1 shows how often the operators checked the interface, and why. The results showed that the operators mainly looked at the current interface to check the required torque, the time it took them to assemble an object, and when something went wrong. In general, they looked at instructions mostly when interaction was needed.

Table 4.1 Frequency of reasons that operators look at instructions

<table>
<thead>
<tr>
<th>Reasons to look at instructions</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required torque for screwing machine</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Assembly time</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Something goes wrong</td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Learning new steps</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Must look at station 240</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Deviations from normal</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Lose their place in the process</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>“When it’s needed”</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>When production stops</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>If RFID tag does not react</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
The operators were also interviewed to gain quantitative as well as qualitative data. In the interviews, 21 out of 28 operators expressed a positive view of using ARSG, 6 were neutral, and one expressed concerns. The positive views were unprompted, but came sporadically from the operators after an explanation of the technology and how it could be related to their future work situation.

This paper fulfilled objectives 1.2 and 1.3.

4.1.3 PAPER 3: AUGMENTED REALITY SMART GLASSES FOR INDUSTRIAL ASSEMBLY OPERATORS: A META-ANALYSIS AND CATEGORIZATION

This structured literature review provided a comprehensive overview of previous research on ARSG in manufacturing. The review searched through four databases for all literature reviews related to AR in assembly, industry, manufacture, or maintenance since 2015. The seven review papers identified were then meta-analyzed by analyzing keywords and other central aspects mentioned. The results were sorted based on their relevance to ARSG and assembly, and categorized into three perspectives with corresponding categories. This created an overview of theoretical work done previously and provided a basic understanding of how the different areas of interests are connected.

The conclusions drawn in the analyzed literature reviews showed that there are still significant knowledge gaps in the area of ARSG for assembly operators, thus validating the relevance of the thesis.

This paper fulfilled research objective 0.2.

4.1.4 PAPER 4: AUGMENTED REALITY SMART GLASSES FOR OPERATORS IN PRODUCTION: SURVEY OF RELEVANT CATEGORIES FOR SUPPORTING OPERATORS

This literature review gave an overview of the operator perspective, as categorized in Paper 3. The review explored the categories of assembly instructions, human factors, design, and validation in the two categories support and training. Exploring these categories together provided a holistic understanding of the state of the art in relation to operator assembly support, as well as suggesting important future work.

This paper fulfilled research objective 1.1.

4.1.5 PAPER 5: AUGMENTED REALITY SMART GLASSES IN INDUSTRIAL ASSEMBLY: CURRENT STATUS AND FUTURE CHALLENGES

In the third literature review the final two perspectives were explored to complement the findings from Paper 4 with the two missing perspectives of manufacturing engineering and technological maturity from Paper 3. Some of the key findings from the manufacturing engineering perspective were related to improving support for creating instructions. These include help for non-programmers in creating instructions, and help for orienting parts based on CAD data. There were also preliminary findings that instructions could be automatically extracted from video recordings. However, there are continued challenges to automatically generating AR instructions. There are guidelines for evaluating and buying ARSG for assembly support, but they need to be further broadened and validated. Product-integrated sensors have facilitated ease of access to the status of individual products, but there is still work to be done to integrate
the data from these sensors for ARSG instructions. Validating ARSG designs in systematic and comparative tests is still an emerging topic, and learning and prototype factories have proven to be useful test environments.

FOV and battery capacity are key technological demands from a technological maturity perspective. However, the demands need to be reevaluated once ARSG becomes integrated in manufacturing.

This paper fulfilled research objective 2.1.

### 4.2 ANSWERS TO RQS

This section provides complete answers to the prerequisite RQ and RQ 1 as well as a partial answer to RQ 2. For each RQ the objectives are first thoroughly presented and answered before the entire RQ is answered.

#### 4.2.1 PREREQUISITE: INDUSTRIAL RELEVANCE

The prerequisite for starting this thesis was formulated as a question: “Is the thesis relevant to industrial partners and novel for the scientific community?”

To answer this, two research objectives were defined:

1. Ensure relevance and feasibility for industrial partners at management level.
2. Conduct a literature review on ARSG in manufacturing.

The first objective was primarily assessed through Paper 1 (Danielsson et al., 2017). At the time of its publication, the use of AR in actual production was limited as previously described in Chapter 2. Experiments to determine relevance could be performed by creating a demonstrator, which also served the purpose of disseminating the results to the public and industrial representatives. A representative from VCC provided input to design decisions to ensure industrial relevance. By displaying the demonstrator at fairs and allowing lay people to interact with it, it was easier for them to understand the concept of AR and HRC. Industrial managers from both VCC and other companies showed great interest in the concepts. This gave them a better understanding of the potential for the technology and practical evidence that it could be implemented. Many discussed their own ideas for using the technology. The combination of Paper 1 and the subsequent dissemination ensured that the thesis is relevant to the manufacturing industry and that it is feasible to implement the technology.

The second objective was covered in Paper 3 (Danielsson et al., 2019). A structured search for other literature reviews of AR in manufacturing showed that this review had covered previous research well. Paper 3 included publications from 2015 to 2019. It was assumed that since literature reviews by their nature look backward in time, any literature reviews earlier than 2015 would review papers too old to be relevant. One of the papers reviewed, for instance, (Wang et al., 2016), reviewed papers between 1990 and 2015. Another aspect of time is that AR in general, and ARSG in particular, has seen large advances in the last few years, making a long time span even less relevant. Reviewing literature reviews and doing a meta-analysis gave a broad overview of the research field of ARSG for the manufacturing industry. The mapping that was done for this thesis showed good consistency between the reviewed papers, which gives credence to the mapping being consistent with the literature. The conclusions and future work in the reviewed papers pointed out research gaps relevant to this thesis. The gaps included real-time tracking for industrial scenarios (Wang et al., 2016), poor hardware maturity (Fraga-Lamas et al., 2018), and a need to integrate AR with other contemporary systems (Damiani et al., 2018). Palmarini et al. (2018) concluded that a number
of areas in AR need to be improved, but that AR is close to being deployable to its full potential in industry within maintenance. As a whole, the papers showed that AR still had some challenges but was also nearing maturity for industrial application. These conclusions were drawn during the analysis, but were excluded from Paper 3 due to size limitations. This provided an academic affirmation that the field is starting to mature but there are still important gaps.

To summarize, the answer to the prerequisite question is that yes, the thesis is relevant to the industrial partners in accordance with the results presented above. As regards to scientific contribution the results presented above show that there is a relevant research gap to be filled, to the best of the author’s knowledge.

4.2.2 RQ1: OPERATOR PERSPECTIVE

The first RQ was: “What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?”

To answer this, three research objectives were defined:

1. Conduct a literature review on ARSG in manufacturing from an operator perspective.
2. Ascertain that operators are willing to work with ARSG.
3. Identify operators’ needs in information systems.

The first objective was met in Paper 4 (Danielsson et al., 2020a) which explored the operator perspective as previously defined in Paper 3 to provide a deeper understanding of the operator perspective. The paper divided the operator perspective into a number of categories. In the category “Assembly instructions,” the current status was summarized by stating that there were no common standards for designing and distributing instructions. Operators had expressed an interest in having individual and dynamic instructions better suited to their needs (Danielsson et al., 2018). Future challenges lie in fully digitalizing and standardizing instructions to facilitate ARSG implementation. In the category “Human factors,” it was found that although the weight of ARSG equipment obviously should be kept to a minimum, the weight distribution was generally seen as being more important. The optimal weight distribution depends on the angle of the head – in general the center of mass should be inversely related to the angle of the head; that is, the center of mass should be toward the back of the head when leaning forward (Chihara and Seo, 2018). Video-based ARSG seems to induce more motion-sickness than optical see-through, although, according to (Vovk et al., 2018), the topic needs more study. In the “Design” category, it was found that there are currently several guidelines for designing interfaces for AR in general. Some important factors are the need to find a balance in how much guidance to give (Gavish et al., 2011), and the need to support procedural and semantic memory (Kourouthanassis et al., 2015). Designers should provide virtual “funneling” to help in orienting (Biocca et al., 2006, Schwerdtfeger et al., 2011), and combine force sensors and AR to improve error detection (Dalle Mura et al., 2016). In the category “Support,” it was shown that task routine is harder to achieve when product life-cycles decrease and variants increase (Hold et al., 2016). A particular case presented by the industrial partner VCC was single inspection point (SIP) stations. At these stations operators regularly receive new assembly details to inspect. However, the main problem for operators was not learning new things to inspect but rather unlearning the old things they used to inspect. In the category “Training,” it was found that there are several limitations in current ARSG research in that many experiments have used students and simplified assembly tasks such as LEGO assembly tasks (Werrlich et al., 2017). AR-based training has also mostly been compared to paper- or video-based instructions, not face-to-face
training, and most measurements have been on assembly time rather than quality and training transfer rates (Werrlich et al., 2017). Werrlich et al. (2018) attempted to close the gap on training transfer rates with ARSG in industrial environment, and found that errors can be reduced if operators are given a quiz no the task they just trained on. It has also been found that adding intelligent support can significantly improve training results (Westerfield et al., 2015). Johansson et al. (2017) also found a wish from operators to have dynamic support, which seems to support the findings of (Westerfield et al., 2015). In summary, the first objective provided a deep theoretical understanding of the current state of operator perspectives on ARSG, as well as future challenges to focus on.

The second objective was fulfilled in part through Paper 2 (Danielsson et al., 2018). Paper 2 found a clear interest from operators in working with ARSG, with only one operator expressing concern, 6 remaining neutral, and 21 expressing spontaneous positive reactions. Since that publication there has been further development of ARSG. (Campbell et al., 2019) provides examples of ARSG being used by assembly operators in production. To the best of the author’s knowledge, this was not the case at the start of this thesis. This can be seen as an indicator of the novelty of the general field of ARSG as assembly operator support. Through the second objective it was ascertained that operators are indeed willing to work with ARSG, as presented here. This simplifies implementation of ARSG as operator support.

The third objective was fulfilled through a combination of Paper 2 (Danielsson et al., 2018) and Paper 4 (Danielsson et al., 2020a). Paper 2 contributed observations and interviews with operators. The observations and subsequent interviews revealed that operators looked at instructions for things that provided feedback, for instance, to confirm that they had used the correct torque for screwing operations, or how long they took to perform one assembly cycle. When asked when they looked at instructions, many operators mentioned that they looked when something went wrong, that is, when things did not go as expected. They also expressed that more individual instructions would be of value. Paper 4 contributed through one of the categories of the operator perspective being “assembly instructions.” The research reviewed identified important aspects of how to design assembly instructions, such as using multimedia instructions (both text and pictures) (Irrazabal et al., 2016), adapting instructions according to experience level (Wolfartsberger et al., 2019), and keeping instructions as simple as possible with minimal text (Mattsson et al., 2016).

To summarize, RQ1 was answered mainly through the results of Paper 2 and Paper 4, with some of the main highlights presented in this section.

4.2.3 RQ2: MANUFACTURING ENGINEERING PERSPECTIVE
The second RQ was: “What do manufacturing engineers and technicians need in ARSG so the technology can be integrated into, maintained, and updated in a production system?”

To answer this, two research objectives were defined:

1. Conduct a literature review on ARSG in manufacturing from an integrator and technical perspective.
2. Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.

The first objective was met through Paper 5 (Danielsson et al., 2020b), which explored the manufacturing engineering and technological maturity perspectives as previously
defined in Paper 3 to provide a deeper understanding of these perspectives. The manufacturing engineering perspective had three topics to explore: authoring, infrastructure, and validation. The technological maturity perspective had four topics to explore: technological demands, enabling technology, ARSG, and tracking.

On the topic of “Authoring,” there is some support for creating AR content without programming skills (Bocevska and Kotevski, 2017) and limited AR experience (Erkoyuncu et al., 2017). There was also support for advanced features such as simulating occlusion through calculating video-depth from Kinect cameras (Gimeno et al., 2012), using CAD data to detect orientation (Mourtzis et al., 2017), and preliminary results in automatic generation of multimedia instructions for assembly operators (Kaipa et al., 2018). Some future challenges lie in improving functionality and reducing lead times in instruction authoring and generation.

On the topic of “Infrastructure,” the current status includes product-integrated sensors for decentralized input (Paelke, 2014). This allows products to track their own status and enhances the surrounding environment by providing a digital coordinate system that allows ARSG systems to determine where they are (Yew et al., 2016). There are also evaluation guides for choosing AR equipment (Palmarini et al., 2017, Syberfeldt et al., 2017). Future challenges lie in providing high data rates of around 25 Mbps and a latency of around 1 ms (Li et al., 2018). The guidelines for ARSG investment also need to be validated and broadened.

The topic of “Validation” showed that specialized learning factories are useful test environments for AR (Juraschek et al., 2018, Hennig et al., 2019). It was also found that “published evaluation and test results often cover out-of-date hardware or prototype systems” (Paelke et al., 2018 (p.26)). Future challenges identified were to enable usability tests of visualization and generally a more adaptable test platform (Paelke et al., 2018).

The topic of “Technological demands” identified a general lack of standards for AR as regards vertical industrial application (Ji et al., 2019). Some technologies need to be improved, for example, the FOV needs to be extended (Syberfeldt et al., 2017), battery capacity needs improving (Wang et al., 2018), and system data needs to be integrated with enterprise data (Wang et al., 2016).

The topic of “Enabling technology” was divided into three subtopics: “Technological level,” “FOV,” and “Battery.” The “technological level” subtopic found that the technological readiness level (TRL) of relevant technologies varies. Smart glasses (SG) without AR functionality have a TRL of 9, AR displays have a TRL of 7, and tracking, interaction, and user interfaces (UI) a TRL of 5 (Lacueva-Pérez et al., 2018). Other estimations of AR TRL varied from 4 to 7 (Eckert et al., 2019, Salvador et al., 2019, Harrison et al., 2019). There is a need to improve industrial adaptation and raise the TRL of the individual components that make up ARSG. The subtopic of “FOV” showed there is an experimental setup with a FOV of 100 degrees diagonally (Dunn et al., 2017), compared to the commercially available Hololens 2 with a FOV of up to 52 degrees (Danielsson et al., 2020b). The “Battery” subtopic found that both battery capacity and how it is measured varies significantly in commercially available ARSG (Danielsson et al., 2020b).

The topic of “ARSG” mapped different commercially available or previously available ARSG systems between 2013 and 2019, based on the findings of (Fang et al., 2019, Kumar et al., 2018, Syberfeldt et al., 2017). There is great variation in the properties of ARSG. For instance, the weight can vary from 69 to 579 grams and the FOV from 15 to 52 degrees diagonally. Many companies have discontinued production of ARSG. This
indicates that ARSG is still an emerging market where a few strong actors are taking the lead in development.

The “Tracking” topic investigated which tracking technologies had been identified in the literature and which were suitable for industrial settings. The technologies were grouped into electro-magnetic, inertial, magnetic, ultrasonic, and vision-based (DiVerdi and Hollerer, 2007, Chatzopoulos et al., 2017, Joshi et al., 2019). Many tracking solutions used a hybrid approach by combining different tracking techniques to compensate for different weaknesses (Chatzopoulos et al., 2017). It was found that Bluetooth low energy (BLE) can be used to estimate the general position of an object and be used with vision-based AR as a hybrid tracking system (Tsai and Hsu, 2016). BLE beacons are also likely to be a key enabling technology for the Internet of Things (IoT) (Jeon et al., 2018). Radio frequency identification (RFID) can similarly be combined with cameras to provide a hybrid tracking solution (Sun et al., 2016). Microelectromechanical systems (MEMS) have made it possible to reduce the size of sensors such as accelerometers, gyroscopes and magnetometers (del Rosario et al., 2015). However, the small size has introduced problems with drifting (Sheng-lun et al., 2017), as well as noise and magnetic interference (Artemciukas et al., 2016). Magnetometers, gyroscopes and accelerometers have been used to complement image processing to provide hybrid tracking (Artemciukas et al., 2016).

Research objective one provided a deep and broad understanding of the current technological maturity of ARSG and possible ways to implement it. It also showed what support is available for integrators to enable ARSG on the factory floor in the long term.

At the time of writing this thesis, the second objective has not yet been fully met. Further information can be found in the section on future publications. The preliminary results are the findings in the literature review presented in the first objective of the RQ above.

4.3 SUMMARIZED RESULTS

This last section of Chapter 4 briefly summarizes the results. The first RQ was the prerequisite: Is the thesis relevant to industrial partners and novel for the scientific community? The findings presented show that the thesis is relevant for industrial partners and, to the best of the author’s knowledge, novel for the scientific community.

RQ 1 asked: What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly? Some of the key findings show that operators want dynamic and individual instructions, and that the design of ARSG needs to consider ergonomic factors, particularly weight distribution. Information must be presented so that it is both safe and easy to understand.

RQ 2 asked: What do manufacturing engineers and technicians need in ARSG so the technology can be integrated into, maintained, and updated in a production system? Some of the key preliminary findings were that tracking technologies suitable for industrial use exist, but guidelines for evaluating ARSG still need more research.
SUMMARY AND FUTURE WORK
CHAPTER 5
SUMMARY AND FUTURE WORK

This chapter summarizes the RQs and the results to date. The thesis and its current state are then evaluated, followed by a plan for the remaining research needed for a PhD degree.

5.1 SUMMARY
This thesis has presented two RQs that build on each other toward a framework for integrating an interface for ARSG into an assembly production system. The current work has given answers to the prerequisite, RQ1, and partially for RQ2. The prerequisite objective showed that the thesis is a valuable contribution to both theory and practice. RQ1 was answered, providing an overview of the theory and insight in how operators currently interact with instructions, and how they would like to interact with ARSG. RQ2 received a partial answer in surveying the literature. The following section outlines how RQ2 will receive its final answer, as well as other relevant future work.

5.2 FUTURE WORK
Two more publications are planned to merge the perspective of RQ 1 and RQ 2 into a framework. The first publication, Paper 6, is related to the first creation and validation of the framework. Objective 2.2 is to “Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.” It will provide the perspective not yet covered in order to provide a base for the merging into a framework. Further work will be to evaluate the information gathered from RQ 1 and RQ 2, and will provide a holistic view of both the operator and integrator perspectives. This will then be synthesized into a framework and is simply the process of creating the framework to be evaluated and used for integrating ARSG in production. The last step will be to evaluate the practical usefulness of the framework for industry in making strategic decisions about ARSG, and will serve as the final validation of the thesis by validating the framework in an industrial setting.

The second publication, Paper 7, is also related to the further improvement and validation of the framework. This is because of the iterative design used to improve on the framework from Paper 6. These two publications should cover all the further research objectives to the extent that satisfying answers can be given to all RQs, thereby finalizing this research project and fulfilling the main requirements for a PhD degree.
5.2.1 PAPER 6: FRAMEWORK CREATION AND EVALUATION

Paper 6 is currently being written. Its practical contribution will lie in the creation of an evaluation framework to help in evaluating this specific case for operator support. It will assess how high to rank the option of investing more time in researching ARSG investment options. The framework is in the form of a web-survey with multiple options and follow-up questions. The design of the framework is based on the knowledge gained in the previous papers and the experience of industrial managers and experts in production and technical development.

5.2.2 PAPER 7: FRAMEWORK REFINEMENT AND EVALUATION

Paper 7 will be an iteration of the design of the framework in Paper 6 to further improve on it based on the data gathered from the evaluation in Paper 6. The combination of the theoretical foundation, industrial involvement, empirical testing, and iterative process should provide a satisfactory answer to research objective 2.2 as well as further objectives related to the final creation and validation of a framework. Thus all the objectives this thesis has outlined will have solutions and the RQs will have been fully answered.
REFERENCES
REFERENCES


BULLEIT, W. M. 2015. The engineering way of thinking: The idea. STRUCTURE, 58.


GAVISH, N., GUTIERREZ, T., WEBEL, S., RODRIGUEZ, J. & TECCHIA, F. Design guidelines for the development of virtual reality and augmented reality training


NELLES, J., KUZ, S., MERTENS, A. & SCHLICK, C. M. Human-centered design of assistance systems for production planning and control: The role of the human in Industry 4.0. 2016 IEEE International Conference on Industrial Technology (ICIT), 2016 Taipei. IEEE, 2099-2104.


OXFORD ENGLISH DICTIONARY "manufacture, v.", Oxford University Press.


WERRLICH, S., NGUYEN, P.-A. & NOTNI, G. 2018. Evaluating the training transfer of Head-Mounted Display based training for assembly tasks. PETRA 18:


PUBLICATIONS


The 50th CIRP Conference on Manufacturing Systems

Assessing Instructions in Augmented Reality for Human-Robot Collaborative Assembly by Using Demonstrators

Oscar Danielsson*, Anna Syberfeldt, Rodney Brewsterb, Lihui Wangc

*University of Skövde, Klangsvegen 3A, Skövde 541 34, Sweden
bVolvo Car Corporation, Komponentvägen 2, Skövde 541 36, Sweden
cKTH Royal Institute of Technology, Tekniska högskolan, Stockholm 100 44, Sweden

* Corresponding author. Tel.: +46-500-448-596; fax: +46-500-416-325. E-mail address: oscar.danielsson@his.se

Abstract

Robots are becoming more adaptive and aware of their surroundings. This has opened up the research area of tight human-robot collaboration, where humans and robots work directly interconnected rather than in separate cells. The manufacturing industry is in constant need of developing new products. This means that operators are in constant need of learning new ways of manufacturing. If instructions to operators and interaction between operators and robots can be virtualized this has the potential of being more modifiable and available to the operators. Augmented Reality has previously shown to be effective in giving operators instructions in assembly, but there are still knowledge gaps regarding evaluation and general design guidelines. This paper has two aims. Firstly it aims to assess if demonstrators can be used to simulate human-robot collaboration. Secondly it aims to assess if Augmented Reality-based interfaces can be used to guide test-persons through a previously unknown assembly procedure. The long-term goal of the demonstrator is to function as a test-module for how to efficiently instruct operators collaborating with a robot. Pilot-tests have shown that Augmented Reality instructions can give enough information for untrained workers to perform simple assembly-tasks where parts of the steps are done with direct collaboration with a robot. Misunderstandings of the instructions from the test-persons led to multiple errors during assembly so future research is needed in how to efficiently design instructions.

Keywords: Augmented Reality, Human Robot Collaboration, Assembly

1. Introduction

1.1. Current industrial challenges

Customers are becoming more and more individualistic, products are getting more variation and the global market drives for shorter lifecycles for products [1-4]. This puts a demand on the industry to deliver more variants on their products and to introduce new products more often. Robots are becoming more flexible but are currently not flexible enough to cost-effectively replace all human workers [5]. A limitation that currently exists for a large part of robotics implementations is safety-concerns for humans [6]. Robots have traditionally needed large areas to work to allow for safety precautions such as safety-fences [7] but are currently being taken out of the fences to interact with human workers. If robots can become safe enough for humans to efficiently interact with them in the manufacturing industry, there are great advantages to be had with the flexibility, precision, and quality skills of humans and the endurance and strength of robots [8]. Robots can now work in collaboration with humans and currently there is a lot of research into making robot interaction more dynamic and efficient without creating risks for humans [9, 10].

The aforementioned demands from the market combined with future collaborative robots means that future human operators are likely to face an increase in product variation, shorter life-cycles of products (and thereby more relearning) and collaboration with robots. This puts an increased demand
on workers to learn more operations simultaneously and learn new products more often. How can this be achieved without reducing quality and efficiency? This paper has two aims. Firstly it aims to assess if demonstrators can be used to simulate human-robot collaboration. Secondly it aims to assess if Augmented Reality-based interfaces can be used to guide test-persons through a previously unknown assembly procedure.

1.2. Augmented Reality

Augmented Reality (AR) makes it possible to present virtual information in a direct connection with objects in the real world [11]. AR works by connecting the real world with the virtual, for instance with specific patterns that are pre-known. When a camera captures and digitalizes what is seen in front of it software can recognize the pattern and it can use the information of where the pattern was recognized to superimpose digital information on top of the rendering from the camera, thereby creating a mix between virtual and real information. This means that AR can show digital information in a real setting and in a specific context, for instance by highlighting real objects. As a result there have been many studies on how to use AR to present assembly instructions that has shown positive results [12]. But although there are positive results there is still more studies needed regarding how the instructions should be presented and how to comparatively evaluate them [12].

2. Demonstrator

2.1. Demonstrator as test-bed

To our knowledge there is no factory that currently have implemented Human-Robot Collaboration combined with Augmented Reality in production. A demonstrator was therefore created where a person will collaborate with a Human-Robot Collaborative robot, a UR3 robot from Universal Robots. A simplified car-model that can be assembled and dis-assembled by hand was developed and can be seen in Fig. 1.

The greatest advantages of using a demonstrator in user-tests are the authenticity and the modularity. The demonstrator allows a test-person to interact directly with a real HRC-robot in an assembly-scenario and thereby simulates a real situation. It is not as believable as real industrial assembly but it does not need to disrupt any real industrial assembly either. The currently developed demonstrator is limited to one test-person and one workstation and is thereby limited in comparison to industrial assembly that is mostly done with close connectivity between workstations and operators. Since the demonstrator is fully developed for experimentation it is also modular and can be changed depending on what needs to be tested. Together these two advantages means that the demonstrator can put a test-person in a semi-authentic situation and, depending on complexity of needed modifications, it can also be modified depending on findings within minutes or hours.

In the first iteration, the car-model was created with wood and the pieces were held together with friction between the pieces. A drawback with this model was that test-persons only had to identify, orient and position the individual parts; there was no need to fasten any pieces with anything else but friction. To make the car-model similar to more generic assembly, a new model was created. The pieces were 3D-printed which allowed for more detailed parts to be created. The new car-model had increased complexity in that thumbscrews were now needed to fasten some parts.

Fig. 1 First iteration of demonstrator.

2.2. Augmented Reality Interface

To present the instructions for the test-persons a spatial top-view Augmented Reality system was created. The platform for the system was the game-engine Unity-3D. In the first iteration AR was implemented with the help of the Vuforia AR-system for Unity. The AR-system was built for Android and launched on an Nvidia Shield Tablet that can be seen at the top of Fig. 1. This tablet was chosen since it has both a USB-connection and mini-HDMI connection which was necessary to both have communication between the AR-system and the Robot Control system and to be able to project the visual information on a screen for the test-person to see. Test-persons worked with the table seen in Fig. 1 in front of them. This set-up meant that they had the work area in front of them, pieces to assemble at their sides, a screen giving the test-persons AR-instructions and a UR3 robot to their left that they had to collaborate with to assemble the car.

2.3. Second iteration of interface

Two big drawbacks with the chosen version of the AR-system was the low battery-life of a tablet that has to continuously have an active camera and the mixing of two
platforms. The tablet runs on Android and the Robot Control System runs on Windows and communicates with TCP via USB. We therefore made a second iteration where the Vuforia AR-system was replaced with ARToolKit, which supports the Windows-platform.

The AR-tracking was using the inbuilt multimarker functionality of ARToolKit with 6 markers. There was a redundancy in the number of markers to allow test-persons and the robot to move freely in-between the camera and the markers.

The AR-tracking was using the inbuilt multimarker functionality of ARToolKit with 6 markers. There was a redundancy in the number of markers to allow test-persons and the robot to move freely in-between the camera and the markers.

---

The interface was designed to guide the test-person with a combination of textual information and AR to highlight parts of specific interest in each step. Fig. 2 shows what the test-person would see on the screen in front of them when beginning their test. The text in the middle explain in general terms what they are to do. To the right they can see voice-commands that the system currently accepts. The interface needed a voice-recognition-security of at least 85 % in order to avoid false positives. Values between 60 % and 100 % were shown to the test-person, values between 60 % and 85 % were shown in red to indicate that the system had detected a possible command but was not sure enough. Values above 85 %, in Fig. 2 the value is 89 %, were shown in green to indicate a correctly recognized command.

Once the test-person gave a start-command the interface would remove the introduction text and present all textual information in the upper right corner of the screen so as to not cover the areas of the screen where the test-person would work. An example of the interface during assembly is seen in Fig. 3. The top part of the text-area contained specific instructions for the test-person on what they were to do. Just below this the test-person could see their overall progress through the construction. Below this recognized and available voice-commands would be seen as previously explained in connection to Fig. 2.

---

2.4. The car-assembly

In the first iteration of the demonstrator, the test-persons had to assemble the entire car. For the second iteration, we changed this so that the test-person only had to assemble parts of the car. The three reasons for this were that we had introduced more complex parts to assemble and did not want to increase overall effort for test-persons, that not all parts were of interest seen to Human-Robot Collaboration, and a minor reason was also that the most common situation is that assembly workers only build part of a product.

The second iteration had a total of 11 steps for a test-person to perform and is presented in Table 1. The level of Human-Robot Collaboration (HRC) is defined as direct, indirect or no HRC. Direct means there is direct interaction between the test-person and the robot, in these cases haptic control of the robot. Indirect means that the robot or human support each other but have no direct interaction, in these cases the robot holds the assembled car in a fixed position to ease assembly.

---

### Table 1 Car-assembly steps

<table>
<thead>
<tr>
<th>Text-instructions</th>
<th>HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead front and position according to marking.</td>
<td>Direct</td>
</tr>
<tr>
<td>Lift the robot-arm ca 1 decimeter.</td>
<td>Direct</td>
</tr>
<tr>
<td>Take left roof and fasten between front and back.</td>
<td>No</td>
</tr>
<tr>
<td>Lead left sub frame to marked position.</td>
<td>Direct</td>
</tr>
<tr>
<td>Lift the robot-arm ca 1 decimeter.</td>
<td>Direct</td>
</tr>
<tr>
<td>Take left door and fasten at marking.</td>
<td>No</td>
</tr>
<tr>
<td>Take two lock-rings and assemble one at each protruding assembly-pin.</td>
<td>No</td>
</tr>
<tr>
<td>Take two wheels and tread on the protruding assembly-pins.</td>
<td>No</td>
</tr>
<tr>
<td>Take five thumbscrews and assemble one at each assembly-pin.</td>
<td>No</td>
</tr>
<tr>
<td>Take two thumbscrews and assemble at the wheels.</td>
<td>Indirect</td>
</tr>
</tbody>
</table>
3. Methodology

3.1. Tested software

A pilot-study was performed for the second iteration of the interface to test how intuitive the interface was for new test-persons. The main goals were to see if the assembly was complex enough to require instructions to finish and that the assembly was feasible to finish for a test-person without previous instructions. This was to evaluate whether the demonstrator needed any major revisions before more in-depth user tests.

To compare how different designs of the interface affect test-persons, two versions of the AR-interface was implemented. Both versions were identical apart from that in one version the parts where the test-person should initiate actions were blinking and in the other version they were not blinking.

As explained in section 2.3, the test-persons interacted with the interface with the help of voice-commands. In each step they could issue two voice-commands that both did the same thing. This was to allow an alternative if the test-person had problems to pronounce the command clear enough for the software to recognize. There were two different versions of the voice-commands. One word-versions, for instance “start/begin” and multiple word-versions, for instance “start demonstrator/begin building car”. All four possible combinations were connected and set up for the user-study. Program 1 had blinking and short commands, program 2 had no blinking and short commands, program 3 had blinking and long commands, and program 4 had no blinking and long commands.

3.2. Test-group, environment and test-layout

Four groups of high-school students from local technical schools were used as test-groups. The students were chosen since they are very likely to have a career within the manufacturing industry. This makes them representative of parts of the future workforce within the manufacturing industry and their attitude towards this solution is valuable in the context of future workforce employment. The ages were self-reported in the interval 15-17. Genders were also self-reported and are presented in table 2.

Table 2 Group composition

<table>
<thead>
<tr>
<th>Group</th>
<th>Program</th>
<th>Females</th>
<th>Males</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>7</td>
<td>17</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>7</td>
<td>19</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>7</td>
<td>18</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>4</td>
<td>14</td>
<td>3</td>
<td>21</td>
</tr>
</tbody>
</table>

Each group partook separately from each other. In each group 3 volunteers were chosen to perform the assembly. Table 2 shows which group had which program and shows that group 3 mistakenly got the same program as group 2. Of those chosen to perform the assembly, one stayed in the room and used the demonstrator while the other two left the room to avoid learning-effects. The room layout was a lecture classroom with a pitched floor and it was well lit during the tests. The students were seated in the front three rows of the auditor and the demonstrator was placed on the floor in front of them.

After the first test-person had performed the assembly it was led aside to a table to fill out a usability-questionnaire. Then the next test-person was brought in to perform the assembly and the observing students were given questionnaires. After the second test-person was finished it was also led to the table to fill out a usability-questionnaire and the third test-person was led in. Finally the third test-person was also led to the table to fill out the same usability-questionnaire as the other two.

During each assembly one test-assistant noted times the test-person asked for help and when they did not do as instructed by the AR-interface. The language used for the entire study was Swedish.

3.3. Questionnaire-design

Both questionnaires used a five-level Likert-scale. The test-persons filled in 10 questions regarding the interface and the questions were based on the SUS-test [13] but translated to Swedish. The observing students filled in a questionnaire with 6 questions regarding general interest and 5 questions regarding the information displayed on the screen for the test-person.

3.4. Error-sources

The students chosen for performing the assembly were those who raised their hands first when we asked for volunteers and are therefore likely to have a positive bias for trying new technology. While the groups were mixed, volunteers were all male. The remaining students observed the test-persons and could interact with them even though this was discouraged and thus influenced the test-persons behavior. Program 4 was not tested due to a miss during execution of the test.

We did not manage to create a perfect alignment between the virtual and real world, which could have reduced understand-ability with the test-persons. The questionnaire for the test-persons was translated from English to Swedish, which can have affected the outcome.

4. Preliminary results

The first iteration was primarily used as a proof of concept that the demonstrator was feasible and the general layout understandable by test-persons. It was tested with volunteers at two different exhibitions. The tests indicated that the system was intuitive enough and on a difficulty level that allowed for most of those testing to be able to complete the task. For this reason there was no major revision of the setup from the first to the second iteration of the demonstrator.

The first iteration was also specifically presented for industrial representatives from the car-manufacturing industry to assess future industrial relevance. The response we
received was that the concept was seen as relevant seen to industrial challenges in the near future. The data from the user-study is inconclusive. The SUS-scores of the groups were 80.8, 75, 32.5 and 77.5. Due to all the possible error-sources, there can be many different reasons for the different outcomes between group 3 and the other three groups. Group 1, 2 and 4 followed the same trend in the SUS when broken down to individual questions as can be seen in Fig. 4.

![Fig. 4 Average SUS-score per question](image)

A summary from the test-protocol shows that of the 12 test-persons, all of them made errors in at least one of the steps. Of the total of 144 assembly steps, 75 steps were performed with at least one deviation from the given instructions. In open discussions after the tests many of the test-persons and students from the observing group pointed out that it was unclear that they should read the instructions in the upper right corner.

5. Summary

5.1. Conclusions

This paper has two aims: to assess if demonstrators can simulate human-robot collaboration and to assess if AR-based interfaces can guide test-persons through assembly. Regarding the first aim, the paper has shown that demonstrators can be used to create a modular test-environment that allows a test-person to perform real assembly in collaboration with a robot. The results from the pilot-study were distorted since the test-persons had their peers behind them when working. Despite this they managed to go through all the steps of the instructions. Based on this it can be said that the demonstrator has reached a level of maturity that enable persons without prior assembly-experience to independently work through all the steps of the demonstrator. This answers the second aim of this paper. But the amount of errors when working independently is far too high to be acceptable. The amount of errors shows that the assembly is complex enough to require instructions. Therefore the task in the demonstrator is of a satisfying complexity but the instructions need to be clearer. The screen shows a top-view of the assembly-area and is thus limited in how instructions can be shown.

While the current results have not given specific insight in how different designs affect the performance of test-persons it has given validity to the method of using demonstrators to test assembly-instructions. Further validity of the method was given from the feedback from the industrial representatives.

5.2. Future work

The demonstrator will be tested in more in depth user tests. Future tests will also be performed in a more controlled environment to reduce error-sources. Test-persons will work alone and be recorded to allow for more detailed observation of types of errors and where they focus when they work. The demonstrator itself will also need revision and future work for it includes:

- Increasing Augmented Reality tracking accuracy.
- Changing or adding camera-angles from which the assembly area is displayed in the interface.
- Layout of the different parts of the interface needs to be revised and also how the different parts are presented to ensure that test-persons find them.
- The information design will be updated.
- Increased system functionality such as animation to provide opportunities to use the strengths of AR-technology more effectively.

References


Operators perspective on augmented reality as a support tool in engine assembly

Oscar Danielsson a,*, Anna Syberfeldt a, Magnus Holm b, Lihui Wang b

*University of Skövde, PO Box 338, Skövde, Sweden
*KTH Royal Institute of Technology, 100 44, Stockholm, Sweden

* Corresponding author. Tel.: +46-500-448596; fax: +46-500-416325. E-mail address: oscar.danielsson@his.se

Abstract

Augmented Reality (AR) has shown its potential in supporting operators in manufacturing. AR-glasses as a platform both in industrial use are emerging markets, thereby making portable and hands-free AR more and more feasible. An important aspect of integrating AR as a support tool for operators is their acceptance of the technology. This paper presents the results of interviewing operators regarding their view on AR technology in their field and observing them working in automotive engine assembly and how they interact with current instructions. The observations and follow-up questions identified three main aspects of the information that the operators looked at: validating screw torque, their current assembly time, and if something went wrong. The interviews showed that a large amount of the operators were positive towards using AR in assembly. This has given an insight in both the current information interaction the operators do and their view on the potential in using AR. Based on these insights we suggest a mock-up design of an AR-interface for engine assembly to serve as a base for future prototype designs.

© 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 51st CIRP Conference on Manufacturing Systems.

Keywords: augmented reality; engine assembly; operator

Nomenclature

AGV Automated Guided Vehicle
AR Augmented Reality
ARSG Augmented Reality Smart Glasses
HRC Human Robot Collaboration

1. Introduction

The fourth industrial revolution will stand to change how we manufacture products. It will allow more dynamic flows of information and thereby enable swifter changes in production [1]. This will change the work tasks for operators drastically, who will have to handle more product variants and more frequent updates of work tasks. Industry 4.0 will also likely lead to larger responsibilities for operators. One solution to handle this is to implement information systems that can give operators needed information. Augmented Reality is one type of technology that might be used to support future operators [2].

AR is defined by Azuma et. al. to have the following characteristics: combining real and virtual objects in a real environment, running interactively and in real time, and aligning real and virtual objects with each other [3]. According to Azuma et. al. [3], AR can potentially apply to all senses and in this paper the focus is on visual AR specifically. AR has been shown to be able to increase efficiency in assembly tasks by giving information in context, thereby simplifying interpretation of data and reducing time and errors in doing so [4]. Implementations of AR can be categorized into three categories: head-attached, hand-held and spatial [5]. Rapid advances within head-attached solutions, specifically regarding Augmented Reality Smart Glasses, ARSG, has made this type of implementation a suitable platform for assembly support [6]. Therefore this paper limits itself to ARSG and when AR is mentioned in the rest of this paper in regards to the study and conclusions it implies ARSG.
While AR has made much progress in different fields, it is still struggling to reach the factory floors [7]. Handheld devices limits operators effectiveness, head-worn displays are heavy and limited in focal depth and resolution, and large screens take up space [7]. Smart glasses are however becoming increasingly lighter and getting better technical functionality [6]. Wang et. al. found that there are limitations in current AR systems in regards to assisting complex assembly processes [4]. One of the issues they identified as currently limited was intuitive user interfaces.

This paper focuses on the operators’ perspective on using AR to support assembly tasks. The aim of this focus is to gain a better understanding of industrial operators as interface users to facilitate more intuitive user interfaces in the future. The operators’ perspective is analyzed through observations of interaction in actual assembly to get a better understanding of the current situation. It is also analyzed through interviews that both complement the observations by giving the operators a chance to give a deeper explanation of their view. The interviews also gives an insight in how much the operators trust AR technology. This is relevant since user trust of an information system will affect the user’s efficiency when working with it [8, 9].

This paper is a continuation of our previous work within assembly support for operators, which has focused on evaluating different AR support systems from an operators perspective and the technology’s suitability for guiding operators through HRC assembly [6, 10, 11]. This paper focuses directly on operators themselves to observe their behavior and interview them regarding their views.

2. Case study

This section describes the layout of the factory and the operators’ assembly tasks, how data was collected, how the operator observations were setup, how the operator interviews were setup, ethical considerations, and possible error-sources and how they were remedied.

2.1. Layout and assembly tasks

The interviewed and observed operators are all from one section of engine outer assembly of the Volvo Car Corporation engine factory in Skövde. There are four assembly lines, each with eight sequential stations placed in a U-formation. The engines are transported on Automated Guided Vehicles, AGVs, from station to station and stops at a specific point at each station. Each operator follows one engine from the first to the last station. After the last station they move to the first station where a new engine waits for them. Figure 1 gives an overview of one such U-formation with 8 stations.

![Fig. 1. Overview of an assembly line.](image1)

Each station is equipped with a monitor displaying station specific information. The monitors are all mounted above the engine at its fixed position. The most common information displayed is feedback on which screws and bolts to use and the results from the screwing machine whether the screwing process was of sufficient force or not. Figure 2 shows a detailed view of the instructions available for the operators. The left-most instruction contains detailed instructions for each step, the middle instruction shows possible specific details to check, and the right-most instruction is a digital screen that gives feedback on the operator’s progress based on data from the production system. The screen shows the operator available time left on the current assembly cycle and how many screws that had been fastened with the right torque for instance. If the operator went beyond available time or if incorrect torque was used on a screw, the system gave this feedback to the operator.

![Fig. 2. Close-up of instructions available for the operators.](image2)

2.2. Data collection

Two data collection strategies were used, observing the operators while performing their assembly tasks and interviews. One researcher performed all observations and interviews.
2.3. Observation setup

The goal of the observation was to gather quantitative data about how the operators interacted with current information systems. It was executed by following an operator during one lap of assembly. One lap consisted of 8 stations from 1 to 8 as in figure 1. Operators were asked to consent to the observation before proceeding and none declined. The observer placed himself as to avoid being in the way for the operator while still being able to see where to operator was looking. For each station the number of times the operator looked at the monitor or other information systems was counted by subjective observation of the operators gaze. When the operator looked for approximately half a second or more in the direction of an instruction (a computer screen, lit lamp, or a piece of paper with instructions) or interacting with another person directly connected to work performance and when the gaze was roughly half a second or more it was counted as an observation. Time spent looking was not recorded or measured.

After following an operator for one lap, and if it did not disturb production, he or she was informed about what had been observed and were asked if he or she generally looked often on instructions and what things he or she looked on.

2.4. Interview setup

The goal of the interviews was to gather a deeper understanding of the Operators’ views on the need for information in their current work environment as well as their views on other information systems.

The interviews were semi-structural and individual. Each participant filled in a consent-form that informed them of the general goal of the data-collection: to gain knowledge in how operators view instructions in their work and how they currently interact with them. The extended purpose of creating a more efficient learning of new instructions and allowing for a more dynamic production was also explained. They were also given the option to provide an e-mail address if they wanted to know more about the results of this study. All interviews were audio-recorded to facilitate deeper analysis afterwards.

The interview questions were: age, how many years they have worked with assembly in a factory, how many years they have worked at their current position, how often there are changes in their tasks in production, how the company informs about the new tasks, if the operator complements the information in any way, how often they check up things in documentation (with the follow up questions: what they check then, how easy it is to understand, if it is easy to find), the operator’s view on being able to do personal adjustments, how the operator would design the information flow if he or she had free hands, and if they had any other ideas or thoughts based on what had been brought up in the interview.

2.5. Ethical considerations

Operators’ work in assembly is stressful [12]. Each operator has an individual RFID-tag that the use to login to each station. Any errors in assembly can therefore be tracked down to individual level. While this means operators are used to being monitored this can also be a source of stress due to constant observation and measurement of performance. It was therefore emphasized by the data collector to the operators that the purpose of the data collection was for research of new technologies to display instructions and that the data would not be connected on an individual level.

During the observations they were not told what was being observed until afterwards when the purpose of the observation and what was being observed was revealed. No operator declined being observed which greatly simplified data collection.

All interviews started with the person being interviewed being presented a consent-form that informed about the purpose of the study, that the interview would be recorded and they had the right to abort the interview at any time with no motivation needed. Who had access to the recording was stated as very limited university staff. This was not more precisely specified since who would analyze the data was not determined at the time of the interviews.

2.6. Potential error sources

The observer made sure to place himself as to be out of the way for the operator while maintaining a good field of view of the operator’s work. This meant moving in an assembly line while simultaneously making observations. This combination of structured subjective measurements and an active environment can have had a negative effect on the accuracy of the data. Video-recording the operators in production was not deemed feasible due to permissions needed and integrity. This was in part remedied by having one data collector and following an observation protocol, thereby reducing the risk of inter-measure discrepancy. The observer has also previously worked with industrial assembly for one year and was thereby used to this form of environment. The observation data from the first day was used to learn what could be feasibly observed and was not used in analysis.

3. Results

This section summarizes the results from the observations, summarizes the results from the interviews, and presents an AR-design based on the previously mentioned results.

3.1. Observation

A total of 35 observations were done. 19 observations were done on males and 16 on females. Two observations (one male and one female) were incomplete since there was a break before completing a full lap and one observation (female) was incomplete because of the shift ending. Of the 35 observations, 24 gave comments after the observation about what they look at when looking at the instructions in general in their daily work. The most common (10 operators looked at this) was checking the torque on screwing stations. The second most common (9 operators looked at this) was assembly time, and the third most common (8 operators looked at of this) was checking when something goes wrong. A full list of the
operators’ self-reported reasons for looking at the instructions are shown in table 1.

Only two observations were done of an operator interacting with another operator related to their task. In one instance a colleague showed that an assembly piece had been moved to a more efficient position. In the other instance the operator wanted to verify with a colleague that a certain assembly piece were to be used. Social interaction was frequent but not measured. Interaction with signs was in the form of “pick-by-light”, a system where a lamp would light up to indicate which detail to assemble at a specific product. The light would switch off when an RFID-tag held at the operator’s wrist came close to the light.

No statistically significant patterns could be observed based on gender or experience regarding how often operators looked at instructions.

Table 1. Operator observations (self-reported)

<table>
<thead>
<tr>
<th>View on AR</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque of screwing machine</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Assembly time</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Something goes wrong</td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Learning new steps</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Must look at 240</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Deviations from normal</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Forget themselves</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>“When it’s needed”</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>When production stops</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>If RFID tag does not react</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>More when interrupted</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Automatically check in beginning or end</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2. Interviews

A total of 28 interviews were held. The interviewed operators were chosen from the same group as the observed operators and some operators were chosen for both observation and interview. The first five interviews had a different set of questions and was used mainly as a test of the questions. The remaining 23 interviews had a modified set of questions based of the result from the first five. In the first group, 3 of the operators were male and 2 were female. In the second group 13 were male and 10 were female.

At the end of each interview the purpose of the study and the technologies involved was explained. Each participant was asked if they knew of the term “augmented reality” and it was known by 6 of the operators. Based on their reactions when the technology was explained and how it could affect their future work a large amount in both groups, 4 of 5 and 17 of 23, audibly exclaimed positive interest. Examples that was interpreted as positive are (translated from Swedish) “It sounds very interesting, of course I would like to see how this goes.”, “Shit, how cool!” and “That would have been something.” Two of the operators showed positive interest in the technology but expressed concerns that they did not think the management of the company would like to spend the resources to invest it. But since they showed positive feelings regarding the technology in itself they were counted as positive.

Of the remaining operators, 6 showed no clear reaction to the possibilities of the technology and one operator expressed concern. The concern was (translated from Swedish) “God how creepy.”. She expressed this when augmented reality was explained by using the example of a digital green arrow following a pen in its movements. The results can be seen summarized in table 2.

Table 2. AR acceptance.

<table>
<thead>
<tr>
<th>View on AR</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>12</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Neutral</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Negative</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3. AR-design

Since the operators showed a clear interest in using AR and since AR can simplify distribution and presentation of assembly instructions it is of value to further investigate how AR can be used as support for the operators in their work. The current design is limited in that the screens are mounted in a specific position which limits from which angles the operators can see the screens. This has been solved in the current layout but is a limiting factor in where tasks and information regarding tasks can be placed. Based on the presented observation and interview data we have created a design suggestion for how an AR interface could present information to the operators.

Figure 3 shows an engine from an operator’s point of view. Figure 4 shows an example of how instructions could be shown to an operator in one assembly step. The operator is to place the detail that is marked blue in the position that it is seen on figure 4. Then two screws are to be fastened with the correct torque. The blue marking in the middle highlights the current detail to assemble. Two bolts have been attempted to be fastened in this example where the first one (top right corner of the blue marking in the middle) is highlighted green, indicating a correct torque. The second bolt is marked red, indicating incorrect torque. In the current system, operators can see correct torque via a green/red lamp on the screwing machine or alternatively how many.

Checking torque of screws was the most common reason for the Operators to check instructions according to their own view. The red highlighting also shows an example of how an error can be displayed to the operator. Checking if something went wrong was one of the second most common reasons to check instructions. The other second most common reason to check instructions was time, how much time the Operator had left on the current cycle. This AR-design presents information that the operators state is the most important to check and it is presented in similar colors and design as the current information systems that they use. It is possible that this design will not be effective in actual assembly but these two factors makes this design a good basis for future empirical studies.
4. Conclusions

A high number of the interviewed operators showed positive reactions to augmented reality in connection to providing support in their work, indicating a high acceptability among the Operators regarding the technology.

Observations done showed that operators look on instructions mainly to check screwing torque, assembly time and if something went wrong. The suggested AR-design uses this as a base as to what operators find as important information to display.

The local managers for this section of production were pleased with the results and insights from this evaluation. The data helps the managers what positive values the operators see and which threats they see. What is mainly lacking from their perspective is comparative data that can be gained from tests on a prototype to show more concrete increases in efficiency.

The analysis of the observations done indicate better understanding of to how create intuitive user interfaces for operators and how to assess operator acceptance of AR. Furthermore, the operators view on AR as an information platform can support when estimating operator readiness and willingness to adapt when using this technology and thereby help in strategical decisions regarding further use of AR.

4.1. Future work

Although the gathered data is comprehensive it is limited to one factory so it would be useful to extend this data in the future to more factories to account for possible differences in cultures between companies and factories. The suggested layout of information, while relevant to the operators according to their answers and from the data gathered from observations, is just a mockup. The gathered data is based on self-reported acceptability however and needs to be validated further in a more concrete setting. To fully validate its usefulness for the operators a functioning interface needs to be developed. It is unlikely to get permission to test such an interface in real production, at least in earlier stages of testing. A testing environment with similar tasks being performed could provide a suitable test-case and would further validate such an interface design. While actual production would be an ideal environment to prove that the technology is ready, it might be less optimal for first tests. The first iterations are likely to disrupt production too much. More suitable would be to have a test-environment with similar tasks but with less critical cycle-times.

Acknowledgements

The authors would like to thank the operators and management at the assembly line in the Volvo Car factory in Skövde for their immense help in gathering this data.

References


Augmented Reality Smart Glasses for Industrial Assembly Operators: A Meta-Analysis and Categorization

Oscar DANIELSSON¹,1, Magnus HOLMA, and Anna SYBERFELDTa
aUniversity of Skövde, Department of Engineering Science, Högskolevägen, Skövde 541 28, Sweden

Abstract. Augmented reality smart glasses (ARSG) are an emerging technology that has the potential to revolutionize how operators interact with information in cyber-physical systems. However, augmented reality is currently not widespread in industrial assembly. The aim of this paper is to investigate and map ARSG in manufacturing from the perspectives of the operator, of manufacturing engineering, and of its technological maturity. This mapping provides an overview of topics relevant to enabling the implementation of ARSG in a manufacturing system, thus facilitating future exploration of the three perspectives. This investigation was done using a meta-analysis of literature reviews of applications of augmented reality in industrial manufacturing. The meta-analysis categorized previously identified topics within augmented reality in industrial manufacturing and mapped those to the scope of the three perspectives.

Keywords. Augmented Reality, Literature Review, Assembly, Assembly Operators

1. Introduction

A competitive and fast-growing market is pushing manufacturers to become more efficient and productive, as well as more agile, responsive, and customized [1]. Customers are increasingly asking for individual products, pushing the change from mass customization to mass personalization [2]. Increased product variation and an increasingly complex shop floor environment are putting more pressure on assembly workers to handle more information. Despite technological advances, these assembly workers are still likely to continue to be an important part of manufacturing [3]. So the future information-intensive shop floor environment requires operators to be able to handle and process a dynamically changing environment [4]. One possible way of supporting them in this is through digitalizing information using augmented reality (AR) [5].

Augmented reality smart glasses (ARSG) can potentially be of great support to operators in industrial assembly by providing contextual, interactive, and digital information in the operators’ field of view (FOV). However, there are only a few examples of their actual implementation in industry [6]. The aim of this paper is to investigate what previous research has been done in relation to industrial implementation,
application, and long-term maintenance of ARSG for operators. The added value of this mapping is that it facilitates more in-depth research by providing an overview of relevant topics.

2. Methodology

The methodology used for this paper is based on [7]. To improve understanding of the existing literature, a scoping review was made of literature reviews of AR in industry. On the basis of these reviews, the following databases were chosen: IEEE Xplore, ScienceDirect, Scopus, and Google Scholar [6]. Table 1 shows the search phrases.

<table>
<thead>
<tr>
<th>Database</th>
<th>Search phrase</th>
<th>Limitations</th>
<th>Matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Google Scholar</td>
<td>allintitle: “augmented reality” (survey OR review) (industry OR manufacture OR assembly OR maintenance)</td>
<td>Since 2015, no patents, no quotes</td>
<td>7</td>
</tr>
<tr>
<td>IEEE Xplore</td>
<td>(“Publication Title”: (“augmented reality” (survey OR review) (indust* OR manufact* OR assemb* OR maint*)))</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>ScienceDirect</td>
<td>Title: “augmented reality” (survey OR review) (industry OR manufacture OR assembly OR maintenance)</td>
<td>Since 2015, review articles, research articles, book chapters, conference abstracts, replication studies</td>
<td>2</td>
</tr>
<tr>
<td>Scopus</td>
<td>TITLE (“augmented reality” (survey OR review) (industry OR manufacture OR assembly OR maintenance)) AND PUBYEAR &gt; 2014</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

After filtering for unique hits, a total of seven matches were found [5, 6, 8-12]. These reviews and studies were then analyzed to obtain an overview of relevant topics to explore. The analysis was done by examining the review papers and identifying categorizations of AR used in industrial assembly applications. Categorizations outside of scope were not considered. Through a meta-analysis, those categorizations within scope were grouped into three different perspectives: operators (Perspective 1 in Figure 1), manufacturing engineering (Perspective 2), and technological maturity (Perspective 3). The term “operators” is defined in this context as humans working on an assembly line and performing assembly tasks. The term “manufacturing engineering” is defined as the planning, preparation, integration, and maintenance of ARSG in an assembly line. These perspectives were chosen to cover aspects needed to enable the use of ARSG in industrial assembly. The operator perspective takes the end user into account. The manufacturing engineering perspective takes the surrounding infrastructure and administrative staff, such as maintenance and integration staff, into account. The final perspective takes technical feasibility into account. Together, these perspectives give a holistic understanding of what is needed to bring ARSG into practical use in production.

3. Results and Discussion

This section begins with the analysis of each literature review and then presents the synthesis into the three perspectives. For each literature review, a table presents the identified themes, keywords, and topics. Each entry in these tables is within the
The scope of this paper is accompanied by a set of numbers, representing the category and subcategory they fall into in Figure 1.

**Paper 1** *Augmented and virtual reality applications in industrial systems: A qualitative review toward the industry 4.0 era*, identified nine key technologies, which are presented in Table 2 [11].

<table>
<thead>
<tr>
<th>Key technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis on three dimension space</td>
</tr>
<tr>
<td>Calibration</td>
</tr>
<tr>
<td>Collision detection</td>
</tr>
<tr>
<td>Display interaction technology</td>
</tr>
<tr>
<td>Human-computer interaction</td>
</tr>
<tr>
<td>Object detection and recognition technology</td>
</tr>
<tr>
<td>System modeling technology on space and geographic environment</td>
</tr>
<tr>
<td>Tracking, positioning and registration technology</td>
</tr>
<tr>
<td>Model rendering</td>
</tr>
</tbody>
</table>

**Paper 2** *A systematic review of augmented reality content-related techniques for knowledge transfer in maintenance applications*, analyzed the state of the art in authoring, context awareness, and interaction analysis in the context of maintenance applications [10]. The results from the studies reviewed can only be validated for AR fields in maintenance, but the approach can be used as a basis for understanding other areas. The paper is a qualitative analysis that used thematic categorization to organize the data into the categories presented in Table 3.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Operation</th>
<th>Task</th>
<th>Knowledge</th>
<th>Authoring</th>
<th>Context awareness</th>
<th>Interaction analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Design</td>
<td>Monitoring</td>
<td>Procedural</td>
<td>Users</td>
<td>Contexts</td>
<td>Data</td>
</tr>
<tr>
<td>Medium</td>
<td>Assembly</td>
<td>Guidance</td>
<td>Declarative</td>
<td>Rules</td>
<td>Rules</td>
<td>Automation</td>
</tr>
<tr>
<td>Large</td>
<td>Diagnosis</td>
<td>Collaboration</td>
<td>Automation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repair</td>
<td>Simulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Paper 3** *A review on industrial augmented reality systems for the Industry 4.0 shipyard*, identified the most relevant industrial tasks and sectors where AR can add value to the Industry 4.0 shipyard [9]. Table 4 presents its findings.

<table>
<thead>
<tr>
<th>Service</th>
<th>Manufacturing</th>
<th>Sales &amp; marketing</th>
<th>Design</th>
<th>Operations</th>
<th>Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuals &amp; instructions</td>
<td>Quality assurance</td>
<td>Product displays &amp; demos</td>
<td>Collaborative engineering</td>
<td>Heads-up displays</td>
<td>Job-specific training</td>
</tr>
<tr>
<td>Service instructions &amp; verifications</td>
<td>Maintenance work instructions</td>
<td>Logistics, retail space optimization</td>
<td>Inspection of digital prototypes</td>
<td>Digital product controls</td>
<td>Safety &amp; security training</td>
</tr>
<tr>
<td>Remote expert guidance</td>
<td>Performance dashboards</td>
<td>Augmented brand experience</td>
<td>Augmented interface</td>
<td>Augmented operator manuals</td>
<td>Expert coaching</td>
</tr>
<tr>
<td>Improved service and self-service</td>
<td>Assembly work instructions</td>
<td>Augmented advertisement</td>
<td>Error diagnosis</td>
<td>Augmented interface</td>
<td></td>
</tr>
</tbody>
</table>

**Paper 4** *A systematic review of augmented reality applications in maintenance*, investigated the state of the art of AR applications in maintenance for operator support, and future developments of AR in maintenance [6]. Table 5 presents the categories derived from the data extraction from the selected papers in the review.
Table 5. Paper 4: Comprehensive categories derived from article data extraction [6].

<table>
<thead>
<tr>
<th>Field of application</th>
<th>Maintenance operations</th>
<th>Hardware</th>
<th>Development platform</th>
<th>Tracking method</th>
<th>Interaction method</th>
<th>Authoring solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation industry</td>
<td>Dis/Assembly</td>
<td>3D HMD</td>
<td>2.1 Mid/Low-level</td>
<td>1.3 Text</td>
<td>2.1 Manual</td>
<td></td>
</tr>
<tr>
<td>Plant maintenance</td>
<td>Repair</td>
<td>Hand held display (HHD)</td>
<td>Libraries of functions</td>
<td>Features-based</td>
<td>1.1 Audio</td>
<td>2.1 By annotations</td>
</tr>
<tr>
<td>Mechanical diagnosis</td>
<td>Desktop PC</td>
<td>2.1 Software development kit (SDK)</td>
<td>3.3 Marker-based</td>
<td>Static 2D/3D</td>
<td>1.3 Dynamic 2D/3D</td>
<td>2.1 By “boxes”</td>
</tr>
<tr>
<td>Consumer technology</td>
<td>Training</td>
<td>Projector</td>
<td>2.1 Game Engine</td>
<td>3.3 Others</td>
<td>1.3 Dynamic 2D/3D</td>
<td>2.1 Automated</td>
</tr>
<tr>
<td>Nuclear industry</td>
<td></td>
<td>Haptic</td>
<td></td>
<td>2.1 3D modeling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote applications</td>
<td></td>
<td></td>
<td></td>
<td>3.1 Sensors</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Paper 5, Literature review of augmented reality application in the architecture, engineering, and construction industry with relation to building information, presented a subset of the findings of [13], in four phases to develop a complete AR application [8]. The related technologies according to [8] are presented in Table 6.

Table 6. Paper 5: Architecture of AR application in four phases, modified by [8] from [13].

<table>
<thead>
<tr>
<th>Data phase</th>
<th>Computing phase</th>
<th>Tangible phase</th>
<th>Presentation phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Cloud computing environment</td>
<td>2.2 Localization technologies</td>
<td>3.4 Portable devices</td>
<td>1.1 Natural user interface</td>
</tr>
<tr>
<td>BIM</td>
<td>2.2 GPS</td>
<td>3.4 Cheap</td>
<td>3.3 Gesture</td>
</tr>
<tr>
<td>2.1 Internet</td>
<td>2.2 RFID</td>
<td>3.4 Light</td>
<td>3.1 Motion capture</td>
</tr>
<tr>
<td></td>
<td>2.2 Barcode</td>
<td></td>
<td>2.1 Wearable</td>
</tr>
</tbody>
</table>

Paper 6, A comprehensive survey of augmented reality assembly research, grouped AR assembly research into three main categories and twelve subcategories, presented in Table 7 [5].

Table 7. Paper 6: Main categories and subcategories identified by [5].

<table>
<thead>
<tr>
<th>1.5 AR assembly guidance</th>
<th>1.6 AR assembly training</th>
<th>AR assembly design, simulation and planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 Interactive instructions</td>
<td>1.6 Assembly training for procedural tasks</td>
<td>1.7 Human computer interaction</td>
</tr>
<tr>
<td>1.5 Multimedia-instructions</td>
<td>1.3 Feedback for user’s action</td>
<td>Assembly design and planning</td>
</tr>
<tr>
<td>1.5 Context-awareness</td>
<td>1.3 Design guidelines</td>
<td>Assembly simulation</td>
</tr>
<tr>
<td>2.1 Authoring</td>
<td></td>
<td>2.1 Usability evaluation</td>
</tr>
<tr>
<td>2.1 Effectiveness evaluation</td>
<td></td>
<td>2.1 Usability evaluation</td>
</tr>
</tbody>
</table>

Paper 7, Augmented reality technology in the manufacturing industry: A review of the last decade, reviewed journal publications on AR technology in the manufacturing industry between 2006 and 2017 and found 69 technical papers and 70 application papers [12]. By analyzing and grouping the keywords into thematic fields, the authors of that paper identified a total of 69 unique thematic fields in the two categories technical and application papers, merged and presented in table 8.
Table 8. Paper 7: Thematic fields of AR in manufacturing industry, found by [12], listed alphabetically.

<table>
<thead>
<tr>
<th>Thematic fields</th>
<th>3D</th>
<th>3.3 Finger detection</th>
<th>Manufacturing</th>
<th>Robotics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance sampling</td>
<td>Footwear</td>
<td>3.3 Marker</td>
<td>3.2 Safety</td>
<td></td>
</tr>
<tr>
<td>Algorithm</td>
<td>3.3 Gesture</td>
<td>Mixed reality</td>
<td>3.2 Scene analysis</td>
<td></td>
</tr>
<tr>
<td>Artificial, augmented and virtual reality (AAVR)</td>
<td>Handheld AR</td>
<td>Mobile</td>
<td>3.4 Scene structure and integration modeling language (SSIML)</td>
<td></td>
</tr>
<tr>
<td>1.5 Assembly</td>
<td>Haptic</td>
<td>Mobile augmented reality (MAR)</td>
<td>2.1 Semantics</td>
<td></td>
</tr>
<tr>
<td>2.1 Authoring</td>
<td>1.5 Head Mounted Display (HMD)</td>
<td>1.5 Natural interface</td>
<td>3.1 Sensors</td>
<td></td>
</tr>
<tr>
<td>3.2 Bare-hand</td>
<td>3.1 Human-computer interaction (HCI)</td>
<td>3.2 Object tracking</td>
<td>2.2 Smart factory</td>
<td></td>
</tr>
<tr>
<td>Building information modeling (BIM)</td>
<td>1.3 Human-machine interaction (HMI)</td>
<td>Ontology</td>
<td>Spatial augmented reality (SAR)</td>
<td></td>
</tr>
<tr>
<td>3.2 Calibration</td>
<td>3.2 Indoor</td>
<td>3.2 Optical see-through (OST)</td>
<td>Telematics</td>
<td></td>
</tr>
<tr>
<td>3.1 Camera</td>
<td>Information systems</td>
<td>3.2 Optical see-through HMD (OST-HMD)</td>
<td>Telerobotics</td>
<td></td>
</tr>
<tr>
<td>Collaboration</td>
<td>3.2 Intelligent algorithm</td>
<td>3.1 Pattern recognition</td>
<td>3.2 Tracking</td>
<td></td>
</tr>
<tr>
<td>3.1 Computer aided design CAD</td>
<td>3.1 Interaction</td>
<td>Picking</td>
<td>15 Training</td>
<td></td>
</tr>
<tr>
<td>3.5 Context-awareness</td>
<td>3.1 Kinematics</td>
<td>Prototyping</td>
<td>2.4 Ubiquitous computing</td>
<td></td>
</tr>
<tr>
<td>3.1 Control</td>
<td>3.1 Kinetics</td>
<td>Quality control</td>
<td>1.2 User interface</td>
<td></td>
</tr>
<tr>
<td>3.1 Design</td>
<td>Layout planning</td>
<td>3.1 Real time</td>
<td>1.3 User test</td>
<td></td>
</tr>
<tr>
<td>3.1 Display</td>
<td>3.1 Learning</td>
<td>3.1 Registration</td>
<td>3.1 Visualization</td>
<td></td>
</tr>
<tr>
<td>3.1 Ergonomics</td>
<td>Maintenance</td>
<td>Remote assistance</td>
<td>VR</td>
<td></td>
</tr>
<tr>
<td>3.1 Eye-tracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1. Meta-analysis

The identified themes, keywords, and topics in the reviewed papers were categorized into the three chosen perspectives. They were also subdivided into more specific topics under the perspectives, as shown in Figure 1. This was done by interpreting the meaning of each theme/keyword/topic, sorting them one by one, and grouping them into categories. If it was unclear how to interpret a term, the description provided in the literature was used. If this was not sufficient to fully understand the term, the source(s) cited was used. The categories for each perspective were also related to each other based on their contents and internal role within the perspective.

Perspective 1, operators, has the following categories and interrelations: Assembly instructions is the category that is the main purpose of ARSG for operators, that is, enhancing their capability to quickly understand complex assembly instructions. The category Human factors is on the same level and relates to aspects needed to support the operators in regard to safety and ergonomics. Design is the category pertaining to how to design an interface that gives effective assembly instructions while not hampering the human factors of the operators. Validation is the category of ensuring that the design does what is intended. Finally, there are the two categories of support and training. Support relates to being able to support operators in full production. Training relates to training operators on more complex tasks outside of full production. Validation also needs to take these separate purposes into account.
Perspective 2, manufacturing engineering, has the following categories and interrelations. **Authoring** is the category of how to create content using authoring tools for the designed interface of ARSG for assembly instructions. **Infrastructure** is the category of specific limitations and possibilities that manufacturing puts on ARSG, which affects what is possible in regards to authoring tools. **Validation** is the category of ensuring that the contents created by the authoring tools are compatible with the remainder of the infrastructure in the factory.

Perspective 3, technological maturity, has the following categories and interrelations. **Enabling technology** is the category of specific technologies that makes ARSG and useful interfaces possible. **Technological demands** is the category of the general developmental level of ARSG-related technologies and how well they meet market demands such as price and weight. **HMD** (head-mounted display) is the category within which ARSG are located. **Tracking** is the category related to the system’s ability to identify AR content in the real world.

4. Conclusions and Future Work

This paper performed a meta-analysis of literature reviews related to the scope of implementing ARSG for industrial assembly and mapped the identified themes, keywords, and topics to three perspectives: the operator, manufacturing engineering, and technological maturity perspectives. The results summarized in Figure 1 show how the perspectives can be further divided into interrelated subcategories. There is a general
consistency when comparing the categories across the different papers, indicating that the categories and perspectives are suitable and that the field in general is well mapped.

The scope of this paper was to provide a brief overview of the relevant literature on ARSG. Future work is needed to more thoroughly investigate the chosen perspectives. The categories and their relationships also need to be validated.

References

Augmented reality smart glasses for operators in production: Survey of relevant categories for supporting operators

Oscar Danielsson*, Magnus Holm#, Anna Syberfeldt#

*University of Skövde, PO Box 408, 54128, Skövde, Sweden
#Corresponding author. Tel.: +46-500-448-596. E-mail address: oscar.danielsson@his.se

Abstract

The aim of this paper is to give an overview of the current knowledge and future challenges of augmented reality smart glasses (ARSG) for use by industrial operators. This is accomplished through a survey of the operator perspective of ARSG for industrial application, aiming for faster implementation of ARSG for operators in manufacturing. The survey considers the categories assembly instructions, human factors, design, support, and training from the operator perspective to provide insights for efficient use of ARSG in production. The main findings include a lack of standards in the design of assembly instructions, the field of view of ARSG are limited, and the guidelines for designing instructions focus on presenting context-relevant information and limiting the disturbance of reality. Furthermore, operator task routine is becoming more difficult to achieve and testing has mainly been with non-operator testers and overly simplified tasks. Future challenges identified from the review include: longitudinal user-tests of ARSG, a deeper evaluation of how to distribute the weight of ARSG, further improvement of the sensors and visual recognition to facilitate better interaction, and task complexity is likely to increase.

Keywords: augmented reality; assembly operator; literature survey; augmented reality smart glasses

1. Introduction

Industry 4.0 is one of a number of initiatives that have been undertaken to improve manufacturing, mainly by enabling more customizable production through the use of Information and Communications Technologies (ICT) [1]. However, while technology such as robotics are being used to a greater extent, assembly workers are still likely to have a central role in manufacturing operations [2]. An increased need for flexibility and adaptability in future production systems is likely to lead to a demand for cognitive aids such as augmented reality (AR) [3]. Production managers and HR managers have previously predicted that support tools on the shop-floor will become increasingly important and several of them mention AR as a probable technology to be integrated [4]. This can now be seen in that while adoption levels of AR are still low in industry in general, there are already examples of AR being used in manufacturing operations [5].

This aim of this paper is to explore the operator perspective of using AR smart glasses (ARSG) in assembly. This will contribute to a better understanding of the current status and future challenges of ARSG in relation to assembly operators and thereby help facilitate a faster application of ARSG in assembly. The paper will achieve this aim by reviewing categories that are relevant for the operator perspective. A previous scoping review of ARSG for industrial assembly operators identified six categories covering an operators perspective: assembly instructions, human factors, design, validation, support, and training (as seen in Figure 1) [6].

The connection between the categories in Figure 1 that was established by [6] can be described as follows: The two main perspectives of ARSG for operators are assembly instructions and human factors. Assembly instructions are the main purpose for operators to use ARSG but human factors is also critical to ensure operator safety. Both of these categories needs to be considered in ARSG design. The design needs to be validated...
and validation in turn depends on how the ARSG are to be used, as a live support in production or as a separate training tool. Based on these connections the categories assembly instructions, human factors, design, support, and training are explored in this paper.

Fig 1. Operator perspective of ARSG in assembly using categories adopted from [6].

2. Background

There are generally three ways through which a user can experience AR: worn on the user’s head (head-mounted), held in the user’s hand (handheld), or through equipment placed in the user’s environment (spatial) [7, 8]. Handheld solutions are generally unsuitable for operators since they need both hands for assembly tasks. With a spatial solution the operator does not need to wear any extra equipment, but it limits where AR can be displayed to only close to the equipment. It is also limited as it can only display 2D objects on physical surfaces [9].

Head-worn AR can be further categorized into, for instance, contact lenses, helmets, and headsets (smart-glasses) [8]. This paper defines ARSG as a wearable device with one or two screens in front of the user’s eyes that can merge virtual information with physical information in the user’s field of view (FOV). The definition is similar to that used by [10] but broader. The motivation for this is that as ARSG continues to improve it is a reasonable assumption that all head-worn AR will be light and small enough to be considered as smart-glasses. The main advantages of ARSG are that the display is in the operator’s FOV, can display information in full 3D, and is hands-free. The main disadvantages are that ARSG currently have a more limited battery-life and FOV compared to spatial and handheld solutions.

Four ways to implement AR in ARSG is projection based, eye multiplexed, optical see-through, and video see-through [11]. Retinal projection (1 in fig.2) is a fifth way, where thin parallel light beams are focused into the user’s eyes [12]. Projection based AR (2 in fig.2) is implemented with projectors worn on the user’s head and retroreflective materials placed in the environment [13]. Eye multiplexed AR (3 in fig.2) is a virtual scene registered to the physical environment but not composited with the real world view. Video see-through (4 in fig.2) combines virtual content with a real-time video stream of reality and presents the result on a screen in front of the user [14]. Optical see-through (5 in fig.2) creates AR in the user’s FOV, usually by directing the light of the virtual scene through half mirrors or prisms [11]. Optical see-through is currently the most common solution used in commercial ARSG [15]. ARSG displays can be monocular (one eye views a screen, A in fig.2), binocular (both eyes view the same screen, B in fig.2), or dichoptic (each eye views different screens, enabling depth perception, C in fig.2) [16]. Dichoptic is preferable for ARSG if spatially sensitive information should be displayed.


3. Assembly instructions

Assembly operators need instructions on how to perform his/her assembly tasks, and more instructions are needed the more complex the task is [17]. Since products are updated and replaced regularly, operators need updated instructions to perform the correct assembly. Operators and white-collar workers at three different plants within the same global production network where interviewed by [17] in regards to areas of improvement within assembly instructions. Some problems they identified were slow updating processes (it could take three weeks for instructions to be updated at one plant), a technical language that was hard to understand, irrelevant information, a lack of feedback on errors made, and a large variation in teaching quality due to operators learning from each other. Limits on teaching quality have been identified in other reviews as well [18]. Operators also wanted more individualized and dynamic instructions and which problems that occurred, and their prevalence, varied between the plants [17]. In another case it was found that instructions should focus on clearly marked pictures and be as simple as possible with minimal text [19]. But according to [20] written text should not be removed completely. They found that users using multimedia instructions (both text and pictures) had less errors, faster learning times and were less affected by secondary tasks compared to single media instructions (only text or only picture).

Task complexity also has an influence on how to best design instructions. By dividing users into three experience levels, [21] adapted the instructions to show the right amount of information for each operator. This was implemented in a multi-modal system where the operators used ARSG.

One case study that observed and interviewed operators in an engine assembly factory found no gender or experience differences in how often operators needed to look at assembly instructions [22]. It was further found that the main reasons operators gave for looking at instructions were for checking the torque of the screwing machine, assembly time, and if something goes wrong. In general, the reasons for operators to look at instructions were for things that needed to be checked
(such as the torque of the screwing machine), deviations from normal (if something goes wrong for instance), or things that varies (like assembly time). The operators were also interviewed about their opinions of ARSG and expressed clear positive reactions towards the possibilities of more dynamic and individual instructions.

To summarize, the current status in industry is that there is a lack of standards in regards to development and distribution of assembly instructions. Assembly workers have expressed interest in individual and dynamic instructions. Cognitive research has found multimedia instructions to be less mentally demanding, leading to less learning time and fewer errors. Digitizing assembly instructions would enable individual and dynamic instructions. However, it is important to recognize that standardizing the format and handling of instructions is necessary to facilitate digitization.

4. Human factors

Equipment that humans are to interact with and use needs to take ergonomic aspects into consideration and this is even more important for equipment used within assembly since it is usually used with a high frequency or for extended periods of time. Ergonomic issues within AR have so far, according to the findings of [23], mostly been tested in laboratory settings within the scientific literature.

An ARSG solution means that some form of equipment will be worn by the operator on his/her head. One important aspect from an ergonomic perspective is the weight of the ARSG. Night vision goggles are another type of head-mounted equipment and [24] found that reducing the length of the protruding part of night vision goggles had little effect on reducing neck muscular strain. The main issue they identified was instead how much weight was placed off from the center of the user’s skull. However, [25] tested different weights and centers of mass for one pair of experimental HMD with different poses. They found that which center of mass (COM) to use varied depending on the pose; if the user was in a neutral position it was best to keep COM around the top center of the head, if the user looked up the COM should be placed forward, and if the user looked down the COM should be placed backward, as illustrated in Fig. 3. They also found that a lower mass reduced the neck joint torque ratio, a measure used as an indicator of physical workload. Evaluation of fatigue from extended usage was an aspect identified as valuable future work and [25] further hypothesized that intended duration will determine the recommended upper mass limit due to the strong correlation between duration and load.

![Fig. 3. Shifting of COM depending on head-pose (adopted from [25])](image)

Using a video-based HMD can affect users’ efficiency. When comparing movements and time to finish identification tasks between using and not using an HMD, [26] found that when participants used a HMD to perform a simple object location targeting task they needed more time and made larger movements, implying that using a HMD hinders performance, possibly due to time delays in feedback. The HMD used in the experiment was a form of video-based AR. They also found that the larger movements could affect users’ sickness levels negatively. Areas they identified as interesting for future studies were more extensive studies with more participants and longer exposure time, analyzing simulator sickness and its relationship between posture and performance, as well as if HMDs affect the transfer of training. Similarly, [16] found that video-based HMDs cause significantly more visual discomfort, such as visually induced motion sickness, compared to traditional displays such as TV-screens. Video-based HMD also has an added safety-risk in case of power-failure. Motion sickness in optical see-through HMDs is still an understudied subject according to [27], but they found that participants experienced insignificant motion sickness when using Microsoft Hololens, an optical see-through HMD. This could indicate that an optical see-through HMD would be more suitable in regards to preventing visual motion sickness.

In summary, both the weight and the displacement of the weight of ARSG are important ergonomic factors for operators. The COM should be positioned close to the center of the skull when working in neutral positions, and towards the front or back respectively when looking up or down. Video-based displays can cause significant motion sickness. Microsoft Hololens, an optical see-through HMD, caused insignificant motion sickness which could indicate that optical see-through HMDs cause less motion sickness but further studies are needed.

5. Design

Designing for AR introduces novel challenges and possibilities compared to traditional screen-based interfaces. It is therefore important to know what is known regarding designing for AR in general, and for ARSG in particular.

Designing interfaces for mobile AR requires its own set of design principles compared to general AR and mobile systems in general, so [28] proposed a set of interaction design principles for development of mobile AR applications. The principles were:

1. Use the context for providing content
2. Deliver relevant-to-the-task content
3. Inform about content privacy
4. Provide feedback about the infrastructure’s behavior
5. Support procedural and semantic memory

The principles were based on mobile AR and the limitations of smartphones but they may still be relevant to ARSG. Using the context for providing content is important since interaction is bound to the physical environment, but this is most important when the physical environment changes. The second principle is to minimize cognitive overhead from interacting with both the system and the real world by minimizing content. Since assembly operators have a high workload this principle is likely to be very relevant. The third principle is probably of lesser relevance in an industrial setting than for private usage, but it
can still be relevant to let operators know what activities are logged. Providing feedback about the infrastructure’s behavior is important since users still interact with real world objects and might depend on external service providers. Applications should therefore be able to adapt to different availability. This principle is of lesser relevance in an industrial setting where all objects the user interacts with can be assumed to be a part of the same infrastructure. The last principle is to support procedural and semantic memory by making the interface and interactions easy to understand which is highly relevant.

A more general set of guidelines, including both AR and VR, and applied to both assembly and maintenance training is proposed by [29]. The first guideline is to start the training with an observation of the task to create a mental model of the assembly. The second is to combine physical and cognitive fidelity since they have complementary advantages. The third is to have the right amount of guidance aids since too much reduces learning. The final guideline is to provide enriched information about the task to promote deep learning. There are however indications that AR will only help an operator if the task is difficult [30].

The operator perspective is also an important aspect of the design. A minimal viable solution for an ARSG-based training system was found based on an engine assembly case [31]. The following features were identified as the most important:

1. The HMD shows the assembly procedure.
2. The HMD shows the relevant parts to pick.
3. The HMD is always available as a training support.
4. The HMD solution works as a “training island” and works separately from the line.

Spatial navigation in an AR interface compared to a traditional screen interface differs in that there is no clear limitation; with a screen a user knows where to look for information but in an AR setting the information could be behind them. A proposed solution to this is a virtual funnel leading the user to the target, a solution that reduced the time needed to find objects and perceived cognitive load for users [32]. This concept has been further explored with different variations such as different forms of the funnel (circular or square) for instance [33]. After six test iterations they arrived at a solution that could guide the user with different visual cues depending on how big the angle was between the user and the intended target. AR might also be used to help operators navigate team tasks by increasing their ambient awareness and by guiding their visual attention [34].

Interaction in the interface will likely differ in an AR implementation compared to a screen-based implementation since the user has a higher degree of mobility and probably do not have a mouse and keyboard in front of them. To make navigation more intuitive, [35] comparatively evaluated a mixed reality (MR) prototype that used a ‘tangible interface’. A physical cube that was tracked by the system allowed the user to navigate in the interface. At the time tracking technology was limited and fiducial markers were used on the cube to allow for it to be accurately tracked. Microsoft Hololens allows for gesture recognition, allowing the user to interact in a similar manner but without an intermediary artifact. Sometimes operators make mistakes and an ARSG system needs to detect these mistakes to allow for correct interaction. Force sensors can detect that parts are picked and placed at the correct position but not that they have the correct orientation, but by combining force sensors with an AR-system more errors can be detected and presented in an ARSG-system [36].

In summary, designing ARSG-interfaces means different challenges compared to a completely digital screen-based interface. AR means placing digital information in the real world and when presented in ARSG this gives the user a hands-free interaction with a bigger environment than a traditional screen-based interface. Design guidelines suggest in general to minimize information in any given context to what is needed in those contexts and to help orient the user to the correct physical location. When interacting in a completely digital world the developer can be seen as omniscient in where all things the user interacts with are. But in AR the world needs to be digitized if the results of interaction are to be interpreted in an ARSG system.

Future challenges lie in improving sensors and visual recognition of parts to allow for more accurate digitizing of the real world. Since ARSG have not been available for a long time or to a wide array of people, guidelines will need to be further tested to ensure their robustness.

6. Support

The role of assembly operators has become increasingly complex, from almost being seen as a machine to now having an increasing number of tasks and responsibilities [4]. Global competition has diversified manufacturing companies’ product range, leading to an increased complexity for assembly workers that in turn affects quality. This can be somewhat alleviated by simplifying the assembly tasks [37]. But due to an increased number of variants and shorter life-cycles of products it is more difficult for assembly operators to achieve task familiarity and routine [38]. While some assembly operator stations currently contain routine work that the operators learn fast there are already stations that require frequent relearning, for instance single inspection point (SIP) stations. Here operators need to inspect different details of products depending on what is currently having quality issues and this can vary from day to day. According to R Lindgren Brewster (personal communication, February 13, 2019), Industrial Business Optimization Manager at Volvo Car Corporation, SIP-stations are complex for operators to learn. The main problem is not to learn new things to inspect, but to stop inspecting things that are no longer a quality issue, leading to waste.

To summarize, some operator tasks are already so complex that learning new tasks, and unlearning old tasks, could benefit from information support through ARSG. Given the shortening of life-cycles of products as well as more simultaneous products it is a likely scenario that task complexity will continue to increase in the future, creating more operator tasks that have a need for increased information support.
7. Training

Training a new operator using on-the-job training (OJT) is one common method of training new operators [39]. Instructions can however be hard to understand for novice operators, who require adequate training before working on the assembly line [40]. This leads to a loss in efficiency that ARSG could help to improve by allowing operators to become independent and efficient workers faster.

AR research for industrial applications has been a research topic since the 1990's, but there are still severe limitations in that most test-participants are students and assembly tasks are often simplified, many times using LEGO models [41]. AR based training is also mostly compared to paper- or video-based instructions rather than face-to-face training and most measurements are on time rather than quality and training transfer rates [41]. And also, in most studies monitors or handheld devices has been used [41].

Research on transfer rates from using AR in industrial environments is still very limited. In an effort to close this gap, [42] performed an evaluation of slightly different AR headset interfaces. They found that errors can be reduced by adding a quiz on a task an operator has just been trained on. Most AR training systems are not intelligent but adding intelligent support can significantly improve training results [14]. This seems to support the wish from operators to have dynamic support, found by [17].

In summary, most research regarding AR training for operators has been done using simplified tasks and other equipment than ARSG and it has been done by non-operators outside an industrial environment. Adding intelligent support and quizzes to the training can improve the training results.

8. Conclusions

This paper has investigated ARSG for industrial assembly from an operator perspective. Table 1 presents a summary of the findings.

Table 1. Summary of current status and future challenges per category.

<table>
<thead>
<tr>
<th>Category</th>
<th>Current status</th>
<th>Future challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly instructions</td>
<td>• Lack of standards</td>
<td>• Digitization</td>
</tr>
<tr>
<td></td>
<td>• Worker interest in individual and dynamic instructions</td>
<td>• Standardization</td>
</tr>
<tr>
<td>Human factors</td>
<td>• Video-based ARSG can cause efficiency losses</td>
<td>• Deeper evaluation of COM on ARSG</td>
</tr>
<tr>
<td></td>
<td>• Limited FOV in current ARSG</td>
<td>• Longitudinal tests of ARSG</td>
</tr>
<tr>
<td></td>
<td>• Interface potential safety risk</td>
<td>• Expansion of FOV</td>
</tr>
<tr>
<td></td>
<td>• Weight of ARSG should be kept a minimum</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>• Guidelines exists, focuses on presenting context-relevant information and limit disturbance of reality</td>
<td>• Sensors and visual recognition needs further improvements</td>
</tr>
<tr>
<td></td>
<td>• Sensors and visual recognition allows ARSG to interact with real world objects</td>
<td>• More verification and iteration of guidelines</td>
</tr>
</tbody>
</table>

It shows that there is currently a lack of standards in design of assembly instructions. Operators have also expressed interest in more customized and dynamic instructions as well as in using ARSG, and the increased complexity and updates leads to a need for dynamic instructions. The main future challenges regarding assembly instructions lie in improving standardization and digitization to enable ARSG compatibility.

In the human factors category it was found that video-based ARSG can cause efficiency losses and that there is a general limit of ARSG FOV. There are potential safety risks and the weight should be kept at a minimum, but the placement of the weight is also important. Future challenges identified are that weight and COM should be further evaluated and improved on, that more longitudinal user tests with ARSG are needed and that FOV in general needs to be expanded.

The current status in the design category is that available design guidelines focus on presenting context-relevant information and to limit disturbance of reality. Improvements in sensors and visual recognition has opened up more design alternatives by making it possible for ARSG to interact with real world objects. But future challenges lie in improving sensors and visual recognition. Current guidelines also needs to be further improved on and adapted to industrial settings.

In the support category the current status is that operators face complex and often changing tasks and that task routine is increasingly difficult to achieve. Future challenges lie in that this complexity is likely to increase in the future.

The current status in the training category is that many tests are simplified and not performed by operators. Few of the AR-studies has been done with ARSG and there has been few quality and training transfer measurements. Future challenges lie in performing more studies, mainly longitudinal ones.

The main contribution of this paper lies in that it gives a synthesized overview of what has been achieved and what still needs to be achieved when it comes to ARSG for operators within previously identified relevant categories. This overview will help to give an overall understanding of the current potential of ARSG as well as guide further improvements of ARSG for the use of industrial operators.

Future works include considering other relevant perspectives such as manufacturing engineering and technological maturity, further described in [6]. A more exhaustive review of the categories explored in this paper could also be beneficial, particularly validation which was only indirectly explored in this paper through the support and training categories.
PAPER 5
Augmented reality smart glasses in industrial assembly: Current status and future challenges

Oscar Danielsson*, Magnus Holm, Anna Syberfeldt

Production and Automation Engineering, University of Skövde, Kanikegränd 3A, Skövde, Sweden

ARTICLE INFO

Keywords:
Augmented reality
Smart glasses
Industry 4.0
Literature survey

ABSTRACT

This article aims to provide a better understanding of Augmented Reality Smart Glasses (ARSG) for assembly operators from two perspectives, namely, manufacturing engineering and technological maturity. A literature survey considers both these perspectives of ARSG. The article’s contribution is an investigation of the current status as well as challenges for future development of ARSG regarding usage in the manufacturing industry in relation to the two perspectives. This survey thereby facilitate a better future integration of ARSG in manufacturing. Findings include that commercially available ARSG differ considerably in their hardware specifications. The Technological Readiness Level (TRL) of some of the components of ARSG is still low, with displays having a TRL of 7 and tracking a TRL of 5. A mapping of tracking technologies and their suitability for industrial ARSG was done and identified Bluetooth, micro-electro mechanical sensors (MEMS) and infrared sensors as potentially suitable technologies to improve tracking. Future work identified is to also explore the operator perspective of ARSG in manufacturing.

1. Introduction

The role of industrial operators has seen several changes, from being seen almost as a machine in the 1920’s, to currently having an increasing range of responsibilities and tasks, and to the prediction that future operators will be expected to interpret information and act accordingly [1,2]. The fast and profound changes that have impacted manufacturing industry have of course also affected manufacturing personnel. In particular, operators on the industrial shop floor there are less margins for error, changing work methods, and new technologies. This has led to both new demands but also new possibilities. Presently there is no indication that this process will slow down. The predictions of what industry 4.0 can bring rather indicates the opposite will be the trend and change will accelerate.

In this technology driven scenario it is important that the operators’ work and working conditions are considered as a part of the general development of future manufacturing. As the available production data and product variations increases on the industrial shop floor, the pressure on assembly operators to handle this vast information flow increases as well, surpassing what is humanly possible. Assembly operators therefore need decision support that simplify this information. Augmented reality (AR) can provide effective support for assembly operators to help them visualize information and to place it in its context.

There has been a notable move within manufacturing from mass production to mass customization, brought about by ever increasing customer demands [3]. Industrial management representatives predict increasing importance of decision support tools for operators, AR being one such technology mentioned by managers interviewed by [1]. One of the trends within cyber-physical based manufacturing systems in recent years is smart manufacturing based on AR [4]. The AR market was predicted to grow substantially in the coming years to more than a billion users by 2020 [5]. One type of AR that shows good potential for industrial applications are AR smart glasses (ARSG) [2,6].

The aim of this article is to review the current status of ARSG from an industrial perspective and identify what challenges remain before successful implementation on the shop floor becomes viable. Even though many see the potential for AR in industry, companies are largely still performing ‘proofs of concept’ and the enabling technologies for AR (eyewear and headsets) are not yet sufficiently robust for continuous use in harsh working environments [7]. Quandt, Knoke, Goroldt, Freitag and

Abbreviations: AR, Augmented Reality; ARSG, Augmented Reality Smart Glasses; HMD, Head Mounted Display; IMU, Inertial Measurement Unit; MEMS, Micro-electro-mechanical systems; SG, Smart Glasses; TRL, Technology Readiness Level; RFID, Radio Frequency Identification; UWB, Ultra wideband.

* Corresponding author.

E-mail address: oscar.danielsson@his.se (O. Danielsson).

https://doi.org/10.1016/j.jii.2020.100175

Available online 13 October 2020
2452-414X/© 2020 Published by Elsevier Inc.
Thoben [8] found that industrial AR has specific constraints compared to other application areas that can lead to application barriers. Aspects they found to be particularly lacking were reliability, work safety fulfilment, and overlay accuracy.

Fig. 1 presents two relevant perspectives to consider regarding ARSG as operator assembly support that have been identified [9]. This article explores these perspectives: the technological maturity of ARSG related technology and the manufacturing engineering perspective of ARSG. The main contribution of this paper is to determine the current status of ARSG within research and commercially available technology and to compare this with the needs of the manufacturing industry to see what future challenges needs to be addressed before ARSG can be integrated into production to a greater extent. Thus the paper will contribute a technical foundation for better uptake and integration of ARSG’s into manufacturing assembly.

Manufacturing engineering is a very broad area and within this paper the scope is limited to the aspects of integrating, maintaining and updating ARSG as a support tool for operators in assembly lines. This definition is also connected to the production preparation process.

Shook and Marchwinski [10] describes production preparation process (3P) as: “A disciplined method for designing a lean production process for a new product or for fundamentally redesigning the production process for an existing product when the design or customer demand change substantially.”

A cross-functional 3P team examines the total production process, developing a number of alternatives for each process step and evaluating these against lean criteria. Using simple materials, the team then mocks up the process to test assumptions before equipment is ordered or installed in the final configuration.” [10 p. 65]

Three questions were identified as important to seek answers for in this survey:

**Q 1:** What previous works has been done in regards to integration, maintenance, and updating of ARSG interfaces for operators into a production system? The answer to this question provides better understanding of the current state of research and development of ARSG.

**Q 2:** What is the technical development level of ARSG in regards to usage as assembly support? This question puts the general technological maturity of ARSG into the perspective of usage as an operator support tool.

**Q 3:** What needs do manufacturing engineers and technicians have in using ARSG and their interface from a manufacturing engineering perspective? The focus of this question is on the administrative personnel and their needs in regards to implementing and maintaining ARSG in a production system.

Section 1 has developed the aims and motivation for this article. This is followed with some background to ARSG in industry in Section 2. Section 3 then explains the structure of the literature survey. The first perspective explored is manufacturing engineering presented in Section 4 and the second perspective, technological maturity is given in Section 5.

Discussion of the findings are presented in Section 6 and finally Section 7 presents the conclusions drawn.

### 2. Background

As the technological base for AR has improved there has been a rapid growth of the field of AR [5]. Bottani and Vignali [11] found that more than half of all journal papers with an AR focus in manufacturing industry featured only five countries: Singapore, Germany, Italy, USA, and China, and many countries only had two published journal papers. They believe this indicates that AR in manufacturing is still in its infancy. They also noted that most implementations in current literature has so far been carried out in laboratory settings.

The technology to display AR can generally be classified in three areas: on the user’s head (head-mounted), in the user’s hand (handheld), or installed in the environment (spatial) [12,13]. A handheld solution limits the user’s efficiency by tying up at least one hand. With a spatial solution the user does not need to wear any equipment, but it limits workstation design by requiring equipment to be installed in the environment. A spatial solution is also limited to displaying virtual information on surfaces, and cannot visualize mid-air objects [14].

Head-worn AR can be categorized and implemented in different ways depending on their size and placement, for instance contact lenses, helmets, and headsets (smart-glasses) [13]. This article uses a more simplified categorization in that all forms of head-worn AR system are referred to as ARSG. Rauschnabel, Brem and Ro [15] defines ARSG as: “Augmented Reality Smart Glasses are defined as wearable Augmented Reality (AR) devices that are worn like regular glasses and merge virtual information with physical information in a user’s view field.” [15 p. 6]. A similar definition is given by [16]. This article broadens their definition by including all forms of head-worn devices in the category ARSG. This is motivated by the assumption that processing power and batteries will improve over time to a point where all the necessary performance for most uses can fit in a device that can be worn like regular glasses, at which point there would be no added value in increasing the size of a pair of ARSG.

Billinghurst, Clark and Lee [5] describes four possible ways to implement AR in head mounted displays (HMD)’s: projection based, eye multiplexed, optical see-through and video see-through. A fifth way of implementing AR in HMD’s is retinal projection, which works by focusing thin parallel light beams into the user’s eyes [17]. Projection based AR uses projectors worn on the head combined with retoreflective material in the environment [18]. Westerfield, Mitrovic and Billinghurst [19] describes eye multiplexed AR as a virtual scene registered to the physical environment but not composited with the real world view. Advantages they see is less demands for accuracy but with less intuitiveness than other implementations. They further describe video see-through as a system that uses a camera to capture the real world of a user, then adds virtual content to create AR, and then presents this to the user.

![Fig. 1. Two perspectives on ARSG for assembly with their corresponding topics and section number, partial results of [9].](image-url)
user on a screen. Optical see-through creates AR by combining a view of the real world with virtual images, usually achieved through directing the light of the virtual images through half mirrors or prisms [5]. This allows the user to continue to see the real world in real time while seeing AR content. Optical see-through is the most common solution currently for commercially available ARSG [6]. Regarding displays in HMD’s there are three possible choices: monocular (one eye views a screen), binocular (both eyes view the same screen), or dichoptic (each eye views a different screen, enabling depth perception) [20].

3. Structure of the literature survey

As previously described, Fig. 1 presents the results of a scoping review of ARSG for industrial assembly operators [9]. The perspectives of manufacturing engineering and technological maturity are explored in this article. The definition of these perspectives and their sub-topics are based on those of [9].

The manufacturing engineering perspective is defined by the topics: authoring, infrastructure, and validation. The authoring topic explores how authoring tools can be improved to allow developers to create operator instructions in ARSG more efficiently. The infrastructure topic explores how ARSG can be integrated into a production system, which information that can be provided to the ARSG interface and what limitations an industrial environment places on ARSG. The validation topic explores how authoring tools, their created content, and ARSG can be validated to be compatible with a production system.

The technological maturity perspective is divided into the topics of: ARSG, enabling technology, technological demands, and tracking. The topic ARSG is named differently from that used in [9] due to the definition of ARSG used in this paper. This paper specifically explores currently available ARSG, their specifications, and the trends of the ARSG market. Enabling technology is the topic that explores technologies that enables ARSG to be used in practice. Technological demand is the topic that explores the limitations that are put on ARSG when being used for industrial assembly. Tracking explores further which types of sensors can be used for achieving AR and their suitability for industrial environments.

4. Manufacturing engineering perspective

The manufacturing engineering perspective explores the topics of authoring, infrastructure, and validation, as described in Section 3.

4.1. Authoring

Global competition drives a constant need for the manufacturing industry to seek ways to optimize their production. Therefore if ARSG are to be used to present assembly instructions, the process of updating the instructions or creating new ones entirely needs to be simple enough that it can be done as a regular part of current continual improvement.

Bocevska and Kotevski [21] suggest an approach to author AR content that does not require programming skills or expertise in computer science. Similarly, Erkoynucu, de Amo, Dalle Mura, Roy and Dini [22] show that maintenance personnel with limited prior AR experience can create AR content to be used in maintenance. Authored content was also compared by tests with paper-based instructions and the authored content led to participants performing the maintenance tasks at around half the time of that of those using the paper-based instructions [22]. Pham and Xiao [23] instead presents preliminary results from a system that can automatically analyze video of mechanical assembly and extract tasks from it. The system still needs to be improved in its accuracy of object and hand gesture recognition. Gimeno, Tena, Orduna and Fernández [24] developed an authoring tool that allowed non-programmers to develop prototypes faster than programmers using traditional tools. Kinect cameras were used to create a depth map to provide occlusion capability [24]. Another possible support in creating content is algorithmic analysis of CAD-data that supports detection of axis and direction for each part in an assembly/disassembly task, thus allowing faster manual creation of instructions [25]. Kaipa, Morato, Liu and Gupta [26] presented a design framework for automatically generating instructions for operators. The framework can generate and order tasks from high-level assembly tasks that have previously been generated from assembly planning. [27] have created a concept for a learning design for both students and industrial stakeholders to implement automated reconfigurable digital assistance systems. This system would have an interaction device and among the systems they identified ARSG were mentioned. They planned to implement, test, and evaluate this concept in the TU Wien Pilot Factory Industry 4.0 for industrial use cases.

In the commercial market there is now specialization towards specific markets rather than just providing general AR authoring. An example of AR authoring aimed towards industrial applications is the company PTC’s industrial AR platform [28]. This AR platform has already been implemented into production in some manufacturing companies and it is predicted that many more will do this within a year [29].

In summary, there currently exists authoring tools for AR that are specific for industrial production. Support for automated assembly instruction generation has been investigated that includes depth recognition for correct AR occlusion and improved interfaces have helped simplify the authoring process in general. Future challenges include improving automated instruction generation to further reduce lead times for assembly instruction generation.

4.2. Infrastructure

For ARSG to be able to present dynamic instructions it is desirable that they are connected, directly or indirectly, to the surrounding production system. In this way feedback from tools, for instance if the torque was correct when tightening a screw, can be integrated into the interface and the instructions can be made relevant when errors are detected.

General requirements for AR applications in the industrial sector are summarized by Quandt, Knoke, Gorldt, Freitag and Thoben [8] and validated through two case studies, one within maintenance and one within weld fabrication training. They identified three categories of requirements, the first being requirements during development and integration, consisting of cost-effectiveness, data security, and applicable regulations. The second requirement being during set-up, consisting of set-up time and system reliability. The final requirement type was operational, consisting of accuracy of presentation, real-time capability, and ergonomics.

If each product can store its own assembly process on an individual RFID then this would enable decentralization of production information which could be used for easier access for an ARSG interface [30]. Another way of supporting ARSG by enhancing the surrounding environment is presented by Yew, Ong and Nee [31]. They describe a manufacturing system that has a digital coordinate system that corresponds to the real world. Natural visual landmarks in the environment are used to help viewing devices navigate where they are to present AR content in the correct positions. Manufacturing resources within this landscape can then interact using customizable interfaces [31]. Connectivity is also an important issue and AR has been identified to need a high data rate of around 25 Mbps as well as a very low latency of around 1 ms [32].

Investment in the infrastructure of a production line requires insight in the costs and benefits in relation to specific needs of each production line. To choose an appropriate ARSG for a specific infrastructure a company management can use a step by step evaluation of available ARSG’s to compare which ARSG are the most suitable for their specific needs [6]. Another form of evaluation is proposed by Palmarini, Erkoynucu and Roy [33] who, on the basis of a literature review,
developed a set of questionnaires to evaluate a maintenance task to determine if AR could improve operator performance and which combination of AR hardware, development platform and visualization method to use, if any. Future work pointed out by the authors are validating the process and extending the process with ergonomic and economic aspects.

To summarize, surrounding infrastructure can provide ARSG’s with feedback, through product-integrated status and visual landmarks in the production facility, to allow for more accurate and dynamic interaction, both for navigation and for determining product status. Guidelines for making strategic decisions regarding ARSG for assembly exists but are still in need of validation and do not take economic aspects into account.

4.3. Validation

A holistic view on how to implement and validate AR in an assembly task is proposed by Chimenti, Iliano, Dassisti, Dini and Failli [34], starting with a preliminary analysis of the assembly procedure and through a set of intermediary steps refining the procedure down to assembly instructions. Once you have a set of detailed assembly instructions you select which AR hardware to use, define a user interface, implement the software and validate the design [34]. A current limitation is that: “Published evaluation and test results often cover out-of-date hardware or prototype systems.” [35, p.26]. To mitigate this, Paclke, Röcker and Bulk [35] developed a test platform with test applications to systematically evaluate ARSG in industrial settings. The test platform evaluates hardware through sensors and assesses usability, comfort, and ergonomics through user tests. The test platform is also compact and flexible to allow easy setup in different locations, including a real factory environment. Future work identified included extending the framework with a more customizable questionnaire and a wider set of visualization options to enable usability tests of visualization.

AR can also help in testing in learning factories [36]. It can be used both for enhancing learning by for instance visualizing steps such as painting and pollution that learning factories cannot feasibly have or through presenting data, such as power flow, visually. A learning factory can also be used to test out new technology in a relevant environment before implementation in a real setting [36]. This can allow for more complex tests of ARSG in a relevant industrial setting. Hennig, Reisinger, Trautner, Hold, Gerhard and Mazak [37] presents the TU Wien Pilot Factory, which they define as a combined demonstration, pilot, and learning factory. In their definition, a demonstration factory allows for accurate and fast way without disturbing current production facilities. They more specifically identify a lack of human-machine interaction vertical industry application in industrial scenarios according to [38]. They more specifically identify a lack of human-machine interaction standards and unified norms, high construction cost, and a lack of references for enterprises to the deployment of AR. Syberfeldt et al. point out some areas in need of further development to allow ARSG to be successfully integrated into the industrial shop floor [6]. These areas are: extending the field of view (FOV), making the glasses wearable, developing guidelines for user interface design, enabling benchmark evaluation, and improving voice-based interaction in noisy environments. Of these areas FOV is within the scope of this survey. Other limitations in current AR systems in general are intuitive user interfaces, integrating the systems with enterprise data and time-consuming authoring procedures [39], the latter two having been discussed in the previous chapter. And there are as yet no long term studies regarding the use of AR hardware, which relates to Section 4.3 [40]. Given that ARSG are mobile devices there is a need for more powerful batteries [41]. Internet connectivity will also put a strain on batteries and a challenge for future 5G development is to develop low energy solutions [32]. Given that AR in general and ARSG specifically is just on the verge of being broadly implemented in industrial shop floors [29], it is possible that more technological demands will become apparent in the future that have not been possible to predict before ARSG becomes more widespread in manufacturing industry.

In summary, there is currently a need for improved battery technology and extending the FOV. But more demands, that have not yet been predicted, could become apparent as ARSGs are implemented at a broader scale.

5.2. Enabling technology

To implement a pair of ARSG there are a multitude of technologies needed and it is beyond the scope of this survey to present an exhaustive analysis of them all. This section instead presents the current status and possible future developments in some specific areas that have been identified as important for future developments of ARSG in the context of operator support. The areas are: batteries [41], and FOV [6].

An important aspect of investing in ARSG as assembly instruction support is the technological level of ARSG. AR is a fairly new technology without widespread adoption in the industry and it has not yet reached maturity, except in some areas such as picking [42]. While smart glasses (SG) in themselves have been found to have a TRL of 9, AR technologies are at a lower level [43]. For industrial use, ‘Augmented Reality Tracking Techniques’, ‘Interaction Techniques and User Interfaces’, and ‘Augmented Reality SDK’s’ all have a TRL of 5 and ‘Augmented Reality Display Technologies’ have a TRL of 7 according to [43]. It was similarly found by [44] that AR has a TRL between 6 and 7. The TRL of AR has been found to be between 5 and 6 for military use [45]. In medicine AR TRL follows a rough bell curve from 4 to 7 [46]. However, even though there are many ARSG available for consumers (see Table 1 and Fig. 2), a reason for them not previously having been in industrial use is because of restrictions within shop floor usage [43]. More recent developments have seen some use of AR on the industrial shop floor, although ARSG are still not a common technology [29]. Regarding connectivity, an identified future evolution scenario of 5G is Enhanced Mobile Broadband (eMBB) which could potentially support AR [4].

Another area of interest is the extension of battery life through improved energy efficiency [47] or better battery technology [6, 41]. Um et al. also tested a solution of transmitting captured images from ARSG to a server for processing and re-transmitting the results, thus reducing the strain on the batteries [48]. The servers were placed in the architecture in the form of edge computing. This solution would also
have the added advantage of being less dependent on specific ARSG interface designs. The results did not show an improvement in time with current wireless technology [48]. Szajna et al. also proposes a setup using edge computing but uses it to monitor the production line rather than visualization [49].

A person that has a normal eye vision has a FOV of about 150° with one eye and about 180° with two eyes [50]. It is however inaccurate to compare this FOV directly with a mechanical camera system since, for instance, visual acuity in the human eye is not evenly distributed and individuals can have various visual limitations [51]. There is currently no video-based or optical see-through HMD that can provide AR with the same FOV as that of a human. An experimental setup makes it possible to achieve a FOV of 100° diagonally [52].

To summarize, while ARSG have been found to have a high technological maturity with a TRL of 9 for SG, however, there are still limitations in individual components and in regards to industrial adaptation. Current battery-technology or techniques to minimize battery drain do not allow full usage of ARSG through a normal workday and even experimental setups cannot reach the FOV of the human eye.

5.3. ARSG

This topic explores the general development of the emerging ARSG market. Previous publications have mapped ARSG, for instance [6, 53]. Table 1 presents some ARSG that have been released or scheduled for release since 2013 until the present, sorted by year and name. Since ARSG is an emerging market there are some ARSG that are no longer available. Some companies have since the release of their ARSG discontinued or exited the ARSG market altogether, been incorporated into other companies, or declared bankrupt. This is indicated in Table 1 with italic text.

To make comparisons of battery capacity more accurate both estimated hours of usage and battery size in mAh are declared when data has been available. What many of the companies specify on their websites is that battery life greatly depends on features in usage, which might partly explain the wide span of estimated battery life. Other aspects that affect this are the battery size and hardware such as processors and sensors.

When comparing the specifications of ARSG it can be seen that there is a substantial variation between them. Weight varies between 69 and 579 g. The FOV ranges from 15 to 90° diagonally and the battery capacity varies between 1 and 12 h. Within the timeframe of 2013–2019 there are several examples of companies that have exited the ARSG market, indicating some volatility. The general market for ARSG is however growing and there are manufacturing companies investing resources into researching the use of ARSG in assembly operations. The latest generation of ARSG, for example Microsoft Hololens 2 and Magic Leap One creator edition has achieved a FOV of 52 and 50° respectively. For the Hololens 2 this is an improvement of about 50% in three years.

To summarize, the authors believe that in the last six years there has been an emerging ARSG market that is now starting to stabilize with strong actors making fast progress. Some of the future challenges the authors see is improving battery life, reducing prices, and ergonomic strain. Batteries need to be improved at least to the point where full AR functionality can be used for one work shift, alternatively easily exchangeable external batteries can allow an undisrupted work flow. While prices for high end ARSG are affordable for most manufacturing companies, if they were to be introduced on a broad scale on the shop floor.

<table>
<thead>
<tr>
<th>Company</th>
<th>Name</th>
<th>Release</th>
<th>Weight (g)</th>
<th>FOV (diagonal)</th>
<th>Battery hours</th>
<th>Battery mAh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penny</td>
<td>C Wear Extended</td>
<td>2013</td>
<td>115</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>VUZIX</td>
<td>M100</td>
<td>2013</td>
<td>72</td>
<td>15</td>
<td>1-6</td>
<td>3800</td>
</tr>
<tr>
<td>Epson</td>
<td>Moverio BT-200</td>
<td>2014</td>
<td>96</td>
<td>23</td>
<td>6</td>
<td>2720</td>
</tr>
<tr>
<td>Optinvent</td>
<td>ORA-2</td>
<td>2014</td>
<td>90</td>
<td>23</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>Atheer</td>
<td>Air Glass</td>
<td>2015</td>
<td>350</td>
<td>50</td>
<td>8</td>
<td>3100</td>
</tr>
<tr>
<td>ODG</td>
<td>R-7</td>
<td>2015</td>
<td>170</td>
<td>30</td>
<td>1-6</td>
<td>1300</td>
</tr>
<tr>
<td>Sime</td>
<td>G3</td>
<td>2015</td>
<td>72</td>
<td>20</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Sony</td>
<td>SmartEyeGlass</td>
<td>2015</td>
<td>77</td>
<td>20</td>
<td>1.3</td>
<td>–</td>
</tr>
<tr>
<td>DAQRI</td>
<td>Smart Glasses</td>
<td>2016</td>
<td>335</td>
<td>44</td>
<td>–</td>
<td>5800</td>
</tr>
<tr>
<td>Epson</td>
<td>Moverio BT-300</td>
<td>2016</td>
<td>69</td>
<td>23</td>
<td>6</td>
<td>–</td>
</tr>
<tr>
<td>Epson</td>
<td>Moverio BT-2000</td>
<td>2016</td>
<td>290</td>
<td>23</td>
<td>4</td>
<td>2 × 1240</td>
</tr>
<tr>
<td>Sime</td>
<td>G3</td>
<td>2015</td>
<td>72</td>
<td>20</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Microsoft</td>
<td>Hololens</td>
<td>2016</td>
<td>370</td>
<td>40</td>
<td>–</td>
<td>3200</td>
</tr>
<tr>
<td>VUZIX</td>
<td>M300</td>
<td>2017</td>
<td>140</td>
<td>20</td>
<td>2–12</td>
<td>160 internal 860 external</td>
</tr>
<tr>
<td>Menvision</td>
<td>Meta 2</td>
<td>2017</td>
<td>420</td>
<td>90</td>
<td>Tethered</td>
<td>Tethered</td>
</tr>
<tr>
<td>Magic Leap</td>
<td>One creator edition</td>
<td>2018</td>
<td>325 head + 415</td>
<td>50</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>Microsoft</td>
<td>Hololens 2 pre-order</td>
<td></td>
<td>566</td>
<td>52</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Shadowcreator</td>
<td>Action One</td>
<td>–</td>
<td>–</td>
<td>45</td>
<td>–</td>
<td>4000</td>
</tr>
</tbody>
</table>
floor it would in total constitute a large expenditure. This expenditure would replace current operator support which is usually paper instructions or computer screens and would therefore be both a big and a new expenditure. The current tradeoff that can be seen in Fig. 2 is that in general the higher the FOV the heavier the weight, which can be a big challenge if assembly operators are to use ARSG during their entire work shift.

5.4. Tracking

Tracking is the topic of how an AR-system can track its position in relation to the real world. Without tracking there can be no AR and as such it is a critical technology for ARSG. A widespread definition of AR is that it should fulfill three requirements [55]:

1. Combine reality and virtuality
2. Real time interactivity
3. Registered in 3D

As Billinghurst, Clark and Lee [5] describes it, tracking is related to the third criteria, enabling an AR-system to keep track of the real world to be able to correctly place digital content in relation to the real world. Their use of the term tracking refers to the combination of two phases. The first is the registration phase, which determines the pose of the viewer in relation to the anchor in the real world. The second is the tracking phase, which updates the viewer compared to the previously known pose. Table 2 presents a combined list of tracking technologies identified by [56–58]. Different tracking methods have different strengths and weaknesses and one way to compensate for this is to use a hybrid approach where different technologies are used in combination [56].

Bluetooth is a widely supported technology that can be used for indoor positioning [59]. Bluetooth-based beacons using Bluetooth low energy (BLE) can be used to estimate the general position of the user and in a hybrid tracking combined with vision-based AR to give feedback to the user [60]. A further advantage of using BLE beacons for general position tracking is that they are likely to be a key enabling technology for the Internet of things (IoT) [61]. Jeon, She, Soonsawad and Ng [61] gives a thorough summary of the current state-of-the-art of BLE beacons.

Since GPS-based solutions only work outdoors [56,62], they are not further considered in this survey.

Infrared (IR) light emitting diode (LED) markers can be used for tracking the position and orientation of objects and thereby enabling AR [63]. The IR markers prototyped by Urtans and Nikitenko [63] worked up to 1.5 m from the camera with comparable fiducial markers working up to 3 m away. Similarly they found that marker identification time was 290 ms, three times slower than with IR markers, mostly limited by the frame-rate of the IR camera, although this was still fast enough for real-time applications. A general drawback with marker solutions is that it requires placement of markers on objects that are to be tracked. Usage of infrared cameras in industrial environments is currently limited due in part to a lack of interfaces, but recent advances in small infrared cameras may open up more widespread use [64].

Radio frequency identification (RFID) is implemented by placing a tag on the object to track which can be identified through a reader equipped with an antenna that can read the tag remotely [65]. By combining RFID tags with depth cameras, Sun, Xie, Cai, Wang, Wu and Lu [66] managed to identify and distinguish up to 15 tags simultaneously with an average match ratio of 91%. RFID tags can be used to identify products in both assembly and disassembly for AR guidance [67].

Ultra-wideband (UWB) can detect the user position through sending a signal from the user and then using triangulation of the signal to 3–4 base stations around the user [68]. The signals are affected negatively by metal however and the equipment should be placed as far away as possible from metallic objects [68]. This limits its usability in industrial settings.

Lu and Song [69] note that since Wi-Fi signals are widespread in most buildings today and since they do not require sophisticated devices to track they are an interesting tracking technology. However, they also further note that there are several drawbacks to using Wi-Fi for tracking. For instance the accuracy is usually only within several meters and layout changes will affect the signals. Wi-Fi is also limited to 3 degrees of freedom. They do however see a value in using Wi-Fi and image-based localization together for hybrid tracking, with Wi-Fi providing a rough position of the user to limit the queries of the image-based localization.

Wi-Fi can also be used to compensate for drift in an inertial measuring unit consisting of an accelerometer and gyroscope as proposed by [70]. Their solution works without first having to perform fingerprinting of the area, a common technique for Wi-Fi tracking where the signal strength of an area is mapped beforehand. This contributes to their solution being more resilient to changes in the environment such as moving objects and makes it more suitable for an industrial environment.

Micro-electro-mechanical systems (MEMS) have enabled miniaturization of a number of sensing components, including triaxial accelerometers, triaxial gyroscopes, and triaxial magnetometers, which have made it possible to include them in most smartphones [71]. But their small size causes their readings to drift [72]. Besides drift, noise and magnetic interference also affect the sensors readings [73].

Accelerometers measure how much a mass is deflected from its starting position when being affected by a force, and by combining three perpendicular accelerometers it is possible to measure all components of vector acceleration for an object [74,75]. One proposed improvement for accelerometer-based positioning is to try to estimate the accelerometer drift based on outdoor GPS drift data and using this to reduce drift errors [72].

Gyroscopes measures angular velocity and a MEMS gyroscope can measure the rate of rotation around three axes [76]. These types of MEMS gyroscopes are widely available in for instance smartphones, drones, and IoT devices [76].

Magnetometers measures the strength and direction of the magnetic field around it [77]. One MEMS magnetometer implementation used in smartphones is the Hall effect method [78], which is currently one of the dominant technologies in consumer electronic devices [79]. A Hall effect sensor is implemented by sending a current through a thin metal plate, and when magnetic field hits the plate perpendicularly it will generate a voltage that can be measured [80]. But a drawback of Hall effect sensors is that they have a limited range [81]. Magnetic sensing on large range motions can suffer from significant errors in position estimation due to magnetic disturbances [81]. Many industrial environments contain strong low-frequency magnetic disturbances such as AC

<table>
<thead>
<tr>
<th>Group</th>
<th>Technology</th>
<th>Environment</th>
<th>Industrial suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-magnetic</td>
<td>Bluetooth</td>
<td>in</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Differential GPS</td>
<td>out</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td>out</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Infrared</td>
<td>in</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Real-time kinematic (RTK)</td>
<td>out</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td>in</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>RFID</td>
<td>in</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>UWB</td>
<td>in</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Wi-Fi</td>
<td>in</td>
<td>Yes</td>
</tr>
<tr>
<td>Inertial</td>
<td>Accelerometer</td>
<td>in/out</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Gyroscopes</td>
<td>in/out</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetometers</td>
<td>in/out</td>
<td>Limited</td>
</tr>
<tr>
<td></td>
<td>Magnetic beacons</td>
<td>in</td>
<td>Unknown</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Markers</td>
<td>in/out</td>
<td>Yes</td>
</tr>
<tr>
<td>Vision</td>
<td>Nature feature</td>
<td>in/out</td>
<td>Yes</td>
</tr>
</tbody>
</table>
noise from power-lines, fork-lifts, machinery, and tools [82]. Based on this the industrial suitability of magnetometers on their own currently has clear limitations.

By combining data from a gyroscope and accelerometer it is possible to track the pose, speed and position of a pair of ARSG which thereby provides inertial navigation [54]. [54] uses these inertial measurements in combination with visual tracking which are run in parallel and filtered through an extended Karlman filter. Another similar hybrid solution proposed by [73] uses a Kalman filter to complement image processing techniques with sensor array measurements from three different types of sensors: magnetometer, gyroscope, and accelerometer.

Magnetic beacons can be used as a low-cost navigation solution according to [83]. Their proposed solution requires the installation of magnetic beacons at intervals of 4–6 m but does not require recalibration after installation and a low resolution magnetometer like those in a smartphone or tablet can be used as receiver. Another advantage they described was that the method utilized low frequency magnetic fields that have a high penetration ability and is less contaminated by high magnetic background compared to direct current (DC) fields. They did not test it for industrial environments.

One hybrid tracking solution proposed by Alahmadi and Yang [84] was to use a smartphone’s accelerometer and magnetometer to extract directional data. This data was then used to remove candidates from a list of possible targets that had different directional readings, thereby reducing the search space.

Ultrasonic tracking can achieve high tracking accuracy but are at the same time sensitive to temperature, occlusion and ambient noise [56]. Ultrasonic background noise can easily interfere in industrial use cases [85]. It is therefore not explored further in this survey.

Vision based tracking methods using an ordinary camera is the most common technique for linking the real and the virtual spaces [86]. There are some different ways to categorize vision based tracking. The categorization by [86], summarized in Fig. 2, defines two main categories of methods: 3D model based techniques and Coplanar based techniques. A broader categorization that also includes categories that are not widely used presently is made by [5] and summarized in Fig. 3.

Visual tracking methods can be based on feature tracking or model tracking, the difference being that in feature-based tracking the system detects salient features in the images and in model-tracking the system has a model of the scene that it tries to detect from the images [87]. Siltanen further states that visual tracking methods can also be divided into those that require a priori knowledge (for example model-based tracking) and those that use ad-hoc methods (for example feature tracking).

Based on Siltanen, Palmarini et al. AR-tracking can be divided into the following categories: Model-based, Features-based, Marker-based, and Others [88]. The first three categories are a-priori vision-based tracking techniques and 90% of the articles of AR studied in maintenance used this technique, with marker-based tracking being the most common (52%). Wang, Ong and Nee [39] found marker-based tracking to be the most common within AR in assembly. Markerless AR is the more flexible alternative since it does not require markers to be placed in the environment [89].

In summary, there are many possible solutions for achieving a connection between the real and the virtual. Table 2 presents a summary list of which technologies are most suited for industrial uses. Bluetooth and RFID are two technologies that can give a good estimated position of objects and they also have further uses besides AR tracking for assembly instructions, which means that the cost of implementing these trackers can be divided between more gains. Combining visual tracking with inertial measurement units (IMU) such as gyroscopes, accelerometers, and magnetometers can provide extra stability in the tracking results.

6. Discussion

Two perspectives of ARSG for industrial assembly have been explored within this literature survey. A summary of the findings are presented in Tables 3 and 4, one for each perspective.

The manufacturing engineering perspective is shortly summarized in Table 3. Authoring is currently a work intensive procedure but preliminary results show that content can be automatically extracted from

![Fig. 3. Vision based tracking categorization made by [5].](image-url)
video-recording of assembly steps and support for non-programmers can make it possible to reduce the required skills for content creation. The technologies for automatic content creation are however still not robust enough to reliably create instructions in the general case and need to be further improved. Digitalization of factories has made it possible to decentralize product data so that production status is more readily available. Sensors can support ARSG by linking the digital and real world through other ways than optical recognition although there needs to be further improvement of sensor capabilities. There are guidelines available to help industrial managers in making strategic decisions regarding ARSG but these guidelines need to be validated and broadened to give a more complete picture. Systematic and comparative testing of ARSG is still an emerging topic and test platforms need to be further developed to take more aspects into account.

The manufacturing engineering perspective can thus be summarized that tools and guidelines exists but are still in an early stage of development. There is a need to further study the manufacturing engineering perspective to identify relevant parameters for ARSG as assembly operator support and how this can be practically achieved and main perspective to identify relevant parameters for ARSG as assembly support. This survey presents current research and market data regarding ARSG and relates the findings to industrial application. The contribution this can lead to is both a deep and broad understanding of the current state as well as future challenges for ARSG implementation into the industrial shop floor as an operator support tool.

This survey has focused on the technical and manufacturing engineering perspective of ARSG as support for operators in the industrial shop floor. The operators’ perspective with aspects such as ergonomics is an important perspective that is connected to the two perspectives explored in this survey, as described in [9] but have been left out due to the scope of this particular survey. A survey or literature review exploring that perspective is a suggested future work.

### 7. Conclusions

This literature survey had the aim to identify what still needs to be solved before ARSG implementation on the shop floor is possible by surveying the current status of ARSG from an industrial perspective. Two perspectives with accompanying sub-topics were explored with the summary results presented in Tables 3 and 4. Three questions of supplementary interest were also asked. The following section presents the answers this survey has identified.

**Q 1:** What previous work has been done in regards to integration, maintenance, and updating of ARSG interfaces for operators into a production system?

**A 1:** AR interfaces have been investigated for a long time but as technology has matured it has been possible to focus more specifically on ARSG adapted software. Updating ARSG interfaces has mostly been explored through improving authoring tools. Integration depends in part on standardized communication between different components in production systems to enable interface feedback to assembly operators. This is something that Industry 4.0 aims to provide, but a development of increased standardization is not dependent on Industry 4.0 and likely to continue regardless. Maintenance of ARSG software as a topic is less explored, possibly due to the early stages of adaptation in the manufacturing industry.

**Q 2:** What is the technical development level of ARSG in regards to usage as assembly support?

**A 2:** While the general TRL of SG is 9, the individual parts needed to improve SG into ARSG are still at a lower TRL. AR displays are at TRL 7 and tracking, interaction, and UI at TRL 5, both central for creating ARSG. In general terms the development level of ARSG is currently at such a level that it can be used in actual production in a limited capacity but is still at an early stage of implementation and as such still needs further development before large scale adoption can readily take place.

**Q 3:** What needs do manufacturing engineers and technicians have in ARSG and their interface from a manufacturing engineering perspective?

**A 3:** Manufacturing engineers and technicians primarily need to know how to integrate the ARSG in the production line, maintain, and replace them when they become outdated. This requires that ARSG follows standards that makes them compatible with the surrounding infrastructure. A challenge in the current ARSG market is the great diversity in hardware specifications, with large variance of weight, FOV, and battery life it can be a challenge to handle the differences. If multiple types of ARSG are bought there could be a significant variance in their capabilities that needs to be considered.

This survey presents current research and market data regarding ARSG and relates the findings to industrial application. The contribution this can lead to is both a deep and broad understanding of the current state as well as future challenges for ARSG implementation into the industrial shop floor as an operator support tool.

### Table 4

Summary of findings in technological maturity perspective.

<table>
<thead>
<tr>
<th>Technological maturity perspective</th>
<th>Current status</th>
<th>Future challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological demands</strong></td>
<td>• Larger FOV needed</td>
<td>• Reevaluating demands once ARSG becomes integrated in the manufacturing industry</td>
</tr>
<tr>
<td>• Stronger batteries or less battery consumption needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Enabling Technology</strong></td>
<td>Technical level:</td>
<td>• Improve individual components</td>
</tr>
<tr>
<td>• SG TRL 9</td>
<td>• Industrial adaptation</td>
<td></td>
</tr>
<tr>
<td>• AR displays TRL 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Tracking, interaction, and UI TRL 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• FOV:</td>
<td>• Further improving FOV in ARSG</td>
<td></td>
</tr>
<tr>
<td>• FOV of 52 degrees diagonally commercially available (100 experimentally)</td>
<td>• Further improve battery capacity and battery usage</td>
<td></td>
</tr>
<tr>
<td><strong>Battery:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Capacity varies greatly in available ARSG</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ARSG</strong></td>
<td>• Improve battery life</td>
<td></td>
</tr>
<tr>
<td>• Emerging market</td>
<td>• Reduce price</td>
<td></td>
</tr>
<tr>
<td>• Few strong actors taking lead</td>
<td>• Reduce weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Increase FOV</td>
<td></td>
</tr>
<tr>
<td><strong>Tracking</strong></td>
<td>• Implementing Bluetooth and RFID infrastructure</td>
<td></td>
</tr>
<tr>
<td>• Bluetooth and RFID suitable and synergy is possible</td>
<td>• MEMS sensors accuracy is lower</td>
<td></td>
</tr>
<tr>
<td>• IMU MEMS sensors can improve visual tracking</td>
<td>• Reduce magnetometer sensitivity to noise</td>
<td></td>
</tr>
</tbody>
</table>

[11] There are still some technical limitations in regards to hardware for broad usage, but research has shown AR to be feasible for manual assembly assistance [90]. To some extent AR is already used in production practice within the areas of visualization of production systems and the picking process [91] as well as in production to a limited extent [29]. ARSG is likely to be more prevalent once battery technology and FOV has been improved further. Commercial ARSG manufacturers are making fast improvements in terms of battery, FOV, and other hardware as well as general hardware and software design. Visual tracking has been greatly improved and MEMS sensors are also being improved, allowing hybrid tracking methods that can further improve tracking accuracy which will allow more possible uses of ARSG as operator support.

The technological maturity perspective can thus be summarized that while ARSG are currently not suitable for being used through an entire workday for operators, they are being improved on at a rapid pace, driven by a growing commercial market. There is now both research and practical implementation of ARSG taking place at an ever increasing pace and tracking technologies are getting closer to a seamless integration of the real and the virtual.
Author’s contributions

All authors have contributed significantly to the planning, editing, writing, and information gathering for this article.

Funding

This article has been partially supported by the SYMBIO-TIC project (H2020 grant number 637107). The project had no direct involvement in the submission of this article.

Declaration of Competing Interest

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

Acknowledgements

The authors would like to extend their gratitude to Professor Philip Moore for his invaluable feedback on the contents and format of this article.

References

PUBLICATIONS IN THE DISSERTATION SERIES
PUBLICATIONS IN THE DISSERTATION SERIES


Oscar Danielsson received his MSc in Automation Engineering from the University of Skövde in 2015. He has been working as a research assistant at the University of Skövde since 2013.

In this thesis Oscar uses a mixed method design science approach to investigate how augmented reality smart glasses can be both used by operators and integrated, updated, and maintained over time by manufacturing engineers and technicians.