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Resilient Manufacturing: Use of Augmented Reality to Advance Training and Operating Practices in Manual Assembly

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***Abstract*—**This paper outlines the results of an experimental research on deploying an emerging augmented reality (AR) system for real-time task assistance (or work instructions) of highly customised and high-risk manual operations. The focus is on human operators' training effectiveness and performance and the aim is to test if such technologies can support enhancing the knowledge retention levels and accuracy of task execution to improve health and safety (H&S). An AR enhanced assembly method is proposed and experimentally tested using a real industrial process as case study for electric vehicles' (EV) battery module assembly. The experimental results revealed that the proposed method improved the training practices and performance through increases in the knowledge retention levels from 40% to 84%, and accuracy of task execution from 20% to 71%, when compared to the traditional paper-based method. The results of this research validate and demonstrate how emerging technologies are advancing the choice for manual, hybrid or fully automated processes by promoting the XR-assisted processes, and the connected worker (a vision for Industry 4 and 5.0), and supporting manufacturing become more resilient in times of constant market changes.

***Keywords*—**Augmented reality, extended reality, connected worker, XR-assisted operator, manual assembly 4.0, industry 5.0, smart training, battery assembly

I. Introduction

DIGITAL manufacturing technologies (DMT) such as immersive technologies present the potential to enhance productivity rates and flexibility in manufacturing in times of mass customisation. After a decade of a stagnant productivity rate, the arrival of the 4th Industrial Revolution (I4.0) is expected to create up to USD3.7 trillion in value to global manufacturing by 2025 [1]. The novel generation of manufacturing facilities fostered by I4.0 widely adopts different technologies to digitalise manufacturing [2]. Manufacturing digitisation brings the goal of higher resilience that can be achieved by moving from a hierarchical structure to an integrated or interconnected structure [3]. Transforming manufacturing resilience could add £26bn of productivity value to the economy [4].

The current global scenario is represented by fast changes in customer requirements, which ultimately impact on products' complexity, volume of production and quicker time to market. The paradigm shift from mass production to mass customisation has greatly impacted on the complexity of products and processes [5], [6], but also in the workforce and businesses as a whole; if businesses are not able to quickly respond to market changes, they can face severe consequences and lose competitive advantage. In this scenario, manufacturing resilience represents a common goal amongst manufacturers, who often struggle to understand what it means and how to increase their resilience levels. Improving resilience in manufacturing is more challenging in the presence of manual operations due to the limitations in human adaptation and learning [7]. How best adapt manual operations poses unique challenges for manufacturers that seek for effective workforce (re)training and doing right-first-time solutions [8].

In this research, we aim to study how immersive or extended reality (XR) technologies enhance manufacturing resilience through optimising work instructions for manual assembly operations. For that, we propose an AR enhanced assembly (AREA) method to assist operators in both training and operations in a real industry application of EV battery module assembly as case study for testing and validation. The method was developed using an XR-assistance technology, also called light guide systems or projection-based AR. Experimental studies involving 62 participants have been carried out for data collection. The results are analysed and compared with the traditional paper-based method.

This paper is organised as follows: Section II presents the research background. The research idea is presented in Section III. The research methodology is provided in Section IV. Section V shows the case study details, followed by the results and analysis in Section VI. Finally, the conclusions are given in Section VII.

II. Background

Mass customisation has emphasised the important role played by human operators and manual assembly processes in increasing flexibility of manufacturing systems at all functions [8]. In addition, manual operations are crucial for the social sustainability attained by the manufacturing sector [8], [9]. Nevertheless, in a mass customised environment, human operators are overwhelmed by an enormous component variety and change in specifications and quality requirements, having to adapt their tasks from product to product with limited learning opportunities [10], [11]. Such complex environment is overwhelming to human operators and further leads to high stress levels, high absenteeism and turnover rates, which in turn

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become a major challenge for manufacturers to be resilient and remain competitive.

Manufacturing companies are constantly confronting the challenges of competitive markets and lack of know-how of application of technology innovations within their manufacturing environments [7]. Implementing new technologies to improve manufacturing resilience has been challenging for several reasons, including fast speed of technological change, uncertainties and risks around the factory of the future vision (or lack of a strategic road map), and people barriers to technology adoption. Based on this scenario, Fig. 1 summarises key factors that can be controlled and targeted to improve manufacturing resilience levels. The factors have been split into: i) key challenges and impacts on *processes* (or manufacturing activities); ii) key indicators of manufacturing systems that *businesses* must seek to improve; and, iii) key challenges and impacts on the *people* (or workforce).

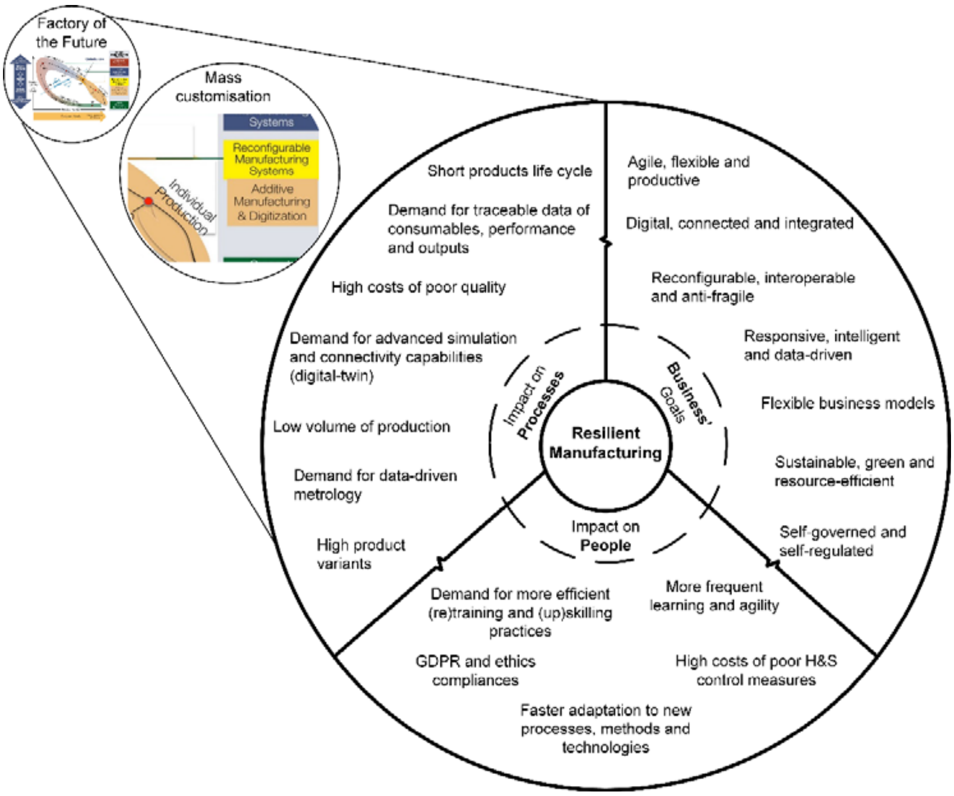

Fig. 1 Impacts of mass customisation and the key factors on business, process and people to achieve resilient manufacturing

This paper addresses the *process* and *people* challenges faced by a manufacturer of EV battery modules represented by the high costs of poor quality and high H&S risks due to the hazardous voltage, ranging from 60 volts to approximately 600 volts, during the manual assembly process. While a fully automated process could resolve those issues, there was no business case for an automated solution given the low volume and high number of product variants, resulting on the choice for a manual assembly operation. However, manual operations raised additional challenges due to H&S to the human operators and their vulnerability to errors, which could lead to delays, defects, poor product quality, and severe accidents in the workplace. Given this scenario, the manufacturer was faced with two challenges:

- How to improve the effectiveness and H&S of the training and operating practices for battery modules assembly; and
- How to advance the work instructions method to support the worker/trainee in a safe and timely manner and reduce the process' vulnerability to human error.

Based on the aforementioned, this paper undertakes a people-centred approach to tackle the major *process* challenges to ultimately, improve *business* resilience indicators. Consequently, the research question addressed in this paper can be defined as: how can emerging technologies help advancing (re)training and (up)skilling practices, and improve the performance and H&S of workers?

III. Research Idea

Firstly, this paper proposes that extended reality (XR) such as AR, and other core emerging technologies such as computer vision can advance a new range of process configuration, so called, XR-assisted processes, to help addressing the trade-offs between level of automation and resilience gains (see Fig. 2). In this concept, manufacturing resilience has 4 main forces: Product Customisation indicator, Flexibility indicator, Productivity indicator and Quality indicator.

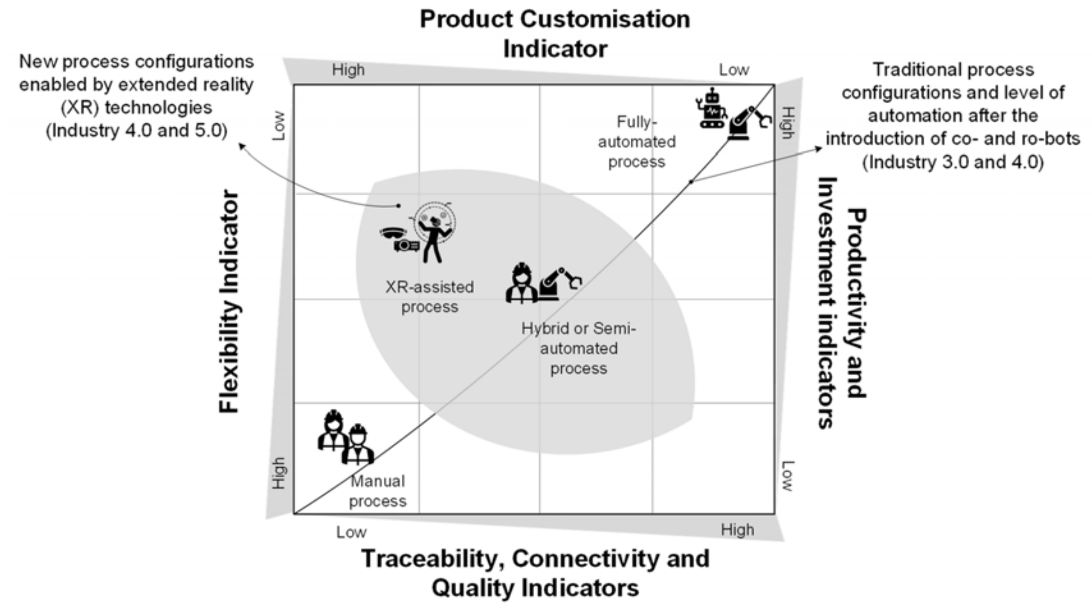

Fig. 2 Trade-offs between level of automation and key resilient manufacturing factors: introducing XR-assisted process

Fig. 2 illustrates that XR are transforming manual operations into XR-assisted hybrid processes, which can support in increasing key resilience indicators such as traceability, flexibility, productivity and quality without having a major impact on costs. Therefore, the research question of this paper is addressed by proposing the use of AR and computer vision technologies (also known as light-guide or projection-based technology), to develop a method that provides real-time assistance to the worker/trainee during the assembly of EV's battery modules.

The proposed AREA method will provide real-time and interactive instructions to the worker/trainee by using features such as pick-by-light, process visualisation and real-time quality verification and validation [11], [12]. The projected AR visual information, adaptiveness and responsiveness of the system to real events, offer a more advanced and interactive training experience compared to traditional methods such as paper-based work instructions. In addition, the AREA system is coupled with a flexible and user-friendly platform to create and reconfigure standard operating procedures with minimal effort.

The expected benefits of using the AREA method include improving the training effectiveness and operator performance to reduce human error; this way, such method will promote improved capabilities impacting on higher productivity, responsiveness, agility and flexibility. The next section presents the methodology of this research.

IV. Methodology

This research developed an experimental study using a real-world manufacturing application as case study. A five-step approach was used (see Fig. 3) to develop the research idea, and experiments were planned for data collection. The data were analysed using pre-defined rules and the results were discussed.

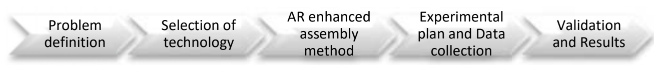

Fig. 3 Five-step research approach

Details of Experimental Plan and Data Analysis

An experimental plan is necessary to test the proposed AR method for its ability to improve the training practices with considering workers'/trainees' knowledge retention levels and accuracy of task execution. Consequently, the criteria and methods of analysis are stated as follows:

- Criteria 1: training effectiveness, which will be determined by the knowledge retained by the participants on the process steps after 24h from the training.
- Criteria 2: H&S, determined by the number of errors made by the operator when performing the assembly process (or the accuracy of task execution). Experiments using the traditional paper-based method were carried out for comparison's sake.

The experiments were performed with 62 participants, who were equally split into two groups, for data collection. Each group was assigned with one method of training: AR and paper-based. During the experiment, each participant was given 5 minutes to learn the assembly process using the respective training method. After 24hs from the training, the participants responded to a questionnaire with 10 questions related to the process steps of the assembly process. Finally, their responses were scored according to the following rules: A) Wrong answers = 0 points, B) Partially correct answers = 1 point, and C) Correct answers = 2 points. The total score of each participant was converted into a proportion considering the maximum points each participant could have achieved (i.e., 20 points). Finally, the results were analysed.

The following section presents the case study to test and validate the proposed approach.

V. Case Study: AR-Assisted Training for EV's Battery Modules Assembly

A. Problem Definition

The engineers of an automotive company are working on a project to manufacture highly complex high-density battery packs for EVs. The products comprise a high variety of components and requirements. A fully automated solution is not financially viable and the current training and operating method using paper-based work instructions poses major challenges given that its high vulnerability to human errors, consequently, it would not meet H&S requirements and could imply poor quality and productivity. Consequently, there is a need for an advanced system to improve the training and operating capabilities of this manual assembly operation.

B. Selection of the Technology

After screened several emerging technologies, an AR-assistance system comprised of projection-based AR, computer vision and a manufacturing operations management (MOM) software was selected. Its capabilities and features to provide real-time and interactive work instructions were appealing to minimise the vulnerability of the process to human error as well as to provide an advanced training experience for the workers/ trainees.

The AR system works based on a set of process steps designed within the MOM software (a digital twin of work instructions). For that, the computer vision system uses object and motion recognition, based on RGB, infrared and depth cameras to train the MOM for all the parts and process requirements at each step. Then, the projection-based AR feature is trained to provide real-time light-guided assistance such as picking/placing by light and further information such as written or visual instructions (e.g., text, image or video). Once the process is initialised (in training or operation mode), the augmented work instructions are given at each process step, while the computer vision captures the operator's actions in real-time and the MOM uses those inputs to trigger the next action autonomously. The system recognises when a mistake is made by the operator and a set of actions can be defined accordingly, e.g., stop the process until it's done correctly or call for help.

C. Development of the AREA Method for EV's Battery Modules

To develop the AREA training and operating method using the selected technology, firstly, the standard operating procedures (SOP) or work instructions, which included 10 process steps, were developed. Secondly, the process steps were created in the MOM software, which required the SOP, the CAD parts for visualisation, and the requirements and tolerances. After that, the pick/put-by-light features and the quality and H&S verification and validation checks were defined. Finally, the AREA method was tested by expert engineers before running the experimental trials. Fig. 4 illustrates the process to develop the AREA method.

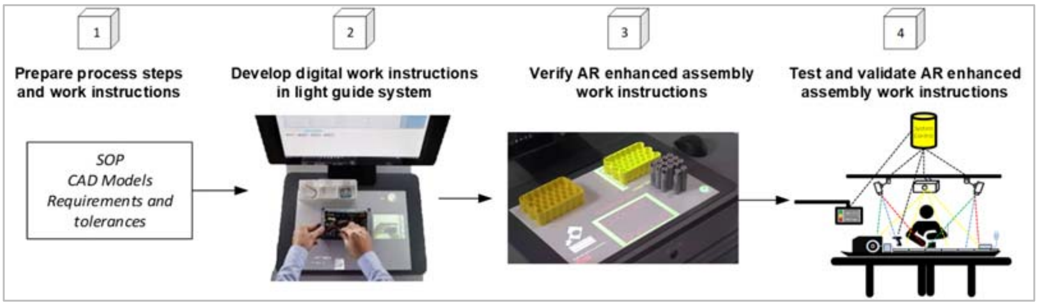

Fig. 4 Development of AR enhanced assembly (ARE) method for EV battery modules

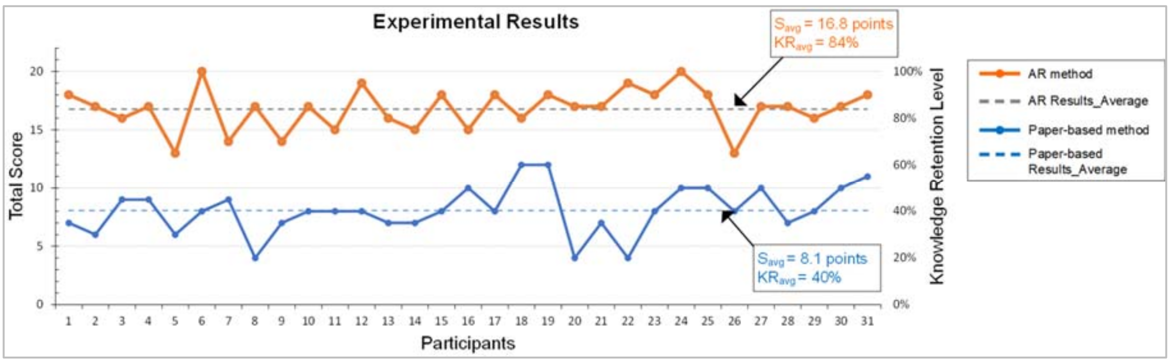

Fig. 5 Experimental results for the two groups of participants based on AR and Paper-based methods, where S_{avg} and KR_{avg} stands for average of total score and average of knowledge retention level, respectively

Similar process was followed to develop the paper-based method, which replicates the same process steps but presents the work instructions in the traditional paper format.

The experimental trials were carried out based on the experimental plan provided in Section IV. The data collected are analysed and the results are presented in the next section.

VI. Results and Analysis

The results from the experimental trials for the participants performance using the AREA and the paper-based methods are shown in Figs. 5 and 6.

Fig. 5 shows the total scores and knowledge retention levels of the participant. The results in this graph reveal that the participants who were trained using the AREA method achieved a better performance compared to the participants who received the paper-based training. Furthermore, the AREA method achieved an average of 84% (16.8 out of 20 points) of knowledge retention, more than the double of the average of the paper-based group (40%, 8.1 out of 20 points).

A further assessment was carried out considering the accuracy of task execution (Fig. 6), where the participants received scores depending on their performance at each process step. Fig. 6 shows a histogram with the responses from the groups trained using the AREA and paper-based methods.

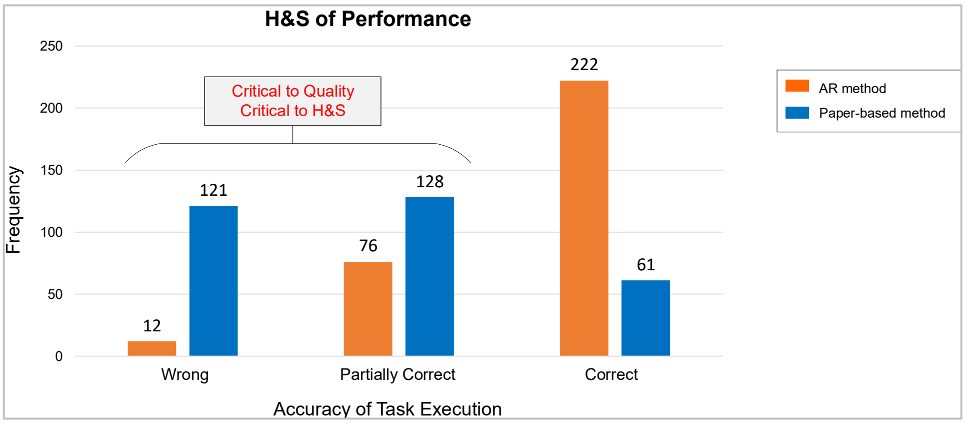

Fig. 6 Experimental results based on accuracy of task execution and H&S

The experimental results show that 80% of the tasks performed by the participants trained using the paper-based method presented mistakes, of which 40% (121 tasks) were performed wrongly whereas the results from the AREA method show that 70% of the tasks were performed correctly, and only 4% (12 tasks) were totally wrong.

Given the scenario where operational mistakes will lead to high costs of poor quality and high H&S risks, the experimental results of this research demonstrate the importance of deploying emerging technologies such as XR to develop more effective and robust training and operating practices. As a result, processes are less vulnerable to human error, the workforce is supported to cope with the challenges of mass customised production environments and businesses improve their resilience levels.

VII. Conclusion

This research work stemmed from the need to support an automotive manufacturing supplier working on a new battery for EVs. Consequently, this research had a direct impact on a manufacturing company by providing the evidence to develop a solution that will enhance their training and operating practices, and ultimately, improve their resilience levels.

The results of this research validate crucial benefits of deploying AR systems to support companies in becoming more resilient through improved training and operating practices of manual assembly operations.

The proposed AREA method improved the training outputs of EV's battery modules assembly by increasing the knowledge retention levels from 40% to 84%, and by increasing the accuracy of task execution from 20% to 71%. Such improvements are critical for processes with high number of product variants, high costs of poor quality and high H&S risks, such as mass customised manufacturing environments. The AREA method results supported minimising human errors and, consequently, maximising quality, productivity and workers' H&S during manual assembly processes; ultimately, providing positive impacts on business productivity, agility and flexibility.

The results of this research demonstrate how AR technologies are advancing the choice for manual, hybrid or fully automated processes when there is not a financial viability of implementing full automation. The main findings can be used as recommendation for manufacturers to re-think their (re)training and (up)skilling practices and manual operations capabilities.

Although it is out of scope of this paper, the proposed solution using the AR system also demonstrated great potential to improve process traceability, connectivity and workers' wellbeing. Such aspects will be considered in future research. We can conclude that given the current challenges faced by manufacturers, such emerging technologies bring great capabilities to overcome the challenges of human factors, and businesses can therefore become more resilient to both internal and external changes, yet securing jobs.

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