Advances in Intelligent Systems and Computing 793

Waldemar Karwowski
Stefan Trzcielinski · Beata Mrugalska
Massimo Di Nicolantonio · Emilio Rossi
Editors

Advances in Manufacturing, Production Management and Process Control

Joint proceedings of the AHFE 2018 International Conference on Advanced Production Management and Process Control, the AHFE International Conference on Human Aspects of Advanced Manufacturing, and the AHFE International Conference on Additive Manufacturing, Modeling Systems and 3D Prototyping, July 21–25, 2018, Loews Sapphire Falls Resort at Universal Studios, Orlando, Florida, USA

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Editors
Waldemar Karwowski
University of Central Florida
Orlando, FL, USA

Stefan Trzcielinski
Poznan University of Technology
Poznan, Poland

Beata Mrugalska
Poznan University of Technology
Poznan, Poland

Massimo Di Nicolantonio
Architectural Department
University of Chieti-Pescara
Pescara, Italy

Emilio Rossi
Architectural Department
University of Chieti-Pescara
Ortona, Italy

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AHFE 2018 Series Editors

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9th International Conference on Applied Human Factors and Ergonomics and the Affiliated Conferences

Proceedings of the AHFE 2018 International Conferences on The Human Aspects of Advanced Manufacturing, Advanced Production Management and Process Control, and Additive Manufacturing, Modeling Systems and 3D Prototyping, held on July 21–25, 2018, in Loews Sapphire Falls Resort at Universal Studios, Orlando, Florida, USA

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Preface

Contemporary manufacturing enterprises aim to deliver a great number of consumer products and systems through friendly and satisfying working environments for people who are involved in manufacturing services. Human-centered design factors, which strongly affect manufacturing processes, as well as the potential end users are crucial for achieving continuous progress in this respect. Researchers around the world attempt to improve the quality of consumer products and working environments. The AHFE International Conference on Advanced Production Management and Process Control (APMPC) promotes the exchange of ideas and developments in production, sustainability, life cycle, innovation, development, fault diagnostics, and control systems. It addresses a spectrum of theoretical and practical topics. It provides an excellent forum of exploring frontiers between researchers and practitioners from academia and industry. It offers the possibility of discussing research results, innovative applications, and future directions. The AHFE International Conference on Additive Manufacturing, Modeling Systems and 3D Prototyping focused on cutting-edge design and manufacturing processes; it welcomes papers that cover articles, case studies, and multidisciplinary studies specifically focused on ergonomics research, design applications, engineering processes, experimental purposes, and theoretical methods applied the themes of Digital Modeling Systems, Additive Manufacturing, and their cross-sectional convergences.

This book presents the results of their work. We believe that such findings can either inspire or support others in the field of manufacturing and process control to advance their designs and implement them into practice. Therefore, this book is addressed to both researchers and practitioners.

The papers presented in this book have been arranged into eight sections.

I. Human Aspects of Advanced Manufacturing and Production Planning
II. Human Factors in Complex and Large-Scale Manufacturing Systems
III. Development and Implementation of Human Knowledge
IV. 2D/3D Digital Modeling
V. Applications for 3D Printing

VI. Safety Analysis and Process Control
VII. Applications in Industrial Processes: Work Stress and Cognitive Evaluation
VIII. Approaches and Methods for Production Management

The presented chapters depict the influence of worker experience and the technology used to improve work effectiveness. Next, the comparison of non-expert and expert work is studied to find patterns that can be used to improve the technique of performing different tasks by less skilled employees. The third section deals with outcomes ergonomics have on industrial quality and safety, while the fourth and final section of this book is focused on ergonomic design of future production systems.

The contents of this book required the dedicated effort of many people. We would like to thank the authors, whose research and development efforts are published here. Finally, we also wish to thank the following Editorial Board members for their diligence and expertise in selecting and reviewing the presented papers:

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Human Aspects of Advanced Manufacturing and Production Planning

Transfer Analysis of Human Engineering Skills for Adaptive Robotic Additive Manufacturing in the Aerospace Repair and Overhaul Industry

Richard French(✉), Hector Marin-Reyes, and Michalis Benakis

Physics and Astronomy, The University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK
{R.S.French,H.Marin-Reyes,M.Benakis}@Sheffield.ac.uk

Abstract. The desire for smart "lights out factories" which can autonomously produce components for high value manufacturing industries is described by the Industry 4.0 solution. This manufacturing methodology is appropriate for newly designed components, which take advantage of modern materials, robotic and automation processes, but not necessarily applicable to overhaul and repair. The aerospace overhaul and repair industry remains heavily dependent on human engineering skills to develop repair and re-manufacturing techniques for complex components of high value.

Development of any advanced, intelligent multi-agent robotic additive re-manufacturing system requires correct interrogation of metallic materials thermal properties, system control and output. Advanced programming of robots, data interpretation from associated sensory and feedback systems are required to mirror human input. Using process analysis to determine stimuli, replacement of human sensory receptors with electronic sensors, vision systems and high-speed data acquisition and control systems allows for the intelligent fine tuning of multiple heat input parameters to deposit the additive material at any one time. The interaction of these key components combined with novel robotic technology and experienced welding engineers has made possible the construction of a disruptive robotic re-manufacturing technology.

This paper demonstrates the design process and analyses the outputs sourced from observation and the recording of highly skilled human engineers when conducting manual remanufacturing and repair techniques. This data is then mined for the transferable control input parameters required to replicate and improve human performance.

This industry-academia research intensive collaboration between VBC Instrument Engineering Limited (UK) and The University of Sheffield has received project funding from the Engineering and Physical Sciences Research Council (EPSRC, 2006–2010), the Science and Facilities Technology Council (STFC, 2011–2013) and Innovate-UK with the Aerospace Technology Institute (2014–2018).

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Keywords: Human skills · Robotic system · Additive manufacturing
Aerospace

1 Introduction

1.1 Aerospace Repair and Overhaul Industry

Aircraft turbofan or jet engines are highly complex structures, composed of approximately 30,000 individual components [1]. Component design materials selection and both manufacturing and in-service tolerances of each component drives optimum performance of the engine. However, harsh environmental and prolonged operational conditions result in physical wear of engine components, introducing a variety of defects. Operating in a high pressure/temperature environment, in combination with foreign object impact, leads to wear, distortion, dents and cracks on blades, vanes, blade-integrated disks (Blisks) and such other components [2]. Introduction of such defects can lead to catastrophic events, resulting in huge costs, both societal and economic. In order to prevent such failure, the turbofan engines are required to be removed from the aircraft and overhauled after ~30,000 h of operation [3], a limited number of take-off/landings, the greatest contributor to wear.

Maintenance, repair and overhaul (MRO) is defined as the process of ensuring that a system or equipment, continually performs its intended functions, reliably and safely under acceptable constrains [4, 5]. MRO operations required by complex products in the aerospace industry result in high MRO costs. Many manufacturing companies have altered their business strategy to support the servicing of their products through the entire lifecycle. The main reason behind this shift is to allow long, intensive operational periods of high cost engines to quickly yield a profit for the customer. To guarantee the lifespan of the engine, repairs on worn components and manufacturing spare parts is essential to ensure long term reliability [6].

Engine components of particular interest to the aerospace engine overhaul companies are vanes, turbine blades and compressor blades. Their high value increases the need of repair instead of replacement. The blades of a turbofan engine are the most critical part, used in different stages of the engine with different sizes and roles. Their performance is based on their aerodynamic body, where even a small change in the geometry of the blade can result in a large change on the engine's performance and efficiency. It is therefore of major importance to maintain the original shape of the engine blades, while the repaired component conforms to and acceptable dimensional tolerance as defined by the original manufacturer. The traditional process for engine blade regeneration is mainly separated in four stages: pre-treatment, material deposition, re-contouring and post-treatment. Stages of pre-inspection and post-inspection are also included before, in-between and after the aforementioned stages, to identify defects, select appropriate restoration procedures and ensure the quality of the restored component.

1.2 Additive Manufacturing

The work presented on this paper is focusing on the second stage of the blade regeneration, which refers to the material deposition process. The techniques currently used for material deposition vary according to the material and the damage of the blade. For patch-repairs plasma arc welding is used to weld the patch joint without additive material. Crack-repair on the blade's body is carried out through brazing or welding depending on the size of the crack. Tip-repair is done via additive arc welding with filler material or via material cladding using laser welding, due to low heat input requirements. The tip-repair, due to blades "sulfidisation" and crack formations during operation, occupies the majority of the volume repaired in aeroengine components [7]. This paper follows the current developments of a robotic welding system for tip-repair of compressor blades, by means of Additive Manufacturing (AM) using Pulsed-Arc Tungsten Inert Gas (TIG) welding.

The thin tip of the compressor blades requires low heat input during repair, to ensure the mechanical properties of the material. In order to achieve acceptable control of the heat input, an advanced TIG welding power source, the Heat Management System (HMS) provides a high frequency pulsed weld current [8, 9]. An industry-academia collaboration between the University of Sheffield (UoS) and VBC Instrument Engineering Ltd (VBCie), described in Sect. 1.3 below, has developed the advanced HMS system.

The majority of aerospace component repairs are performed manually, by highly skilled welding engineers. The reasons behind the lack of automation is a combination of the complex geometries of the workpieces, individual repair requirements per blade type and the high purchase price of automated systems.

Traditionally, a human engineer will inspect the component to assess its level of damage. Should the repair criteria be met, the component is sent to the pre-treatment stage to undergo de-coating and surface grinding. Following this process, a welding engineer will apply the additive material to the manufacturer's predefined dimensions and welding procedure (WPS).

In order to automate the AM process, adaptive machining techniques are needed. Machine vision systems work in conjunction with advanced sensory systems, to generate data for a robotic or CNC welding platform. Generically these platforms use a robotic arm equipped with a welding torch to follow the component shape using measurement data. This adapts with the changing, complex requirements of the component's geometry and mimics the hand-eye coordination of a human welding engineer.

To monitor the transfer of human engineering skills to a robotic welding system, UoS performed a series of welding trials with the Nuclear Advanced Manufacturing Research Center (NAMRC). The aim of the trials was to firstly monitor the welding process in real-time, to be able to predict the quality of a manual weld, detecting errors and defects as they occur. The results of this research were presented [10] and this current research follows the transfer of the data collected during the trials to advance the robotic welding systems adaptability and performance.

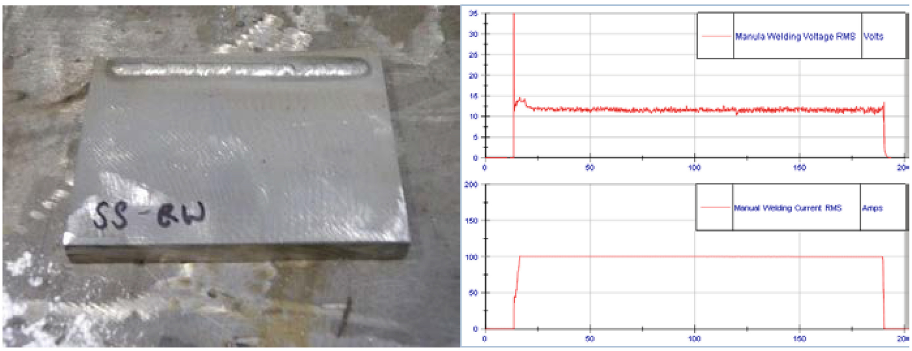
1.3 The Academia Industry Collaboration

UK Small Manufacturing Enterprise (SME), VBCie have been in partnership with the Enabling Sciences for Intelligent Manufacturing Group (ESIM) based at UoS since 2006. Multiple innovative low Technology Readiness Level (TRL) projects have been developed, this research has increased in TRL substantially up to present day. As part of the UK High Value Manufacturing CATAPULT the NAMRC is part of UoS. The NAMRC enables its industrial partner network companies, based in the nuclear industry manufacturing supply chain, to develop new and improved manufacturing capabilities as part of the "Fit for Nuclear" programme. The UoS groups have collaborated on a number of projects aligned with fusion welding for high value manufacturing.

2 Human Skills Extraction and Implementation

2.1 TIG Manual Welding – NAMRC Welding Trails

Figure 1a shows the welding voltage and current obtained while welding two stainless steel plates with 152 mm length at 1.25 mm/s welding speed. The filler wire used is the same type as the SS plates. No visual defects or significant variations on the measurements were detected so it was determined it was a good weld.



a) b)

Fig. 1. (a) Manual TIG welding on a SS plate at the Nuclear AMRC, (b) Electric measurements of the arc welding from an experienced welding engineer

The build-up of the weld pool has been found to be closely related to the oscillation of the human hand while travelling alongside the welded joint and this oscillation is different under different WPS. Figure 1b. shows that the human hand oscillates from up to down at a frequency of 1.5 Hz. The extraction of the human hand oscillation frequency can be obtained in real-time using a prototype high speed data acquisition system (DAQ) developed by the UoS ESIM group.

3 Towards Industry 4.0

At the beginning of the fourth industrial revolution, the traditional aerospace remanufacturing factory transforms into a futuristic intelligent entity able to interoperably perform tasks with limited human interaction, driven by data and decentralized decisions. Beneath the term Industry 4.0, underlie four basic design principles: interconnection, information transparency, decentralized decisions and technical assistance. The adoption of these four design principles from manufacturing systems results in a controlled environment where quality assurance is achieved in parallel with cost and waste reduction.

The robotic welding system under development was designed to implement Industry 4.0 principles and reshape the aerospace remanufacturing industry. Initial experimental results presented [11] demonstrate modular design and interconnection of physical subsystems, to transparent data management and intelligent sensing. The individual subsystems are under constant development, adapting and advancing in a concurrent engineering ecosystem. Advances currently under evaluation are presented aligning with the Industry 4.0 concept adaption.

3.1 Weld Evaluation and Fault Detection

Real-time weld process monitoring, using high-speed intelligent sensing is essential as part of the Quality Assurance (QA) and Quality Control (QC) requirements of the advanced robotic welding system. Traditionally a finished component used in the aerospace industry undergoes evaluation through a series of inspection and non-destructive testing (NDT) techniques. These techniques, range from ultrasonic to x-ray inspection, have major drawbacks of high cost and duration of time. The greater flaw is post-manufacturing inspection, results in a high volume of scraped products when defects are detected. Performing non-destructive evaluation in real-time, provides the benefit of adjustable input parameters and process conditions which give a highly optimised finished component.

An example applicable to the regeneration of compressor blades is illustrated in Fig. 2. During the welding process where additive material is deposited on the tip of the blade, a variation occurs in the power supply, resulting in lower heat input to the material, Fig. 2a. The result of this variation shows lack of fusion in the weld (red colour). In this case the welding engineer completes the operation as normal, and post weld inspection detects the defect effectively scrapping of the part under regeneration. Conversely, presented Fig. 2b a real-time weld monitoring system detects the slight variation of the power supply as it occurs (green area). This triggers a signal that highlights the need for a change in the process parameters, and another subsystem adjusts the power to its new level. As a result the process continues with the corrected parameters, preventing the defect from lack of fusion to occur.

The high-speed DAQ has been proven to detect anomalies resulting in poor weld quality [11]. By monitoring the welding process with the DAQ system, implementation of data-processing techniques allows feedback to the robotic welder via a newly developed Arc Voltage Control (AVC). When combined DAQ and AVC data allows

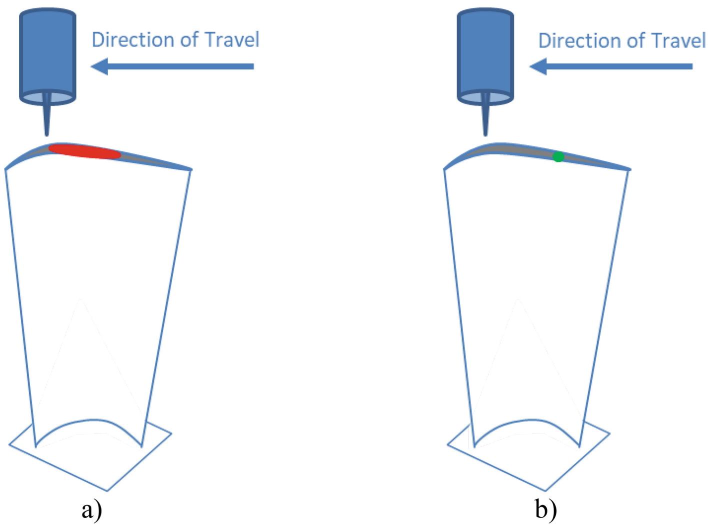


Fig. 2. A compressor tip-repair process. (a) a slight alteration on the power supply occurs in lack of fusion in a part of the weld (red), (b) the alteration is detected and a signal is triggering corrections, avoiding the formation of the defect.

for the adaptive development of partial human intelligence drawn from experienced welding engineers.

3.2 Automatic Voltage Control (AVC)

During the manual welding process, the human engineer uses their natural senses to monitor the welding process, adjusting their movements to control the heat input to the workpiece. These adjustments include, changes of direction and travel speed of the welding torch, electrode and workpiece distance. Variation in the distance between the electrode and the workpiece (arc gap), corresponds to changes in the voltage of the arc. The application of an electromechanical subsystem to maintain a preset arc gap (Fig. 3), achieves consistent voltage control. The AVC receives data from the DAQ monitoring system and reacts by positioning the electrode accordingly. By providing greater control of the system, achieves better control of the amount of heat delivered to the workpiece (heat input) and a stable process.

4 Welding Trials and Discussions

Analysis of GTAW welding machines to improve welding performance involves the monitoring of signals and generation of commands over an interface. Response to GTAW technique variation requires intelligence which has proven exceptionally challenging to develop for the complex profile (curved) and super alloy materials (heat input and distortion) now utilized by aerospace engine manufacturers. Experienced

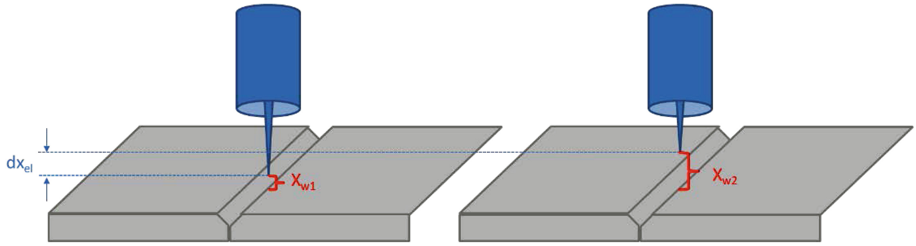


Fig. 3. Automatic Voltage Control (AVC) by altering the distance between the electrode and the workpiece. A change in the electrode position *(*dx_{el}*)*, corresponds to a change in the voltage, which is proportional to the workpiece distance ratio $X_{w1}{:}X_{w2}$.

welding engineers dynamic inputs alter the weld deposition or AM characteristics (size, shape, depth and micro-structure) by varying parameters termed CLAMS (current, length, angle, manipulation and speed) [3, 10]. They use their knowledge and apply their skills almost automatically by subtly fine tuning CLAMS to achieve the required result. Automated repetition of CLAMS data enables production of the correct weld deposition with high repeatability but with the inability to respond to a change in dynamics or conditions.

Figure 4 shows the arc welding voltage and current measurements performed on the edge of a flat stainless steel plate of 1.5 mm width thickness, using a WPS created with the CLAMS tuned by experienced welding engineers from VBCie.

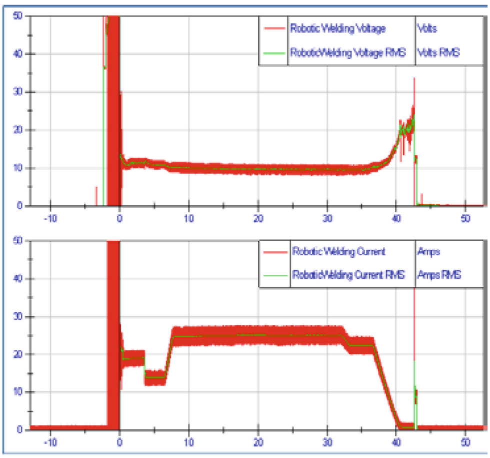
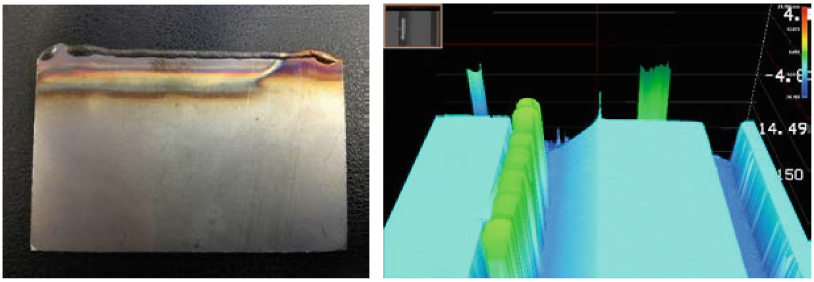


Fig. 4. Arc welding voltage (top) and current (bottom) of the IP-50 welding machine from VBC Ltd.

Measurements were performed using bespoke high speed sensors [10, 12]. The measurement signals have been filtered in real-time with a low-pass filter and cutoff frequency of 10 Hz. Different current levels were tuned to allow the weld pool to settle at the start and end of the WPS. The total travel distance of the welding torch over the test piece was 60 mm.

While Fig. 5 shows the 3D scan of the outcome of the robotic welding when the AVC is not active, Fig. 6 shows the 3D scan outcome of the adaptive robotic welding when the AVC is active.



a) b)

Fig. 5. Robotic welding with AVC OFF (a) Flat SS plate, (b) 3D image

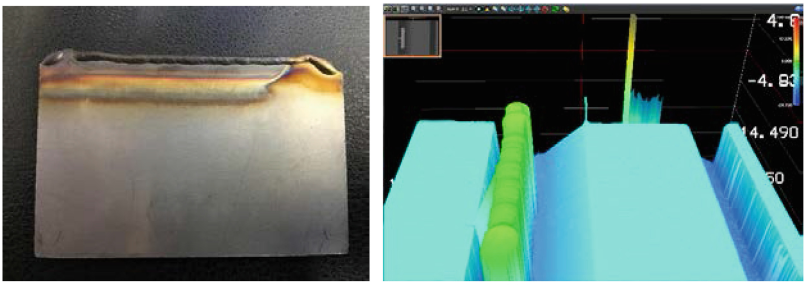
Figure 7 compares the heights of test samples shown in Figs. 5 and 6. A downslope due to the melting of material at the end of the test sample can be seen when the AVC is active (graph in green). This effect is expected because more additive material needs to be deposited at the end of the outer edges to allow for the grinding process. However, when is the AVC is not active (AVC OFF, graph in red), the melting temperature of the material is too cool, even though the corresponding welding current in the WPS is suitably to achieve the correct melting point or fusion. Therefore, the AVC allows additive filler material to be fed in to the plate for the build-up or AM to occur by compensating the distance between the electrode tip and the turbine blade tip.

5 Conclusions

The repair or regeneration of high value aeroengine components is heavily dependent on large elements of manual welding. Because of the complex geometries and the large variety of non-uniform wear and deformation found on individual pieces, the automation of the remanufacturing process is extremely challenging. In order to achieve advances in this automation, human engineering skills need to be observed and recorded during the process, analysed and transferred to robotic welding systems.

A series of experimental welding trials were performed by the ESIM Group of University of Sheffield and its industrial partners, NAMRC and VBCie, providing the data used for training a robotic aerospace welding system. By applying design principles shaped by the Industry 4.0 concept, the robotic system adapts to changes in the repair process, resulting in better QC and increased success rates.

An AVC module has been developed, in order to achieve machine control of the arc welding voltage. The module receives data provided by a high-speed real-time process



a) b)

Fig. 6. Adaptive robotic welding with AVC ON (a) Flat SS plate, (b) 3D image

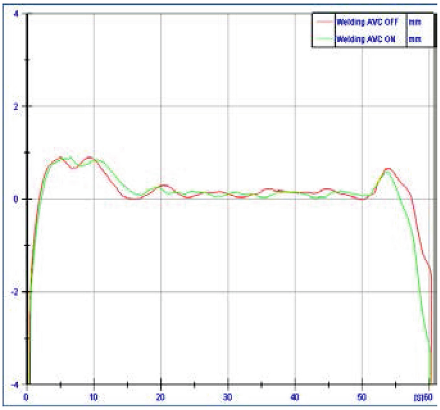


Fig. 7. SS plate heights with AVC ON (green) and without AVC (red). Very similar but at the end of the torch falls over the edge when AVC ON.

monitoring system and controls the voltage by altering the distance between the electrode and the workpiece.

The interoperability required by Industry 4.0 in a smart factory allows modular subsystems to perform such decentralized decisions, increasing production speed and assuring quality.

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References

1. Denkena, B., et al.: Engine blade regeneration: a literature review on common technologies in terms of machining. Int. J. Adv. Manuf. Technol. **81**, 917–924 (2015)
2. Yilmaz, O., et al.: A repair and overhaul methodology for aeroengine components. Robot. Comput.-Integr. Manuf. **26**, 190–201 (2010)
3. French, R., Marin-Reyes, H.: High value intelligent aerospace turbofan jet engine blade re-manufacturing system. In: Schlick, C., Trzcieliński, S. (eds) AHFE Advances in Intelligent Systems and Computing, vol. 490. Springer, Cham (2016)
4. Geng, J., et al.: A design method for three-dimensional maintenance, repair and overhaul job card of complex products. Comput. Ind. **65**, 200–209 (2014)
5. Zhang, Z., et al.: A cloud-based framework for lean maintenance, repair, and overhaul of complex equipment. J. Manuf. Sci. Eng. **137**, 11 (2015)
6. Ulhmann, E., et al.: MRO – challenge and chance for sustainable enterprises. In: 2nd International Through-life Engineering Services Conference (2013)
7. Compressor blades repair and overhaul. Rolls-Royce Plc Internal Report (2002)
8. French, R., Marin-Reyes, H.: Welding performance evaluation of the VBCie IP50 TIG orbital heat management system. In: IIW International Conference, High-Strength Materials - Challenges and Applications, Helsinki, Finland, July 2015
9. French, R., et al.: Real-time welding evaluation system assessment using the TIG orbital welding process on ultra-thin wall tube joints in titanium and stainless steel. In: IIW International Conference, Green Welding Technologies for Effective and Reliable Manufacturing, Shanghai, China, June 2017
10. French, R., et al.: Advanced real-time weld monitoring evaluation demonstrated with comparisons of manual and robotic TIG welding used in critical nuclear industry fabrication. In: Trzcielinski, S. (eds) AHFE 2017, Advances in Intelligent Systems and Computing, vol. 606. Springer, Cham
11. French, R., et al.: Intelligent sensing for robotic re-manufacturing in aerospace — An industry 4.0 design based prototype. In: IEEE International Symposium on Robotics and Intelligent Sensors (IRIS), Ottawa, ON, pp. 272–277 (2017)
12. French, R., et al.: A Robotic re-manufacturing system for high-value aerospace repair and overhaul. In: Chen, S., Zhang, Y., Feng, Z. (eds.) Transactions on Intelligent Welding Manufacturing. Springer, Singapore (2017)

Evaluation of Order Picking Processes Regarding the Suitability of Smart Glasses-Based Assistance Using Rasmussen's Skills-Rules-Knowledge Framework

Nela Murauer(✉) and Steffi Gehrlicher

BMW Group, Max-Diamand-Str.5, 80788 Munich, Germany
nela.murauer@bmw.de, steffi.gehrlicher@gmx.de

Abstract. Augmented Reality (AR)-technologies are an important part in the change towards digital manufacturing. Fields of application are assembly, order picking and maintenance. For a full-shift study evaluating smart glasses in order picking processes, we selected the most suitable workplace in logistics area using Rasmussen's Skills-Rules-Knowledge framework. Since the classification into Rasmussen's three levels of human behavior has been quite subjective so far, we propose a more objective approach based on a pairwise comparison and a cost-utility analysis. Developing this method, we define numeric boundaries between the three levels of Rasmussen's framework. After the evaluation by ten experts, we selected the best workstation for our future full-shift study at BMW Plant Munich.

Keywords: Rasmussen's Skills-Rules-Knowledge framework · Smart glasses Augmented Reality · Logistics · Order picking processes

1 Introduction

The increasingly dynamic transformation process changes from a traditional flow production to a smart factory. The usage of wearable devices supports the change towards digital manufacturing. Especially Augmented Reality (AR)-technologies such as smart glasses provide a benefit in facilitating hands-free work while simultaneously displaying additional information. Our research project tests smart glasses for order picking-processes in full-shift usage.

Before testing begins, it is necessary to select the best picking workplace at our automotive plant for the employees. Relying on the Skills-Rules-Knowledge framework of cognitive control levels [1], activities can be classified into three levels: *skill-based, rule-based* and *knowledge-based*. [2] assumed that AR is only helpful in all rule-based activities. Skill-based activities have no need for displaying information and knowledge-based activities are too complex and unexpected to prepare enough information in the AR-glasses. Each picking process consists of several steps of varying complexity. In our new evaluation methodology, we add previously unlisted cognitive process steps to analyze the possibility of AR-assistance. Our evaluation procedure is similar to a *utility analysis*. Every work task is rated according to the criteria of activity

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itself, the required information for the task, the experience and the error susceptibility. The activity-criterion is subdivided into *perceptual, motor* and *cognitive workload*, based on the Model Human Processor [3]. Logistics experts weight these categories using a pairwise comparison. Afterwards they evaluate the activities by category. Multiplying the weighting factor by the absolute score and adding up the individual categories yields a classification score. A higher classification score indicates knowledge-based and a lower one implies skill-based behavior. Previously, assessed examples of a literature review serve a basis for dividing the three Rasmussen-levels. Calculating the proportion of rule-based activities at each workstation supports the comparison of each workstation regarding AR-technologies.

2 Related Work

2.1 Augmented Reality in Assembly and Order Picking

Augmented Reality (AR) refers to augmentation of the reality by displaying virtual information. The combination of reality and virtuality creates a new environment between real world and virtual world [4]. The use of AR-visualizations is possible in different fields of applications. Various studies in the military context [5], in architecture [6, 7], in health sciences [8, 9] in order picking [10–15] and in assembly [16, 17] show the wide range of future possibilities of this technology.

In the production context literature research reveals many studies using head mounted displays (for the purpose of this paper we refer to 'smart glasses') for assembly or order picking processes. Most publications do not describe the selection of the test environment. [15] compare order picking and assembly processes with the assistance of projection and smart glasses. For their laboratory study, they build an order picking workstation and ask the test participants to assembly LEGO® animals. [14] evaluate smart glasses in order picking processes as well. Similar to [11–13, 15], [14] build their study environment by themselves and do not select a special workstation in a real production plant, which benefits especially from the AR-usage compared to other workstations. [18] focus their laboratory study on ophthalmological impacts on workers analyzing assembly and order picking tasks supported by smart glasses. [18] create three different tasks to shed light on the usefulness for AR-support. Where additional context-sensitive visualization of information is helpful, AR-support can be considered. [2] presents an interesting approach analyzing different tasks using Rasmussen's Skills-Rules-Knowledge framework. [2] classifies assembly tasks into the three levels of human behavior (*skill-based, rule-based* and *knowledge-based)*. We explain Rasmussen's framework in detail in capture 2.2. According to [2], especially the medium level of rule-based human behavior is suitable for AR-support. [10] relies his workstation selection on research from [2]. [10] defines rule-based order picking tasks as complex activities of high training effort, where support by additional information is needed. After comparing test conditions of assembly, order picking and quality assurance, he selects an order picking workstation as test environment. Hence, [10] focuses on the best test environment and not on choosing the best AR-supportable activity during the selection process.

Our research project is a field study in an automotive production plant. Thus, we decided to select our test environment according to [2] based on Rasmussen's Skills-Rules-Knowledge framework [1], which we explain in detail in the following (Fig. 1).

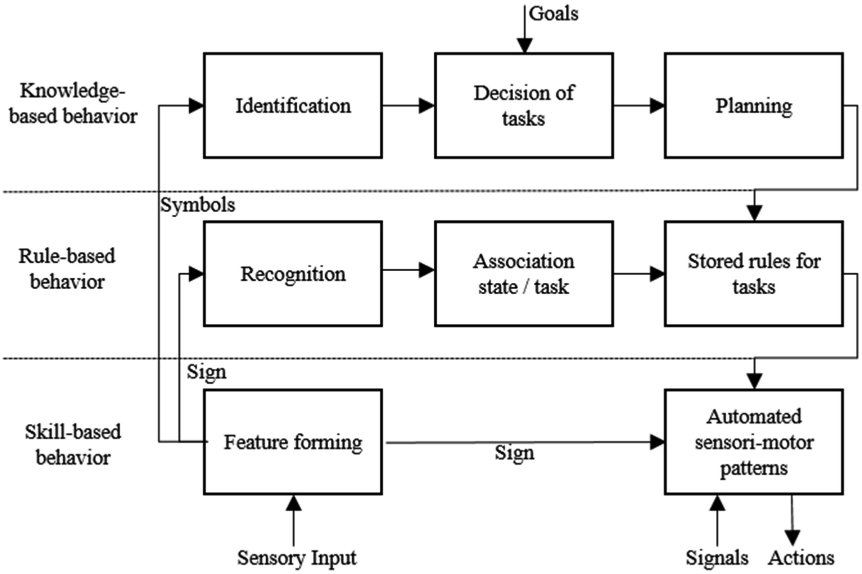

Fig. 1. Skills-Rules-Knowledge Framework

2.2 Skills-Rules-Knowledge Framework

Rasmussen's framework describes three regulation levels of human behavior: skill-based, rule-based and knowledge-based behavior. 'The skill-based behavior represents sensory-motor performance during acts or activities which, following a statement of an intention, take place without conscious control as smooth, automated, and highly integrated patterns of behavior' [1]. He names drawing or simple assembly tasks. 'At the next level of rule-based behavior, the composition of such a sequence of subroutines in a familiar work situation is typically controlled by a stored rule or procedure which may have been derived empirically during previous occasions, communicated from other persons'know-how as introduction or a cookbook recipe, or it may be prepared on occasion by conscious problem solving and planning' [1]. At this level of behavior humans profit from stored and usual behavioral patterns, which they learned in similar situations in the past. Actions base on if-then-rules [19]. The knowledge-based level describes goal-controlled considerations, which action alternative would be the best to achieve the goal. [1] defines this level as follows: 'During unfamiliar situations, faced with an environment for which no know-how or rules for control are available from previous encounters, the control of performance must move to a higher conceptual level, in which performance is goal-controlled and knowledge-based'.

Table 1 shows examples of already classified tasks to a level of human behavior according to Rasmussen's framework.

Table 1. Examples of skill-, rule- and knowledge-based tasks in literature

Activity	Skill-based	Rule-based	Knowledge-based	Reference
Steering behavior	Experienced driver	Novice driver	Swerving	[20]
Driving	Stabilization	Driving maneuvers	Guided by navigation-system	[21]
Navigation planning	Daily way to work	Selection between known ways	Foreign metropolis	[20]
Water tap	Turning	Sensor below tap	Foot pedal	[20]
Pressure flow sensory	Signal	Sign (if valve is open, then…)	Symbol (functional thinking)	[1, 22]
Height control of an airplane	Keep height	Adjust angle of climb	Motor speed too low	[1]
Assembly	Clip assembly	Harness assembly	Assembly of window regulators	[2]
Orientation in a city	No auxiliary means (known city)	Following landmarks	Supported by map	[23]

Classifying a task into one of the three levels depends on the person's experience level. Training and repetition should cause a level-down grade, but this level 'jump' is not taken into account. Thus, different training states lead to smooth transitions instead of clear boundaries between the performance levels [1, 2]. According to [2], task classification can change from rule-based to skill-based with repetition.

2.3 Utility Analysis and Pairwise Comparison

The methodological context of this paper is based on a *utility analysis*, which prepares a 'systematic decision-making' between competing alternatives in order to identify the alternative with the highest utility score [24]. Such a utility analysis structures the evaluation of all possible alternatives in six steps. The first step identifies each possible alternative, the second step designs a matrix with all alternatives and criteria for a comparison of these alternatives, while the third step standardizes the evaluation scale, for example '1-2-3'. The fourth step attributes a specific weight to the evaluation criteria using *pairwise comparison*. Pairwise comparison supplements the inter-relational weighting between the evaluation criteria in the 'n x n – matrix' comparing each processual criterion with all other processual criteria. In each cell, the choice is between two processual criteria [24, 25]. In pairwise comparison, ratings may be 2 points for 'criterion A is more important than criterion B', or 1 point for 'criterion A is just as important as criterion B', or 0 points for 'criterion A is less important than criterion B'. The principle diagonal stays unassessed and grey in the matrix. The fifth step sets a partial utility value and the last step computes a final utility score by multiplication of partial utility scores with the weighting factors [24, 26, 27]. Afterwards, each partial result of one alternative is then summed up to an outcome score. The ranking orders the alternatives from the highest to the lowest score.

3 Methodology

In order to select the most suitable workplace for the usage of smart glasses, the process steps of the workstations are correlated with the levels of the Rasmussen model. The workstations are more suitable for AR-use when they contain process steps, which belong to rule-based behavior. For such an approach, the process is divided into small tasks until each task contains only one activity type. In doing so, process descriptions of the MTM (methods of time measurement) indicate times for the individual process blocks. These are typically reach, grasp, bring, position, release.

To assess the process steps objectively, the principle of utility analysis is applied. The process steps are assessed under a set of criteria. Each criterion is evaluated separately. This procedure requires a uniform rating scale. The pairwise comparison of the individual criteria leads to the weighting of the criteria. A multiplication of the individual partial scores by the weighting scores and the subsequent addition of these outcomes give a classification value, which allows a comparison of the different process steps. This resulting value is referred to as 'Rasmussen index' 'r'.

$$r_n = 1/3\left(p_a a_{m,n} + p_a a_{s,n} + p_a a_{c,n}\right) + p_i i_n + p_e e_n + p_s s_n \quad (1)$$

Rating categories are the complexity of the activity (a_n), amount of required information (i_n), experience (e_n) and error susceptibility (s_n). The *activity* category involves evaluating the complexity and difficulty of the process step. For a more detailed assessment of the category *activity*, we introduce the three subcategories *motor, sensory* and *cognitive* based on the model Human Processor [3]. *Sensory* describes the seeing, hearing and feeling, *motor* symbolizes effort and *cognitive* represents the processes in the human brain. These four overall criteria are weighted by using pairwise comparison in expert interviews. The *activity* score in the pairwise comparison results from dividing the sum of motor-driven, sensory and cognitive scores by three (Fig. 2).

The rating scale is a 1-2-3 scale. In the *activity* category, a 0 score for "no activity" is also a valid rating. Evaluating a 'remember' process step, for example, does not require motor activity. All other activities are classified from low to high. The number of required information can be evaluated as 1 (dispensable), 2 (supportive) and 3 (essential). Experience scores are considered in reverse order, whereas lower experience leads to a higher classification in Rasmussen model. Under the condition, that someone has a lot of experience and a certain routine in fulfilling a task, the activity can fall by one level in the Rasmussen. The higher the error susceptibility of a process step, the more complex and less automated it is. Therefore rating scores can be 1 (barely), 2 (moderate) or 3 (high) (Tables 2 and 3).

In order to assign different values of the Rasmussen index 'r' (see formula 1) to the three levels of the model, we conducted a literature analysis on example descriptions,

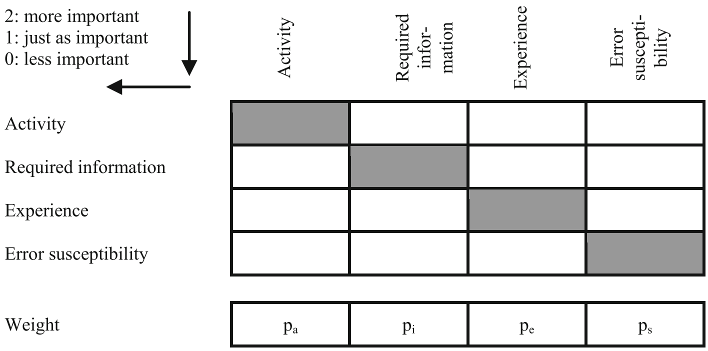

Fig. 2. Pairwise comparison for classifying tasks into Rasmussen's framework

Table 2. Rating scale

Category	Rating			
Activity	0 (none)	1 (low)	2 (moderate)	3 (high)
Information		1 (dispensable)	2 (supportive)	3 (essential)
Experience		3 (barely)	2 (moderate)	1 (substantial)
Error susceptibility		1 (barely)	2 (moderate)	3 (high)

Table 3. Rasmussen's framework – Boundaries between levels

Level	Rasmussen index 'r'	Smart glasses support
Knowledge-based	2.60–3.00	Complicated
Rules-based	1.50–2.59	Reasonable
Skill-based	0.79–1.49	Not reasonable

which already classified these according to the Rasmussen levels. The research project verifies these classifications through the procedure described above. The assumption is that the associated level was already established. Using the results of our industrial use case (generated by expert interviews) determine the prioritization values p_a, p_i, p_e and p_s. By calculating the Rasmussen index 'r' and considering existing classification for the literature examples into the three levels of the model, three ranges of values are found. Having identified these ranges, each value now references a level.

Using the described approach, human behavior can be classified to the skill-based, rules-based, or knowledge-based level. The evaluation shall be based on expert interviews. The obtained values of the surveys are averaged. It shall be emphasized that the item *experience* can be assessed with a specific person in a specific situation. For example, a driving task is rated differently for a beginner than for a substantially experienced motorist. Changing the *experience* variable from 3 to 1 may lead to classification of the task at a lower level. This is a solution to one of the main criticisms of the Rasmussen framework.

4 Industrial Application

At the BMW Plant Munich we will test the usage of smart glasses in order picking processes. Until now, a screen displayed required information for order picking processes. Smart glasses shall show this information from now on. It is essential to choose the most suitable out of nine possible so-called supermarkets (order picking workstations in the logistics area) for a full-shift study.

We prepared the expert interviews analyzing so-called "standard work sheets", which explain the order picking process step-by-step. During this comparison, we noted that the process descriptions differed in detail. This suggests that different logistics planners described the standard worksheets. For this reason, we standardized the nine process descriptions to the same level of detail. Process descriptions in the production environment describe physical and visible activities. Cognitive processes are missing. Thus, we added the process steps memorize, read and compare visual information. After comparing the workstations, we noticed that the process of each workstation contains the same basic process steps. These are *grasping, reading, memorizing, comparing visual information, spatial orientation, walking, positioning without prior selection, positioning with selection, final control, switching monitor* and *cleaning workstation.*

Ten production experts from various divisions of the company, for example logistic planning, assembly planning, operative factory logistics, quality and process improvement in the plant and the innovation areas in logistics and engine construction, were evaluating.

4.1 Pairwise Comparison

Every expert conducted the pairwise comparison by him- or her-self. It was noticeable that, quality experts classify the experience as less important than error susceptibility. Planning experts, on the other hand, classify the experience as more important than the error susceptibility and rely on the experience-based recognition and correction of errors. After averaging the values, the relative weighting of the activity itself was about 21%, the number of required information about 26%, the experience about 29% and the error rate about 24%. The one-third of the criterion activity gives a weighting of about 7% for the sensory, motor and cognitive load. Figure 3 shows all determined values.

4.2 Evaluation of the Process Steps

After pairwise comparison, the experts individually assessed the basic process steps using the rating scale defined in the section above. At an order picking workstation the 'final control' is the most complex activity. Due to different skill- and education-levels in different contexts or jobs, we advise a context-specific evaluation.

Amongst the most important process steps in so-called supermarkets are picking, orientation in space and positioning with selection. The participating experts rated the grasping as predominantly sensory and motor demanding but considered the cognitive load low. To execute grasping activities the worker needs additional information. In our evaluation, error susceptibility of the grasping movement was also low rated. Spatial

2: more important
1: just as important
0: less important

	Activity	Amount of infor-mation	Experience	Error suscepti-bility
Activity		14	10	12
Amount of information	6		11	9
Experience	10	5		7
Error susceptibility	8	11	13	
Sum	24	30	34	28
Weight	0.206897	0.258621	0.293103	0.241379

Fig. 3. Pairwise comparison in industrial application

orientation is cognitively demanding and due to strain on the eyes, it also stresses the sensory activity according to expert opinion. In these situations, motor activity may be neglected. Experts evaluate the required information to guarantee spatial orientation indispensable, such as for example the worker's own position in the room and the arrangement of the warehousing positions. For this task the amount of required information is high. Since disorientation can occur, the results of the evaluation regarding error susceptibility is also comparatively high. Positioning with the option of selection, for example the placement of the component in the correct target bin is sensory, motoric and cognitively demanding. In this process step, information about the correct target bin is necessary. The error susceptibility reaches with a value of 2.9 almost the maximum value on the rating scale. Confusion errors with the positioning of components are frequent errors in the order picking. These occur in our experience more frequently than omission errors. Particularly noteworthy are the evaluations of the process steps of the final inspection and the workstation cleaning: The final check is considered to be sensory and cognitively demanding, while it is not challenging in motor activity. In addition, the number of required information and the error rate are classified as particularly high. The process step of keeping the workplace clean is in part sensory demanding through visual perception, but in part relatively simple activity with a lower susceptibility to errors. The process step can be made without additional information. Further evaluations can be found in Table 4.

The experience is classified according to common employee characteristics as the 'typical worker' at a workstation. Serial production, for example, mainly uses experienced employees. Therefore, the experience in this case is commonly rated to a standard of 1. However, if the Rasmussen model is used to view a learning case, the experience of the unskilled worker should be adjusted to 3. The process steps memorize, read and leave retain the experience value 1 in both scenarios, since these activities are independent of the workplace and are often carried out in everyday life. Thus, every adult human is classified as an experienced worker.

After calculating the Rasmussen index, all process steps are assigned to the levels of skill-based, rule-based, and knowledge-based behaviors. In a standard case, all

Table 4. Evaluation of exemplary order picking process

Process step	Sensory activity	Motor activity	Cognitive activity	Required information	Error susceptibility	Experience	r	Experience	r
Grasping	1.9	2.8	1.0	1.2	1.2	1.0	**1.29**	3.0	**1.87**
Reading	1.9	0.3	2.1	2.8	1.9	1.0	**1.77**	1.0	**1.77**
Memorizing	0	0	2.9	1.5	2.8	1.0	**1.56**	1.0	**1.56**
Comparing visual information	0.5	0.3	2.7	2.9	2.8	1.0	**1.96**	3.0	**2.55**
Spatial orientation	1.7	0.2	2.8	2.7	2.1	1.0	**2.10**	3.0	**2.41**
Walking	1.1	2.5	0.8	1.0	1.0	1.0	**1.10**	1.0	**1.10**
Assembly	2.2	2.8	1.1	2.0	2.2	1.0	**1.70**	3.0	**2.35**
Positioning without selection	1.0	2.1	0.9	1.7	1.0	1.0	**1.25**	3.0	**1.83**
Positioning with selection	2.0	1.9	2.2	2.2	2.9	1.0	**2.13**	3.0	**2.57**
Final control	2.0	0.9	3.0	2.9	2.8	1.0	**2.13**	3.0	**2.71**
Switching monitor	1.0	1.0	1.1	1.0	2.0	1.0	**1.25**	3.0	**1.83**
Cleaning workstation	1.2	2.1	1.0	1.0	1.0	1.0	**1.09**	3.0	**1.68**

process steps are skill-based or rule-based. Whereas grasping, walking, positioning without selection, switching the monitor and cleaning the workstation are skill-based tasks. Reading, memorizing, comparing visual information, spatial orientation, assembly, positioning with selection and final control are rule-based tasks and are therefore suitable for the use of AR-technologies, according to [2].

When we consider training scenarios, level 'jumps' may occur. The final control assessment changes from a rule-based to a knowledge-based level. Scores for the grasping, the switching of the monitor (frequent accidental skipping of slides), the positioning without selection and keeping the workplace clean change from the skill-based behavior to the rule-based level. Walking is the only process step belonging to skill-based behavior. This evaluation shows that AR-technologies can significantly support more process steps during training. A reduction of the visualizations with increasing experience in the process steps is an option.

4.3 Workstation Selection

Analyzing the evaluation of the nine possible workstations, we conclude that all nine workstations include rule-based process steps and are at first glance suitable for AR-support. Under this precondition, the choice between the workplaces changes into a new challenge of ranking the workplaces according to their 'suitability'. For the purpose of our research project, gaining experience and representative data for as many different process steps as possible is beneficial. The benefit is the transferability of the observations from the reference workstation to other workplaces in the BMW logistical world. Specifically, suitability of the workstation denotes not only choosing a workplace for testing. Furthermore, it requires that the workplace is adequate for subsequent roll-out and that the observations of AR-testing are indicative of the general benefits of AR-use for logistics.

Exploring the differences in workstation reveals that the processes differ in variability and in the amount of rule-based process steps at each workstation. Detailed analysis of the different workplaces is theoretically possible using the MTM-descriptions of the process, but the sub-processes in the MTM-evaluation cannot represent the added cognitive activity. Thus, the obtained percentages in rule-based time slices compared to the entire process time is underestimated. Our study describes individual cognitive elements and thus contains more task elements, which impairs comparison with the MTM basic processes.

Therefore, our approach still gives priority to the variability facing rule-based process steps. Thus, we decided that selection based on the percentage of rule-based tasks is preferable irrespective of the loss in precision of the method. The selected workstation for the test, where footwell claddings are picked, contains 75% rule-based process steps in the case of series production and is particularly suitable for the test due to its versatility (picking with pre-assembly). In comparison, other processes include 56.67% to 44.44% rule-based process steps.

To complete the selection we analyzed the environmental conditions such as light conditions, workplace dimensions, the ability to display indoor navigation, as well as the shelving construction. Examining the lighting condition, we focus on avoiding glare, darkness and reflections. A spatial delimitation of the workstation ensures occupational safety. Whereas unobstructed field of view increases the usability of visual guidance. Generally, due to the current hardware limitations, shelf dimensions have to correspond with actual limitations of tracking technologies.

5 Discussion and Conclusion

In consideration of our future full-shift study, we compared nine possible workstations at the BMW Plant Munich in terms of their suitability for AR-usage. Following the approach from [2], we used Rasmussen's Skills-Rules-Knowledge framework for evaluating every process step.

The literature research shows a lack of objective approaches to classify tasks into Rasmussen's framework. Consequently, we proposed a new method for an objective classification. The first step is a pairwise comparison of the categories activity, required information, error susceptibility and experience. The second step is an evaluation of the individual process step according to the four categories. A so-called Rasmussen index 'r' results from summing up the category's weighting multiplied by the individual evaluation value. With our new method, we evaluated established examples in literature, which already classified tasks according Rasmussen's framework. In this way, we were able to define numeric boundaries between Rasmussen's levels of human behavior. These are the first concrete numeric boundaries for Rasmussen's Skill-Rules-Knowledge framework. Our evaluation is based on specific evaluation in expert interviews and is therefore comparatively more objective than previous classifications. Although the average value of expert opinions still contains subjective evaluations, involving a large number of persons into the evaluation ensures the validity [28].

Future research is invited to review and refine our defined boundaries by evaluation of more experts of different areas of expertise pertinent to the specific workplace.

Starting with the assumption that smart glasses support rule-based tasks especially well, we compared the percentage of rule-based tasks at our nine possible workstations. Finally, we selected the workstation with most rule-based process steps as a test environment for our study. The other supermarkets are also supportable by smart glasses, but the worker needs the AR-support in comparatively less process steps. The ranking of the relative amount of rule-based process steps could be used in chronological order for a further roll-out plan of smart glasses in logistics area.

After identifying supportable process steps using AR-technologies and considering additional research projects, we focus on designing the user interface of smart glasses involving the employees, which work at our selected workstation. According to [29], the completeness of the information, the arrangement and the legibility of the information are relevant for the picker and for his error rate and performance. We use our workers' expertise in a design-thinking workshop for realizing a user interface, which fulfills all demands and satisfies the pickers' needs during the order picking process. Hereby we hope to increase the acceptance of the AR-technology and prepare for the best possible conditions for our full-shirt study at BMW Plant Munich.

References

1. Rasmussen, J.: Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. IEEE Trans. Syst. Man Cybern. SMC-13, (3), 257–266 (1983)
2. Wiedenmaier, S.: Unterstützung manueller Montage durch Augmented Reality-Technologien, vol. 1. Shaker, Aachen (2004)
3. Card, S., Moran, T., Newell, A.: The Psychology of Human Computer Interaction. Erlbaum, Mahwah (1983)
4. Azuma, R.T.: A Survey of augmented reality. Presence: Teleoper. Virtual Environ. **6**(4), 355–385 (1997)
5. Wanstall, B.: HUD on the head for combat pilots. Interavia **44**, 334–338 (1989)
6. Tamura, H., Yamarnoto, H., Katayama, A.: Steps towards seamless mixed reality. In: Mixed Reality – Merging Real and Virtual Worlds, pp. 59–84. Springer, Berlin (1999)
7. Runde, C.: Head Mounted Displays und Datenbrillen, Einsatz und Systeme. Virtual Dimension Center (VDC), Fellbach (2014)
8. Tönnis, M., Günthner, O.P., Karl, D., Lienhard, R., Zeppenfeld, K.: Augmented Reality – Einblicke in die Erweiterte Realität. Springer, Heidelberg (2010)
9. Juan, C., Alcaniz, M., Monserrat, C., Banos, R., Guerrero, B.: Using augmented reality to treat phobias. J. IEEE Comput. Graph. Appl. **25**(6), 31–37 (2005)
10. Tümler, J.: Untersuchung zu nutzerbezogenen und technischen Aspekten beim Langzeiteinsatz mobile Augmented Reality Systeme in industrieller Anwendung. Fakultät für Informatik, Otto von Guericke Universität Magdeburg, Dissertation (2009)
11. Reif, R., Walch, D.: Augmented & virtual reality applications in the field of logistics. Vis. Comput. **24**, 987–994 (2008)
12. Funk, M., Sahimi Shirazi, A., Mayer, S., Lischke, L., Schmidt, A.: Pick from here! – an interactive mobile card using in-situ projection for order picking. In: UbiComp 2015, Osaka, 07 September 2011 (2015)

13. Schwerdtfeger, B., Klinker, G.: Supporting order picking with augmented reality. In: IEEE International Symposium on Mixed and Augmented Reality, 15–18 September, Cambridge (2008)
14. Guo, A., Baumann, H., Gilliland, S., Tech, G.: Order picking with head-up displays. IEEE Comput. **48**(6), 16–24 (2015)
15. Büttner, S., Funk, M., Sand, O., Roecker, C.: Using head mounted displays and insitu projection for assistive systems – a comparison. In: Proceedings of the 9th ACM International Conference on Pervasive Technologies Related to Assistive Environments, PETRA 2016, p. 44, Corfu (2016)
16. Theis, S., Pfendler, C., Alexander, T., Mertens, A., Brandl, C., Schlick, C.M.: Head-Mounted Displays – Bedingungen des sicheren und beanspruchungsoptimalen Einsatzes. BauA Report, Project F 2288, Dortmund Berlin Dresden (2016)
17. Korn, O., Funk, M., Schmidt, A.: Design approaches for the gamification of production environments: a study focusing on acceptance. In: Proceedings of the 8th ACM International Conference on Pervasive Technologies Related to Assistive Environments, PETRA 2015, Corfu (2015)
18. Kampmeier, J., Cucera, A., Fitzsche, L., Brau, H., Duthweiler, M., Lang, G.K.: Eignung monokularer Augmented Reality – Technologien in der Automobilproduktion. In: Klinische Monatsblätter für Augenheilkunde, Georg Thieme Verlag, Stuttgart, pp. 590–596 (2007)
19. Poitschke, T.M.: Blickbasierte Mensch-Maschine Interaktion im Automobil. Lehrstuhl für Mensch-Maschine-Kommunikation, Technische Universität München, Dissertation (2011)
20. Bengler, K.: Expert interview. Lehrstuhl für Ergonomie, Technische Universität München, 12 May 2017 (2017)
21. Winner, H., Hakuli, S., Wolf, G.: Handbuch Fahrerassistenzsysteme Grundlagen, Komponenten und Systeme für aktive Sicherheit und Komfort. Vieweg Teubner Verlag, Wiesbaden (2009)
22. Wickens, C., Gordon, J., Lui, Y.: An Introduction to Human Factors Engineering. Pearson Prentice Hall, Upper Saddle River (2004)
23. Goebel, M.: Expert interview, 18 April 2017 (2017)
24. Zangemeister, C.: Nutzwertanalyse in der Systemtechnik. Wittemannsche Buchhandlung, Munich (1973)
25. Gottmann, J.: Produktionscontrolling: Wertströme und Kosten optimieren. Springer Gabler, Wiesbaden (2016)
26. Oehme, O.: Ergonomische Untersuchung von kopfbasierten Displays für Anwendungen der erweiterten Realität in Produktion und Service. Shaker Verlag, Aachen (2004)
27. Kranefeld, A., Strausberg, M.: QM-Methoden in der Praxis – Nutzwertanalyse. Weka Media, Augsburg (2009)
28. Bechmann, A.: Nutzwertanalyse, Bewertungstheorie und Planung. Rombach GmbH, Freiburg (1978)
29. Gudehus, T.: Logistik-Grundlagen-Stategien-Anwendung. Springer, Heidelberg (2005)

A Test Platform for the Evaluation of Augmented Reality Head Mounted Displays in Industrial Applications

Volker Paelke[1(✉)], Carsten Röcker[2,3], and Jendrik Bulk[1]

[1] Hochschule Bremen, Flughafenallee 10, 28199 Bremen, Germany
{volker.paelke,jendrik.bulk}@hs-bremen.de
[2] inIT - Institut für industrielle Informationstechnik, Hochschule Ostwestfalen-Lippe Langenbruch 6, 32657 Lemgo, Germany
carsten.roecker@hs-owl.de
[3] Fraunhofer IOSB-INA, Langenbruch 6, 32657 Lemgo, Germany
carsten.roecker@iosb-ina.fraunhofer.de

Abstract. This paper presents a test platform for the systematic evaluation of head-mounted displays (HMDs). The focus is on an augmented reality (AR) test application for assembly tasks, which supports tests that are flexible in terms of complexity and scope, thus enabling the realistic assessment of usability, comfort and ergonomics by the test users.

Keywords: Head-Mounted Displays (HMDs) · Augmented Reality (AR)
Test platform · Evaluation · Assembly

1 Introduction

There is a great deal of interest in augmented reality (AR) applications in research and teaching, for entertainment, as well as for use in industry [1–3]. Besides stationary [4] and hand-held systems [5], in particular head-mounted displays (HMDs) are gaining increased attention. For professional use in industry it is necessary to select displays that meet the requirements of operators and users in terms of usability, ergonomics, functionality and robustness. The evaluation of AR HMDs is complex, covering aspects like the quality of the display (including aspects such as field of view, resolution, contrast, visibility under different lighting conditions), handling, reliability, robustness and usability, as well as the wearing comfort and ergonomics (weight, balance, run time on batteries) [6]. While some of this information is provided as technical data by manufacturers this is usually insufficient to assess more complex aspect like comfort and ergonomics.

In this paper we report on a test platform that includes a suite of test applications for the systematic evaluation of AR HMDs in industrial settings. The test applications allow conducting user tests with standardized tasks, thus enabling easy comparison between different displays. To realistically assess aspects like wearing comfort and ergonomics users have to work with a system in a realistic setting for extended periods – this in turn requires test tasks that are scalable in complexity and duration.

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The test suite supports the creation of customized tests tasks that cover a large range of task complexity and task duration.

2 State of the Art

Researchers recognized at an early stage that the quality of the display is of critical importance for the usability of an AR system. Already in 1995 Rolland et al. [7] examined both the technological issues involved in AR display usability, as well as central perceptual and human factors such as depth perception, user acceptance, and safety. In 1997 Azuma [8] discussed the advantages and disadvantages of various display technologies and identified important display qualities such as resolution and contrast. Numerous evaluation studies of AR systems exist in the literature and many of these include the evaluation of different displays (e.g., [9] or [10]).

Existing studies can provide general guidance in the selection of an AR display, such as selecting a suitable display type for an application (e.g. HMD vs. Handheld vs. Projection [11]), but are often of limited use in the selection of a display for a specific development project in industry. A key factor is the rapid development of AR hardware in recent years and the fact that AR hardware has only recently reached the maturity and reliability for productive use in industrial applications. Published evaluation and test results often cover out-of-date hardware or prototype systems.

The aim of our platform is therefore to support the evaluation of HMDs by means of a standardized and partially automated procedure. The use of AR displays to assist in picking and assembly tasks has been investigated in research for a long time [12, 13] and is now established as a product in the market (e.g. [14]), which makes this application well suited for test purposes.

3 Evaluation Platform Requirements

As part of our project, a test platform for HMDs is developed consisting of two parts: a hardware test bed that allows to measure key parameters of HMDs in a largely automated way and an interaction part with standardized user tests. In this paper, we focus on the interaction part that is currently being validated in user tests with common AR HMDs like the Epson Moverio, Microsoft Hololens and Vuzix glasses. The hardware test bed has recently been completed as a functional prototype and consists of a platform on which a mannequin head is mounted with two high-resolution cameras at the eye positions (Fig. 1).

The platform is equipped with sensors and actuators. The sensors measure the mass and balance of the HMD, and the motion actuators allow to move the head to measure latency and lag. The cameras make it possible to automatically measure several important aspects such as field of view, contrast and occlusion.

The interaction part of the evaluation platform was designed to enable user tests that measure important qualities of AR HMDs that are difficult or impossible to derive from the raw data provided by the hardware test bed, e.g. wearing comfort and user fatigue. Wearing comfort and fatigue can only be realistically assessed by human users

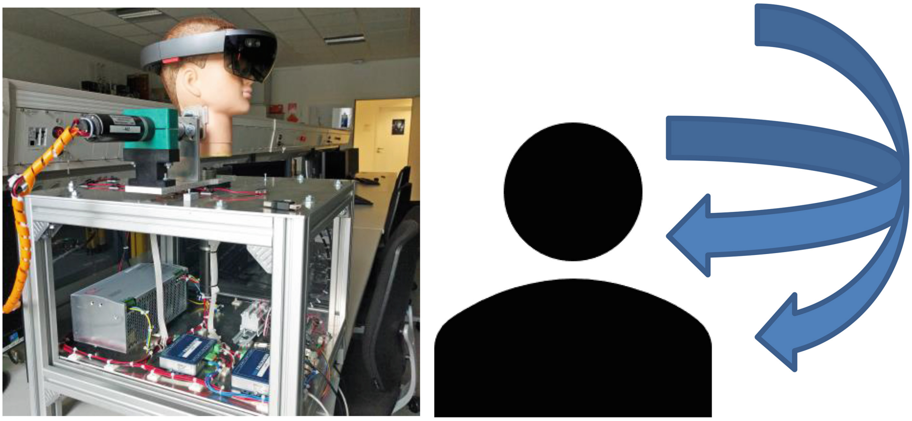


Fig. 1. Hardware part of the test platform and moving directions of the platform

after prolonged use of a HMDs in a realistic setting. Other qualities like readability of information and recognizability of graphics in different places in the field of view are also more realistically assessed by user tests.

Requirements for the test tasks were derived from in-depth discussions with practitioners using AR in industrial applications in industry, research and university settings. From the results the following requirements were established regarding the test tasks, the test environment and the implementation (Table 1).

The same process was also used to establish a collection of variables (qualities) that should be determined in the tests with users (Table 2).

Based on these requirements solutions were developed in an iterative user centered design process to cover the tasks, tests, implementation and data collection as presented in the following subsections.

4 Test Tasks

Typical tasks that are currently supported by industrial AR applications are navigation, information visualization and assembly or maintenance guidance. While these are all suitable as potential realistic test tasks our initial focus is on assembly and maintenance guidance tasks because these allow to address the additional test requirements of limited training, replication and limited setup in an easier way. Navigation tasks typically require extended test areas with significant set up costs and are therefore difficult to replicate. Information visualization tasks can be difficult to scale, especially if they are to be performed by untrained users. While simple information visualization tasks can be performed without previous training it is difficult to derive realistic and useful test scenarios that extend usage time to an hour or more. More complex visualization tasks are suitable for longer tests, but usually require previous training and domain expertise. Assembly and maintenance tasks can be designed to be performed by users with limited training and experience and are well suited for tests. In our first test

Table 1. Overview over requirements for the test tasks

Type of requirement	Description
Task requirements	• Realistic tasks: The tasks should be realistic tasks that are representative of typical industrial usage scenarios • Wide range of task complexity and duration: The tasks should be easily scalable in their complexity and duration
Test requirements	• No or limited training required: Test users should be able to complete a task without the need for previous (professional) training • No tools: Test users should be able to complete a task without the need for expensive and potentially dangerous tools • Limited setup: The task environment should be limited and self-contained, so that tests can be performed both in controlled lab settings as well as working production sites • Safe tasks: Test tasks should be safe to perform by large and diverse user groups with different backgrounds and experience • Replication: It should be possible to replicate the test environment at different locations
Implementation requirements	• Efficiently expandable: The design of the evaluation platform should allow for efficient creation of new test tasks • Reusable and affordable: The materials used by test users in the evaluation should be affordable and reusable across a large number of tests • Portability: It should be possible to adapt the test tasks to a wide variety of AR HMDs with different tracking and interaction modalities and port them to different operating system environments

Table 2. Overview over variables for user tests

Variable	Explanation
Completion time	Time required to complete a task
Errors	Errors made/corrected during the task and errors persisting in the final result
Fatigue	Measure of user fatigue
Attention	Measure of user attention/distraction
Cybersickness	Collection of data on cybersickness symptoms
Acceptance	Feedback on technological and social acceptance of the AR HMD
Perceived utility	Feedback on the perceived utility of the AR system
Perceived usability	Feedback on the perceived usability of the AR system
User experience	Feedback on the user experience of the AR system

application we have implemented several picking and assembly tasks. The assembly of objects makes for a clear and motivating scenario for test users and the duration and complexity of a test can (within reasonable limits) be adjusted both through the size and complexity of the object to be assembled and through repetition of the assembly task itself. In future versions we plan to expand the scope of tasks to include information visualization/read-out tasks that can be combined with the assembly and maintenance tasks.

5 Tests

One potential issue with using industrial assembly tasks in user tests is that the tests have to take occupational health and safety issues into account, especially if (power) tools are involved. Regulations often require previous training, supervision and special insurance, which make it difficult to recruit large and diverse user groups for testing. Since 2001, we have successfully used construction toys like fischertechnik [15], Lego [16] and Makeblock [17] in augmented reality demonstrators and test applications. A large and diverse group of users has used these construction toys in AR applications over the last 3 years in which we conducted public outreach activities in the MobileGameLab. The MobileGameLab is a STEM laboratory in Bremen (Germany), where children, students, senior citizens and other groups can gather experience with emerging technologies like AR and also create their own applications and projects. Based on these experiences and requirements we developed the initial set of picking and assembly tests based on components from fischertechnik and Lego construction toys. As toys these are certified as 'safe-to-play-with' for age groups 8 and up. The toys are requiring no tools to assemble and allow for easy replication of tests across multiple instances and sites. For the creation of assembly test tasks, the different construction set systems we have identified specific advantages and disadvantages (Table 3):

Due to these differences we currently use Makeblock only for mobile robotics projects and focus on the use of Lego and fischertechnik for the test platform. Fischertechnik seems to be best suited for a generic test platform, because a flexible subset of elements (suitable for placement in a typical assembly workplace) allows to cover a wide variety of models. Lego seems to be well suited for more specialized casual applications, e.g. use in demonstrators and fair presentations, where a specific set of blocks can be acquired for the specific assembly scenario.

6 Implementation

The use of construction toys allows for an easy modification and extension of assembly tasks to adapt to specific requirements and test scenarios. The elements of both fischertechnik and Lego models can be easily reused across many test and are affordable, especially if second hand elements can be purchased in bulk. This allows to create a library of 3D models that can then be used to create picking and assembly instructions. To support a wide variety of AR HMDs with different tracking and interaction modalities on different platforms and different operating systems the test applications are implemented in Unity, because Unity support is available for all current mainstream AR HMDs. Unity also provides support for other platforms like mobile devices which can often be of interest as an independent reference.

Table 3. Overview over different construction set systems with specific advantages and disadvantages

Construction set	Advantages/disadvantages
Lego	• individual bricks widely available in bulk both new and second hand • extremely large collection of objects with assembly instructions available • well known and familiar as toys to many test participants, easy to get started for new users • small give-aways can be great motivators, especially for casual tests in fair settings, losses in less controlled settings common (everyone knows someone who could use a hand full of Lego bricks…) • well suited for objects with a focus on appearance, somewhat limited for complex mechanics (e.g. mobile robots) due to limited solidity of models • very large number of different bricks available, making the selection of a flexible subset suitable for a large set of different tasks difficult • parts are very simple to assemble, it is not possible to show a more different task than sticking bricks together
Fischertechnik	• individual elements widely available in bulk both new and second hand in Germany, less common in other parts of the world • large collection of objects with assembly instructions available, active communities in Germany and the Netherlands • not that well known to many test users, viewed as less toy like and more professional, easy to get started for new users • more difficult to create small affordable give-aways, less losses - possibly due to perception as professional parts vs. toys • well suited for complex mechanics (robust and durable assemblies), more limited for models with focus on nice appearance • limited number of standard elements, allowing for a flexible subset from which many different models can be constructed • many different parts with special techniques for assembling but still simple enough to do without any Fischertechnik experience
Makeblock	• currently no established second-hand market for individual elements • smaller community, strong focus on mobile robotics models • largely unknown to many test users, viewed as less toy like and more professional, requires some instruction to get started for new users • requires some tool use, assembly more involved and time intensive • very difficult to create small affordable give-aways, less losses - possibly due to perception as professional parts vs. toys • very well suited for mobile robots (very robust and durable assemblies), less flexibility for other models • limited number of standard elements, but also limited coverage of possible models

The Unity development environment and the large collection of tools available for it allow for fast and effective creation and modification of test tasks. For future versions we plan to further automate the creation of appropriate visualization and instruction elements from the 3D models.

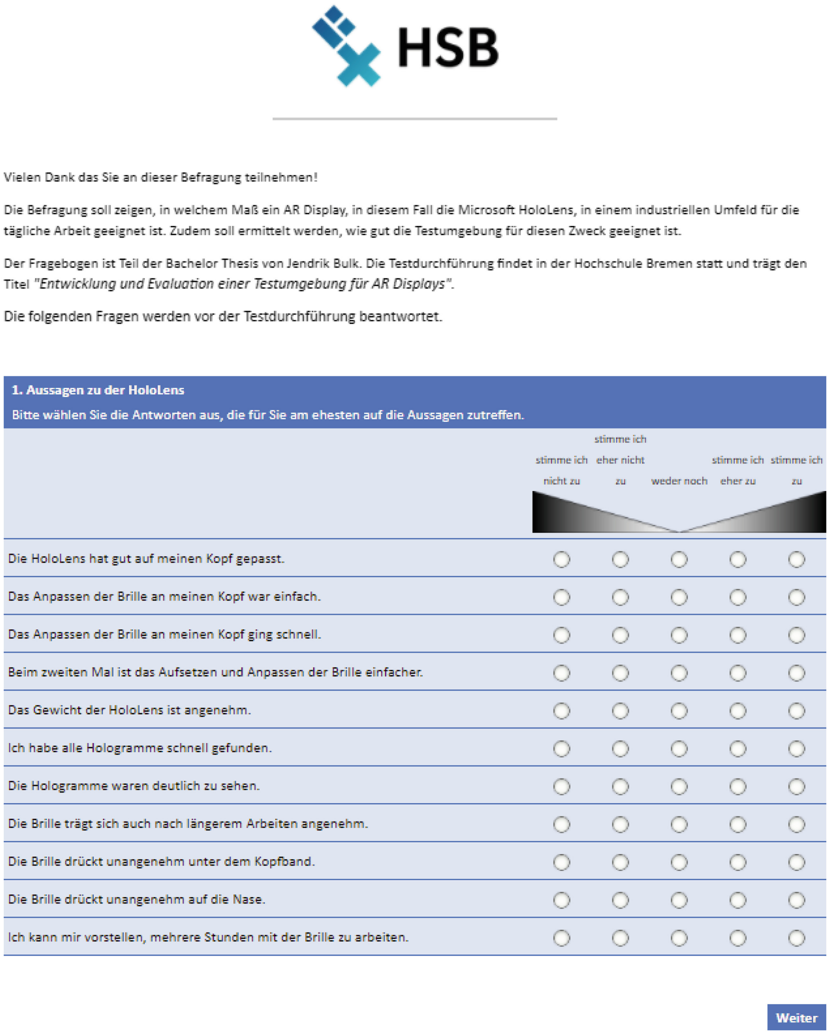
7 Data Collection

There is a large collection of variables (qualities) that can be of interest in the evaluation of an AR HMD. A small set of these can be captured directly in the test application, e.g. Task Completion Time. However, most variables are best measured by prompting users to provide feedback, e.g. user experience (UX) and technology acceptance, while others can be measured either through user questionnaires or sensor instrumentation, e.g. fatigue and user attention.

In the current version of the test environment we record those variables that can be derived directly from user interaction in the test software (#of user interactions, task completion time) and use questionnaires to capture the remaining variables. There is a set of widely used standardized questionnaires that address the variables of interest, e.g. IsoNorm and SUS to rate usability related variables, AttrakDiff for UX related variables and Nasa-TLX to measure the task load perceived by the user. However, presenting users with a complete set of these questionnaires that cover all variables of interest has proven to be impractical. Test participants would have to answer far to many different questions that are sometimes overlapping in the different questionnaires and the differences in wording can cause additional confusion, prompting users to abandon the questionnaire and drop out of the test. We have therefor developed an initial questionnaire (Fig. 2; currently in German only) that aims to cover the variables of interest in a coherent way, with wording adapted for industrial AR applications and with the number of questions reduced to a practical minimum. For the future we aim to refine the questionnaire by enabling test designers to limit the number of questions depending on the variables of interest in a specific test setup, by validating the questionnaires results against the established standard questionnaires and by translating the questionnaires to other languages, starting with English.

8 Experience with the Test Setup in Different Configurations

Figures 3, 4 and 5 show different test setups, using a variety of AR glasses (and alternative techniques like projection) in a variety of settings. Our approach is flexible enough to enable user tests in all these settings with minimal adaptation. A simple ad-hoc setup (Fig. 4) allows conducting tests everywhere, without the need for additional infrastructure. Such an approach is especially useful in early exploratory stages of evaluation. A low-cost workspace setup provides a realistic simulation of an industrial workspace in a way that can be easily and cheaply replicated (Fig. 5). Such a setting is especially useful to conduct tests with large numbers of participants or at different locations. Tests in a real factory environment (Smartfactory OWL, Fig. 3) enable more realistic tests and are especially useful to validate the external validity of previous test results. Different setups have been used with multiple Lego and fischertechnik models in different tests and demonstrations, e.g. at the Hannover Industry Fairs in 2014, 2015, 2016, 2017, in the SmartFactory OWL since 2016 and in the MobileGameLab since 2017 with a wide variety of users and test tasks.



Vielen Dank das Sie an dieser Befragung teilnehmen!

Die Befragung soll zeigen, in welchem Maß ein AR Display, in diesem Fall die Microsoft HoloLens, in einem industriellen Umfeld für die tägliche Arbeit geeignet ist. Zudem soll ermittelt werden, wie gut die Testumgebung für diesen Zweck geeignet ist.

Der Fragebogen ist Teil der Bachelor Thesis von Jendrik Bulk. Die Testdurchführung findet in der Hochschule Bremen statt und trägt den Titel *"Entwicklung und Evaluation einer Testumgebung für AR Displays"*.

Die folgenden Fragen werden vor der Testdurchführung beantwortet.

1. Aussagen zu der HoloLens
Bitte wählen Sie die Antworten aus, die für Sie am ehesten auf die Aussagen zutreffen.

	stimme ich nicht zu	stimme ich eher nicht zu	weder noch	stimme ich eher zu	stimme ich zu
Die HoloLens hat gut auf meinen Kopf gepasst.	○	○	○	○	○
Das Anpassen der Brille an meinen Kopf war einfach.	○	○	○	○	○
Das Anpassen der Brille an meinen Kopf ging schnell.	○	○	○	○	○
Beim zweiten Mal ist das Aufsetzen und Anpassen der Brille einfacher.	○	○	○	○	○
Das Gewicht der HoloLens ist angenehm.	○	○	○	○	○
Ich habe alle Hologramme schnell gefunden.	○	○	○	○	○
Die Hologramme waren deutlich zu sehen.	○	○	○	○	○
Die Brille trägt sich auch nach längerem Arbeiten angenehm.	○	○	○	○	○
Die Brille drückt unangenehm unter dem Kopfband.	○	○	○	○	○
Die Brille drückt unangenehm auf die Nase.	○	○	○	○	○
Ich kann mir vorstellen, mehrere Stunden mit der Brille zu arbeiten.	○	○	○	○	○

Weiter

Fig. 2. Questionnaire (currently in German only)

9 Observations and Outlook

Experiences in tests with users have shown that even inexperienced users can quickly understand how to carry out complex assembly tasks using AR visualization. The central objective in our test scenarios is currently a realistic use of the HMDs over a long period of time in order to enable the test users to be able to evaluate aspects such as usability, wearing comfort and ergonomics of the HMD.

This goal has been achieved. We have conducted extensive tests with AR displays including the Microsoft HoloLens, Epson Moverio and Vuforia, as well as custom built displays.

Fig. 3. AR assembly system with AR glasses (left) and projection (right) in SmartFactoryOWL

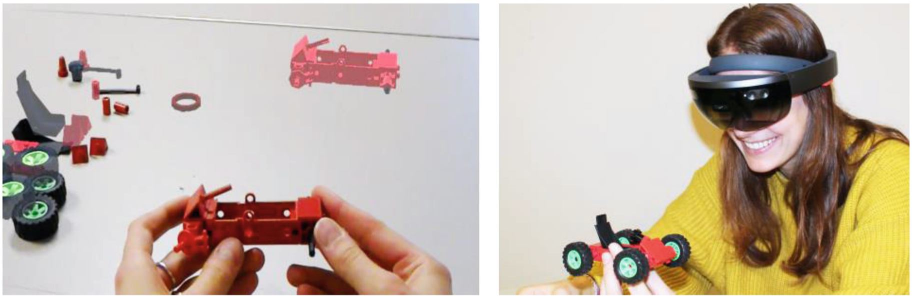


Fig. 4. Minimalistic test setup with Microsoft Hololens

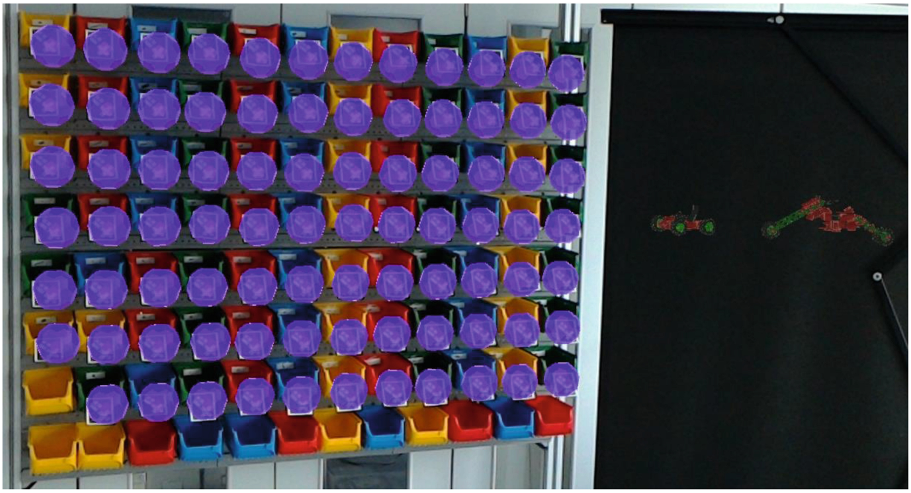


Fig. 5. Low-cost workspace with Microsoft Hololens

The use of assembly tasks with construction toy systems as an application scenario has proven to be valuable, since it allows efficient creation of test tasks at different levels of complexity and cost-effective creation of test workspaces.

The visualization techniques used in the assembly tasks have so far not been subjects of investigation and we have used simple techniques that are easy to implement and that have proven to be easy to understand in previous demonstrators. In the minimalistic setup (Fig. 4) we use simple animation of augmented 3D ‘doppelganger’ objects of the building blocks to be moved. This presentation is easy to create and well understood, but can be tiring in longer test tasks, as the users see a lot of animation all the time. Test users have also commented that it would be useful if the last component that was assembled would be highlighted.

Rack based test workspaces with boxes (Figs. 3 and 5) can use more simplistic information to indicate the required part (from box number to visual augmentation of the box) that is less tiring for users in longer test tasks. Such a setup also allows to extend tests to wearable displays without camera and tracking functionality, since the clearly identifiable boxes also allow picking by direct instruction (e.g., box A3) and without AR visualization. For the future we plan to extend the test framework with a wider set of visualization options to experiment with the usability of visualization techniques in addition to the display hardware.

References

1. Büttner, S., Sand, O., Röcker, C.: Extending the design space in industrial manufacturing through mobile projection. In: Adjunct Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI 2015), pp. 1130–1133. ACM Press (2015)
2. Büttner, S., Mucha, H., Funk, M., Kosch, T., Aehnelt, M., Robert, S., Röcker, C.: The design space of augmented and virtual reality applications for assistive environments in manufacturing: a visual approach. In: Proceedings of the International Conference on Pervasive Technologies Related to Assistive Environments (PETRA 2017), pp. 433–440. ACM, New York (2017)
3. Fellmann, M., Robert, S., Büttner, S., Mucha, H., Röcker, C.: Towards a framework for assistance systems to support work processes in smart factories. In: Holzinger, A., Kieseberg, P., Tjoa, A.M., Weippl, E. (eds.) Machine Learning and Knowledge Extraction. Proceedings of the International Cross Domain Conference for Machine Learning and Knowledge Extraction (CD-MAKE 2017). LNCS, vol. 10410, pp. 59–68 Springer, Heidelberg (2017)
4. Flatt, H., Koch, N., Röcker, C., Günter, A., Jasperneite, J.: A context-aware assistance system for maintenance applications in smart factories based on augmented reality and indoor localization. In: Proceedings of the 20th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2015), Luxembourg, 8–11 September 2015, pp. 1268–1271 (2015)
5. Sand, O., Büttner, S., Paelke, V., Röcker, C.: smARt.Assembly – projection-based augmented reality for supporting assembly workers. In: Lackey, S., Shumaker, R. (eds.) Virtual, Augmented and Mixed Reality. LNCS, vol. 9740, pp. 643–652. Springer International Publishing, Cham (2016)

6. Paelke, V., Röcker, C., Koch, N., Flatt, H.: User interfaces for cyber-physical systems: expanding the designer's toolbox. In: at – Automatisierungstechnik, vol. 63, no. 10, pp. 833–843. De Gruyter, Oldenbourg (2015)
7. Rolland, J.P., Holloway, R.L., Fuchs, H.: Comparison of optical and video see-through, head-mounted displays. In: Proceedings of SPIE 2351, Telemanipulator and Telepresence Technologies, vol. 293, 21 December 1995
8. Azuma, R.: A survey of augmented reality. Presence Teleoperators Virtual Environ. **6**(4), 355–385 (1997)
9. Özbek, C., Giesler, B., Dillmann, R.: Jedi training: playful evaluation of head-mounted augmented reality display systems. In: Proceedings of SPIE, Stereoscopic Displays and Virtual Reality Systems XI, San Diego, USA, vol. 5291, pp. 454–463, May 2004
10. Büttner, S., Röcker, C., Sand, O.: Using head-mounted displays and in-situ projection for assistive systems – a comparison. In: Proceedings of the 9th ACM International Conference on Pervasive Technologies Related to Assistive Environments (PETRA 2016). ACM, New York (2016). Article No. 44
11. Paelke, V., Büttner, S., Mucha, H., Röcker, C.: A checklist based approach for evaluating augmented reality displays in industrial applications. In: 8th International Conference on Applied Human Factors and Ergonomics (AHFE 2017). Springer, Los Angeles, July 2017
12. Baird, K.M., Barfield, W.: Evaluating the effectiveness of augmented reality displays for a manual assembly task. Virtual Reality **4**, 250–259 (1999)
13. Radkowski, R., Herremaa, J., Olivera, J.: Augmented reality based manual assembly support with visual features for different degrees-of-difficulty. Int. J. Hum. Comput. Interact. **31**(5), 337–349 (2015)
14. Ubimax Frontline Productpage. www.ubimax.com/en/portfolio/#frontline
15. fischertechnik Homepage. www.fischertechnik.de
16. lego Homepage. https://www.lego.com
17. Makeblock Homepage. https://makeblockshop.eu

Sociotechnical Design of Industrial Transport Vehicle and its Interaction with Humans in Manufacturing Systems

Jana Jost(✉), Thomas Kirks, Michael Fiolka, and Stuart Chapman

Fraunhofer Institute for Material Flow and Logistics IML,
Joseph-von-Fraunhofer-Str. 2-4, 44227 Dortmund, Germany
{jana.jost, thomas.kirks, michael.fiolka,
stuart.chapman}@iml.fraunhofer.de

Abstract. The future of robotics keeps great challenges ready, especially when it comes to Human-Machine-Interaction. The robot EMILI is developed for a direct interaction with humans and represents a novel class of equipment in manufacturing systems. It features an innovative display-design, which enables a new kind of communication with human individuals. EMILI's design is based on different scientific models – as a usability measure, we verified the development advance with the initial purpose of the display and performed an investigative survey, which uncovered misleading features of the display and led to improvement potential in design and user experience.

Keywords: User interfaces · Human-machine systems · Cognitive ergonomics
Autonomous transport vehicles

1 Introduction

The ongoing digitalization in industrial applications leads to rising requirements for machines, systems and assistance devices. To a greater extend, Cyber-Physical Systems (CPS) which connect the physical and virtual world are part of today's production and logistics facilities. Not only are complex machines becoming more intelligent and connected, also simple things e.g. bin are equipped with intelligence and are part of Cyber-Physical Production Systems (CPPS). Although, automation in production and logistics facilities is increasing, there will always be processes, e.g. picking, in which the human worker with his cognitive abilities is more efficient than any robot [1]. Employees are still subject to various physical and mental demands [2]. Thus, the aim of companies is to assist workers by new technologies while handling economic goods and through that integrate him better into complex CPPS [3]. It can be assumed that the cooperation between technical assistance systems and human beings within a "Social Networked Industry" will evoke a change in psychological and especially cognitive demands [4]. To achieve this, the interaction between humans and machines has to be designed in natural and intuitive ways and CPS have to adapt to the human worker [3].

One type of CPS is the Automated Guided Vehicle (AGV), which transports goods in warehouses and manufacturing systems. There is a variety of AGV on the market,

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which differ, e.g. in the payload. Nearly all of those miss natural interaction possibilities and therefore do not focus on psychological aspects. Usually, fleet management systems control the behaviour of those vehicles. Therefore, the vehicles themselves offer no or only unidirectional, limited interaction possibilities with human workers.

2 Background

For a bidirectional interaction between humans and machines, expressing emotions is one mayor challenge, which has to be faced and managed in a user-centered design.

2.1 Facial Action Coding System (FACS)

For many years now, the connection between emotions and facial expressions is an investigated subject in the field of emotion psychology. From a scientific side of view, it is not always possible to interpret expressions right [5]. Whilst interpretations may be uncertain and faulty, describing human faces is a well-processed matter. The “Facial Action Coding System” (FACS) developed by Ekman and Friesen in the late 70s is a method of describing a face by a short code. This code is based on the muscles situated in the human face, which are summarized into so-called “action units” (AUs). These AUs consist of the corresponding number of the muscles or the muscle group, as well as a letter marking the intensity, which is ranging from “A” (lowest) to “E” (highest). Therefore, the code consists of a combination of numbers and letters, which provides a precise description of the muscles in action and the resulting expression. For interpretation purposes, Ekman and Friesen provided a table to predict possible emotions from human faces described by the system. They also recommended using these assignments with caution due to possible controversial signals and the lack of evidence for this table. The detected emotions in this chart are constrained to very basic emotions, like surprise, fear or happiness [6, 7]. This system is used in Sect. 4.3 to analyze and develop the different faces of EMILI, and shows both the potential and the limits of the comparison.

2.2 Heuristic Evaluation

A heuristic evaluation is a usability analysis that helps to determine usability problems in the user interface design. In 1990, Nielsen [8] in collaboration with Molich developed ten heuristics, which function as a rule of thumb rather than guidelines for usability. Meaning that the usability principles can be accommodated to the individual design which has to be examined. The heuristic evaluation is suited to use in the early stages of the iterative design process, because the evaluator does not necessarily needs to use the system and can examine the interface on paper for example. The aim of the heuristic evaluation is to identify violations of the ten usability principles and record those violations with explanations according to principles, which have not been fulfilled. Further, the evaluator can give design advice on how to remedy the usability problems.

The heuristic evaluation is not intended to replace other usability testing methods, but can identify major usability problems in the beginning of the iterative design process.

2.3 Circumplex Model

An approach by Russel [9] claimed that emotional states can be arranged in a two-dimensional space alongside the axes arousal-sleep and displeasure-pleasure (Fig. 1). Russel states that emotions are not independent from one another and are related to each other. His point of view suggests that emotions do not stand for themselves, are organized in a circular model around the "zero", and directly connected to facial muscles.

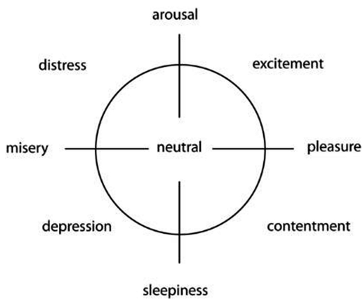

Fig. 1. Circumplex model of affect [9]

The capability to show and transfer emotion is crucial for the human-robot-interaction. Whereas speech transfers meaning and emotion, non-verbal communication relies on body gestures and facial expressions to express the emotional state. If robots do not express any communication or emotion, this could be interpreted as "cold" towards the human. Thus, it is necessary that robots convey their emotional status. Since robotics develops rapidly and their embodiment makes them more humanoid (anthropomorphic), they have the additional features of using postures or gestures to express their emotional state than solely screen robots.

It was revealed that arousal (the level of energy) and valence (negative or positive tendency) decline as the head is moving downwards. Consequently, moving you head up raises the two dimensions. This finding shows that changes in head movement influence the interaction between human and robot and that head movement can transfer intuitive signs about the emotional state.

3 State-of-the Art in Human-Robot-Interaction

Robots in working environments are almost a common picture in the production industry – embedded in cages or secured from human interference by optical safety measures they perform their purpose with an adamant alacrity. However, working in close quarters in heterogeneous teams of humans and robots may summon unseen kinds of challenges, especially concerning interaction and communication.

3.1 Robot Movement Behavior

A direct interaction between humans and robots evokes several safety concerns because AGVs must not harm humans [10, 11]. There are social as well as cognitive aspects when robots interact near humans [12]. Usually, AGVs are equipped with sensors to detect objects in their path to avoid accidents, e.g. laser scanners. The applicable guidelines only describe the necessity of avoiding direct contact with humans, but not if there has to be a certain distance, in which the robot should stop. Physical safety has the highest priority when working with robots, but neglecting mental safety may decrease the acceptance of the robot [13]. Humans apply the same social rules to computers as they do to humans [14]; this might be true for robots as well. People keeping certain distances from other humans according to the familiarity of the approached person – the so-called "proxemics" – is a well-researched field. The anthropologist Hall introduced four different zones – the intimate distance, which forms a circle up to 0.5 m around the human, the personal distance, ranging from 0.5 m to 1.2 m, the social distance, from 1.2 m up to 3.5 m, and the public distance which is beyond 3.5 m [15, 16].

Humans encounter robots differently; the reaction depends on both universal and individual properties. Takayama and Pantofaru evaluated individual characteristics, like personality and familiarity which contribute to the way people approach robots. Especially people who have or had pets drew a closer average distance to the robot of 0.39 m, while others chose an average distance of 0.52 m [17]. This result seems to fit in perfectly in Halls model regarding intimate and personal distance. Their results support the theory that people use the same social rules with robots as they do with other humans.

As for the universally applicable rules Nakashima and Sato's study shows that an AGV moving towards humans faster than 0.8 m/s triggers a great deal of fear in the user, while a speed of 0.2 m/s does not imply any. There was a proportional correlation of AGV movement-speed and distance kept by the user [18].

Bulter and Agah tested that an AGV movement-speed slower than the human walk-speed was the most pleasant one for people with little experience with robots. They also discovered that the height of a robot makes a great difference in the distance kept to the robot [19]. Hirori and Ito, tested robot heights of 600 mm, 1200 mm and 1800 mm and the distance kept by the test subjects and confirmed these results later [20]. Therefore, robot-height may also cause fear in humans.

3.2 Displaying Information in a Natural Way

Mehrabian reveals that 55% of affective information is transferred by nonverbal elements e.g. facial expressions [21]. Emotions can be expressed by using dimension models (arousal, valence and stance) or categories such as anger and happiness.

In robotics, one has to distinguish robots after their tasks and goals. Robots like Pepper [22] are determined to be "social" robots and help in assisting people. Pepper's main aim as a social companion is to read emotions of its human counterpart and is used as a receptionist. It can recognize clients it met before, engage in a conversation or organize meetings. With its humanlike shape and 20 degrees of freedom (DOF) it can move head and arms. The design of Pepper's face is limited to its eyes and mouth, which are static. Here the key to social behavior are the use of lights around its eyeballs and the use of postures. Additionally Pepper has a touch tablet on her chest, enhancing human-robot-interaction. The tablet displays images, videos and web pages.

The first designed robotic faces in the case of Feelix [23] and Kismet [24] were partly humanlike, because of the constraints of mechanical design and control. This is shown by the immediate and abrupt changes in facial expressions. The design focuses on the components mouth, eyes and eyebrows and is based on the FACS. Feelix has two lips and two eyebrows to convey the six basic emotions. In comparison, Kismet has 15 DOF in his face portraying a set of emotions which are created by a three-dimensional affect space with the components arousal, valence and stance.

The aim of Baxter's LCD face was to involve humanoid features that evoke the impression of a social robot but on the other hand do not raise user expectations beyond its capability. This minimalizes the dangers of the uncanny valley. Further, its emotional status is expressed by using color. In a study examining the effect of color integrated in its display, respondents felt less pleasant and less safe as the screen turned red.

Showing emotion as a robot is a challenging task, especially if expressions using body language are not feasible and humanlike facial expressions have to be used.

4 EMILI – A Newly Human-Robot-Interaction

This paper focus on the system EMILI ("Ergonomic Mobile Interactive Load Carrier for Intralogistics") which represents a combination of simple small load carrier and an ergonomic automated guided vehicle. Besides having the advantages of both system types, the focus lays on physical and psychological ergonomic aspects.

4.1 Concept and Design of EMILI

EMILI has a storage area and the dimensions of a small load carrier. Therefore, it can simply be integrated into existing facilities and processes. The contained characteristics of a vehicle enable EMILI to drive on its own, shows that no conveyor technology is needed. EMILI is adjusting its load handling device via lift functionality according to the workers height (Fig. 2) This ensures the picking of items at ergonomic heights of the worker.

a) b)

Fig. 2. Load handling device – upper lift (a) lowered, (b) raised

Since no external drop off stations are needed, location-independent picking scenarios can be realized. Subsequently, the vehicle is able to interact bi-directionally with the worker. On the one hand, web-based software interfaces exist with which it is possible to control EMILI via App or wearables e.g. controlling EMILI by smart glasses. On the other hand, EMILI has an industrial-grade, robust, energy efficient, bi-stable segmented e-paper display through which the human worker gets direct feedback (Fig. 3).

Fig. 3. Status faces – (a) “Sleeping”, (b) “I’m busy”, (c) “Sorry”

EMILI is controlled by the Robot Operating System [25]. All of the software components are represented through so-called nodes with which it is easy to integrate new functionalities. The interaction with machines and other systems in its environment is realized through a RESTful service interface. Defined GET-requests deliver information e.g. battery state and POST-requests start different functions e.g. stop.

4.2 Interaction Between EMILI and Humans

EMILI was designed to be most intuitive when it comes to interaction between itself and human workers in the field of warehouse logistics. In terms of safety it was designed to enable collaboration with humans, which allows to share the working space without any safety installations like sensors. Hence, a seamless process integration is feasible. Many channels of communication have been taken into account in the design phase. It is possible to interact with it using apps on handheld devices, smart glasses, via its e-Paper display and visual feedback expressed via colored LED. These modalities offer the opportunity for the human to easily see the status and gain control of the robot. Using EMILI’s web interface it is possible to create apps for smart phones, smart glasses or laptops. Smart glasses, in terms of Augmented Reality glasses, offer a wide range of visualization and precise interaction. Virtual objects can be placed right into the field of view of the worker and overlay on the real world shape of EMILI. As an example, in case of power problems, EMILI will indicate to start a maintenance process and a person can wear AR glasses to find more information on the problem. Further, virtual arrows in the view field can point to the exact screws to be loosened to get access to the battery. Virtual guidelines can now help the worker to attach the correct power plugs on the right spot and apply the adequate voltage.

The integrated colored LED strips are mounted at the outline of EMILI. Each of the LED can be switched on, off and altered in color. Thus, row sequences of a single color or different colors can be highlighted or only a few parts can be switched. Here we gain a variable display for the indication of the mood (respectively the state of EMILI), turn signal or indication lights for the load-handling device.

More intuitively is the communication via the integrated display in the front, which enables it to express the overall state using an Emoji-like avatar face, show actual states using specific icons (Fig. 3) and state textual phrases. These parts of the display can be enabled or disabled depending on changes of state and its working progress – also animation like turning signals at both ends of the display can be shown to indicate changes of track direction. This enables the worker to accurately interpret the actual system status without the need of external technology.

Finally, there is also simple voice communication possible, as known from Alexa, Google Assistant or Siri. Using a Bluetooth headset the person interacting with EMILI can give simple commands like “EMILI, follow me!”, “EMILI, stop!” etc.

4.3 Display Analysis

To review how well EMILI’s faces are designed and verify the reliability of the display-design, we compared its faces to corresponding emoji from the Unicode and to examples from the FACS. EMILI mimics human facial expressions and therefore emotional states – that makes the purpose of its face similar to the function of emoji which are designed to express human feelings [26,27]. As stated before, human facial expressions are never to interpret correctly in every situation, and also emoji vary in the reliability of interpretation [5, 28]. Emoji as part of the Unicode are set in their meaning while the appearance is free to design. The comparison is based on the emotion EMILI should present and the corresponding emoji. In the following discourse, three particular examples are chosen from our investigation.

The first expression is EMILI’s “I’m Busy” face (Fig. 4a), displayed by widely opened eyes and raised up lip corners. The corresponding emoji is represented by the Unicode code U+1F61A, which is described as “slightly smiling face” (Fig. 4b). To recreate EMILI’s face with expressions given by the FACS, two human expressions need to be combined. The left photo (Fig. 4c) shows a neutral mouth and widely opened eyes, the code for this picture is 5E. AU 5 pulls up the upper eyelid in an intensity of E, which is the maximum. The right photograph (Fig. 4d) shows a human face with eyes in a neutral position, the lip corners are pulled up slightly. The responsible AU for the lip movement is the AU 12 called “lip corner puller”, the photo is rated 12B. Considering the FACS, AU 12 occurs with the emotion “happy”, whilst AU 5 appears with anger, fear and surprise. Given the fact that AU 12 is only present with the emotion “happy”, EMILI’s “I’m Busy” face has a mixture of happiness und surprise.

The “Sleeping” face (Fig. 5a) is represented by closed eyes and a slightly smiling expression. The comparable emoji with the Unicode U+F1634 is described by “sleeping face” (Fig. 5b). Comparing the two pictures, two differences are obvious – the mouth and the “z” letters above the emoji’s head. EMILI has a smiling closed mouth and lacks the “z” letters, while the emoji has a round, opened mouth. In a study of Miller et al., the “sleeping face” emoji was one of the least misinterpreted, which means that a high parity with this emoji and EMILI’s face could provide a correct interpretation of the shown emotion. Choosing human faces from the FACS for the