Holm, M., Danielsson, O., Syberfeldt, A., Moore, P., Wang, L. (2017)
Adaptive instructions to novice shop-floor operators using Augmented Reality
Journal of Industrial and Production Engineering, 34(5): 362-374
https://doi.org/10.1080/21681015.2017.1320592

ADAPTIVE INSTRUCTIONS TO NOVICE SHOP-FLOOR OPERATORS USING AUGMENTED REALITY

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ABSTRACT

This paper presents a novel system using Augmented Reality and Expert Systems to enhance the quality and efficiency of shop-floor operators. The novel system proposed provides an adaptive tool that facilitates and enhances support on the shop-floor, due to its ability to dynamically customise the instructions displayed, dependent upon the competence of the user. Less attention has been paid to the information content in previous studies where Augmented Reality has been put in an industrial context. More research and development are needed, before an Augmented Reality application can be used on an everyday industrial basis. The presented research focuses the user of the support system, the shop-floor operator.

A comparative study has been made between an existing method of quality control instructions at a machining line in an automotive engine plant and this novel system. It has been shown that the new approach outcompetes the existing system, not only in terms of perceived usability but also with respect to two other important shop-floor variables: quality and productivity. Along with previous research, the outcomes of these test cases indicate the value of using Augmented Reality technology to enhance shop-floor operators' ability to learn and master new tasks.

Keywords: Adaptive instructions; Augmented reality; Shop-floor operators; Expert systems; Shop-floor support.

1 Introduction

Market sectors continuously evolve, demanding features such as rapid adaptability, effectiveness and continuous cost reduction, in order to remain competitive. The importance of shop-floor operators' knowledge, abilities, achievements and collaboration, within and between production teams consisting of both novice and highly experienced shop-floor operators, is becoming more vital as complexity and the demands of the production environment increase. Along with increasing complexity and the amount of data available on the shop-floor, the risk of missing important details due to information overload is likely. The importance of good design that enables functionality of the supporting systems and the display of information that is easy for shop-floor operators to access and use cannot be overemphasised [1-3]. There is a need to develop an adaptive shop-floor support system that facilitates productivity and efficiency. Such a system would focus on the efficient visualisation of shop-floor information and the interaction between shop-floor operators and production systems [4, 5].

Areas such as tourism, gaming and sports are today the main sectors which use applications of Augmented Reality (AR). However, most existing AR applications display static and predetermined information. Research has been conducted on merging AR technology and industrial applications, but few have reached practical industrial usage in the complex and highly challenging nature of the shop-floor [6-10]. General studies focusing education and training, as well as research concerning AR technology and assembly applications, have been conducted [11, 12]. An AR application used for diagnostics and maintenance is presented in [13] and an AR system for virtual training of parts assembly is presented in [14]. Both of these indicate promising results, but also clearly illustrate that more research and development are needed, before a final industrial version is possible.

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If the purpose is simply to guide the user through a number of steps, providing static information could be sufficient. However, such an approach is inflexible and does not adapt to different environmental conditions. A dynamic production system demands that dynamic and adaptive information can be displayed to the user. Assembly instructions visualised through AR technology that uses variants of visual features (arrows, text, animations, etc.) provide dynamic information content to the user.

This paper contributes knowledge regarding how AR technology can facilitate decision support for shop-floor operators. Increased knowledge is vital for utilising the full potential of AR, enabling its wide acceptance and usage on the shop-floor. It is our standpoint that for AR to be used effectively on the shop-floor, a new approach for handling the information content is necessary. This novel approach addresses what individual information should be presented to which shop-floor operator at which point in time and in which form. Little attention has been paid to the information content in previous studies of AR in an industrial context; instead the main focus has been to evaluate the concept of AR technology as such. We believe a key factor to success for any shop-floor system is the acceptance from those who will use the system, in this case, the shop-floor operators. With a high degree of usability and acceptance from the users, we believe that AR technology is one step closer to becoming a well-established tool for shop-floor operators.

This paper presents a framework where AR technology is combined with an expert system (ES), enabling the visualisation of adaptive instructions that are modified to the individual circumstances of each shop-floor operator. As part of the research study, a novel system for realising a framework combining AR and ES, called “Augmented Reality Expert System” (ARES), is devised. An ES is, in principle, a programme that can emulate the knowledge and experience of a human expert, on the basis of sets of rules. Through an ES, the shop-floor operator is able to learn how to perform a task, on the basis of an experts’ knowledge, without requiring the physical presence of a real expert.

The system devised is evaluated through test cases using a demonstrator that represents a control station in an automotive engine plant. During the test cases, instructions presented to pseudo shop-floor operators are modified in response to contextual information. The test cases cover five aspects which, when summated, distinguish them from other reported studies using Augmented Reality:

- **Focus on both usability and performance**

Enhanced effectiveness (i.e. quantitative results) is the focus of a majority of existing studies on Augmented Reality. These studies do not take usability into account [15]. This paper, however, investigates the usability together with achieved levels of productivity and quality.

- **Focus on users with little or less experience**

The novice shop-floor operators with less experience are the ones who benefit the most from using support systems.

- **Focus on the future shop-floor and its operators**

More research and development is needed before an industrial AR-implementation is possible. According to predictions, the future shop-floor will have more ICT tools available. The test case therefore uses participants who presumably may become the future shop-floor operators, high school students attending programs aiming shop-floor work. They have a general high acceptance of integrating ICT into everyday life, including their future working hours.

- **Focus on test cases that can readily be reproduced for future benchmarking purposes**

The demonstrator used in the test cases can easily be replicated and used for future benchmarking, or evaluations.

- **Focus on inexpensive, off-the-shelf consumer hardware**

The presented ARES uses inexpensive consumer products that can be bought in any electronic store.

The paper is organised as follows. Section 2 provides the definitions and general background of the AR and ES technologies, along with the motivation for the research performed and the method used. Section 3 explains the framework of the ARES system proposed. Section 4 presents a description of the test cases performed, evaluating the research presented. The results from the test cases are presented in Section 5 and further discussed in Section 6. The paper concludes in Section 7.

2 Background

This section outlines the definitions and background of AR and ES, along with the motivations for the research performed and the research method used.

2.1 Augmented Reality

Shop-floor teams comprise both novice and highly experienced operators, each with individual levels of knowledge, abilities and experience, which indicates the need of system adaptability. Different information should be given, depending on, e.g., the user’s level of knowledge, but also on the status of the production, e.g., whether a new product variant or an express order is under production [5]. The shop-floor operators' ability to understand and execute instructions can be enhanced by facilitating access to shop-floor information that cannot be obtained through ordinary human senses. Augmented Reality uses digital information which is overlaid onto the real world, thus enhancing shop-floor operators' perception of reality and thereby facilitating production systems' productivity and efficiency [4, 16].

Most ICT devices today, such as smart phones and tablets, have an integrated camera functionality enabling an integration of system information with real-time and real-world images. As indicated in interviews with production managers and HR-specialists, AR is predicted to become a future shop-floor technology [17]. By using AR, it is possible to overlay virtual information onto the real world, giving extensive information to the user and AR has proven to be a promising technology for displaying shop-floor information [4, 18-20].

The scope of AR does not exclude any of the human senses, but the dominant sense used for AR applications is sight. Therefore, subsequent references to AR in this paper mean visual AR. When using sight as the main sense for an AR application, it leads to an intimate interaction with cameras and some kind of information visualisation hardware, such as "usual screens", "see-through-screens" or goggles, etc. However, the hardware used also affects the AR application. The capacity of the hardware (resolution, contrast, time lag etc.) does have considerable impact on the usability of the AR applications.

Augmented Reality applications use some kind of anchor in the physical world (picture, QR code, etc.) to position and orientate virtual objects correctly, in relation to real-world objects. The most common way of implementing anchors is through target images caught by a camera, which is the approached used in the presented test cases. However, current technology limits possible industrial applications, mainly due to available process power, memory and storage in mobile ICT devices, but also due to general weaknesses such as ease of use and integration capabilities [21, 22].

2.2 Expert systems

A shop-floor support system, including its user interface, should be able to adapt to workplace conditions and the individual user's level of knowledge. The shop-floor support system should also be able to collect and reuse users' knowledge. When knowledge gained by one individual is not accessible to others, development and progress are hampered. Access to an expert's knowledge will facilitate the execution of a task, mostly for a novice, of course, but also for an experienced user. Expert Systems is principally a rule-based programme that can emulate a human expert's knowledge and experience and configure the information so that it can be understood and handled by a computer. Through an ES, it is possible to learn how to perform a task, on the basis of an expert's knowledge, without the physical presence of the expert [23, 24]. Possible inputs to an ES are, of course, the experts themselves, but also other data sources, such as written instructions, journals and articles. A recent definition of ES is:

"An expert system can be defined as a set of programs that use the human expertise as knowledge which is stored in an encoded form and may manipulate it to solve problems in a specialized domain. An expert system's knowledge must be coded and stored in the form which the system can use in its reasoning processes performed by the inference engine." [25] [p. 11].

A basic designation of an ES is to use the collected and digitalised knowledge to solve multifaceted problems through reasoning. The knowledge can be represented by "if–then" rules. An ES can handle intricate decision-making logic merged into ES rules which have been derived from large datasets that cannot possibly be handled by any human.

The main motivation for an ES is that human experts are a scarce and expensive resource. In addition, the individual human expert can only appear in one place at a time. By using an ES, it is possible to have unlimited access to an expert's knowledge and utilise it in multiple places and for a diversity of problems at the same time. The expert then has the time to focus on specific problems, thus obtaining more and deeper knowledge.

Expert systems have been used for various industrial cases: process planning, fault diagnosis, as well as the analysis and improvement of different industry sectors [26-29]. Previous research has touched on the idea of using ES technology to generate dynamic information for AR applications, but to the authors' knowledge, ES has not previously been used to make dynamic information available to individual users of an AR application. One early study discussing a teaching application using ES generated instructions is [30]. The developed system individually customises the teaching instructions instead of using static text. Strategies on how adaptability can be implemented in an ES through feedback from the users were explored in [31]. The developed strategies of an adaptive ES created and adjusted its rules in real time. However, neither [30] nor [31] merged any AR technology with an ES. A study discussing expert knowledge, though not an ES, in relation to AR technology is [32]. It compares the time needed to complete an industrial assembly task when the shop-floor operator uses either paper instructions, guidance from an expert or an AR application. The AR application in the study only provided static information. It could be concluded that the longest time required to complete the assembly task was when the operator used the paper instructions. Less time was required when the AR application with static information was used. However, the shortest time period was when the operator was guided by an expert present at the site. An aircraft maintenance system using a mobile device with an implemented ES and a user interface based on AR technology is presented in [33]. The system uses mobile devices with built-in cameras, such as a tablet or a smart phone. When an image is viewed through the camera, the ES displays AR information on the screen. Tests indicate possibilities, but also a problem, since one of the user's hands is occupied with the device.

2.3 Motivation

The research literature indicates that a system which individually and dynamically customises the content of information presented will have a greater impact compared to a static system, thereby increasing the efficiency of the shop-floor operator. However, to tailor dynamic instructions for individual users is not easy. Determining what task-specific information to give to each individual user, in what form, at which moment in time, as well as what information not to show, must be done online. The individual user's prior experience and current skill level drive the level of details of the given instructions required by the user, in order to learn and, with adequate quality, complete the task at hand in the shortest possible time [32, 34].

The work presented in this paper originated at an existing quality control station at one of the production lines of the Volvo GTO Powertrain site in Skövde, Sweden. At this quality control station, the shop-floor operators regularly perform a sequence of measurements to verify the quality of the preceding machining tasks. The station provides a spreadsheet-based system of instructions for the measuring sequence. Volvo GTO Powertrain had indicated that the shop-floor operators approached the quality station and its tasks differently, depending on their level of experience. Due to this variance, two shop-floor operators were asked to participate in an experiment. One of the operators is regarded as an expert, with many years' experience and the other is a relative novice, with little experience. Both of them performed the same quality control sequence at the station. Afterwards, both operators were interviewed regarding the approaches they adopted.

It became obvious that the novice and the expert approached the same quality control sequence quite differently. The novice followed the spreadsheet-based control instructions step-by-step, performing the exact sequence as intended by the author of the instructions. The novice often went back to read the instructions again and to check the correct reference data, what tool to use, etc. The expert, however, knew the instructions from memory and only looked at them if and when any problems occurred. The sequence given in the instructions was not followed by the expert, rather, the measurements were performed in another sequence and no measurement was omitted. When the participants' colleagues were asked about these two different approaches, they confirmed them and stated that the approaches were representative of the two groups of shop-floor operators, namely, novices and experts.

This led to the following question: Could some other system or arrangement be used for the delivery of instructions, in order to enhance compliance of the standard sequence, but also quality as well as productivity?

2.4 Research method

The proposed research programme needed a method of assessing the capability of ARES including possible ICT devices to support the delivery of dynamic decision-making in a shop-floor environment.

The paper comprises three studies that were undertaken:

1. Evaluating possible ICT devices to be used for AR in an industrial environment.
2. Test and evaluation of the current system of providing measurement instructions in the production system (test case I).
3. Test and evaluation of the ARES, in comparison with the results from the current system (test case II).

The production line at Volvo GTO Powertrain is run over two shifts daily, which strictly limits access to the real quality control station for the purpose of conducting tests directly at this station. The best option was to build a demonstrator emulating the actual quality control station and establish scenarios that could be investigated via test cases. Details of the demonstrator are given later in this paper.

A key factor for the success of any system is the level of usability and perceived effectiveness by the ones using the system, in this case, the shop-floor operators [35]. However, high usability does not compensate for low productivity or low quality output, therefore, usability together with productivity and quality were assessed during the test cases.

ISO 9241 [36] is an international standard on Ergonomics of human-system interaction. Through the Isometrics approach [37] it is possible to measure usability. Though the questionnaire used is rather extensive and time-consuming. Another method, well-established, inexpensive, easy to use, but yet effective for assessing usability is the System Usability Scale (SUS) [38-41]. It has been used to assess a broad range of services and products for a long time. The SUS method uses a questionnaire that can be answered within a couple of minutes. The SUS method was chosen for assessing usability during the presented study.

The SUS questionnaire has ten questions. Examples of questions included are:

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.

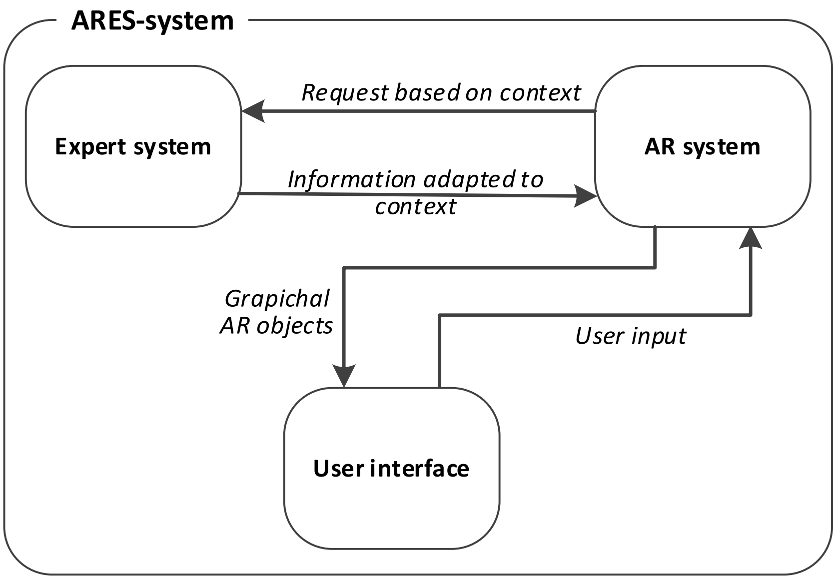

Figure 1. The overall design and information exchange in the ARES-system.

Half of the questions express positive experiences and the other half express negative experiences. The questions are answered using a five point scale ranging from 1 (Strongly disagree) to 5 (Strongly agree). The resulting SUS score, ranging from zero (worst) to one hundred (best), is calculated according to a specific formula [38]. Despite the similarity, the values of the SUS scale are not percentages. The SUS scale can be divided into two rough categories: below 70 and above 70. Several thousand evaluations using SUS for a broad range of products and systems have shown that a product or system with a SUS score below 70 usually has reasons for concern regarding its usability and a SUS-score above 70 indicates a positive usability experience [38-41]. Conclusions from these studies show that usability results from SUS are reliable. The SUS results are not biased by gender, and there is only a minor correlation between age and the SUS score (the SUS score slightly decreases with increasing age).

The SUS method has been used for assessing usability during the test cases, further presented in Section 4. During the test cases were the execution time and number of errors incurred (incorrect or unperformed measurements) used for evaluating productivity and quality respectively. This was done by observing the participants during the test cases. During the observations, any deviations from the instructions were noted along with the time it took to fulfil the tasks. The results from the test cases, usability, productivity and quality, are presented in Section 5.

Since it is anticipated that the participants of the two test cases are representative of future shop-floor operators, students from technical high schools were chosen to participate in the test cases. Forty three students from three classes (17 and 18 years old) participated in the test cases. These classes focus industrial work, why these students are likely to begin their professional career on the shop-floor. Each participant performed the task individually and received the same information prior to starting the task. Experienced shop-floor operators, from Volvo GTO and other companies, are to be engaged during the next planned phase of tests.

3 Overall design of the ARES-system

The ARES provides the user with individualised and enhanced information for each specific task. Such support enhances shop-floor operators' ability to learn and master tasks, compared to an approach that uses predetermined and static information [32]. In addition, using graphical information reduces the users' mental workload, compared to text-based information [42]. The ES of ARES determines the content of the information displayed (what to show and when to show it), while the AR part controls the user interface and displays the information. The overall design including the exchange of information within the ARES is shown in Figure 1.

When implementing ARES, a device with a camera and some kind of display is used. The camera of the ARES device is used for feature recognition and virtual objects are orientated in relation to objects in the real world. The viewer can, no matter the device's position, see the virtual objects aligned with the real world on screen.

The physical system, identified through the anchor, is detected in the AR system and a request is sent to the ES. Information adapted to the physical context is sent back to the AR system from the ES. The graphical AR objects are then shown on the display, positioned according to the anchor. A set of rules implemented in the ARES application steers what kind

Table 1. The first three rules of an ES example.

Condition *Seconds*	**Condition** *Competence*	**Condition** *Top Cover*	**Conclusion** *Render*
< 15	is beginner	is on	Basic text instruction
<= 30	is beginner	is on	Detailed text instruction
> 30	is beginner	is on	Detailed text instruction + Simple animation

of information and how it is presented. The following basic example uses three input variables/conditions to generate disassembly instructions on a screen for an operator (Table 1). The three variables are:

- Time elapsed for current task (seconds)
- Competence level of operator (beginner, skilled, expert)
- Level of disassembly (top cover on/off)

An example (using a tablet) in Figure 2 shows parts of the instructions for performing maintenance on a battery placed in the grey box. The logo of the University of Skövde is used as the AR anchor. The ES from Table 1 steers the application according to the conditions specified. The initial instructions given are general high-level instructions (top left). If the instructions are not performed within the set time (cover removed), additional, more detailed instructions are given (top right). If still more detailed instructions are required (elapsed time), graphical AR objects (green arrows and image of screwdriver) are visualised on the screen.

The AR of the ARES system is developed using the software Unity 3D and the software developing kit, Vuforia is used for the realisation of the AR functionality. Vuforia can implement vision technology for the recognition and image tracking of targets and 3D-objects in real time.

The rendering of the AR features is determined by the ES rules in real time. The implemented ES rules in the ARES are written using the OpenRules format. The ES rules are dynamically analysed in real time, which updates the information content of the AR system. Through this approach, ES rules can be created, changed and extended without reprogramming.

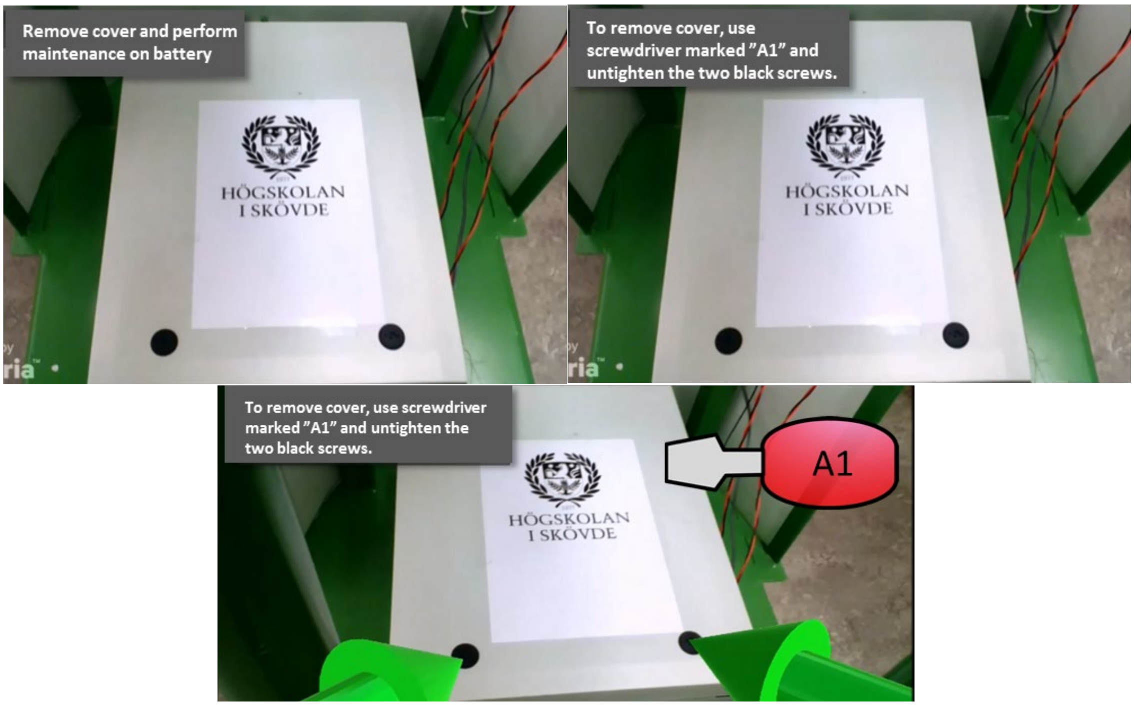

Figure 2. Example of adaptive instructions generated through ARES.

Table 2. Available categories of ICT devices and requirements.

Category of ICT-device	Requirement #1	Requirement #2	Requirement #3
"Usual" computer screen	Yes	No, too heavy and too large	----
Mobile PC	Yes	No, too heavy and too large	----
Tablet	Yes	Yes, eventually too large	To be further elaborated
Smart glasses	Yes	Yes	To be further elaborated
Smart phones	Yes	Yes	To be further elaborated

4 Test cases

This section of the paper describes the demonstrator and the set-ups used for the test cases.

4.1 ICT devices to be evaluated for implementing ARES

The shop-floor operator will wear or carry the ICT device implementing ARES during work, limiting its size and weight. A basic requirement for the device is that it has some sort of display presenting information to the shop-floor operator, but it must also enable feedback from the user. Based on these conditions, the following requirements for choosing, testing and evaluating hardware for the device were identified:

1. Ability to display information to the operator on the shop-floor.
2. Size and weight appropriate for wearing or carrying during a full working day (preferably a mobile solution not occupying the hands of the user).
3. Implementation of ARES.

The available ICT devices (Table 2) meeting requirements 1 and 2 are the three categories: smart glasses, tablets and smart phones. Tablets and smartphones can be considered one category, with regard to implementation of ARES, since both have a screen and a camera, only the size is different. The category of available ICT devices best meeting the requirements is smart glasses, since they do not occupy the hands of the user. Further technical data of tested smart glasses are given in Table 3.

The following four glasses have been evaluated as possible devices implementing ARES (Figure 3):

1. Google glasses from Google have a small screen to the upper right.
2. Mod Live have a small display developed for sports' practitioners such as cyclists and skiers.
3. C Wear from Penny. The displayed information is directly reflected into the iris of the right eye.
4. BT-200 from Epson. By projecting information through prisms in the thick glass, the information is projected to both eyes.

The information displayed by both Google glasses and Mod Live is not in the direct line of sight of the user, thus users must drop their gaze to absorb the displayed information. Further drawbacks are that the development of Google glasses has been terminated by Google and that the display of the Mod Live can only handle simple and limited text, besides information such as bars and diagrams. Mod Live cannot implement any camera functionality. Both the glasses from Penny and those from Epson display information in the direct line of sight and the area available for displaying information covers a considerable amount of the whole field of view. The two glasses use an external device that both powers the glasses and handles computing requirements. The Epson glasses have a built-in camera, but its field of view is so narrow that it cannot be used for image tracking in an industrial setting. The Penny glasses do not have a built-in camera, but can use an external one connected to the additional device. Furthermore, none of the four glasses is able to implement dynamic Augmented Reality information in the main, due to limited or non-existing camera capability. Thus, the conclusion is that the glasses present a promising technology but are not currently suitable for industrial applications. Therefore, as devices for the operators, the best option to pursue with current technology is tablets or smart phones.

Figure 3. Glasses evaluated for the Operator device.
(Upper left – Google glasses; Upper right – Mod Live, to be mounted on ski googles, etc.;
Down left – Penny; Down right – Epson Moverio BT-200)

Table 3. Technical data for smart glasses.

Model	Weight	Resolution of screen	Virtual image size	Camera in glasses	Other
Epson Moverio	96 grams	960*540	40 inches 2.5 meters away for both eyes	Yes	Needs additional device (looks like a smart phone). In line of sight.
Google glass	~70 grams (depending on model)	640*360	25 inches 2.5 meters away for one eye	Yes	Not in line of sight. Not sold any more
Mod Live	65 grams	428*240	11 inches 1.5 meters away for one eye	No	Needs to be mounted on ski glasses or similar. Not in line of sight.
Penny	~100 grams (depending on model)	875*500	70 inches 2.1 meters away for one eye	No, option	Needs additional device. In line of sight.

Operation:	Op 50	Instruction	Station K1	VOLVO
Article :	21428017	Division	33A	Reg.nr: NK-HE3-068-036
Drawing :	21474691			
NC-prog :				Made by : Ks02816
Product :	1002			Revision
				Date : 2016-04-07

Step	Information	Frequens	Tool	Number	Level			Comments
	Operation sheet: 44767, 44025				A	B	C	
	Tool : **T5001**							
A1-A3	Ø21 +/-0,3	*1/15*	*Gauge*	*6232*	X			
	Operation sheet: 44879				A	B	C	
	Tool : **T5003**							
A4-A6	Upper diameter Ø147 +/-0,5	*1/15*	*Calliper*	*6574*	X			
	Lower diameter Ø139 +/-0,5		*Calliper*		X			
	Depth 10,5 mm +/- 0,5		*Calliper*		X			
	Operation sheet: 45609				A	B	C	
	Tool : **T5005**							
B1-2	M8 Thread	*1/15*	*Gauge*	*6627*	X			

Figure 4. Measurement instructions (translated from Swedish) used in the pre-test and test case I. The thick red line indicates the end of the measurement sequence during the tests.

Tablets and smart phones have proven they have enough computing power and include an embedded camera that can enable Augmented Reality applications. It is, however, recognised that tablets have associated drawbacks, such as size and weight, and that users often need to drop their gaze to look at the screen [43]. Smart phones have the same drawbacks as tablets and, although they are smaller and lighter than tablets, they also have smaller screens. Due to the size of the screens, the implementation of ARES is further considered using tablets.

4.2 Pre-test of demonstrator for test cases I and II

A pre-test of the demonstrator set-up was carried out to ensure that the working procedures could be performed in a similar way to those at the Volvo GTO Powertrain quality control station. A demonstrator, together with the tools needed, computer, etc., replicating the actual quality control station, was built, in order to perform the pre-test and test cases I and II without disturbing the in-plant

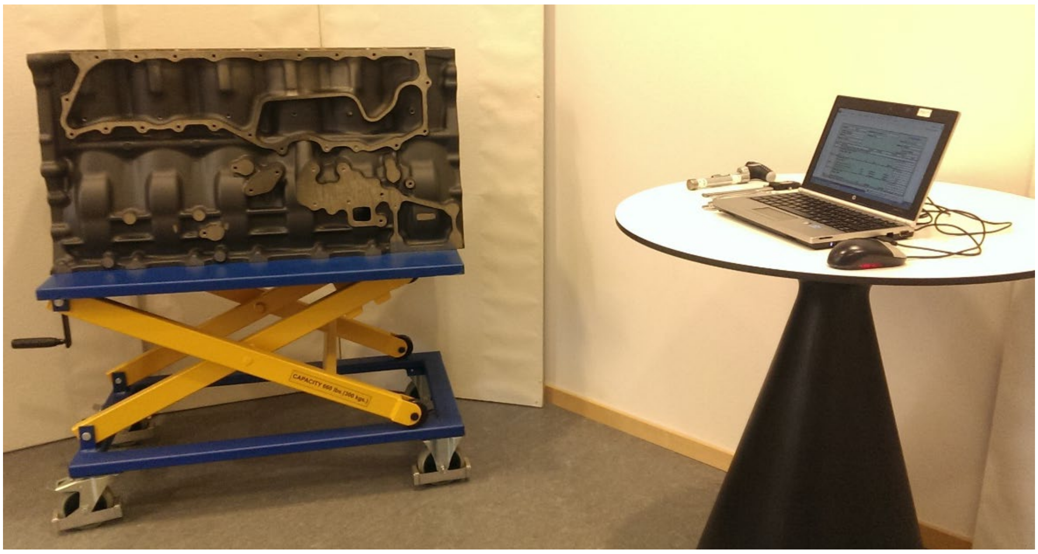

Figure 5. Set-up for pre-test (positions of computer, tools, etc., as on site).

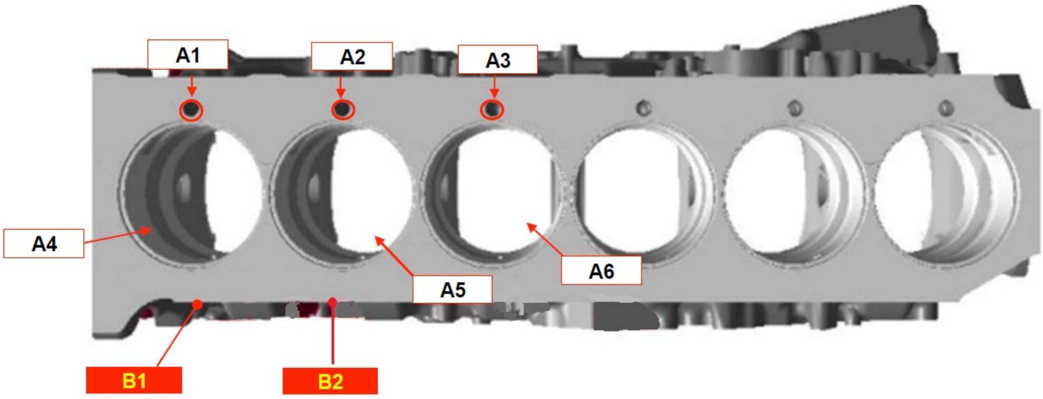

Figure 6. Locations of the measurement tasks.

production. An engine block from the real production line was placed on a lifting table and a sequence of measurements (approx. 15% of the whole quality control sequence) was chosen. This measuring sequence of 14 different measurement tasks was used for both the pre-test and for test cases I and II. The measurement instructions used for the pre-test and test case I are shown in Figure 4. Steps A1-A3 and B1-B2 include one measurement task each, while steps A4-A6 include three different measurement tasks each (Table 4).

The tools used for the measurement sequence are a calliper and two gauges. Some wrenches were also available in the toolset. The set-up of the demonstrator (text instructions, configuration of tools, computer, screen, etc.) was as similar as possible to the site situation (Figure 5). The spreadsheet instructions (Figure 4) were presented together with information on the locations of the measurement tasks (Figure 6).

Eight university students, engaged for the pre-test, were given information about the measurement tasks to be performed, prior to the start of the pre-test. During the pre-test, the participants were observed by the test leader. Upon completion, they scored the usability of the instructions through SUS. The participants of the pre-test were not engaged for test cases I and II.

Table 4. Sequence of measurements

Step	Measurement	Tool	
A1	Diameter 21 mm	Gauge	
A2	Diameter 21 mm	Gauge	
A3	Diameter 21 mm	Gauge	
A4	Diameter 147 mm	Calliper	3 positions
A5	Diameter 139 mm	Calliper	3 positions
A6	Depth 10,5 mm	Calliper	3 positions
B1	M8 Threads	Gauge	
B2	M8 Threads	Gauge	

The pre-test emphatically indicated two areas in need of improvement: poor usability and high error rates. These two issues were primarily due to the long distance between the position of the tools and screen (displaying the instructions) and the position of the engine. The participants often had to move between the screen and the engine, due to problems remembering the exact instructions, which negatively affected the ergonomics and the quality of the performed work. The same behaviour was indicated by the novice operator at the original quality control station. Three changes that could improve the usability of the demonstrator emerged.

The three improvements to the demonstrator, identified during the pre-test, were implemented to eliminate the problems associated with the distance between the information carrier and the actual working position, which had negatively affected the performance during the pre-test [44]. These improvements could also easily be implemented in the real quality control station at Volvo GTO Powertrain.

- The toolset was mounted onto an adjustable arm at the workstation, so that the participants did not have to move between the computer screen and the measuring position during work.

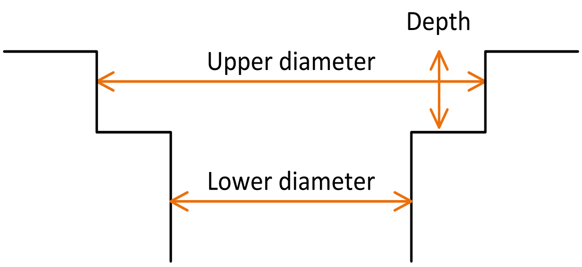

Figure 7. Additional instructions for tasks A4-A6 implemented in test case I (text translated from Swedish).

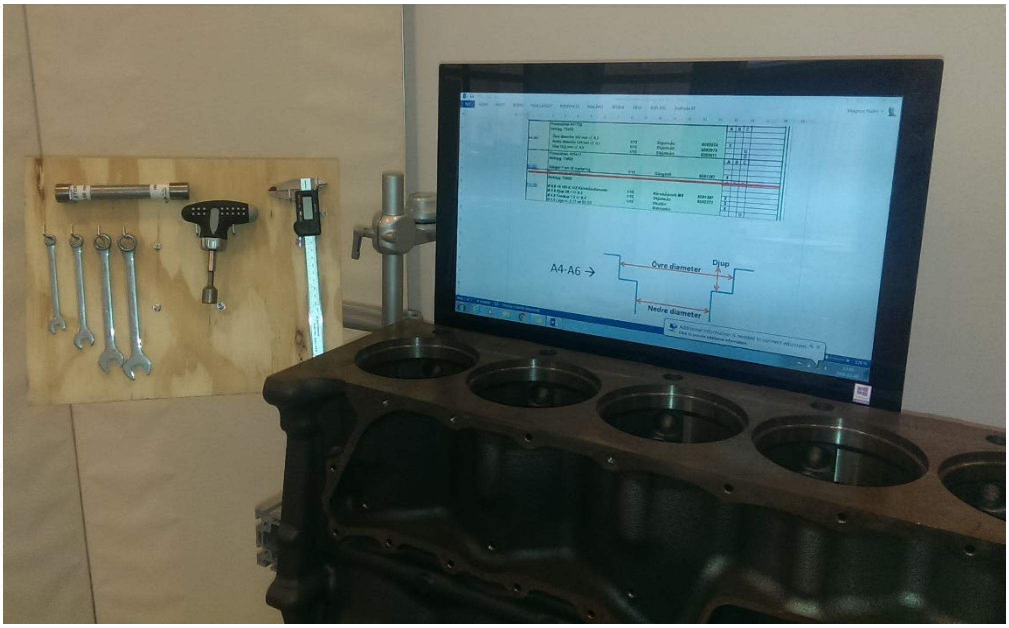

Figure 8. Set-up of test case I.

- The "usual" screen was replaced by a touch screen (which makes scrolling easier compared to the original set-up with mouse and keyboard) mounted onto an adjustable arm. The screen was positioned so that the operator could readily glance at it when working.
- Instructions clarifying measuring tasks A4-A6 were included (Figure 7).

The set-ups for each of the test cases I and II are further discussed in Section 4.3. The SUS-score of the pre-test is presented further in Section 5.

4.3 Test cases I and II

Two different systems for displaying the measurement sequence were used for test case I and test case II. Test case I used the spreadsheet system from Volvo GTO Powertrain and test case II used a tablet implementing ARES. Forty three students (17 and 18 years old) participated in these studies. Test case I had 21 participants and test case II had 22 participants. Each participant performed the task individually and received the same information prior to the start of the study.

Figure 9. Set-up of test case II.

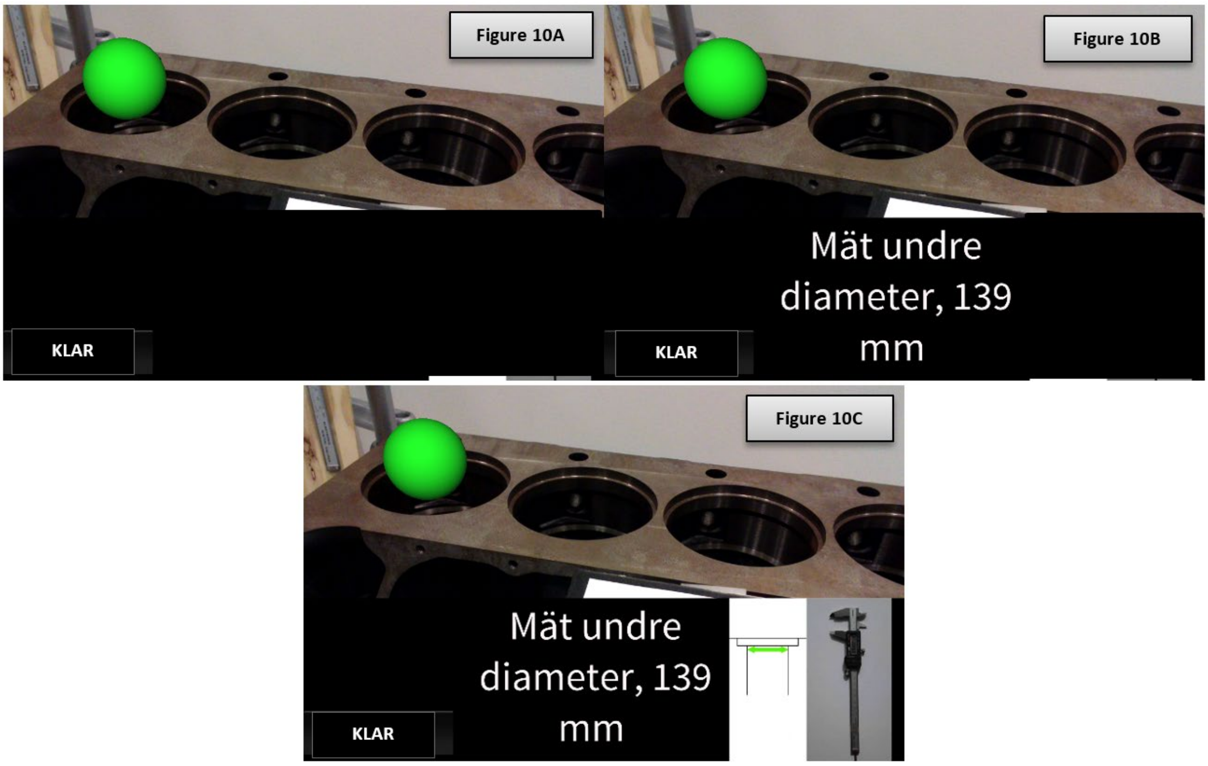

Figure 10A-C. Screen shots providing examples of increasing level and richness of instructions in ARES for measurement task A5.1 in test case II.

Both test case I and II measure productivity (time to finish the task) and quality (number of errors made), along with the usability of each system used.

4.3.1 Set-up in test case I

Test case I used the existing text instructions (Figure 4) at the quality control station and served as a comparison to the ARES in test case II. The reason for implementing the three improvements for test case I and thus distinguishing it from the set-up used at Volvo GTO Powertrain was that the original position of the screen and tools considerably impacted the variables to be measured, i.e., usability, productivity and quality, in a negative way, without the position of the screen and tools being part of the instructions. The resulting set-up for test case I after implementing the improvements is shown in Figure 8.

4.3.2 Set-up of test case II

The purpose of test case II was to evaluate ARES. The measurement sequence and position of the screen and toolset used in test case II were identical to test case I. There were two differences between test case I and test case II: the measurement information on the big screen and the tablet placed in front of the demonstrator executing ARES (Figure 9). The tablet screen displaying the ARES instructions (replacing the spreadsheet instructions) was duplicated onto the bigger screen. All the participants of test case II read instructions from the big screen (as in test case I). The tablet was only used by the participants to open the next measuring task (by clicking a button).

Three screenshots from the tablet implementing ARES exemplifying information presented to the participants during test case II are shown in Figure

Table 5. ES rules of ARES for measuring task 5.1 in test case II.

Condition Seconds	**Condition** Element	**Condition** Render
< 5	is A5.1	Basic AR-position information
<= 10	is A5.1	Basic AR-position information + basic text instruction
>10	is A5.1	Basic AR-position information + basic text instruction + detailed picture + picture of tool

10A-C. The ARES only provided information on the present measurement task, to avoid information overload and to determine that the measurements were performed in the current sequence. Upon finishing one task, the participant pressed the button in the lower-left corner of the tablet (KLAR - Figure 10) to continue to the next measurement task. The picture mounted on the front of the engine block during test case II (Figure 9) acted as the anchor used for the AR functionality.

The screenshots (Figure 10A-C) display instructions for the measurement of the diameter of a cylinder hole. The green sphere indicates the position of the measurement task and, after the set time, additional basic text information is given (Figure 10B). If the user needs further time, a more detailed picture explaining the measurement together with a photo of the tool to use is provided (Figure 10C).

The level of information content displayed to the user is controlled by an ES as part of ARES. The ES uses two input variables, elapsed time and measuring step to be performed. The ES rules for task A5 that generates the instructions in Figure 10A-C are shown in Table 5.

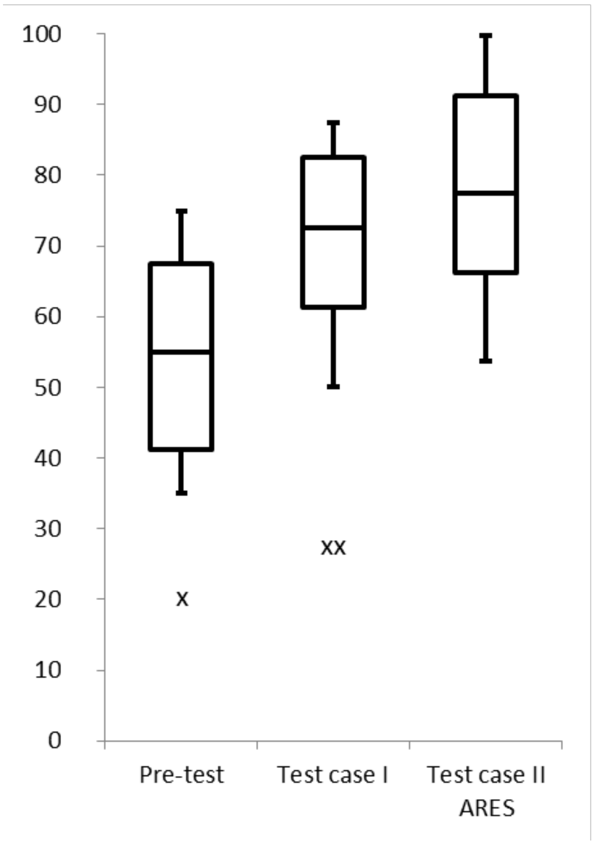

Figure 11. Boxplot of SUS scores for pre-test, test case I and test case II.

Figure 12. Error rates when performing test cases I and II.

Table 6. Mean time (in minutes) required to complete the measurement sequence in test cases I and II, depending on number of errors incurred.

	No error	One error	Two or more errors
Test Case I	4:29	5:47	4:24
Test case II - ARES	3:49	3:43	--

5 Results

This section presents the scoring usability, productivity and quality of the test cases performed comparing the at-site used spread sheet based system with the presented ARES. A boxplot of the SUS scores obtained for the pre-test and test cases I and II is shown in Figure 11. Individual scores outside the lower extremes, so-called single data points, are indicated with “x”. The median SUS score for the pre-test only reached 55, indicating a substantial need for improvements (scores below 70 indicated low usability). As discussed previously, three improvements were made to the demonstrator to avoid unnecessary bias during the subsequent test cases. Test case I obtained higher SUS values compared to the pre-test, confirming that the modifications made enhanced the usability. The ARES evaluated in test case II received an median SUS value of 77,5 compared to test case I which reached an median SUS value of 72,5. The SUS-values in test case I and II indicate possible higher usability for the ARES in test case II compared to test case I. An observation made during the test cases was that the participants in test case I often scrolled back and forth in the document ensuring the correct information, while the participants in test case II just glanced at the screen shortly before addressing each new task.

When analysing the quality (Figure 12) of the work performed and the execution time (Table 6) the differences in output of test case I and test case II become clear. For test case I, 52% of the participants completed the measuring sequence without making an error, 10% had one error, and as many as 38% had two or more errors. In test case II, 68% of the participants completed the measuring sequence without making an error and the rest, 32%, accounted for one error only. None of the participants in test case II made more than one error.

The analysis of the execution times (Table 6) revealed another advantage of ARES. Although more errors were counted during test case I (often completing fewer measurements), it took the participants longer to complete the measuring sequence compared to test case II, where a lower number of errors occurred. The mean time (in minutes) for all the 21 participants who performed test case I was 4:33, while the mean time for all the 22 participants who used the ARES system was 3:47.

Only two participants in test case I had one error and one of them took a very long time to finalise the measuring sequence, which explains the high mean time. The most common error of all the errors made was the omission of one or more measurements in the sequence, thus less time in total was needed.

6 Discussions

The main hardware of ARES is a tablet, which is a relatively inexpensive and standard off-the-shelf product that enables multiple users, without overextending the budget. Using a tablet for an AR application has advantages; most people are familiar with tablets nowadays, facilitating a high degree of acceptance and affinity. The tablet also has both a camera and a screen, thus enabling a fully functioning AR application in one single device. However, there are some disadvantages. Using a tablet for an AR application either occupies one hand of the operator or, if placed on a stand as in test case II, it only covers a limited working area. If applied to larger working areas, the stand has to be moved during operations. The stand might hinder the operator’s work and the tablet may not always be in the operator’s line of sight during work procedures. Also, if a hand, arm or tool obscures the camera, the virtual objects disappear, since the picture used as the anchor for the AR functionality is no longer identifiable by the camera. The virtual objects disappear when the AR system cannot locate the anchor. Smart glasses implementing AR would always be inline of sight, but more research and development are needed before industrial implementations can be achieved.

In test case II, an additional display device was used to mirror the display on the tablet. This enabled the shop-floor operator to read the instructions almost in line of sight, without the tablet occupying the hands of the operator. None of the participants in test case II read the instructions on the tablet; all followed the instructions on the big screen. The set-up of the two test cases was the same and the measurement instructions were displayed on the same screen. The SUS scores indicate that ARES used in test case II eventually reaches higher usability than the spread-sheet based system used in test case I. When taking the productivity and quality results into account, the advantage for ARES is strengthened.

7 Conclusions

The presented system, ARES, enables adaptive instructions to be delivered to individual shop-floor operators. It facilitates the individual's learning process through its ability to dynamically adapt to the user's level of knowledge and experience, and facilitates shop-floor support during production. ARES can be implemented for practical everyday use, not only for novice shop-floor operators, but also for experienced users. ARES has the ability to dynamically display instructions, regardless of whether they are newly introduced or changed instructions, or whether they contain well-known essential information that must not be ignored.

The response from Volvo GTO Powertrain to ARES and the results achieved has been positive. It is aligned with the company's ambition to improve decision support, especially for novice shop-floor operators. Future work include further development of ARES together with extensive testing including also experienced shop-floor operators.

Acknowledgements

The authors express their gratitude to Hampus Albihn, the students from Lichron Technical High School and Volvo Technical High School, along with the shop-floor operators at Volvo GTO Powertrain in Skövde. The authors also thank the reviewers of the paper for helping to improve it. This paper is based on work performed within the research projects SYMBIO-TIC [637107] sponsored by the European Union and YOU2 [20130303] sponsored by the Swedish Knowledge Foundation. The System Usability Scale is a property of Digital Equipment Corporation, 1986.

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