A Collaborative Industrial Augmented Reality Digital Twin: Developing the Future of Shipyard 4.0

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Abstract. Training of workshop operators and maintenance of industrial machinery is a major expense in large companies, since the lack of this process or its poor execution increase the cost and risks associated with the operation and handling of sensitive and/or hazardous machinery. Augmented Reality (AR), specifically Industrial Augmented Reality (IAR), can be useful in such a context, since it is a key technology in the Industry 4.0 paradigm that can enhance worker performance, reduce risks and improve production processes. This article proposes an IAR digital twin system that provides a dynamic way for industrial companies to perform operator training with a full-size model of the real equipment and to carry out a step-by-step in-situ guidance by adding contextual information and alerts so that maintenance processes are performed more safely and efficiently even by operators with a low level of training. The proposed system also allows several users to use devices simultaneously, providing a new way of collaborative interaction, thus facilitating communications and awareness of the environment. In addition, an Industrial Internet of Things (IIoT) system was successfully integrated with the developed system, enabling real-time interaction with the environment. Since one of the aims of the developed system was to provide a smooth user experience, performance tests were carried out with several simultaneous users by measuring their response latency as the number of connected users increased. As a result, it has been identified the IAR layer of the proposed architecture as the bottleneck of the system, as it has to deal with rendering delays.

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1 Introduction

In recent years there has been a significant growth in what is called Industry 4.0, also known as the Fourth Industrial Revolution. This term was firstly used by the German government in 2011 [1,2]. Collecting as much information as possible from business processes and obtaining intelligence to fuel smart manufacturing is one of the pillars of Industry 4.0. Another goal is to achieve physical and digital world convergence through technologies such as cyber-physical systems or digital twins [3]. A digital twin is a virtual replica of a physical entity that allows real-time monitoring and actuation during operation using data and simulations [4].

Among these new industrial developments, the shipbuilding industry is being constantly updated and is incorporating new technologies into its working processes under the Industry 4.0 paradigm. One of the most attractive technologies for the so-called Shipyard 4.0 [5] is Augmented Reality (AR) (specifically Industrial Augmented Reality (IAR)), as well as Mixed Reality (MR), which provide a wide range of capabilities that can be leveraged in order to construct strong and effective solutions able to integrate virtual components in real-world scenarios.

The aim of this article is to study and test the capabilities that Augmented and Mixed Reality (AR/MR) and the Internet of Things (IoT) (and more specifically the Industrial Internet of Things (IIoT)), can provide in order to ease and optimize production and maintenance tasks in an industrial environment while showing real-time information on top of real objects, leading to the idea of creating a virtual digital twin of a ship or of one of its components. To validate this objective, a demo application for Microsoft HoloLens 2 smartglasses [6] was developed. This application allows for training the workshop operators and to provide a dynamic way of guiding them during the building and maintenance processes of the vessels. In addition, the developed collaborative framework allows workshop operators to learn and share their knowledge in an interactive way.

The rest of this paper is structured as follows. Section 2 reviews the latest AR/MR systems for training and assistance, as well as other proposed digital twin projects. Section 3 presents the design requirements, the communications architecture of the proposed system and relevant details of its implementation. Section 4 describes the performed experiments and validation tests, analyzing the key findings. Finally, Sect. 5 is devoted to the conclusions.

2 Related Work

The digital twin is one of the key technologies for Industry 4.0 together with AR/MR and IIoT, since they provide valuable tools for manufacturing, training, healthcare and smart city environments. As of writing, no mature developments that study and integrate these three technologies have been found in the literature. The following cited works are some of the few examples that have been found regarding the integration of these three technologies.

The authors of [7] present a Proof-of-Concept (PoC) of a smart shelf with a system of QR codes that, when scanned, display on F4 smart glasses a remote Matlab simulation of stress analysis using a network of strain gauges. In [8], the authors define an AR framework as a visualization interface for an IoT infrastructure. Such a solution makes use of standard network localization techniques to find near-by device positions, which are sent to the AR devices for tracking them.

The developments previously described, despite integrating AR/MR and IoT partially, are mostly PoCs and do not use sophisticated tracking and interaction systems such as those offered by the Microsoft Hololens glasses. For instance, HoloLens glasses are used in [9], where the authors propose the integration of MR devices with the Mobius platform, one of the open source OneM2M IoT platforms. However, the development is tightly coupled with OneM2M applications and the authors considered that future work will be required to fulfill the requirements of OneM2M.

With respect to collaborative working environments, only a couple of recent preliminary works on collaborative AR/MR applications have been published in the literature. For example, Chusetthagarn et al. [10] demonstrated a PoC for visualizing sensor data in disaster management systems. HoloLens spatial anchors are used in this project via a built-in sharing prefab offered by HoloToolkit, a Unity package for creating a collaborative AR/MR environment. Regrettably, such an implementation is now deemed deprecated. However, it is important to remember that Microsoft has been working on a Microsoft HoloLens sharing system, which includes, among other features, a UDP-based discovery procedure. Nonetheless, despite the fact that the described Microsoft development is, to the authors' knowledge, the most promising collaborative framework option at the time of writing, it is yet undocumented and still not available after the release of HoloLens 2 [11].

Regarding the application of IAR to industrial scenarios, two of the most frequent applications are training and assistance. For example, operators and supervisors can also use assistance systems to get the visual or acoustic information they need to complete a task [12]. This type of information is sent in a ubiquitous and seamless manner, allowing it to be viewed in a context-aware manner.

It is known that well-trained operators have a major impact on productivity. In this scenario, IAR can assist with training by giving contextual knowledge and step-by-step guidance for completing specified operations. In addition, IAR systems can assist in monitoring the trainees' performance after they have completed a task. When training workers to operate machinery like the one used for line assembly, such support and feedback are critical, because they reduce the time and effort spent checking documentation [13] while also improving the accuracy (e.g., by lowering the error rate in assembly tasks [14]) and efficiency of the completed operation. As a result, IAR can shorten new employee training time and reduce skill needs by substantially reducing the influence of prior experience on the learning process. Furthermore, the presented instructions may be tailored to the workers' past experience. IAR emerges as a human-centered tool in this regard, assisting non-expert and less experienced operators in accomplishing new tasks.

IAR has already been shown to be beneficial in a variety of prior aid tasks, such as robot interaction and guiding systems. For example, while directing a telepresence robot, the authors of [15] employ AR as an improved user interface that uses visual cues to improve users' spatial awareness and give more precise dimensions and distances. AR-based methods for directing robot motions have also been described in other recent studies [16], while [17] provides a comprehensive overview of AR-based remote guiding systems.

IAR systems may also provide rapid access to documents such as manuals, 3D models, and historical data [18]. Moreover, IAR aids decision-making in real-world scenarios by integrating physical experience with displayed data that are retrieved in real-time [19].

More complex methods have been recently presented. For example, an olfactory-based AR system was proposed to assist in the detection of maintenance difficulties [20]. In addition, the authors of [21] want to improve a simulation-based support application by integrating contextual awareness using sensors. Another paper that incorporates IoT interactions is [22], which describes a framework for Microsoft HoloLens smart glasses that simplifies AR and IoT device integration. Additionally, by modeling logical items within a virtualized realm and then connecting such a logic with physical realities, IAR can make a significant contribution towards the definition of the characteristics of a digital twin [23].

In [24] authors develop a tool for Unity to create 3D manuals based on traditional paper manuals used in manufacturing industries. They conducted a study when training operators with different techniques: paper, 3D and AR. They concluded that operators who do not use paper are able to get the right training twice as fast in comparison to traditional approaches. It is important to note that, in such a paper, all tests related to AR were performed with projections on screens instead of with Head Mounted Display (HMD) devices like Microsoft HoloLens smart glasses.

A digital twin environment allows for rapid analysis and real-time decisions made through accurate analytics. Initially the term Digital Twin was first used in the aerospace industry [25], but it quickly spread to other areas. In [26] the authors review the academic literature on digital twins since 2003, showing a rapid growth and evolution both in the definitions and technologies used. Bevilacqua et al. [27] describe the development of a theoretical reference model to create a digital twin for risk management in work environments. It is based on a model that integrates data obtained from sensors, experts and historical data. It aims to improve the safety level of operators in the work environment. In [28] a digital twin for an industrial ice-cream machine is proposed. The system is able to use real data obtained from sensors inside the real machine while it is working, or it can be fed by simulated data for fault monitoring and performance assessment.

Regarding systems that integrate AR/MR within a digital twin system, it is important to indicate that AR/MR is commonly used to optimize the integration of the information provided by the digital twin with the real environment. Just a few articles have been found in literature on this topic: among them, the only one that stands out was written by Aschenbrenner et al. [29], who describe the development of digital twins of robotic arms whose visualization is performed with AR devices.

3 Analysis and Design of the AR/MR System

The main goal of the proposed system is to ease and optimize the maintenance and repair tasks of complex machinery in industrial environments by using the advantages offered by AR/MR technologies. Specifically, the developed system is oriented to enable people with a lower technical level to properly perform complex tasks and in a safer way in a shipyard or a vessel, where the availability of highly qualified personnel may involve high transport costs or important delays.

The AR/MR system can guide step by step the person performing the tasks through visual indications and 3D models in order to accomplish them successfully and with less risk.

The use of 3D visual animations improves and speeds up the understanding of the required steps compared to traditional paper manuals or blueprints and, therefore, allows for optimizing the process and increases the guarantees and lowers the risks for the worker and the equipment.

In addition, a digital twin experience was included on the system, making use of the IIoT to integrate real-time information and interactions between the virtual and real models.

The AR/MR system also has the capability of sharing the experience among multiple users, allowing them to interact and see the same pieces and animations at the same time.

3.1 Design Requirements

There are several requirements and features that are desirable for the proposed system and which are mainly related to 3D modeling and the IIoT subsystem, since they are key components of the digital twin experience:

3D Model Requirements

- Visualize 3D models aligned with the real world using the Microsoft HoloLens Smartglasses.
- Seamless user interaction with the virtual environment using the hands to make gestures and manipulate the objects.

- Visualization of 3D animations illustrating different steps of the process.
- Text information and warnings about important or dangerous steps.
- Option to scale and move the object from the original position.
- Menu that follows the user around.

IIoT Requirements

- Get real time data and parameters from the real machine.
- Show visual labels with the data from the IIoT system.
- Allow interaction with the real world through the IIoT system when something changes in the virtual environment.

Shared Experience Requirements

- Allow several users to use the same experience at the same time.
- Align virtual object between the different AR/MR devices and keep them in sync when they are moved, rotated or scaled.
- Keep the status of all the virtual elements synchronized across all the connected devices.

Figure 1 shows the different modules of the designed system as well as the communications architecture. The IIoT layer is composed of the different sensors and actuators that comprise an IIoT network. It can be physically located in the same area where the AR/MR visualization application is running, or it can even be in a different location.

The service layer is in charge of coordinating all the processes as well as managing the different protocols used by the heterogeneous devices. It consists of three subsystems:

- IIoT Service: it is in charge of the communications and management with the IIoT layer. It makes use of the MQTT API through an MQTT broker called Mosquitto [30]. It handles requests related to IIoT data and commands coming from AR/MR devices through the HTTP API. If it is necessary to forward the request to the IIoT layer, it is also in charge of the translation and adaptation of the requests between the AR/MR layer and the IIoT layer. It also takes care of the persistence of the sensor data thanks to a MongoDB database.
- Anchor Sharing Service: this is the service that manages shared AR/MR experiences, ensuring that all devices use the same environment tracking information. To do this, it is necessary to share some data packets called anchors among the devices. These packets are generated at an end device and contain the spatial information necessary for any other device to be able to recognize the environment and to position itself in the same spatial reference system. The Anchor Sharing Service also manages the persistence of the anchors and the distribution of each one to the corresponding devices through the REST API.

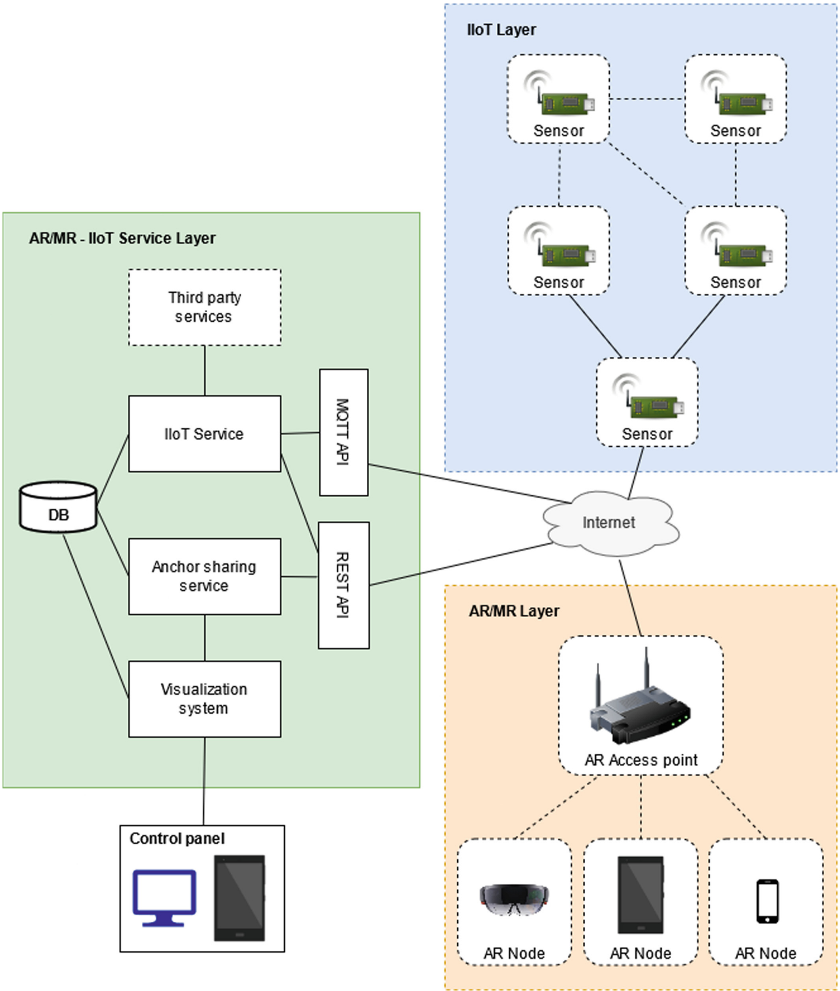

Fig. 1. Architecture of the proposed system.

– Visualization System: this system consists of a control panel that allows the user to visualize the status of the system and the active anchors and sessions at any given moment in time.

The AR/MR layer is composed of the end AR/MR devices (smart glasses or tablets) that users utilize to visualize the 3D information and animations, and to interact with the additional information provided by the IIoT system.

3.2 AR/MR Development

In order to show the capabilities of the proposed system, an application was developed for Microsoft HoloLens smart glasses that allows for visualizing the

3D model of a cooler. The developed solution was aimed at creation of a digital twin that will provide indications on repair and maintenance processes, and will show operation parameters that are measured in real time by hardware sensors embedded on the cooling unit.

The development was carried out using Unity [31]. All models were exported from the source CAD programs and then manipulated and optimized for the augmented reality experience using Blender.

The development was structured in different stages. First, the models were exported and polished in order to optimize them for running on AR/MR devices. In general, CAD models are designed parametrically and contain a very high level of detail. Due to the characteristics of the real-time rendering engines used by AR devices and the limited computational capabilities of embedded devices, a geometry cleaning process is required, which in many cases cannot be fully automated. An example of optimization of one of the parts of the 3D model is shown in Fig. 2, where the original and final models are compared.

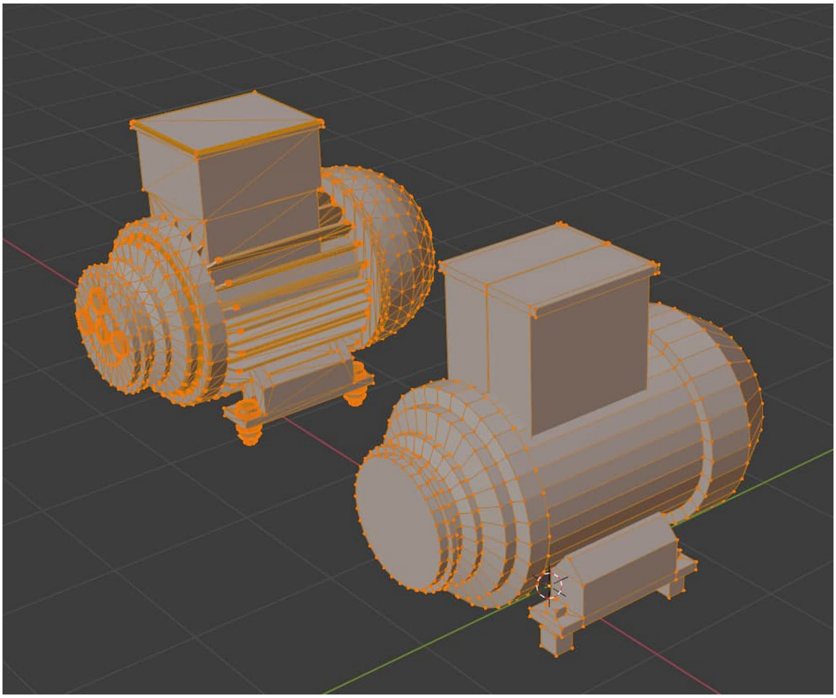

Fig. 2. Optimization example of one of the parts of the 3D model.

In a second stage the model was integrated into Unity and a user interface was developed to manipulate the 3D model and interact with the scene. For such a purpose, the design and interaction recommendations of the HoloLens framework [32] were implemented, thus making the panel follow the user and face him/her.

In a third stage the animations and contextual information for each step were added, including alerts and interaction with the user during the included maintenance or repair processes.

Finally, the sharing system was introduced, allowing several users in the same location to interact with the application at the same time (this collaboration is illustrated in a real scenario in Fig. 3 during the system tests). All users share the same spatial reference system, so that all virtual 3D objects are aligned with reality and, at the same time, they are synchronized among the different devices in such a way that if one user moves the 3D model, it will be moved instantaneously in all the devices that share the same experience. In the same way, the interactions of a user with the model have an effect on the instances of the model in the rest of the devices, favoring communications and collaboration between users.

Fig. 3. Collaborative interaction with the 3D model of the cooler.

To implement the sharing system, a framework to facilitate the communications among the different devices is needed. Unity provides a framework called UNet [33] that allows for creating different virtual elements and for keeping their movements synchronized, providing a set of tools for online game development. Its major drawback is that it is deprecated since 2018 and will soon no longer be available in Unity. As an alternative, there is an open source framework called Mirror [34], which enables collaborative games in Unity, allowing communications between two nodes in a local or remote network. Mirror provides an abstraction layer that allows for synchronizing different parts of the virtual environment in a relatively simple way, removing the complexity associated with handling network operations as discussed in [35]. Due to the previous reasons, and since the programming interface is compatible with Unet and due to the large number of users currently using it, Mirror was the framework selected for the development of the proposed application. In addition, since Mirror is open source, the code will be always available and can be modified in case any change is needed to fulfill the development requirements.

3.3 IIoT Integration

The IIoT Layer is responsible for interconnecting the AR smart glasses and IIoT devices. In order to be compatible with other applications and sensor networks, the use of a secure communications system based on HTTPS is proposed. The HTTP protocol is natively implemented in most AR/MR development environments and facilitates its integration with existing system components. The use of other IIoT-oriented protocols could be tempting, but it is not always straightforward to implement such protocols in the development environments available for AR/MR frameworks, as it is explained in [36]. Moreover, HTTP is not appropriate for sending the large amounts of data that are often needed in 3D AR and MR environments.

The IIoT service can be deployed in the cloud or using cloudlets (i.e., powerful local computers that act as Edge Computing devices). This helps by reducing latency times as the services can be placed closer to the client and, in scenarios with a large number of connected devices, it helps to reduce the amount of traffic generated to the cloud server as data can be preprocessed or aggregated by cloudlets before is sent to the cloud. Specifically, the IIoT services were implemented on top of NodeRed [37], which allows for an easy integration of the different technologies involved. As it can be seen in the architecture diagram (Fig. 5), IIoT devices communicate with the service using an MQTT network, since it is currently one of the most popular technologies for integrating IIoT sensors and actuators. Such an integration makes it compatible with many existent solutions. On the other end, the AR/MR devices communicate with the service by using a REST API via HTTPS for compatibility reasons, as discussed before. The NodeRed service is in charge of keeping the state of the system, converting between protocols and acting as an interface that connects with the persistence layer or database.

As an example, Fig. 4 shows the implemented virtual panels that display real-time information from the IIoT sensors located on the real cooler.

4 Experiments

In order to determine the performance of the proposed system, a testbed was designed using a pair of HoloLens 2 glasses and a desktop computer to determine how a large number of users impacts the latency of the system.

The Mirror framework used to implement the AR communications can be used to develop both desktop and embedded applications. Thus, the resulting communications system is interoperable between heterogeneous devices. This

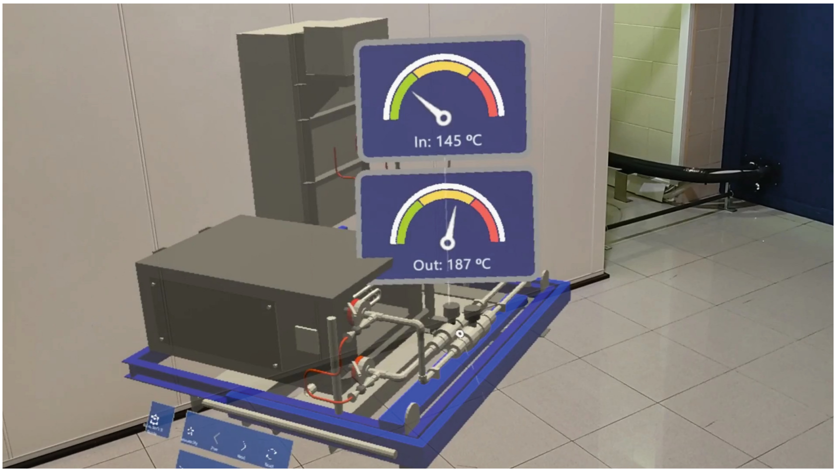

Fig. 4. Virtual panels where the information about a valve is displayed.

allows for developing a graphical desktop application that emulates the communications of a device. Launching several instances of such an application causes the load to increase progressively, in the same way to what would happen if more AR/MR devices were connected to the system and moved around the virtual environment.

Regarding IIoT communications, they are composed of an MQTT part (in the IIoT device layer) and an HTTP part (in the AR/MR device layer). In order to find the most restrictive component of the system, the same previous setup was used (Hololens 2 and a desktop computer). A set of benchmarks was executed in order to determine independently the performance of the MQTT broker (Mosquitto) and the HTTP server (NodeRed) and to obtain the average latencies as the request demand increases. Since the number of requests grows with the number of users, the performed tests can give an idea of the scalability of the whole system.

The technical characteristics of the devices used for testing are the following:

- Desktop computer: Intel Core i7-7700 3.6 GHz (8 cores) CPU, 16 GB RAM and an NVIDIA GFORCE GTX 660 with 2 GB of DDR RAM.
- Router: Sagemcom F@ST 5366S 5G Gigabit (IEEE 802.11 a/b/g/n/ac).
- AR glasses: Microsoft HoloLens 2 (Qualcomm Snapdragon 850, Wi-Fi (IEEE 802.11 ac (2×2)), 4 GB of LPDDR DRAM).

In Fig. 5, the architecture of the designed experimental setup is depicted. At the top are all the emulated clients, which store their measurement records into a database where they will be processed and analyzed.

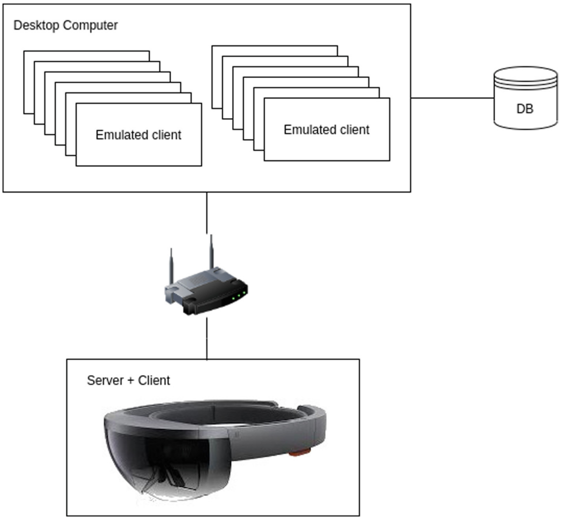

Fig. 5. Diagram of the setup for the experiments.

4.1 AR/MR Layer Experiments

This first set of tests were devised to determine how the developed system behaves depending on the number of contacted users. For such a purpose, the average latency of all connected clients was recorded for different scenarios (5, 10, 15 and 20 simultaneous users). Moreover, a 5 GHz and a 2.4 GHz WiFi network was used for each of the scenarios in order to compare the performance between both of them.

The simulation environment also emulates the 3D model rendering process in order to perform the measurements when considering all the delays that a user would experience during the execution of the application. This means that there is a limit when adding more users, as the computational load of the test computer increases gradually until it reaches a point where the high computational load might compromise the results.

It should also be noted that the evaluation testbed measures the latency since the packet is encapsulated on the source device, until it is processed on the target device and its contents are rendered on the screen. This means that the latency times shown on the results do not include only network latency, but also rendering times and, in many cases, waiting times related to the refresh rate of the device screen. This ensures a more accurate measurement of the response times that a real user would perceive when using the application.

Tables 1 and 2 show the latency measurements taken for both 2.4 and 5 GHz, respectively. On both cases average latency increases as more clients are added to the same shared experience and, as it can be expected, 5 GHz latency is lower. On the other hand, the standard deviation is almost the same on both scenarios and variance is small, which implies that there is a good and stable connection between the smart glasses.

Table 1. Latency experimented by a user on a 2.4 GHz network (ms).

Clients	Average	Standard dev	Variance
5	25.6712	13.4464	0.24392
10	43.9239	20.4037	0.50026
15	64.1954	28.2183	0.87689
20	89.7708	34.7472	1.36900

Table 2. Latency experimented by a user on a 5 GHz network (ms).

Clients	Average	Standard dev	Variance
5	22.4897	13.5303	0.25951
10	37.6301	21.4463	0.562
15	58.6853	32.2307	1.17312
20	82.4164	41.6821	1.86244

4.2 IIoT Layer Experiments

The second set of experiments was devised to be less restrictive than the ones related to the AR/MR communication due to the nature of IIoT data, since IIoT payload are usually light and spaced in time at regular intervals. In order to determine the capacity of the system, two mock endpoints were designed for MQTT and HTTP, and a script was used to simulate the existence of several clients simultaneously. In order to simulate the worst-case scenario, each client launches consecutive requests concurrently and independently of the others without waiting times.

In Fig. 6 it can be clearly seen that MQTT outperforms HTTP. This is expected, since MQTT is a lighter protocol and more suitable for the type of data handled in the IIoT layer. It can be observed that Mosquitto is able to handle more than 200,000 packets before it starts losing some of them. In contrast, NodeRed was able to handle a maximum of 1,500 requests per second.

These results show that MQTT is not going to be the limiting factor in the system. Nonetheless, it should be noted that the capacity of handling 1,500 requests per second is more than enough for most industrial scenarios.

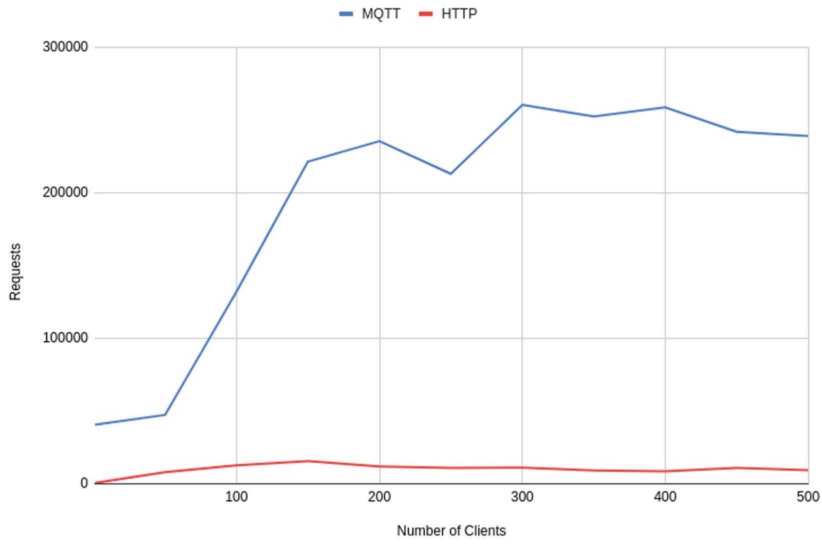

Fig. 6. Linear representation of the number of attended by the system according to the number of concurrent users.

4.3 Results

The obtained results show that slightly better times were obtained in the 5 GHz band, as expected due to the characteristics of such a band and the lower saturation of its spectrum. In any case, it can be observed that all latencies in the AR layer are below 100 ms. It is important to note that these times not only include the network latency but also add rendering times, so these times will be close to the real delays a user will experience when using the developed application.

It has also been determined that the response delay limiting factor is located in the AR layer, as it works with large amounts of data and includes processing times that are almost negligible for the IIoT layer. However, it is important to note that these results are only representative for the described setup. It is viable to vertically scale the system, adding more computational capacity, as well as horizontally, scaling by distributing the load among different devices. Specifically, in the AR/MR layer, the proximity characteristics of the generated and consumed data allow for moving the computation load closer to the end user by using cloudlets, which would greatly improve performance and further reduce the latency experienced by the user [38].

5 Conclusion

The use of IAR along IIoT and digital twin technologies can become an important part of Industry 4.0 factories but, as of writing, the literature includes a small number of systems that make use of such technologies when focusing on maintenance, training and assistance processes. To tackle the previously mentioned issues, a collaborative IAR system for training and guidance in assembly processes was created specifically for this article. After describing the proposed communications architecture, the implementation based on Microsoft HoloLens smart glasses was detailed, including the IIoT integration that led to the development of the digital twin system. The IAR digital twin system was evaluated to determine its limitation capacities. The limiting aspect has been identified as within the IAR layer, which deals with bigger volumes of data and involves rendering delays that are nearly non-existent in the IIoT layer. As a conclusion, some best practices and lessons learned are outlined to guide future IAR developers.

Regarding future work, it will be focused on improving the interaction with the IoT system from the AR application. In addition, some experiments in terms of usability and user performance in industrial scenarios will be carried out, as well as security and network performance of the different protocols used on the system.

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