SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220161

Optimised Shop-Floor Operator Support on an Integrated AR and PLM Framework for Remanufacturing

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Abstract. Product disassembly and inspection are essential operations in a sustainable product life cycle, particularly in end-of-life strategies such as remanufacturing. This study identifies critical aspects of usability of a framework that supports the remanufacturing process and its operators. Two of the challenges faced by operators in remanufacturing are the number of product variants and quality decisions. As a result of these, the performance time and the number of errors committed increase. The integration of Augmented Reality (AR), product lifecycle management and expert systems increase the efficiency of managing stored data and supports the remanufacturing process and its operators. A head-mounted display has been used to run the application, allowing the operator to take it right to the working area. The information displayed during the manufacturing processes includes CAD models or images of the industrial equipment and its components and dynamic information, providing clear instructions easy to follow during the remanufacturing process. The proposed methodologic approach uses the concept of rule-based Expert Systems to determine the information content that is dynamically displayed on the AR device and to optimise the route that should be followed in remanufacturing operations. A pilot testing was done to assess the functional suitability of the final AR application to support the delivery of dynamic information in its final industrial environment. The evaluation was done in a real-working environment selecting the assembly, disassembly and inspection operations as a base. A questionnaire to measure the usability of the system was provided to the test subjects after the testing. The results from the questionnaire show a positive perception of the usability of the framework. According to the result analysis, the framework has high usability and can reduce errors and impaired decision-making.

Keywords. Augmented Reality, Product lifecycle management, Sustainability, Remanufacturing, Industry 4.0.

1. Introduction

Improved efficiency in production lines is a crucial factor that helps to ensure the future of the company and its expansion. The swift evolution of the manufacturing processes and techniques, the increased demand for technological products, and the continuous growth of global ecological consciousness have raised the interest in the concepts of eco-efficiency and circularity [1]. Circular Economy (CE) conceptualises a corrective and reconstructive economy [2] which considers environmental impact, resource

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insufficiency, and economic benefits [3]. CE aims to eliminate the use and generation of hazardous materials and promote End-of-Life (EOL) strategies [2,4] such as remanufacturing, reuse, recycling, and treatment of product components. Therefore, companies nowadays seek to refine the exploitation of natural resources to reach environmental sustainability [5]. Accordingly, it is crucial to identify and understand the challenges faced by the industry to boost the implementation of best practices for circular and efficient production systems.

The continuous appearance of digital technologies and the possible benefits the industry can gain from their implementation has led to a new technological era in which product connectivity integrates with vertical and horizontal manufacturing processes in what is known as Industry 4.0. Additionally, Industry 4.0 technology enablers as the Internet of Things (IoT), big data, cloud computing, data analytics, computer-aided design and manufacturing, virtual models, and Augmented Reality (AR) [6,7] are considered to be essential enablers of CE [8].

Product disassembly and inspection are essential operations in a sustainable product life cycle, particularly in end-of-life strategies such as remanufacturing [1]. This study identifies critical aspects of usability of a framework that supports the remanufacturing process and its operators. Two of the challenges faced by operators in remanufacturing are the number of product variants and quality decisions. As a result of these, the performance time and the number of errors committed increase. Product Lifecycle Management (PLM) is a unified approach that efficiently manages the information related to all aspects of the product life cycle [9], i.e. integrates people, processes/practices, business systems, and technologies. AR technologies integrate computational information over a real-time environment to provide the necessary information to shop-floor operators. This study concludes that integration of AR, PLM, Computational Intelligence (CI) and Expert Systems (ES) provides an information system that yields the necessary information and supports the remanufacturing process and its operators while increasing the management of stored data.

2. Literature reviews

Although Industry 4.0 offers a high level of adaptability and autonomy in manufacturing, some operations remain manual as human operators can perform better than machines. Perception, change adaptability, analysis, and decision-making are areas in which humans have an advantage against Cyber-Physical Systems (CPS). The integration of AR with CPS enables the collaboration between human operators and CI in real-time. [10]

The application of AR technology has progressed rapidly ever since its first appearance in 1968 [11]. Lead time, learning time, and the number of committed errors are frequent Key Performance Indicators (KPI) used to research the benefits of integrating AR with Industry 4.0 to support operators on different operations in the manufacturing process such as remanufacturing [1], maintenance [12,13], assembly and disassembly [14–16], and process simulation and training [17] among others. The integration of AR with other technologies also enables the creation of applications, such as Speech-Enabled AR (SEAR) [18,19] and AR and rule-based ES (ARES) [20]. Nevertheless, more recent studies [21,22] referred that although this technology was already widely used, it still had room to grow and evolve within Industry 4.0, as past issues and limitations are almost over [23].

3. Set-up for Remanufacturing

A head-mounted display has been used to run the application, allowing the operator to take it right to the working area. The information displayed during the manufacturing processes includes CAD models or images of the industrial equipment and its components and dynamic information, providing clear instructions easy to follow during the remanufacturing process. Figure 1 shows the framework for the basic operational process of the AR-ES-PLM integration. In addition, the framework will introduce the possibility to monitor the operator's work from a remote location.

The AR device should display assembly, disassembly and inspection instructions to the operator at the same time that it collects information regarding the ongoing task. Instructions should show what to photograph and when to ensure that the report has the same format independently of the on-site operator. The AR device will keep track of the progress of the different operations, document each completed task and make it available in real-time on a remote PLM/PDM system or database through a wireless network. Otherwise, the information will be stored locally in the AR device and uploaded into the system when possible. Supervisors can consequently check the remanufacturing activities or visualise the treatment/handling history of the industrial equipment from a remote device at any time. The proposed methodologic approach uses the concept of rule-based Expert Systems to determine the information content that is dynamically displayed on the AR device and to optimise the route that should be followed in remanufacturing operations. Operators must log into the system before any operation; the ES then checks if the operator is in the system and decides the amount of information displayed based on the operator's background and expertise.

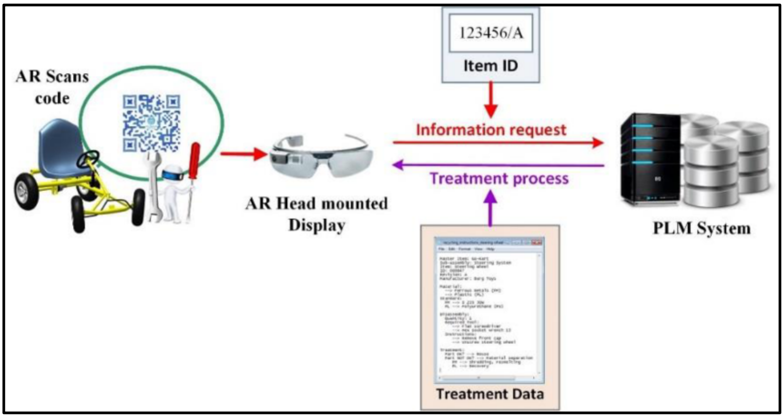

Figure 1. Framework for the basic operational process of the AR-ES-PLM

When the camera of the AR device detects a Product Embedded Information Device (PEID), it sends a request to the online database and the PLM system, which, if there is an item with the provided ID, returns the information related to the remanufacturing process, the sensors, location of the stations and any other relevant information. Otherwise, the system throws an error.

A pilot testing was done to assess the functional suitability of the final AR application to support the delivery of dynamic information in its final industrial environment. The evaluation was done in a real-working environment selecting the assembly, disassembly and inspection operations as a base. Figure 2 (a) shows an image of an experienced operator during the pilot testing and (b) a set of basic instructions for the same operator.

Figure 2. a) Operator testing the AR System in-situ, b) Step-by-step operation instructions

A questionnaire to measure the usability of the system was provided to the test subjects after the testing.

4. Questionnaires to measure usability

According to [24], the objectives for the measurement of usability can be: identify and specify the requisites for user requirement, evaluate if the established requirements for the object of interest under analysis are met, and make comparisons. This study was conducted to analyse if the specified requirements identified in the survey were met and to measure the framework's usability level after its use during the pilot testing. Usability can be evaluated with objective or subjective measurements once the users have tested the object of interest in a real-world context [24]. The subjective measurement of usability is commonly done via questionnaires [25,26]. Therefore, a predefined group of self-administered questions [27] was prepared to ensure that all users replied to the same questions and were not influenced by the authors. The answers were managed anonymously. The questions were designed to be brief, specific, objective, relevant to the measurement and unambiguous as recommended by [28].

The questionnaire design followed the recommendations in [29] to analyse the characteristics presented in Table 1. Specific aspects to evaluate short-term tests were not considered as they were inadequate for this study. ISO standards (1,2,7) were also considered for the survey.

Table 1. Characteristics and sub-characteristics analysed in the survey to measure quality and usability.

Characteristic	Sub characteristic	Objective (Measure the perception of the user)	Question type
Functional suitability	Functional completeness (1Q)	Completeness of the steps offered by the framework.	Likert-type scale (1-5),

	Functional correctness (2Q)	Correctness of the framework to conduct remanufacturing operations. Correctness of the framework processes in their detail and precision levels.	closed questions
	Functional appropriateness (1Q)	Appropriateness of the framework to facilitate the accomplishment of remanufacturing operations.	
	Open question	Provide the participants with an opportunity to add comments or suggestions freely.	Open question
Compatibility	Co-existence (1Q)	Possible integration of the framework within the existing standards of the company.	Likert-type scale (1-5), closed questions
	Interoperability (1Q)	Possible interaction between the framework and the existing standards in the company.	
	Open question	Provide the participants with an opportunity to add comments or suggestions freely.	Open question
Usability (quality)	Appropriateness recognisability (1Q)	Appropriateness of the framework to support remanufacturing operations.	Likert-type scale (1-5), closed questions
	Learnability (2Q)	Provided description of the framework allows learning how to use it with effectiveness and efficiency. Applicable even to other possible users.	
	Operability and aesthetics (2Q)	Framework characteristics such as easiness to understand, visualisation and easiness to use.	
	Accessibility (1Q)	Possibility for people with a wide range of characteristics or backgrounds (e.g. engineers, technicians, etc.) to follow the instructions.	
	User experience (1Q)	Fulfilment of the needs and expectations of the users related to the framework.	
	Open question	Provide the participants with an opportunity to add comments or suggestions freely.	Open question
Usability (quality in use)	Effectiveness (1Q)	Support of the framework to conduct remanufacturing operations.	Likert-type scale (1-5), closed questions
	Efficiency (1Q)	Support of the framework to achieve the remanufacturing goals with the minimum amount of resources.	
	Satisfaction: Usefulness and trust (4Q)	Satisfaction, the usefulness of the system, interest and willingness to apply it in future operations, and trust in the framework functionality to support remanufacturing operations.	
	Open question	Provide the participants with an opportunity to add comments or suggestions freely	Open question
Freedom from risk	Wrong decision mitigation – economical/Environmental/Safety risk (1Q)	Support the framework provides to avoid missing necessary steps or principles on remanufacturing operations and processes.	Likert-type scale (1-5), closed questions
	Open question	Provide the participants with an opportunity to add comments or suggestions freely	Open question
Context coverage	Context completeness and flexibility (1Q)	Applicability of the framework in other remanufacturing organisations.	Likert-type scale (1-5), closed questions
	Open question	Provide the participants with an opportunity to add comments or suggestions freely	Open question

As shown in Table 1, the survey focuses on six main characteristics to be analysed. These characteristics are divided into several sub-characteristics and the questions related to them. There are two types of questions, Likert [31] type scale and open questions, where the test participants could motivate their answers. The Likert scale considers five response alternatives for each question: strongly disagree, disagree, neutral, agree, and strongly agree.

A group of 16 participants was selected based on their experience in remanufacturing operations and their position in the company. The group was composed of participants between the ages of 20 and 55 who had little to no knowledge of AR. An AR tutorial provided the users with initial contact with the technology before proceeding with the system evaluation. The test group was composed of two subgroups of eight people each, experienced users (manufacturing operators) and inexperienced users (other company personnel). Eleven users submitted the questionnaire, six experienced and five inexperienced. These users constituted a representative group of people for the evaluation of the framework. Anonymous computer access to the online questionnaire was provided to all users, who answered the questions individually before a given deadline. The initial questionnaire page contained the procedure to answer the questions and a description of the evaluated characteristics. By submitting the survey, the participants agreed on the use of the answers for research purposes. The responses were gathered and analysed with Microsoft® Excel.

5. Results and Analysis

The survey results measuring the characteristics specified in Table 2 can be seen in Figure 3. The division of questions related to each characteristic is functional suitability (Q1–Q4), compatibility (Q5), usability-quality (Q6–13), usability-quality in use (Q14–19), freedom from risk (Q20), and context coverage (Q21).

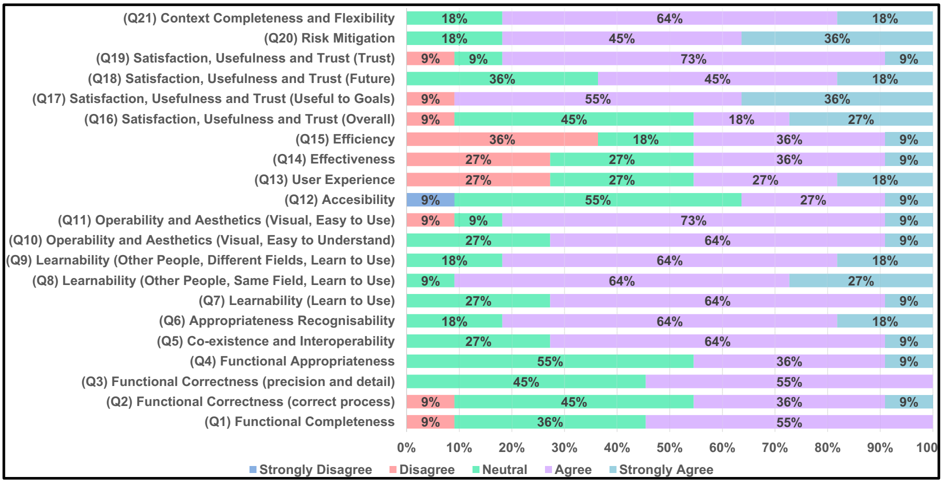

Figure 3. User survey results for each question (N=11).

The best-rated characteristics by the users are those related to the functionality of the framework (Q3-4), co-existence and interoperability (Q5), appropriateness (Q6), learnability (Q7-Q9), operability and aesthetics (Q10), satisfaction, usefulness and trust (Q18), risk mitigation (Q20) and context coverage (Q21).

An individual analysis of the answers to each question is shown in Table 2. According to [32], the median, mode and frequency can be calculated for individual Likert-type questions, whereas the mean and standard deviation are recommended for Likert scale attributes.

Table 2. Statistical analysis of the individual answers provided by the users

Charac-teristics	Mean	Std. Dev.	Sub-characteristic	Median	Mode
Functio-nal suitabili-ty	3.50	0.68	Functional Completeness	4	4
			Functional Correctness (correct processes)	3	3
			Functional Correctness (precision and detail)	4	4
			Functional Appropriateness	3	3
Compati-bility	3.82	0.60	Co-existence and Interoperability	4	4
Usability (Quality)	3.80	0.72	Appropriateness recognisability	4	4
			Learnability (learn to use)	4	4
			Learnability (same field, learn to use)	4	4
			Learnability (different field, learn to use)	4	4
			Operability and aesthetics (easy to understand)	4	4
			Operability and aesthetics (easy to use)	4	4
			Accessibility	3	3
			User experience	3	2
Usability (quality in use)	3.6 5	0.92	Effectiveness	3	4
			Efficiency	3	2
			Satisfaction, usefulness and trust (overall)	3	3
			Satisfaction, usefulness and trust (useful to goals)	4	4
			Satisfaction, usefulness and trust (future)	4	4
			Satisfaction, usefulness and trust (trust)	4	4
Freedom from risk	4.1 8	0.75	Wrong decision mitigation	4	4
Context coverage	4	0.63	Context completeness and flexibility	4	4

Table 2 shows that all the values corresponding to the mean for each characteristics group rated above three. On the other hand, the median and mode for each question mainly were rated four, with the exceptions of questions 2, 3 and 12-16, in which the median value was three and the mode value was mainly three; only questions 13 and 15 obtained a mode of two. The variation in the answers corresponding for each group of characteristics shown in the standard deviation column is also low, except for “Usability (Quality in use)”.

5.1. Analysis of the Results

The results from the survey show a positive perception of the usability of the framework. According to the result analysis, the framework has high usability and can reduce errors and impaired decision-making. The analysis of the users’ perception indicates that the framework has high functional suitability and compatibility with other existing standards in the company. It also has high usability and the ability to reduce errors. The users also believe that the framework offers the possibility of its application in other contexts within the company.

In general, the feedback provided by both types of users, experienced and inexperienced, in the open questions is very positive and in line with the answers provided in the survey. All users agreed that the AR system acted as good guidance during the remanufacturing process that provided clear and straightforward instructions that were easy to follow. Some users also thought that the AR system, if well updated and integrated with the other systems used by the company, could provide an excellent standardised structure for the manufacturing process in other plants and even in other departments within the company. The users also agreed that the AR system could prove a good way of providing help and guidance to new operators who will commit fewer errors and decision-making mistakes due to their inexperience. Some even recommended using image recognition to display overlay information on the object instead of on an image in the AR glasses.

The survey analysis showed a difference in the feedback provided by the users who had previous knowledge of the pilot plant and the users who were new. The users who had previous experience in the plant or participated in a plant tour before the testing could orient themselves and rapidly locate the stations. At the same time, those new to the premises encountered it more difficult to orientate themselves and locate the stations with the provided images. This problem was due to the dynamic environment in the shop-flor, whose appearance may differ slightly from the day the picture was taken. For example, a container close to a pipe in the image shown by the AR system that is not located in the same place the day an operator maintains an unknown plant.

It has been noticed in the comments that some users with vision impairment or colour blindness may experience difficulty understanding the instructions due to the colours used in the AR system. A solution could be the introduction of customised instructions displayed with the appropriate colours for those specific users who need them.

The feedback provided by the inexperienced users is also vibrant and constructive and could help further develop the framework in its eventual use as a teaching tool to form inexperienced operators in the future. For example, some users indicated the need for previous background knowledge before the inspection operations started. Some others would have liked to increase the information explaining the assembly and disassembly processes to understand why they follows a specific procedure.

6. Conclusions & Future work

This paper identifies critical aspects of usability of a framework that supports the remanufacturing process and its operators. A pilot testing was done to assess the functional suitability of the final AR application to support the delivery of dynamic information in its final industrial environment. Additionally, a questionnaire to measure the system's usability was provided to the test subjects after the testing. The results from the study show that the framework has high usability and can reduce errors and impaired decision-making. During the evaluation process, some test subjects contributed with comments regarding the display of information or the feedback received by the system. Regarding instruction display, the idea of customising the display of information depending on the users' needs was introduced. In addition, image recognition software or holograms interacting with the real world were preferred over descriptive pictures for the location of the machines in the plant.

Future work on similar applications could focus on extending the same approach to cover other human operated processes in the remanufacturing industry. Also, to obtain a fully hands-free support, it would be advisable to add image recognition to the proposed framework that allows the use of hand gestures to control the application. Voice recognition is not recommendable since it is believed that in an industrial environment, where the noise of the machines could be loud, the human voice could not be perfectly recognisable. On the other hand, a solution based on eye-tracking could be a good option. This way, operators could be able to select options with the movement of their eyes. Additionally, object recognition could also be an appropriate supplement. Thus, the application will notice whenever each step is completed, and it will automatically proceed to the following steps.

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