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Comparing software frameworks of Augmented Reality solutions for manufacturing

Sri Sudha Vijay Keshav Kolla[a,*], Andre Sanchez[a], Peter Plapper[a]

[a] *University of Luxembourg, 6, rue Richard Coudenhove-Kalergi, Luxembourg, L-1359, Luxembourg*

Abstract

Augmented reality (AR) is a technology that allows overlaying of virtual elements on top of the physical environment. This enhances the perception and conveys additional information to the user. With the emergence of industry 4.0 concepts in manufacturing landscape, AR found its way to improve existing Human-Machine Interfaces (HMI) on the shop-floor. The industrial setting has a wide variety of application opportunities from AR, ranging from training and digital work instructions to quality inspection and remote maintenance. Even though its implementation in the industry is rising in popularity, it is still mainly restricted to large companies due the limited availability of resources in Small and Medium Size Enterprises (SME). However, SMEs can benefit from AR solutions in its production processes. Therefore, this research aims to develop and present the results of comparison of two simple and cost-effective AR software frameworks for Hand Held Device (HHD) and a Head Mounted Device (HMD), which can be applied for developing AR applications for manufacturing. Two AR applications are developed using these software frameworks which are presented in the case study section. Android device is chosen as a HHD and HoloLens is the HMD used in the case study. The development structure can be reproduced by a wider range of enterprises with diverse needs and resource availability.

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Keywords: Augmented Reality ; Industry 4.0 ; Extended Reality ; Mixed Reality ; manufacturing ; HoloLens ; assembly training ; Human-Machine Interfaces ; Vuforia ; Unity ; Mixed Reality toolkit ; Small and Medium Sized Enterprises (SME)

1. Introduction

The new industrial trends such as industry 4.0 or similar terms like cyber physical systems, internet 2025 etc. promotes increased automation and enables intelligent manufacturing systems. However, human interaction still plays a crucial role in manufacturing landscape. The aim of the fourth industrial revolution is not to create factories without human, but to improve the human and machine collaborations combining the advantages of accuracy and efficiency of intelligent machines with human flexibility [1]. On the other hand, growing number of product variants has increased the demands on shop-floor activities [2] such as assembly, quality inspection etc. One way of looking at the problem is to improve the existing Human-Machine Interfaces (HMI) to not only interact with machines but also assist operators to complete shop-floor tasks. The implementation of Extended Reality (XR) technologies in the industry provides workers with visual and interactive information that can improve completion time and error rate of human tasks [3, 4]. However, the industrial use of these technologies is still in its infancy and requires more research into its designing guidelines and application practices. Hence this research is aimed at comparing design and implementation aspects of the two most commonly used Augmented Reality (AR) hardware components. Two simple and cost-effective AR solutions using a Hand Held Device (HHD) and a Head Mounted Device (HMD), which can be applied for training of complex assembly tasks are developed in this research. This helps to validate the software frameworks with a real case study. Android device is chosen as a HHD and Microsoft HoloLens® is the HMD used in this research. The focus of this research is also such that a wider range of enterprises with varying needs can reproduce the development of an AR solution, which are highly appreciated by Small and Medium Sized Enterprises (SME). The focus of research question in this research is twofold. How to develop an AR solution for manufacturing assembly task or for

* Sri Kolla. Tel.: +352 661 486 328
E-mail address: sri.kolla@uni.lu, sri.no1991@gmail.com (Sri Sudha Vijay Keshav Kolla).

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a training task? and what are the benefits of AR instructions when compared to traditional paper instructions? The next part of this chapter gives a brief introduction about Extended Reality (XR) technologies and explains the similarities and differences.

1.1. Extended Reality (XR) Spectrum

There is a still fuzziness in differentiating the terms such as Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) in both research as well as in the industrial sector. The above terms falls into the Extended Reality (XR) spectrum with various degrees of awareness of reality. This section focuses on disambiguation of the fundamental terms used in XR research. Fig. 1 illustrates the XR continuum which encompasses technologies that goes from AR, through MR all the way to VR [5]. The key variable that differentiates these technologies is the awareness of the reality when exposed to the specific system.

The virtual extremity of the continuum is defined as VR, which fully immerses the user by employing only digital components and completely isolating the user from the real environment [6]. In a VR environment, the user is unaware of the reality and completely surrounded by virtual elements. In the other extremity, the real world, which consists of only physical objects without any virtual objects to enhance the operator's perception.

There is a real ambiguity in the current literature when distinguishing AR from MR because both AR and MR makes use of virtual objects overlaid into the real environment. However, for the purpose of this research, a vaguely defined difference between AR and MR from Milgram and Kishino's research is adapted and modified [7]. According to Milgram and Kishno's research [7], MR is an umbrella term for technologies such as AR and Augmented Virtuality (AV). However, the authors of this research bring MR to the same hierarchy as AR and VR and clubs them to an umbrella term XR. As we understand, the main difference between AR and MR is how the digital and real objects interact with each other. AR simply overlays the digital object on top of the real background, without any interactions between them. However, MR on the other hand generates interactions such as occlusion and collision through spatial mapping and physics simulation, which provides further immersion for the user.

2. Literature Review

In our previous research [2] we presented the important components of a typical AR system, advantages and limitations of various hardware solutions (e.g. mobile phone, smart glasses). In our further research, we couldn't find any articles in the scientific databases, which compares AR software design frameworks for different hardware equipment. For example, designing an AR solution in a HHD (e.g. tablet or mobile phone) requires a different set of software and hardware elements compared to designing an AR solution in a HMD (e.g. HoloLens).

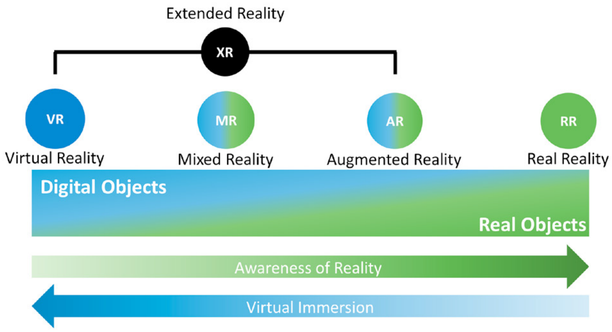

Fig. 1. Extended Reality Spectrum.

This section presents few standalone software frameworks of the AR solutions using various hardware.

The currently existing state of the art literature, the software frameworks specific to AR development in manufacturing for various hardware devices is clearly missing. In our research we found only one paper [1] dealing with AR software framework for HoloLens using a lean graphical representation technique called C4 framework, popular in software development. The interactions among the software elements are presented in the framework. In addition, the framework is suitable for SMEs as most of the software elements are open source and doesn't incur additional costs besides hardware. However, the framework's focus is only on HoloLens/ smart glass and don't cover aspects of the hardware systems such as AR for mobile devices.

In general, the typical work flow of AR includes pre-defined constraints and assembly hierarchy generated from 3D CAD files. This approach is often time consuming as it requires the developer to prepare scenes and interactions for each different assembly. Interactive Manual Assembly Design (ARIMAD) [8], is an architecture that focus on this limitation of AR work flow. The main takeaway of ARIMAD framework is that the system can predict the manual assembly intents based on an assembly constraint analysis. However, besides normal software elements the framework needs 3D bare-hand interaction tool (3DBHI) to facilitate Human-Computer Intervention (HCI). Moreover, the assembly process in the AR environment requires an efficient feature based automatic constraint recognition algorithms making it a complex framework for SME adaptation.

One major issue in using any AR system for overlaying virtual information in real world is that some objects are not visible from a certain view point as the objects close to the viewer obstructs the farther away objects, this is normally known as occlusion [9]. Occlusion occurs mostly in video-overlays as well as video-see through devices such as HMDs. In the framework work AR based systems [10], the researchers used Z-method to process the occlusion by installing a commercial RGB-D camera Kinect 2 to generate the intelligence required for 3D object recognition. In addition, Vuforia and Unity are used for object recognition and instruction data base respectively. The architecture is designed for a HHD (e.g. smart phone) and the authors didn't mention it's extendibility to HMDs. However, this architecture is suitable for SMEs as it is cost-effective and simple to implement.

Other researchers [2, 11, 12] presented similar architectures/ frameworks for the development of AR applications for manufacturing. A summary of the articles is shown in the Table 1.

Table 1. Summary of chosen articles

Summary item	[1]	[2]	[8]	[10]	[11]	[12]
AR for HMD	✓	x	✓	x	✓	x
AR for HHD	x	✓	x	✓	x	x
Projector based AR	x	x	x	x	x	✓
Unity	✓	✓	-	✓	✓	✓
Holo ToolKit	✓	x	-	x	x	x
C# components	✓	✓	-	✓	✓	✓
Vuforia	x	✓	-	✓	✓	✓
Additional Equipment	x	x	-	✓	x	✓
Suitable for SMEs	✓	✓	x	✓	✓	x
Cost-effective	✓	✓	-	✓	✓	x
Scalable	✓	✓	-	✓	x	x
Portable	✓	✓	-	✓	✓	x

3. The proposed software frameworks

The software framework for a Hand Held Device (HHD) is shown in Fig. 2. The framework is inspired from C4 architecture notation [13], a lean graphical representation technique in modelling software architecture. On the contrary to the framework guidelines, only 3 levels are shown in the framework in Fig. 2 and Fig. 3: The context, containers, and components. Level 4, detailing each component of the code, is not in the scope of this research.

The level 1 (context), presents with the big picture. The idea of an operator interacting with an AR android application. At this level, the actors (such as operator) and the software system (Android application) are the focus points. Once having an overall understanding of how the system fits into IT environment, it is recommended by C4 architecture to draw a container diagram (level 2). A container is a runnable application/ unit that executes redefined functions or store data. In the software framework for HHD shown in Fig. 2, we have 2 containers: lean touch [14], unity® scene [15] , and vuforia [16]. The lean touch provides the touch capability to the android application and the vuforia provides the capability of recognizing and tracking the planar images such as QR codes. Unity provides 3D space for the design of the scenes/ animations that are projected in real time through HHD for operator assistance. These applications are open source and reduce the complexities involved in developing standalone applications for each container afresh.

In the level 3, component diagram, the developer can zoom in and fragment each container to major building blocks of the application (or normally executable functions). It is in this level, the interactions among the components are illustrated. Each component shown in Fig. 2 has a specific functionality and interact with one or more components. For example, in the container 'vuforia', the AR camera (function: recognition and tracking of the marker) uses image target (function: positioning and deploying of the 3D models) to overlay virtual instructions in the real world. The other interactions are illustrated in Fig. 2 with the details of each components functionality.

In a nutshell, a container is made up of several components and the software system clubs several containers together.

Fig. 3 presents a similar software framework for Head Mounted Device (HMD). It has only two containers (MixedReality ToolKit and Unity Scene) as we used spatial mapping, an important feature of HoloLens (HMD). Spatial mapping is based on Simultaneous Localization Mapping (SLAM) [17] algorithm that recreates a 3D mesh representation of the surrounding environment from the depth data. Thus, by using spatial mapping, the virtual instructions can be populated and tracked exactly on top of the actual workstation, eliminating the use of markers. Therefore, we don't need an extra container for the recognizing and tracking. However, understanding the features of hardware in hand is a crucial step in implementing a software framework. Otherwise, the features of hardware devices are underutilized.

The HMD device has the capability of interacting through hand gestures, however, this process can get trickier when wearing gloves, extended usage of the device, which are not uncommon in an industrial setting. Therefore, we adapted the MixedReality ToolKit [18] to enable speech commands through Voice Manager. However, the rest of the interactions in Fig. 3 are similar to Fig. 2

4. Case Studies

There are all-in-one AR solutions readily available in the market, with tools to satisfy a wide variety of needs. However, they can be expensive and excessive for simpler training tasks and for the needs of SMEs. Nevertheless, it is possible to achieve satisfactory solutions for SMEs by creating an in-house application combining affordable software, plug-ins, and hardware. Two different software are created using software frameworks presented in the previous section for two alternative hardware set-ups: An Android system, as a more affordable choice, and a HoloLens solution with extended capabilities. The problem to solve is to assemble a gear-box as shown in Fig. 4 with different hardware devices. The final solution remains the same in Android device and in the HoloLens but the approaches are completely different.

The planetary gear-box consists of a combination of 3D printed parts and standard components such as bearings, retainer rings, nuts, and bolts. The inclusion of such parts adds a layer of complexity to the assembly task by requiring to use different tools. The existing literature [10, 19, 20, 21, 22] uses Lego bricks or building blocks in case studies to validate the software for AR. However, by adding additional parts and tools, the application can explore tasks more relatable to the industrial setting such as screwing, fitting, and fastening.

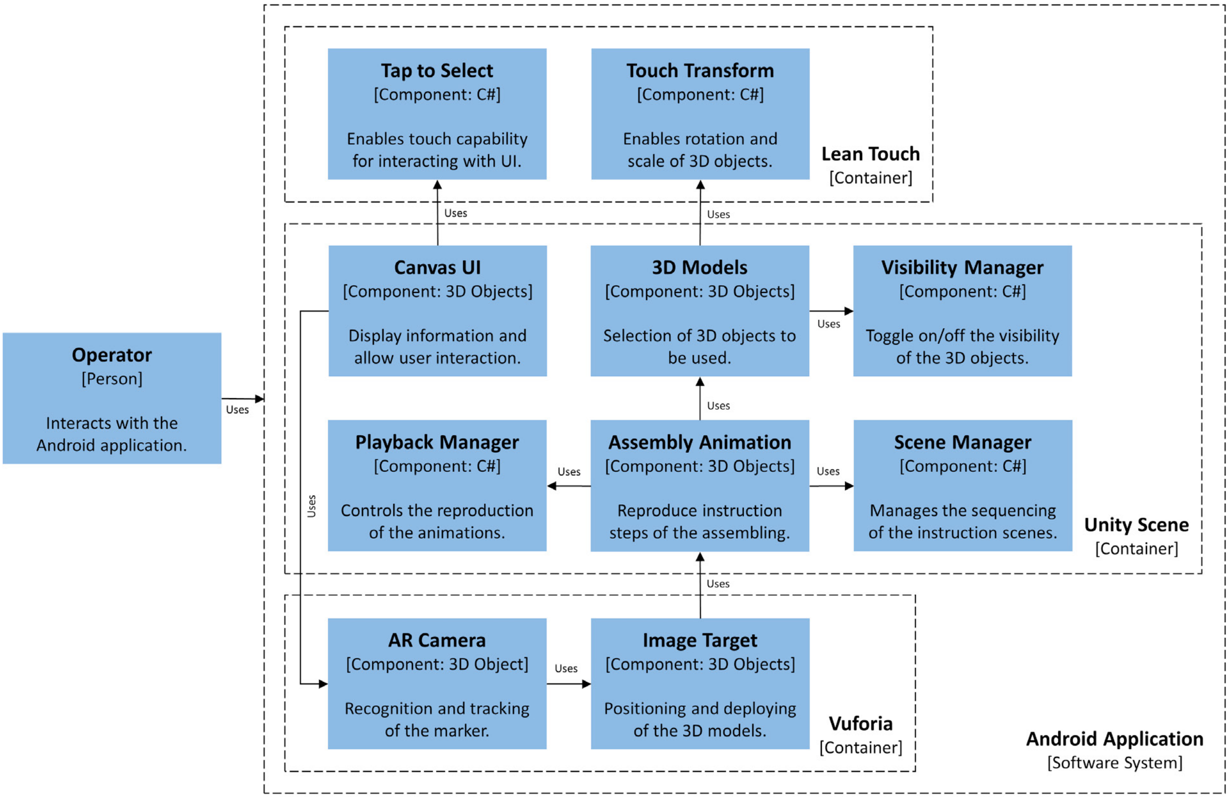

Fig. 2. Software framework for HHD e.g. android device

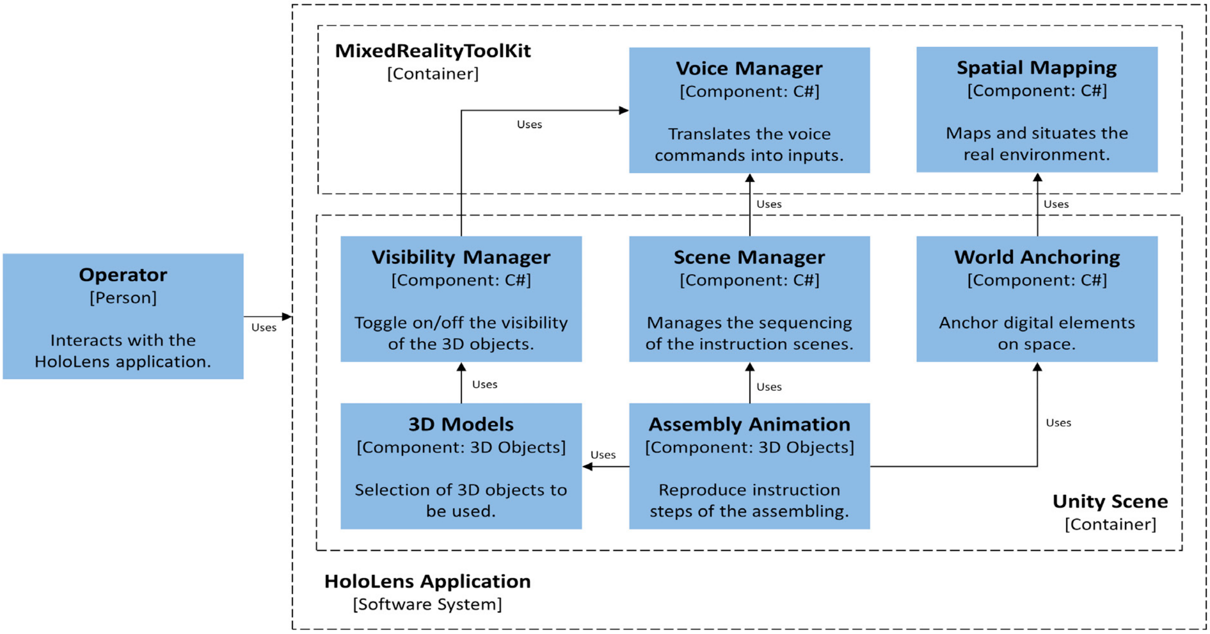

Fig. 3. Software framework for HMD e.g. HoloLens

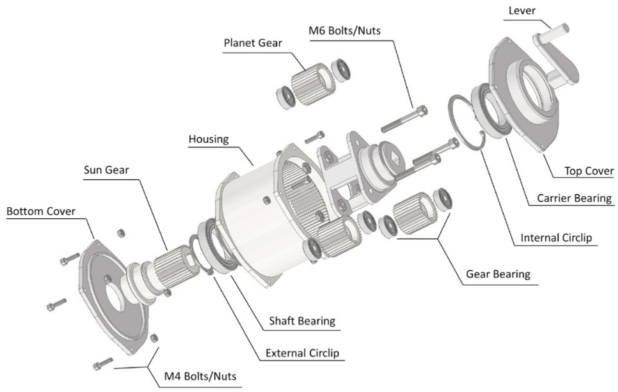

Fig. 4. Exploded view of the gear-box used in the case study

4.1. Android application

In the android application, the instructions to assemble the gear-box are conveyed in a visual manner. The application is installed in an android device (Samsung galaxy A7), the HHD used in this case study. The virtual instructions are overlayed on the real environment for each step of the process. A QR code, which optimized for vuforia tracking, is placed in the real environment for the correct orientation of the virtual instructions. The QR code essentially supports the tracking, recognizing, and orientation of the virtual instructions in the real world. Vuforia adds an image target to the Unity scene, in the form of a fiducial marker, which serves as a reference point for the deployment of the digital information to be augmented. It also includes an AR camera setting to the project that enables the Android device's camera to recognize and track the markers.

The animations can be reproduced and stopped by pressing a playback button in the User Interface (UI), additionally the user can scale and rotate it by pinching with two fingers. Additional information of the parts can be displayed and hidden by tapping each part individually. The UI also indicates the number of parts to be produced in each step on the top right corner. The program is developed from scenes in Unity, which contains all the elements necessary to run it, each step of the assembling instruction is created on a different scene. The user can navigate between scenes by pressing the next and previous buttons on the interface, as shown in Fig. 5. Additionally pause and play buttons are deployed in the UI, in case the operators wants to inspect the assembly steps and parts information before the assembly.

4.2. HoloLens application

As mentioned in section 3, we eliminated the use of markers in the HoloLens application by using spatial mapping technology offered by the hardware itself. Similar to Android application, the virtual instructions on the HoloLens are delivered in animation form with several individual scenes. However, the freedom of having a variable Field of View (FoV) allows the implementation of a couple new features. In addition to animations displaying the work instructions, the HoloLens displays pointers to the parts and the tools used in each assembly step, eliminating the need for labeling the part holders. All these supplementary information streamlines the process of finding and taking parts and tools needed for the assembly. Fig. 6 illustrates the augmented workstation through HoloLens perspective.

Another feature that is different from the android application is that the interaction with the AR system. In android application, we used touch capability enabled by lean touch container. However, touch capability fails while the operator wearing thick industrial gloves. Therefore, in the HoloLens application, we implemented speech interaction modality enabled by MixedReality ToolKit. To prevent overwhelming the user with information, the scene is loaded, by default, displaying only the work instruction. Then, by calling out loud "Parts" or "Tools" the application shows the respective pointers. The same way, the user can say "Next" and "Previous" to navigate through the scenes. We understand that in the noisy industrial conditions speech interaction with HoloLens is not the ideal solution. The future work will focus on the virtual buttons, optical hand tracking, and screen dwell concepts to eliminate the disadvantages of touch and speech modalities.

4.3. System comparison

Two different solutions were developed to solve a same case study problem defined as the training of an operator to assemble a planetary gearbox using virtual instructions. Each solutions differs not only by the hardware employed and the technologies implemented in its software to enable the AR capabilities, but also the way the system is interacted by the user. A comparison between both the AR systems (HHD and HMD) developed in this study are illustrated in Table 2. The features are divided in to three different aspects namely: software, hardware, supported features.

Table 2. Comparison of AR systems (HHD vs HMD)

	Features	Hand-Held Device (HHD)	Head-Mounted Device (HMD)
Hardware	Device	Android device (Samsung Galaxy A7)	HoloLens 1
	Display	Video-see through	Optical-see through
Software	Operating System	Android 8.0 or higher	Windows 10
	Tracking System	Vuforia markers	Spatial mapping (marker less)
	Interaction Modality	Touch	Voice commands and hand gestures
	Field of View (FoV)	Limited	Variable (enabled by operator's head movements)
Supported features	Digital work instructions	✓	✓
	Animation playback	✓	✓
	Animation rotation and scaling	✓	x
	Part and Tool pointers	x	✓
	Portability	✓	✓

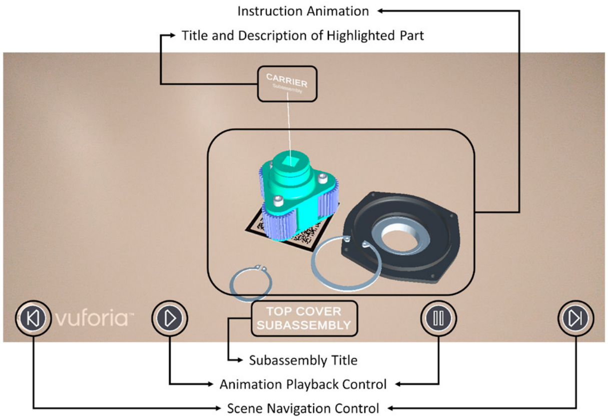

Fig. 5. Android application's user interface

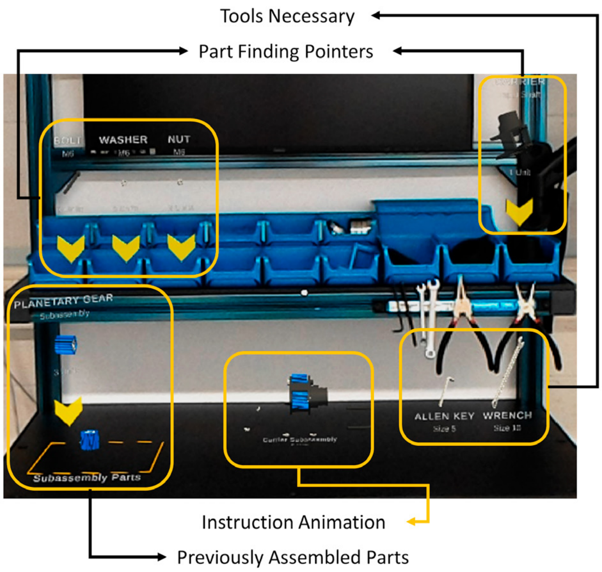

Fig. 6. HoloLens application's user interface

5. Summary

Traditional paper instructions at work is cumbersome and time consuming, especially in the training of new operators. Conveying work instructions through virtual elements in 3D space removes the burden of reading and interpreting written instructions. Additionally, having a visual reproduction of a task to be performed reduces errors prevalent from interpretation divergences. Therefore, both AR systems presented in this work have the potential of outperforming traditional written instructions in training scenarios. This research explored two different software frameworks concerning the development of AR systems for manufacturing with a focus on SMEs. The goal was to develop the AR systems in cost-effective and simple manner using open source software solutions. The C# coding for interactions was manageable with little programming experience. Most of the containers used in both the frameworks comes with C# code that can be adapted to developer's own requirements.

When comparing the solution obtained for HHD with the one for HMD, the limitations of the Hand-Held Device stands out. Fixing the device on a static position defeats the purpose of the Augmented Reality since the animation looses its spatial depth-ness and becomes virtually equivalent to a playback of a regular video of the animation. On the other hand, the HMD solution performed really well for the problem proposed, expanding beyond the instructions by also assisting to find the parts and tools necessary for each step. But this system is not without its own disadvantages, the device is heavy and tiring to wear for long periods. However this problem will be surpassed by technological advancements as new HMD devices are being designed and manufactured by several different developers, which in time will help to disseminate the technology and make it more relatable to manufacturing landscape. Field of View (FoV) is another aspect, where HMD has an unprecedented advantage enabled by the operator's head movement. In HHD, FoV is fixed as the device must be fixed to a holder to solve the case study problem, making some of the additional features in HMD's favor.

In a nutshell, choosing a software framework or the hardware device is based on the problem, capital, in-house skills rather than the advantages and disadvantages of the systems.

For some applications, HHD is a right choice and for some HMD has upper hand.

CRediT author statement

Sri Sudha Vijay Keshav Kolla: Conceptualization, Methodology, Software, Validation, Writing - Original Draft, Investigation, Writing - Review & Editing, Supervision, Project administration. Andre Sanchez: Conceptualization, Methodology, Software, Validation. Peter Plapper: Resources, Supervision, Project administration, Funding acquisition.

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