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AUGMENTED REALITY IN MANUAL ASSEMBLY PROCESSES

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Abstract: *Augmented Reality (AR) is a novel technology that projects virtual information on the real world environment. With the increased use of Industry 4.0 technologies in manufacturing, AR has gained momentum across various stages of product life cycle. AR can benefit production operators in many manufacturing tasks such as quality inspection, work instructions for manual assembly, maintenance, and in training. This research presents not only a typical architecture of an AR system but also both its software and hardware functions. The architecture is then applied to display virtual assembly instructions in the form of 3D animations on to the real world environment. The chosen assembly task in this research is to assemble a planetary gearbox system. The assembly instructions are displayed on a mobile device targeting a static tracker placed in the assembly environment.*

Key Words: ***Augmented Reality, Industry 4.0, Tracking, Smart Factory, Smart Manufacturing, Assembly, Human-Machine Interface***

1. INTRODUCTION

Industry is eager to use technology with steepest gradient, rather than to follow slowly evolving scientific investigations. The dynamics of the shop floor are changing faster than ever before. This new industrial revolution will allow more digital flow of information, transform the industrial workforce, and change how they interact with the shop floor entities. Smart factories will allow mass customization of products in a way that operators will play a key role in dealing with increased product variants and frequently changing work tasks [1]. Industries will soon require a way to train operators with unfamiliar assembly tasks. AR is one such technology that can be used to support future operators. In manufacturing research, applications of AR are observed throughout the product life cycle but significant results are observed in assembly [1,2], quality inspection [3], training [4] and remote assistance for maintenance [5].

AR technology offers many advantages such as reliability, reducing error rates, increased intuitive learning, and traceability. For operators on the shop floor, AR serves as a supportive tool in their day to day operations enabling “digital poka-yoke systems” [6] as it reduces manual errors and rework of complex and unfamiliar assembly tasks. Furthermore, AR introduces a new way to interact with machines and shop floor environment enabling future human-machine interface solutions.

This paper introduces the capacity of AR systems. The benefits of AR and associated challenge are discussed in a SWOT analysis. The state of the art of AR in assembly is presented followed by a typical architecture of an AR system using HHDs (smart phone in our case), software and hardware functions. We also demonstrated a case study to evaluate the feasibility of AR for assembly tasks in a lab environment, using assembly of a 3D printed planetary gearbox. The assembly instructions are superimposed on a marker placed on the assembly workbench. Even though, the practical implementation of AR in manual assembly is performed in a laboratory environment, the authors would like to extend this methodology to manufacturing SMEs after establishing certain maturity to be able to satisfy the industry requirements. By extending this AR prototype with additional features such as interactive customer integration [7] manufacturing industry could enable mass customization to determine individual customer requirements. However, with currently available technology, interactive customer integration is expensive and consumes more design time. With advancements in AR technology, mass customization at a faster and cheaper rate is gaining more attention in the research community [8] [9], which will be explored in our future research.

2. AUGMENTED REALITY: A GLIMPSE

AR combines a set of already existing technologies to superimpose digital information on to the real world. Therefore, AR enhances operator’s perception of the reality supplemented by digital information.

The basic components [10–12] of an AR system consists of a **Capturing Technology (CT)**, such as a camera (or a sensor) to capture the real-world environment. A **Visualization Technology (VT)**, to project virtual models on the real images captured by the camera. Generally used VTs are Hand-Held Devices (HHDs) such as tablets and smart phones, Head-Mounted Devices (HMDs) such as smart glasses, and spatial displays such as projectors. A **Processing Unit (PU)**, to analyze the input data and output virtual information (visual rendering). A **Tracking System (TS)**, such as a marker (for example a QR code). The main function of TS is to trigger the display of virtual information and establish the orientation of virtual data with respect to the physical world. A **User Interface (UI)**, such as a touch display of a tablet, for an operator to interact with digital world. Fig. 1 summarizes the interactions among the components of an AR system. These interactions are explained in detail in section 4.3. Usually in the industry, AR systems with markers are used as they significantly reduce the computing power when compared to marker-less technologies such as target capturing etc. Furthermore, HMDs (smart glasses) are a more suitable option in the industry as they give a hands-free experience when compared to HHDs.

2.1. Benefits of Augmented Reality

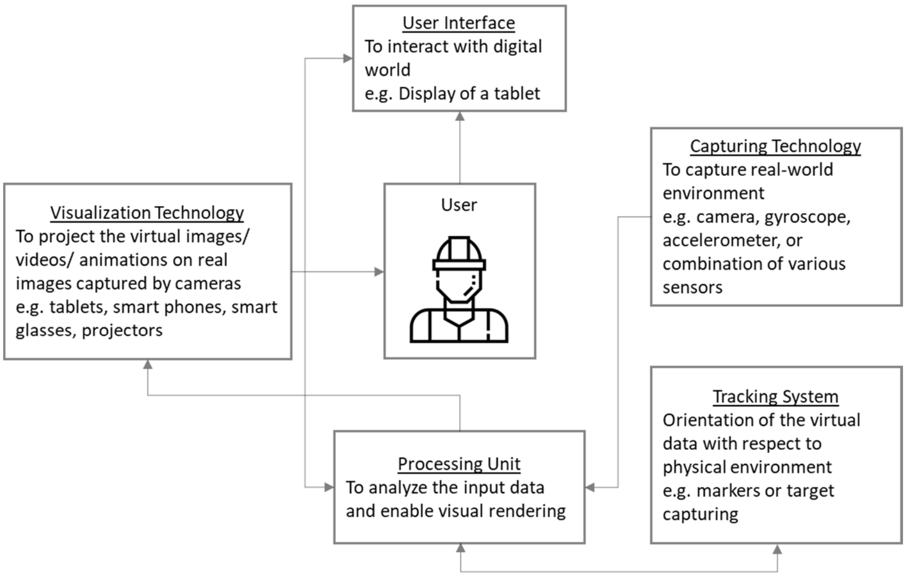

Fig. 1. *Interactions in an AR system (based on [7–9])*

AR has been experimentally tested in manufacturing industry [9,13–15] . The benefits of AR are based on what sort of basic components are used for an application. For example, different VTs offer different advantages over others. The aim of this section is to summarize the underlying benefits of AR [10–12].

In general, for an assembly application HMDs are preferred as it provides operator with hands-free experience and improves operator's perception of the real world, as the view through an HMD is almost intact with the real world. On the other hand, nowadays most people are familiar with HHDs (ex. tablet or a smart phone). Using an HHD reduces the amount of training and allows an operator to directly work with the system with less training. Economically and ergonomically, HHDs are better alternatives to HMDs. In spatial displays, operator's hands are free and he/ she does not need to carry anything. In terms of TS, AR systems with markers are less computer intensive, robust and accurate. Marker-less systems do not need physical markers that has to be placed and maintained in an industrial setting.

Overall, AR applications in manufacturing environment offers enhanced interactivity with the real world through digital lenses. They enhance operator's perception thereby reducing quality defects. AR applications are not computing intensive, both mid-end and high-end devices can be used. Portability is another advantage as AR hardware and AR applications are easily transported from one location to another.

2.2. Limitations of Augmented Reality

Despite the benefits mentioned above, AR inherently has some disadvantages, which are summarized in this section.

HMDs are still uncomfortable to wear, have limited field of view (FOV), and at times display distorted 3D objects. Limited FOV can cause work place accidents and affects the safety of the operators [16] and limited resolution can cause sickness of operators when exposed for long periods of time. The heavy weight associated with existing HMDs is not an ideal option for the operator. On the other hand, HHDs don't provide a hands-free experience which is crucial in the industrial setting. Moreover, HHDs need a physical support to hold them in place and ends up hindering their portability. One more disadvantage of an HHD system is the limited dimension of its display unit (UI) which limits the information that is overlaid on it. AR systems that use markers require physical markers that need to be placed at the right place on the workbench and maintained periodically. On the contrary, AR systems without markers need more computational power for the object tracking in real time.

Overall, the disadvantages in AR systems are associated with the maturity of the available technology. Other aspects such as processing power, battery consumption, limited memory, and connectivity issues are still being improved. In the near future, we will have AR hardware addressing the issues mentioned above with low cost and high performance.

2.3. SWOT analysis of AR systems

A SWOT analysis framework is applied to identify internal and external factors related to existing AR systems. Internal factors include strengths and weaknesses of AR systems within the organization and external factors consolidate opportunities and threats beyond organizational boundaries. The SWOT analysis of existing AR systems is depicted in Fig 2.

Despite successful demonstration of AR applications in the research community, only a few companies have implemented case studies in real industry environment. The above SWOT analysis presents both success factors as well as challenges that AR systems are encountering with the currently existing technology. To summarize the success factors include: interactive features of AR systems between real and digital worlds, hands free experience, reduced site visits and down time, ubiquitous application areas throughout product's life cycle, open source app building frameworks, and technological improvements of AR components. However, some researchers [11] quote that operators acceptance is a crucial challenge to overcome as ergonomics of wear-ability and visual fatigue are prevalent with the current technology. Another issue that can hinder the implantation is in-house skills of employees to design, develop, and scale-up the AR solutions. Currently, there are no standards for the integration of AR systems with the existing IT systems and therefore, privacy and legal concerns are a constant topic of debate between researchers and the industry.

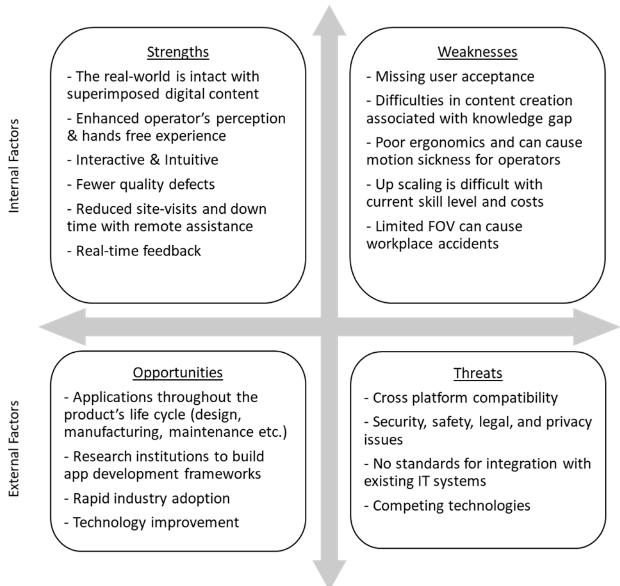

Fig. 2. *SWOT analysis of AR systems*

3. PREVIOUS RESEARCH

AR in assembly research is evolving rapidly in different categories. Researchers have categorized AR assembly in three main categories [12]. Our scope in this paper is to briefly describe one assembly research in each of the following categories: AR assembly training, AR assembly guidance, and AR assembly design, simulation, and planning.

3.1. AR assembly training

Researchers at Department of Industrial Engineering at University of West Bohemia used AR to train the participants on how to assemble an industrial gully trap. They have then compared the first ever assembly time and the number of attempts for learning how to assemble without instructions between conventional paper instructions and AR instructions [15].

A set of 20 participants with no previous experience of assembling a gully trap, tried assembling it using paper instructions. For the first assembly, the participants took 5 to 7 minutes to assemble a gully trap and almost 12 attempts to learn how to assemble it without instructions. The researchers commented that most of the time was spent on looking for parts in the boxes.

In order to tackle the problem above, the researchers have developed a simple AR solution using Unifeye Design software from Metaio® company. The software uses block programming to make a connection between static markers and the 3D model in a workflow editor. The interconnectivity was achieved rather quickly and without tedious programming from scratch. The user can easily move through assembly instructions by pressing up and down arrow keys from a keyboard. Another set of 20 participants with no experience in assembling a gully trap tried the new AR assembly instructions. In the first attempt, most of the participants could assemble it in 2 minutes less than the average time from the participants with the paper instructions. It took almost 10 attempts for the participants to assemble the gully trap without instructions. Overall, the learning process with AR assembly instructions is more efficient than using the paper instructions. The learning time could be shortened significantly for a product with complicated assembly processes.

3.2. AR assembly guidance

Researchers [17] have developed a demonstrator where an operator can collaborate with a Universal Robot® (UR3) to assemble and disassemble a simplified car model using AR assembly guidance system. The AR interface in the first iteration is created in gaming engine Unity-3D® with the help of Vuforia AR-system®. Then, in the second iteration Vuroria AR-system is replaced by ARToolKit®, as it supports windows platform. ARToolKit also support multi-marker functionality, therefore, in their research a greater number of markers are used to allow test operators and robot to move freely in-between the camera and markers.

The car's assembly has 11 steps to be performed of which four with Human-Robot Collaboration (HRC), two with partial HRC, and operator solely does five steps. A tablet is used to track the markers and to interact with the robot control system. The tracked information is displayed on a spatial display screen placed in front of the operator. The AR interface has text as well as limited graphical instructions.

The test results show more than significant errors/ deviations by test operators. For a test group, where all the participants have committed errors, mistakes were made in 52% of all the attempts. The major reasons for significant error rate are that the interactivity of interface is unclear for the test operators since the interface has mainly test instructions with certain graphical marks but neither animations nor 3D views are provided. On the other hand, the camera was at a fixed angle, therefore, it is difficult to access the environment around the assembly operation.

3.3. AR assembly design, simulation, and planning

Among AR assembly design, simulation, and planning projects, objects manipulation has been the interest of researchers [12]. In [18], AR is employed as part of a serious game for teaching the assembly of a car power generator. The study explored the possibility of training a new mechanic apprentice on how to assemble a car power generator in the form of a game aided by AR without the involvement of any physical components. The benefits associated with this research is that the training time has been reduced and there is no need for physical parts assembly, which further reduces resources for disassembly, cleaning, and replacement etc. This assembly simulation process incorporated virtual interaction with virtual objects and do not consider fusing the interactions between real and virtual objects, to get the core benefits of an AR system, which are real-time feedback, better interactivity with physical elements through augmented glasses etc. Over the last few years, the research in AR assembly design, simulation, and planning is going down in manufacturing and the other sectors such as logistics are focusing more on this aspect for digital warehouse planning etc.

4. AR SYSTEM DEVELOPMENT

We used the following 5 step methodology to develop AR for assembly case study [4]. This methodology section describes general steps to follow for a successful AR case study.

1. Problem statement
2. Identification of requirements
3. AR solution design (architecture)
4. AR solution implementation (case study)
5. AR solution assessment (discussion)

4.1. Problem statement:

Available AR solutions in the market use complex architectures, expensive software programs, and are programming intensive. In our case study, we used free open source software, add-ins, and a manageable amount of programming. We believe that such solutions are attractive to Small and Medium Size Enterprises (SMEs) as they often look for simple solutions rather than sophisticated software adoptions.

Another problem we addressed in this research is the knowledge transfer to the other researchers and enterprises. In this paper, we detailed the functions and interactions of each software and hardware element. Following our methodology, it is simple to replicate and reproduce AR assembly case studies.

The last problem addressed in this research is the feasibility of AR using smart phones in a laboratory environment. We try to understand if a trainee can independently learn in the absence of a trainer using AR assembly instructions with animations. Section 4 details this issue.

4.2. Identification of requirements

Before AR solution design, we identified software and hardware elements required for it. In Fig 3, the software elements are placed in digital environment and the hardware elements in the real environment. This section presents the functions of software and hardware elements that are required for a successful AR implementation.

4.2.1 Function of Software Elements

C#: Programming language used to create all the actions and interactions performed within the application.

Vuforia®: A software platform used for the development of augmented reality. It provides the capability of recognizing and tracking planar images, which enables the insertion of virtual 3D models into a real environment viewed through a camera in a desired orientation. The tracking allows the object's perspective to be always aligned with the viewer's perspective, making it appear to be a part of the real environment.

Autodesk Inventor®: Computer-aided design software used for the creation of the 3D models used in this research.

Unity®: A game engine, which creates applications with real-time rendering and interactive 3D environment. The whole application is developed and built with Unity, it creates the interface, animations and runs all the interactions (section 4.3) within the software

Android Application: Captures the input signals, processes the images and renders the 3D elements in the real environment to generate the augmented reality experience.

4.2.2 Function of Hardware Elements

Android Device: Equipment responsible for running the application and allowing it to be interacted by the user through its input/output interface.

Camera: Responsible for capturing the real environment where the virtual elements are going to be projected.

Touchscreen: Acts as the input interface between user and application, as well as visual output medium.

Data Storage: Recording media where the application is installed and ran.

Assembly Parts: Physical parts that are hand manipulated by the user for assembly operations.

Markers: Visual cues that trigger the displaying of the virtual elements on top of the real environment, which also allows its repositioning and orientation through tracking.

4.3. AR solution design (architecture)

Several technological solutions exist to realize both software and hardware functions of an AR system. We chose a HHD (smart phone, Samsung® Galaxy A7) as the hardware device. The reason to choose HHD over HMD is because smart phones have undergone a widespread of its usage and operators do not need extra training to learn how to work with it. As we wanted to keep the costs to a minimum and make this research feasible, we chose readily available devices. One advantage with the smart phone is that it comes with a camera (capturing technology), processing unit, and user interface. The parts of the planetary gear box assembly are 3D printed using a Prusa® i3 MK3. The physical markers are generated using an online tool [19]. Fig. 3 illustrates the architecture of an AR system for assembly guidance to integrate digital and

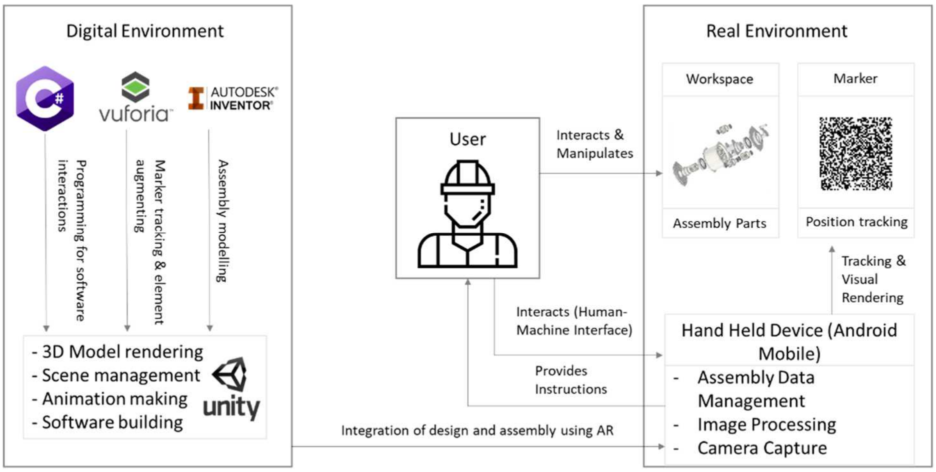

Fig. 3. *Typical architecture of Augmented Reality for assembly using a smart phone*

real environments. Each environment has several functional modules that perform specific tasks as mentioned in *3.2.1*. For designing an AR solution, it is important to understand how these functional elements interact with each other and what interactions enable integration of digital & real environments.

C# & Unity: Unity runs the C# code, which retrieves Unity's operation in order to perform the necessary actions.

Unity & Android: Even though there is no interaction between Unity and the Android device or application, Unity makes use of the Android SDK (Software Development Kit) in order to build the application itself that runs on the android device.

Vuforia & Unity: Vuforia provides Unity with the tracking data necessary for adjusting the perspective of the 3D models accordingly with the movement of the camera.

Inventor & Unity: Even though Unity does not interact with Inventor in anyway, it uses the 3D objects modelled in Inventor that are extracted in .obj format.

Vuforia & Markers: The markers trigger Vuforia tracking, which uses it as a reference point on the real environment. The 3D animations for assembly guidance are projected on to the markers in real environment. This interaction enables the integration between digital and real environments.

Android Device & Android Application & User: The android application accesses the camera of the device in order to capture the images (markers) necessary for running it, as well as it's touchscreen to allow input/output interaction with the user.

User & Assembly Parts: The user interacts with the physical parts and assembles them together with the help of 3D animations.

5. SYSTEM VALIDATION (CASE STUDY)

The parts needed for assembly of a planetary gearbox are 3D printed using Prusa® i3 MK3 kit. Fig. 4 shows the exploded view of the planetary gearbox. Fig. 5 (a) shows the 3D printed parts for the assembly, 5 (b) shows a user manipulating the physical parts using augmented reality instructions.

A total of 10 steps are required to assemble the gear box that are animated using Unity® game engine with the help of other software mentioned in *4.2.1*. Brief description of 10 steps are given below.

1. Two gear bearings (SKF W636-2R) are placed on the planet gear (1 out of 3)
2. Repeat step 1 (2 out of 3)
3. Repeat step 1 (3 out of 3)
4. Planet gear is fixed on the carrier with a bolt and nut (M6) (1 out of 3)
5. Repeat step 4 (2 out of 3)
6. Repeat step 4 (3 out of 3)
7. Shaft bearing (SKF W61907-2Z) and external circlip (DIN 471 35 mm) are placed on the shaft (sun gear)
8. Fit the sub-assembly from step 7 on the housing (ring gear) with an internal circlip (DIN 472 55cm) and close the housing from bottom side using a bottom cover, nuts & bolts (M4)
9. Assemble the top cover with a carrier bearing (SKF W61907-2Z), fixing with the internal (DIN 472 55mm) and external (DIN 471 35mm) circlips. Place the top cover to the carrier sub-assembly from step 6
10. Assemble housing subassembly from step 8 and top cover subassembly from step 9 together using nuts and bolts (M4)

Researchers quoted before [2,15] mentioned that, during a traditional assembly tasks, most of the time is spent on reading the instructions on paper. Therefore, in this research we used AR technology to eliminate text instructions and use universal language of animations to guide the user through the assembling process of the planetary gear. By choosing animations as a medium of instructions, we avoid language barriers of operators in the shop floor. Fig. 6. (a) shows AR instruction of assembling a shaft bearing and an external circlip to the shaft (sun gear) and (b) shows the finished assembly.

The mobile device (smartphone) must be in a stationary position tracking the marker at all times. The instructions are projected on the marker with middle of the marker as a reference point.

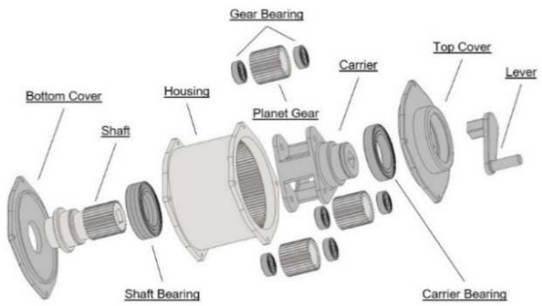

Fig. 4. *Exploded view*

Fig. 5. *(a) 3D printed parts*

(b) User interacting with assembly parts using AR instructions

Fig. 6. *(a) AR instructions for shaft assembly*

(b) Finished shaft assembly

The user who is manipulating the assembly parts can browse through the different steps of the assembly processes by pressing respective button on the touch screen. The developed solution has the following buttons: play, pause, next and previous. The user needs the right parts for a successful completion of the assembly task. Therefore, the developers of this research added a feature to provide users with the information of the parts by simply touching them at any time during the assembly process. Fig. 7. illustrates this feature. The user can also zoom in and zoom out the animations by simply pinching in and out on the display unit. Moreover, touch & rotating two fingers on the display unit can allow viewing different perceptions of the parts.

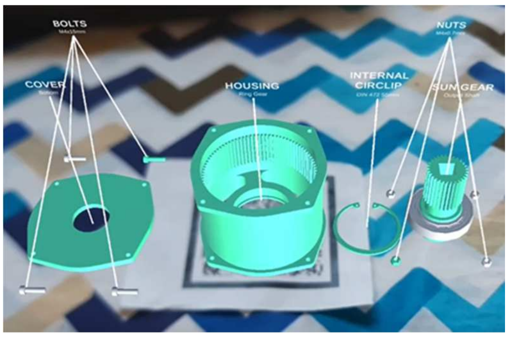

Fig. 7. *Parts information using AR instructions*

6. DISCUSSION

While trying the application and the assembly process of the planetary gearbox, it was evident that the animated instructions gave a better comprehension compared to the written instructions. The mobile device must always be kept on a static position (using a mobile holder) tracking the marker rather than the operator holding it. This enables the free movement of both hands of the operator and allows him to assemble alongside with the instructions. The complete hands-free operation is not achieved in this research as the operator needs to interact with the buttons on the display unit, to access previous or next instructions. AR glasses such as HoloLens® can provide hands-free experience, which will be assessed in our future research. While testing the assembly process of the gearbox, the authors observed that the tasks are less demanding and mental load was minimum using AR instructions when compared to paper instructions. However, it is necessary to verify this with large number of participants in future work. The research has achieved the assembly guidance using AR technology at a lower cost using readily available software and hardware technologies that is very attractive to manufacturing SMEs. Marker-less technologies such as target tracking will be explored in our future research where the augmented instructions are superimposed on the real parts.

In this research, we explored the feasibility of AR for the assembly guidance using animated instructions. Previous case studies [17] of the same kind had issues with interactivity with the app interface which led to the significant error rate in assembly. The app developed in this research addressed the interactivity issue in two folds: one, using the smart phone technology and two, simple design of the app interface. Due to the widespread usage of smartphones in recent years, the operators are already familiar with the smartphones. Therefore, the interactions with smartphone are smoother than with AR glasses. In the design of app, the researchers used familiar buttons such as play, pause, next, and previous that reduces the complexity of interface. The app provided additional features to explore the assembly environment with simple gestures as mentioned in section 5.

The architecture presented in section 4 is developed with the knowledge acquired by the authors during the process of building the AR system. In order to permit the reproduction of this AR system by other researchers and manufacturing SMEs, all the knowledge necessary from software integration to hardware specification is presented in detail. When comparing our architecture to other similar works in the literature, our concern with detailing the approach definitely stands out.

7. CONCLUSION

In this research, the authors addressed problems associated with AR technology in the assembly guidance. A simple and cost effective solution is developed and validated with a case study of assembling planetary gearbox using animated AR instructions. The research also focuses on detailed knowledge transfer of the AR system design for assembly along with the software and hardware functions. The feasibility of the cost effective AR system is tested in a laboratory environment and it was found that the AR instructions enhance the operator's perception of the real environment. Statistical validation with several participants is a focus of our future research.

7. ACKNOWLEDGMENTS

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