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Procedia CIRP 63 (2017) 46 – 51

www.elsevier.com/locate/procedia

The 50th CIRP Conference on Manufacturing Systems

Augmented reality application to support remote maintenance as a service in the Robotics industry

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Abstract

Maintenance of manufactured products is among the most common services in industry and its cost often exceed 30% of the operating costs. Modern manufacturing companies are shifting their focus from products to combined ecosystem of Products- Service Systems (PSS). Towards that end, the main objective of this work is to develop a cloud-based service-oriented system that implements AR technology for remote maintenance by enabling cooperation between the on- spot technician and the manufacturer. The proposed system includes the methods for the record of the malfunction by the end user, the actions required by the expert so as to provide instructions in an Augmented Reality application for maintenance, as well as the cloud- based platform that will allow their communication and the exchange of information. In addition to the above, the proposed system consists of smart assembly/disassembly algorithms for automated generation of assembly sequences and AR scenes and improved interface, aiming to maximize existing knowledge usage while creating vivid AR service instructions. The proposed system is validated in a real-life case study following the requirements of a robotics SME.

Peer-review under responsibility of the scientific committee of The 50th CIRP Conference on Manufacturing Systems

Keywords: Augmented Reality; Remote Maintenance; Product Service System

1. Introduction

In the era of mass production and in the emerging era of mass personalization [1][2] with increased competition between manufacturers, it has become really important to come up with new ways to improve customer satisfaction. Many manufacturers attempt to achieve that by offering high- quality Product Service Systems (PSS) throughout the product's life cycle [3]. PSS is a value proposition strategy that offers products-services and is designed to be: competitive, satisfy customer needs, and have a lower environmental impact than traditional business models. Maintenance service is one of the most commonly used, especially in products that require maintenance frequently. Towards supporting this interface between IT systems and avoiding isolated work, Cloud Manufacturing has been regarded as an enabler and has already formed the basis for new business models [4]. Furthermore, this approach takes into account the usage of CAx systems in manufacturing and the need to develop new instructions providing systems that are more intriguing and more accurate than the traditional ones. Augmented Reality (AR) is a rapidly evolving technology that is used more and more in different manufacturing fields in the last few years [5], [6]. Using the CAD three-dimensional geometries and assembly information, enriched with intelligence, the manufacturer can create a series of AR scenes to support service sequence.

Targeting the Cloud manufacturing and remote maintenance, the main objective of this work is to develop an internet-based, service-oriented system that implements AR technology for enabling tele- maintenance by cooperation of the end user and the manufacturer.

2. State of the art

Maintenance is a core activity of the production lifecycle since it accounts for as much as 60 to 70% of its total costs [7]. This has led to increased need for maintenance planning through product's life cycle and the implementation of more

Peer-review under responsibility of the scientific committee of The 50th CIRP Conference on Manufacturing Systems
doi:10.1016/j.procir.2017.03.154

and more new technologies (cloud manufacturing [4], Dynamically Adaptive Systems for self- maintenance [8], machine monitoring [7]). Despite the effort to limit machine downtime [9], most of service impact on productivity accounts for unexpected breakdown, as it cannot be predicted and quantified in terms of time and required effort. And despite some effort on the field, it requires a time-consuming process which has a negative impact on machine availability. Augmented Reality (AR) is another enabling technology used for dealing with the increasingly complex maintenance procedures [10]. Either by using head-mounted displays [11], [12] or portable devices [13] a number of solutions have emerged, testing various ways of AR system- user interaction (voice commands, gestures, devices- hosted menus). The potential of the newly introduced technology in supporting maintenance tasks is renowned even by large manufacturing companies (BMW [14], Bosch [15]). More recently, the concept of enabling communication between an expert and the on- spot technician (tele- maintenance) has arisen [16], [17] delivering some promising results in synchronous and asynchronous information exchange.

Apart from maintenance, AR has found fertile ground in other fields of manufacturing. Firstly, AR can be used as a mean to vividly project the current status of a warehouse or a production line, allowing constantly monitoring its current status, communication and planning [18], [19]. Secondly, Augmented and Virtual Reality have been proved valuable tools in prototyping and collaborative design [20]. They allow the fast and costless creation of visual prototypes that can be manipulated by more than one user and also, overlaid on top of existing products so as to facilitate customization and reusable engineering [21], [22]. Moreover, Virtual and Augmented Reality have been widely used as means of training technicians in performing assembly tasks [23]. Those technologies provide an intriguing experience for the technician [24] and thus, they are more efficient than the traditional methods [25], [26].

Meaningful information generated by IT tools should be seamlessly shared across the enterprise in order to support different business functions. Cloud manufacturing enables this ubiquitous information provision and enables the creation of intelligent factory networks reshaping the manufacturing business models. Cloud computing systems and cloud manufacturing may play a critical role in the realisation of "Design Anywhere Manufacture Anywhere" philosophy [4]. Another recent study [27] presented the key benefits to manufacturing as a result of adopting the Cloud technology such as scalability to business size and needs, ubiquitous network access [28], and visualisation. However, security and data protection are still challenges that need to be addressed [29]. Issues, such as the resource location multi-tenancy and authentication also need to be tackled in a combined way [30].

The literature review makes apparent that Augmented Reality systems are welcomed in manufacturing. A field that already has implemented cloud features in many of its applications. The contribution of this development compared to existing approaches is the creation of an asynchronous AR remote maintenance support system that implements cloud-based communication between the end user and the manufacturer that facilitates the reuse of existing knowledge.

In addition to that, the developed internet-based and service-oriented system is supported by an assembly/disassembly algorithm that enables the automated generation of the AR scenes and increases the level of automation. The implemented platform is designed to be provided for Product-Service support throughout a product's life cycle so as to reduce the impact of Mean Time to Repair in machine availability, especially in unexpected breakdowns, where external expert contribution in malfunction detection and service sequence may be needed. The developed platform utilizes a cloud database that enables ubiquitous data access and permits the technician to upload the malfunction report and receive the corresponding service sequence in AR scenes by the manufacturer easily. Moreover, the cloud platform facilitates the supervising mechanic in AR scene creation by keeping record of older service sequence that can be fully or partially reused.

3. Architecture design of tele- maintenance system

This paper proposes an innovative Product- Service System that enables tele- maintenance support through Augmented Reality scenes. The platform includes the deployment of a cloud system that will facilitate the communication between the on- spot technician and the expert by enabling feedback reports and maintenance instructions exchange. Fig. 1 presents the architecture of the proposed system and the data exchange between the technician and the manufacturer representative mechanic. In order to achieve the proper functionality of the proposed platform, some key features are established. Each time the remote maintenance framework is called, a three-step procedure is required: (i) malfunction report composition, (ii)

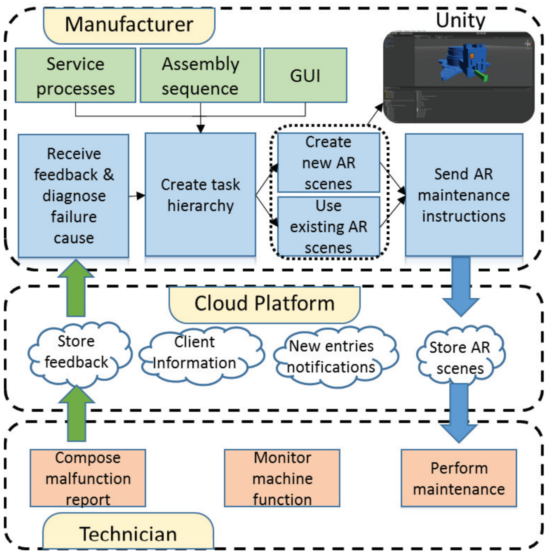

Fig. 1. Architecture of the developed framework

diagnosis and AR maintenance instruction generation and, (iii) maintenance and evaluation.

The first step in the proposed system is registering the malfunction report. Whenever a service is required, regardless if concerning scheduled maintenance or unexpected malfunction, a service report is created prior to any other action. In traditional methods, this is a written report, created by the on- spot technician which describes the problem in text, reports any parts that need to be replaced and, in some cases, defines all the actions needed to address it. In the proposed approach, the technician takes advantage of the communications technologies to create a digitized, data- rich report.

The malfunction report application provides the technician with a set of features that facilitate accurate malfunction capturing, which is essential for remote failure diagnosis. The application is designed to be used through either the proposed AR hardware setup or solely using a mobile device. When on-spot, the operator may record the malfunction by writing explanatory text, which may include sensor data or description on the technician's actions to address the issue, by taking photographs of the malfunctioning or broken down parts, and by recording sound, which may include voicemails or machine noise, using the malfunction report application. The data are then stored locally on the device and uploaded to the cloud platform. The maintenance support provider is notified that a new malfunction report is uploaded.

After viewing the malfunction report, the maintenance support provider begins the main part of the service; malfunction cause identification and AR instructions generation. Remote maintenance may be used to cover both those needs. On the one hand, the AR equipment allows the on-spot technician to create an enhanced failure report which, using the cloud-based feedback mechanisms, can be sent to the manufacturer in short time. In some cases, the expert has to guide the on-spot technician in order to determine the cause of the malfunction; a procedure that may require to exchange feedback on how to gather more information on the problem. To achieve that, the supervising expert may provide some AR instructions to the technician on how to gather additional information and ask for new report. Uncommon failures require increased amount of time to detect with traditional practice and may, even, require the expert to perform on- spot inspection. Thus, remote diagnosis drastically decreases down time.

On the other hand, Augmented Reality is used for visualizing the repair sequence. The maintenance expert has to create an AR instruction scene sequence, which is adjusted to the problem. To achieve that, he takes advantage of two system features: knowledge reusability and automatization. First of all, the expert can consult and reuse similar scenes that are already created for similar tasks, such as lubrication or screw tightening, which can be stored in the cloud database. Moreover, available in the cloud database, the maintenance expert may find the CAD of the product's parts and a set of utilities. These utilities include pre-created part movement, scripts, as well as the GUI that allows the technician to interact with the system. Additionally, an algorithm that automates scene creation in assembly procedures [31] has been implemented. The algorithm receives as input a CAD file of a mechanism and, through consequently moving each part, finds the sequence of assembly/disassembly process needed to be followed. Moreover, the algorithm defines the axis and direction of assembly and disassembly of each part and assigns the fasteners (e.g. bolts, screws) to their corresponding parts. Therefore, the maintenance expert may quickly create AR instructions, divided in perceivable steps, for the assembly and disassembly tasks, that account for a large part of the maintenance procedure. The implementation of these components in the proposed system aims to improve the efficiency of providing remote maintenance support by reducing the required time, while also reducing the effort and AR expertise required from the maintenance expert for designing AR scenes and user interfaces.

Aiming to further reduce the response time of the maintenance support system, each AR maintenance sequence that is created to address a maintenance task will be stored in the cloud database. The same malfunction may come up for more than one customers. Especially scheduled maintenance tasks, tend to occur more than once in a product's life cycle. By introducing proper organizing of the existing AR maintenance instructions in the cloud database (filing per targeted machine and naming according to the task), the maintenance support provider will be available to instantly recall existing AR sequences. As a result, AR maintenance sequence reuse is expected to increase efficiency in maintenance tasks and reduce machine downtime.

After completing the AR maintenance instructions creation, the maintenance expert sends them to the on-spot technician. The communication is again realized through the cloud platform. The technician is notified that the instructions are available, downloads them and performs the maintenance task. After completing the task, the technician verifies that the machine is now fully operational.

4. Implementation of the proposed framework

4.1 Hardware Implementation

Aiming to use a hardware setup that allows the user to move freely and in the same time enjoy a highly usable interface, the combined use of AR goggles and mobile device is preferred [19]. In order to carry out the proposed system, three devices have been used: a set of optical see-through Augmented Reality goggles, a laptop PC and a mobile device. Aiming to provide the end- user with a high quality visual result that also permits him to maintain visual contact with the potentially dangerous environment and not occupy his hands, a set of AR goggles have been used for this system; Vuzix™ Star 1200XL [32]. Secondly, the system described in this paper requires the use of a laptop PC (host- PC). This computer is responsible for executing the AR application, communicating with the mobile device and with the cloud platform. The last part, the mobile device, hosts an interface that allows the operator to interact with the AR application through menus. On top of that, it allows the operator to add information concerning the task. As stated before, the mobile device can also be used an independent tool for feedback recording by the operator, which provides increased mobility. For the needs of this paper, Nexus™ 4 Android smartphone was used.

The proposed system requires the devise to work together so as to provide the desired result. To achieve that, the HMD and the mobile device need to be wired to the host- PC. The operator wears the HMD on his head, adjusts the AR goggles

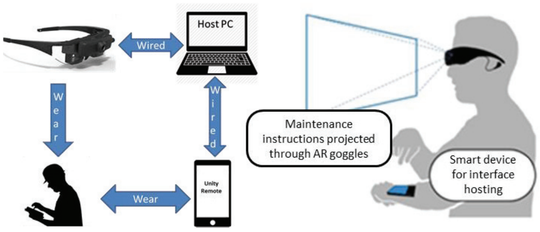

Fig. 2. On- spot operators' hardware setup

and straps the mobile device to his arm. This configuration is designed so as not to limit his mobility. The proposed hardware setup can be seen in Fig. 2 below.

4.2 Software Implementation

For the development of this system two software packages were used. In order to achieve high quality geometry rendering, a commercial cross-platform game creation system was used: Unity 3D™ [33]. It includes a game engine and integrated development environment (IDE) which allows scripting in three programming languages (C# was used for the developed platform). The criteria that led to this choice are:

- It supports a wide variety of object formats permitting extracting the 3D geometries from the CAD files.
- It is able to access dynamic file formats, such as .dll and .xml, and connect to web URLs
- It supports development not only on Windows but also on Android™ and iOS™ applications, so as to create applications that can also be implemented directly to mobile devices

Tracking is a crucial part in Augmented Reality as it positions the virtual environment in the real surroundings of the user [34]. To achieve tracking, it uses the HMD's camera to recognize predefined frame markers in user's field of view. The transformation T between a camera and a marker is:

$$x_c = T \times X$$

Where: X is a point in world coordinates, x_c is its projection in ideal image coordinates and T is the pose matrix. Transformation T consists of translation vector **t** and a rotation matrix **R**:

$$x_c = [R \mid t\,] \times X \Rightarrow \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 & t_x \\ r_4 & r_5 & r_6 & t_y \\ r_7 & r_8 & r_9 & t_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

In addition to that, in order to map between frame marker ideal image (x_c) and observed pixel coordinates (x_{pix}) a camera calibration matrix K is used so:

$$x_{pix} = K \times x_c \Rightarrow \begin{pmatrix} x_{pix} \\ y_{pix} \\ 1 \end{pmatrix} = \begin{bmatrix} f & 0 & p_x & 0 \\ 0 & f & p_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix}$$

As a result, when the camera detects the frame marker:

$$x_i = K \times T \times X_i$$

Where xi are the positions of the four corners of the marker in the camera image and Xi are their corresponding world coordinates (Fig. 3).

The system then calculates M = K × T which is the final transformation matrix and applies it to all visualized geometries, so as to estimate their projection on the virtual environment [35]. With the aim of creating a system whose tracking is accurate and robust, PTC Vuforia SDK, a commercial extension for Unity™, was selected [36].

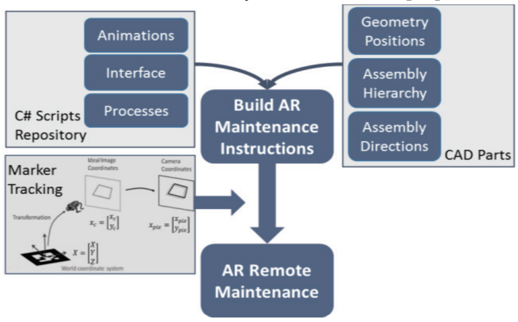

Fig. 3. Architecture of the AR scene

5. Product Service System (PSS) model

The concept of the PSS is a special case of servitization [37]. PSS is a newly introduced strategy of combining the product and the set of services that come with it, in one bundle. This way the manufacturers shift from selling just a product to selling a functionality or a service, which is provided by the product. The manufacturer is responsible for all the actions that will secure that the provided service remains adequate throughout the products' lifecycle [38].

The proposed platform aims to offer a value- adding, product-oriented service [38] that will benefit both the customer, who enjoys robust and high- quality maintenance support, and the OEM/ PSS provider, who gains a critical advantage compared to competitor companies as he is more involved in an extended part of his products' lifecycle [39]. Thus, the PSS provider, exploiting cloud communication and data exchange, may easily interact with the customers, targeting multiple markets with little cost, controlling a large portion of after sales product-related services, increasing the profits, gathering crucial product design feedback (design for maintainability) and creating a stronger connection with the customers. The increased level of automation and the high efficiency of maintenance service of the developed platform allows its implementation in existing business models. Ease of implementation and low implementation cost was one of the main concerns of the developed framework. This is highly important especially for SMEs, as they can increase their influence in the market by providing their customers with unified service solutions of high efficiency together with their products. The implementation of such high-end services allows

SMEs to increase customers' satisfaction, withstand competition pressure and expand their sales networks.

6. Robotics & Automation industrial case

The developed framework was implemented on a case study provided by a robotics SME (Fig 4). The case concerns a real-life maintenance sequence, on which the manufacturer is usually called to deploy specialized personnel that must go on the spot and maintain the machine. More specifically, the maintenance case refers to a battery pack replacement of an industrial robot installed in a Near East country, in a city 1100km away from the use case provider facilities.

This task is crucial for securing robot's continuous function. It commonly requires technicians from the robotics SME to go where the robot cell is installed and perform the tasks. The selected task requires simple actions by the technician, thus can be easily explained remotely. At the same time, it includes all the features that need to be tested. At first, since the maintenance tasks consisted solely of assembly/ disassembly tasks, the smart algorithm automatically created most of the AR scenes. In Table 1, the Excel file generated by the assembly/ disassembly algorithm for this task is presented.

Part Name	*+X*	*-X*	*+Y*	*-Y*	*+Z*	*-Z*	*Tier Num*	*Type*
Robot.1							0	Base
BatteryBase.1	0	1	0	0	0	0	1	Part
Battery.1	0	0	1	0	0	0	2	Part
Battery.2	0	0	1	0	0	0	2	Part
Battery.3	0	0	1	0	0	0	2	Part
Battery.4	0	0	1	0	0	0	2	Part

Table 1. Assembly steps table based on the smart assembly/disassembly precedence algorithm

In the first six columns, the axis and direction of part disassembly is indicated. Moreover, the sequence of disassembly is presented in the "Tier Number" column. Exploiting this information, the developed system may quickly and automatically create the assembly/ disassembly AR scenes, drastically reducing the time required for creating maintenance instructions.

Moreover, the interface is used not only to change scenes but also to input information that cannot be known in AR instructions creation, such as which battery connector is free. This is a crucial part of this maintenance task as the new batteries need to be connected before unplugging the old ones. Based on that input, the system alters the projected AR instructions in the next steps. The steps of the procedure were provided by corresponding industrial partner.

With the current approach, the robotics SME deploys a maintenance expert to go on-spot to perform the maintenance task. This procedure costs 1370€ and requires 9 hours from the time the malfunction is reported until the machine is back online. Applying the proposed approach, the cost is reduced to 150€ and the required time is decreased to 2 hours (Fig. 5). Especially in the case that the task has re-occurred in the past and can be recalled, omitting the time required for creating AR instructions, the required time is further reduced. Thus, the positive impact of applying the proposed framework application is apparent.

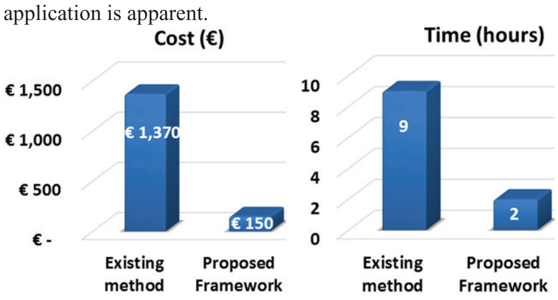

Fig. 5. Required cost and time- Comparison of the two methods

7. Conclusions and future work

This paper presents the development and testing of an Augmented Reality remote maintenance platform that can be used for providing PSS maintenance service. A cloud platform was also implemented as a communication enabler and to assist existing knowledge reuse. This study also takes into account algorithms which increase the efficiency of the procedure and

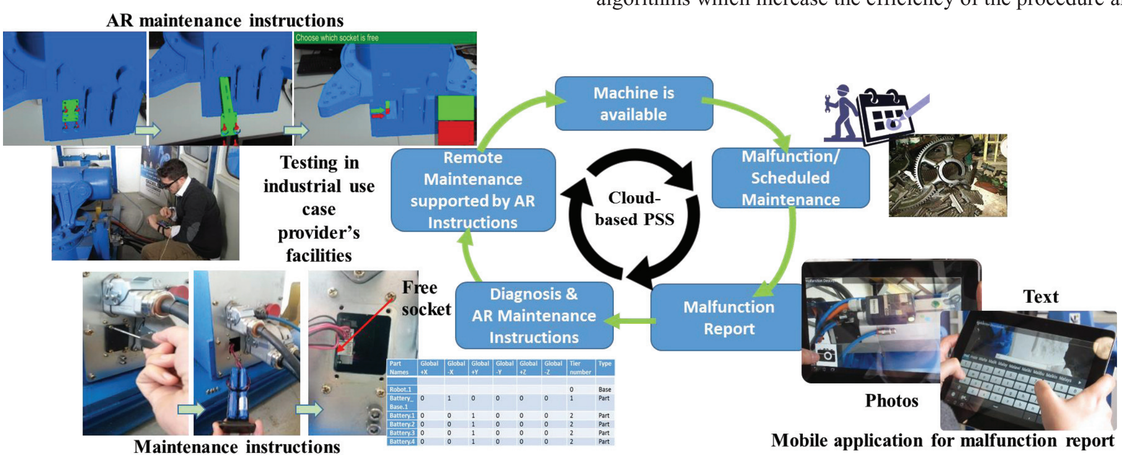

Fig. 4. The sustainable Product Service System

the automation level by reducing the actions and expertise required by the engineer to create the service sequence instructions which can be effortlessly perceived by less experienced technicians. In addition to that, through the proposed remote approach the required maintenance time and cost is highly reduced. Finally, manufacturing companies can provide remote maintenance as a service, increasing their customer's satisfaction and delivering added value solutions.

Future work could focus on integrating the existing system and other systems in an enterprise, increasing interoperability. In addition to that, it is essential to reduce AR scenes designer's cognitive load by increasing the automatization of the procedure.

Acknowledgements

The work presented in this paper is partially supported by the European Union's Horizon 2020 research and innovation project "Customer-driven design of product-services and production networks to adapt to regional market requirements-ProRegio" (GA No: 636966).

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