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RESEARCH ARTICLE

Health-5G: A Mixed Reality-Based System for Remote Medical Assistance in Emergency Situations

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ABSTRACT Mixed reality is the combination of virtual and augmented reality to interactively and believably merge physical and computer-generated environments. This paper discusses the design of Health-5G, a scalable mixed reality-based system that facilitates and supports emergency response by medical emergency teams. Health-5G is supported by a distributed architecture divided into four interrelated applications responsible for advanced computer-human interaction, effective real-time videoconference, medical device integration, and communication infrastructure, respectively. The mixed reality layer is provided by the headset Microsoft Hololens 2™. Health-5G is based on scenarios in which emergency personnel wear mixed reality glasses that can transmit audio, video, and data streams bidirectionally over a 5G network to medical specialists stationed in a hospital at any distance. Thanks to Health-5G, the specialist will be able to access the emergency team's point of view at any time and provide verbal and visual instructions, including gestures and positioning of graphical markers in 3D space. In this way, emergency personnel can provide the best possible care to the patient without having to wait for them to arrive at the hospital, saving a lot of time in scenarios where every second can make a difference. Health-5G also addresses the integration of medical devices and the collection of the patient's medical data in a scalable way through optical character recognition. A case study is discussed where Health-5G is used to attend a patient in the street suffering from syncope due to third-degree atrioventricular block. Latency and performance tests over a 5G network are also discussed. To the best of our knowledge, there is no comprehensive solution in the literature that provides all the capabilities offered by Health-5G in terms of functionality and advanced interaction mechanisms within the context of remote, immersive support in emergency situations.

INDEX TERMS Mixed reality, teleassistance, 5G, visualization.

I. INTRODUCTION

In recent years, more and more applied research work on the use of mixed reality (MR), which results from the combination of augmented reality (AR) and virtual reality (VR) [1], has been published. While in traditional AR the synthetically generated information is simply superimposed on the real world, in MR the virtual and physical environments are fully integrated in order to allow natural and intuitive interactions between users and the computer-generated virtual world.

In the last few years, MR has become very popular, to the point that it is being applied in fields as diverse as video games, industry, marketing, education, and healthcare, among others. Particularly, this technology is also impacting

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on the current healthcare paradigm, speeding up diagnoses, reducing time to care, increasing personalization, and improving outcomes.

As an emergent technology, MR has a great potential in the area of telemedicine, teleassistance and telementoring. Telemedicine focuses on the remote delivery of healthcare services to patients, allowing them to access medical advice and treatment without being physically present. Teleassistance focuses on providing immediate remote support and guidance during medical procedures, primarily targeting real-time interventions. Finally, telementoring is more focused on remote mentoring, skill development, and professional growth of healthcare professionals or students [2]. Thus, the specific context in which the present research work is framed is that of teleassistance in emergency situations. In particular, the aim is to provide an emergency team with the ability to effectively receive real-time medical support from a medical specialist placed in another physical location, such as a hospital.

Figures 1.a and 1.b provide a visual representation of this situation. In Figure 1.a, the reader can see an injured person being treated by the medical staff of the mobile medical unit that responded to the emergency call. The medical emergency team is normally composed of a physician and two emergency medical technicians or paramedics. Note that one of the paramedics is wearing MR glasses. In certain situations, depending on the nature and characteristics of the emergency, the emergency team may need to be assisted by more specialized medical personnel. Typically, the specialized personnel will be physically located at their workstation within a hospital environment, as shown on Figure 1.b.

This support could be provided with traditional solutions based on audiovisual communication via audio and video streams, i.e. real-time videoconferencing. In this context, the medical specialist would be able to see and hear what the paramedic see and hear. However, this approach is limited by two relevant aspects: i) the specialist cannot interact with the emergency team beyond the guidelines they can provide verbally, ii) the attending paramedics do not receive visual feedback that would greatly facilitate the effective application of the medical protocol offered by the remote staff.

The solution proposed in this research work, named Health-5G, relies on a MR-based system that enhances the care capabilities of the emergency unit, thanks to the support provided by the hospital's specialized medical staff. As will be discussed below, the scalable architecture underlying the proposed solution is based on a real-time communication infrastructure deployed over 5G networks.

More specifically, the adoption of an approach based on MR allows the real-time integration of virtual 3D objects in the real environment. In this way, MR allows the technical staff of the emergency unit to visualize and follow protocols based on the indications and actions carried out remotely by the medical specialists. The actions and recommendations associated with these protocols are integrated into the real world thanks to the use of MR glasses, as shown in Figures 1.c and 1.d. The user of the MR glasses will be able to see computer-generated virtual images, perfectly aligned with their perception of the real world, which will help them perform medical assistance tasks.

FIGURE 1. General outline of the users of the system and the interactions between them. a) Emergency unit deployed in the field; b) Medical specialist located within an hospital; c) Synthetic information added over the video stream, medical specialist offering oral and visual instruction to emergency personnel.

For example, Figure 1.d visually reflects, at a high level, the interactions that take place between the mobile team personnel and the medical specialist. These are as follows: 1) observation of the patient, 2) communication between the emergency team and the medical specialist, 3) feedback given by the medical specialist based on the perception of the real world sent by the system, 4) application of the appropriate medical protocol. In addition to the transmission of video and audio, the image shows augmented information about the visualization of the real world made by the person wearing the MR device. On the other hand, Figure 1.c shows how the system would again add virtual information to the video stream that the medical specialist receives from the mobile emergency personnel. This scheme would facilitate communication and interaction between the two parties. The advantages of this proposal can be summarized as follows: the specialist will be able to give precise oral and visual indications to treat the patient without having to wait for the patient to arrive at the hospital or medical center, saving a lot of time in situations where every second can make a great difference.

Health-5G, the proposal discussed in this paper, is supported by a scalable architecture based on the distributed computing paradigm, which is divided into four interrelated applications: (i) Health-5G_Holo, deployed on the Microsoft Hololens 2™ MR device and used by the emergency unit to communicate and receive instructions, (ii) Health-5G_Desktop, deployed on the computer used by the remote medical staff, (iii) Health-5G_Client, running on a processing device embedded in the emergency unit and responsible for collecting data from the medical devices in the emergency unit (e.g. ECG data), (iv) Health-5G_Server, deployed in the cloud and responsible for sending/receiving data to the rest of the applications. At the time of writing this paper, and to the best of our knowledge, there is no comprehensive solution in the literature that provides all the functionality and interaction mechanisms offered by Health-5G within the context of remote, immersive support in emergency situations such as the one described in Figures 1.a and 1.b.

Health-5G was tested in an emergency situation coordinated by the medical staff of the General University Hospital Nuestra Señora del Prado (Talavera de la Reina, Spain) and the Emergency and Healthcare Transport Management of the Health Service of Castilla-La Mancha (Spain). The scenario simulated the medical care of a patient with respiratory problems and chest pain by an emergency unit supported by hospital medical staff. A 5G communication infrastructure was deployed to connect the different applications that compose Health-5G. The feedback from both medical parties was very positive regarding the added value that Health-5G provides, as well as its level of immersion thanks to the use of MR and natural user interfaces. On the other hand, this paper discusses in detail a whole series of experiments conducted to measure the latency and performance of Health-5G, taking into account the real-time communication and interaction requirements needed to successfully manage medical emergencies.

The rest of the paper is organized as follows. Section II provides a state-of-the-art review of the main existing contributions in the field of MR in telemedicine. It also includes a survey of research work where real-time communication infrastructure is particularly relevant in telemedicine and teleassistance. Section III provides a detailed discussion of the architecture designed to support the functionality offered by Health-5G. It addresses issues such as the integration of medical devices, communication based on WebRTC technology, and the use of the human-computer interaction mechanisms employed. Section IV is focused on user interface and user experience. Section V describes the experimental results obtained, reflecting both the case study design and the latency and throughput tests performed. Section VII discusses the limitations of our proposal. Finally, Section VIII presents the conclusions reached and outlines a number of lines of future work to give continuity to this research.

II. RELATED WORK

There is a considerable amount of work published to date that is focused on the use of MR, AR, or VR in the fields of telemedicine, teleassistance and telementoring. Most published work on these subjects relies on AR, which is based on the superimposition of a layer of virtual information over the real world. However, in recent years, more publications on MR, which combines AR with VR, are attracting interest. One of the main differences between MR and AR is that in AR objects are simply positioned in the environment and occlusion relationships between virtual and real objects are not taken into account, whereas MR integrates the model of the virtual environment with the real one, taking into account factors such as occlusions [3].

Extended reality systems can be of interest in this context by providing useful information to the user with or without the direct intervention of professionals remotely (usually by videoconference), by relaying images and audio to guide highly skilled procedures, such as a specific diagnosis or the performance of surgical or emergency interventions such as the transfer of a critical patient by ambulance [4].

Among the papers presenting systems to assist in interventions without using videoconference, the proposal made by Li et al. stands out [5], which compared an AR-based navigation system with a traditional one for endoscopic sinus and skull base surgery. The AR-based system provided rhinologists with more detailed and intuitive visual information, reducing the surgeons' decision time and mental workload when performing complex surgeries. A weakness of this work is that it was focused on the so-called *display mode*, and the interactive capabilities of the proposal are very limited.

In line with the current topic, Lu et al. recently published a paper detailing their experience of utilizing MR in the orthopedic surgical workflow across different scenarios such as preoperative planning, intraoperative guidance, surgical navigation, and telesurgery consultation [6]. The study makes use of Hololens 2 and describes in detail the different modules comprising the system, including Data Collection and 3D Reconstruction, Cloud-Based 3D Model Storage and Rendering, and MR Holographic Imaging.

Another noteworthy study involving the application of MR in medical interventions is that of Mitani et al [7]. This study represents the first reported use of this technology in the field of otolaryngology, specifically for tumor resection. HoloLens 2 devices were utilized for each physician, allowing for the sharing and visualization of the same holograms, alongside an associated system for the generation of specific 3D holograms to aid in preoperative planning and during the intervention.

To conclude the review of the relevant works on this subject matter, in 2021, Ivanov and colleagues reported another instance of the HoloLens 2 device being utilized for surgical interventions and preoperative planning, specifically for median neck and branchial cyst excision [8]. In this case, markers are used for better hologram positioning, and additional third-party software (Maya, Houdini) is employed for hologram generation.

Unfortunately, most of the research cited so far suffers from a major limitation: they tend to focus on 3D visualisation through holograms, but their interactive capabilities are very limited or non-existent. This is an important shortcoming that is addressed in our contribution.

Moving on to telemedicine and teleassistance systems based on videoconferencing, the study published by Wang et al. can be found [9], which presents a HoloLens 1-based system that allow to make a videoconference and the remote intervention of the medical expert through a 3D model of a hand that mimics the doctor's gestures. For video recording it uses the native HoloLens MR Capture (MRC) functionality, for communication it uses UNET, Unity's multiplayer network system (deprecated today) and for the collection of hand gestures the Leap Motion device. Overall positive results were obtained, but this study has some limitations that the authors point out, such as the use of a local network due to bandwidth problems, some discomfort when using the glasses or the scarce documentation for the development of applications for HoloLens 1.

The work by Andersen et al. [10] shows a system (STAR, System for Telementoring with Augmented Reality) that allows a mentor to remotely position annotations in the field of vision of doctors to direct them during surgery, resulting in improved concentration and other variables. This is done using a tablet that acts as an AR device. On the other hand, Davis et al. [11] applied AR to telemedicine. In this case, the problem of telesurgery and its high costs compared to telepresence, i.e. the intervention of a doctor remotely via videoconferencing, is raised. The study uses the VIPAR (Virtual Interactive Presence and Augmented Reality) system to communicate doctors in Vietnam and Alabama, a system that allows, in addition to establishing a videoconference, highlighting important anatomical parts and providing complex technical demonstrations for the other doctors remotely.

Recently, Zhang et al. presented a study on the application of MR in telemedicine for remote collaboration in neuroendoscopic procedures [12]. The system consists of a local video processing station, a MR head-mounted display (HMD), and a remote mobile device connected through 4G or 5G. The study describes the system's setup, analyzes video latency, technical feasibility, clinical implementation, and potential future business models. The system was used in 20 neuroendoscopic procedures with satisfactory results, achieving a delay of only 184 ms when using 4G and an average of 23 ms when using 5G. Markers were easily placed by remote instructors and visualized by local surgeons, enabling distance collaboration between Boston, Massachusetts and Jingzhou, China. However, there is no discussion about the dependencies on MR hardware devices and the underlying software libraries, which is a challenge in real environments.

Another recent study related to remote assistance and telementoring using MR is presented in the work by Tadlock et al. in 2022 [13], which explores the impact of this technology on combat casualty care-related procedures. The authors introduce a system composed of different devices, including HoloLens 2, HYC Vive Pro VR Headset, and additional cameras to record the environments of both novice participants and mentors. The use of this system was compared to the usual procedure (audio-only mentoring) using a 5-point Likert scale-based questionnaire. In this initial feasibility study, no improvements were found when using the MR system, which could be due to the small sample size and the limited variety of novice types. A limitation of this work, addressed in our proposal, is the impact of synchronous communication when supporting clinical staff.

The use of AR for triage in emergency settings is explored by means of a similar system [14]. The results were that registration using the AR glasses was 92% accurate compared to 58% for the traditional method, although it took more than twice as long as the traditional method to triage patients.

Finally, it is worth reviewing the network infrastructure used in other research works to support real-time communication in telemedicine systems. A relevant tool is represented by WebRTC, an API that allows P2P communication of audio, image and binary data in real time. Web RTC offers low latency and is compatible with the most recent web browsers, making it ideal for videoconferencing.

However, there is not much work using WebRTC in real applications for telemedicine and teleassistance services. In a previously reviewed publication by Wang et al. [9], it is noted that in general, when adopting WebRTC, the design and implementation details are very abstract and it is difficult to know which WebRTC components are being used. In the same work, they tried to use WebRTC but failed to integrate it with the game engine Unity.

Another publication by Jang-Jaccard et al. [15] describes a case study of the development of a videoconferencing system for use in a real telemedicine application based on WebRTC, enabling communication between healthcare staff and patients. The application consisted of a web-based application and mobile devices with Google Chrome were used to use the system. This is a very comprehensive study, being one of the first and few works that exposes in detail the architecture and implementation of such a system. Some limitations of this study are that the video calls only allow for two participants, and that the overall system is not prepared for a high volume of users. It is also worth noting that no measurements were made regarding latency or quality of the video calls.

Antón et al. published a paper presenting a system called *KinectRTC*, based on Microsoft Kinect and WebRTC for the purpose of telerehabilitation of patients through videoconferencing and multimodal data streaming [16]. It was noted that in unfavourable scenarios (e.g. long-distance network), high latencies and packet losses were anotated, and it was also registered that the variability in the network state significantly affects the data transmission, with differences in performance at different times between the same locations. So, the system was developed to adapt the information sent according to the bandwidth of the used network.

Within the communications section, in addition to WebRTC, there are other technologies to achieve a full-duplex connection in real time, although not all of them meet the requirements of this type of applications. The most popular ones, apart from WebRTC, are HTTP Live Streaming (HLS), Dynamic Streaming Over HTTP (DASH), Real-Time Messaging Protocol (RTMP), and Real Time Streaming Protocol (RTSP). Some works that use these technologies with themes related to telemedicine and video streaming or the establishment of videoconferences will be presented below.

An interesting work in this regard is the aforementioned study by Wang et al. [9], that presents a system that uses a HoloLens 1 device which allows establishing a video conference and remote guidance through a 3D hand model. In said work an appendix is provided in which the problems encountered when implementing a videoconferencing system in HoloLens are reported, as well as the different options that were evaluated. First, they tried WebRTC, but they had trouble integrating it into their project, resulting in very poor performance on an iPhone and also having incompatibilities in some of the HTML5 components. The next protocol they tested was HLS, which they managed to make work correctly, but with the trade-off of excessive latency time. The next options were RTMP and RTSP. RTMP required a flash player on the client side, which was very restrictive in terms of compatibility with other platforms plus they failed to integrate it with Unity. They were finally able to use RTSP in Unity through a plugin called AVPro Video, achieving very low latency streaming. They also used the DASH protocol (Dynamic Streaming Over HTTP) to reduce the latency in sending the video collected by MR Capture to the HoloLens device.

The study carried out by Teng et al. exposes a telemedicine application for streaming video captured by a camera to a virtual reality headset [17]. In this case they use the "Acer Windows MR" headset and use the RTSP and HLS protocols to achieve integration with virtual reality, since RTSP itself is not generally supported by VR applications. Despite achieving good results, the latency problem when using HLS makes an appearance again, registering a minimum delay of two seconds, and noting this point in the future work section as one of his priorities to improve.

Finally, it is convenient to cite one of the most notable works due to the amount of detail it provides. Such research work presents a system capable of collecting and transmitting 3D videos captured by a paramedic helmet and displaying the video on a remote computer with a stereo effect [18]. In this case, the protocol used for video streaming is RTSP. He also briefly reviews the different technologies for this purpose, noting that HTTP-based protocols, such as Apple's HLS, despite their high compatibility, have the disadvantage of adding latency to the stream, unlike RTSP or RTMP, which are low latency but are not always compatible with most online and local players.

Lastly, it is worth highlighting the field of 5G and its recent application to the field of telemedicine. Some interesting studies related to the use of this novel 5G technology in the areas of teleassistance and telemedicine will be presented.

The healthcare industry is rapidly growing, and the increasing number of remote-end applications requires a powerful communication network to connect patients, healthcare professionals, medical equipment, and other stakeholders for effective information sharing [19]. In this regard, 5G mobile networks are expected to revolutionize telemedicine and transform the future of healthcare delivery. High speed, high capacity, ultra-low latency, seamless connectivity, high reliability, and low power consumption are among the key features of 5G [20].

In relation to the topics addressed in this work, it is worth noting some interesting points regarding the direct application and usefulness of 5G technology in healthcare [21]. In the fields of extended reality, high data rate and channel capacity are required to stream VR and AR contents with high throughput in AR, MR, and VR applications. Low latency is crucial for real-time applications. A significantly high bandwidth is necessary for high-resolution 360° immersive video streams, and seamless connectivity is required to ensure the availability of these applications.

Recently, Zhu et al. presented the first experience of using a MR and 5G-based system in a surgical intervention of an Inferior vena cava filter [22]. The article emphasizes the advantages of 3D holograms over traditional methods that use physical image models, which need to be constructed, sterilized, and are more difficult to handle. Moreover, with the help of 5G communication, it is possible for experts to remotely guide the doctors present in the surgery by visualizing holograms and the viewpoint obtained from the camera of the glasses in real-time and with minimal delay.

In a previously mentioned work published by Lu et al. [6], 5G technology is also used to support collaboration among physically separated specialists. The system presented in the work employs a 1 Gb/s 5G network and successfully enabled 4K resolution video conferencing and the transmission of 3D holograms and additional information. In this regard, another previously cited work also presents a system which employs 5G, in addition to 4G, to perform remotely guided surgical interventions using MR, highlighting that the system was approximately 8 times faster in transmitting images and information when using 5G compared to 4G [12].

III. HEALTH-5G ARCHITECTURE

The architecture of Health-5G is based on a distributed computing paradigm. Particularly, Health-5G is composed of four applications with differentiated responsibilities divided into two different areas: i) advanced computer-human interaction based on MR and effective support for videoconference and ii) support for medical device integration and communication infrastructure.

Regarding the first area, Health-5G relies on Health-5G_Holo and Health-5G_Desktop:

- Health-5G_Holo. MR-based application that runs on the headset Microsoft HoloLens 2, which is used by the emergency team.
- Health-5G_Desktop. Desktop application used by the medical specialist that provides remote support from a hospital or medical center.

Regarding the second area, Health-5G is supported by Health-5G_Client and Health-5G_Server:

- Health-5G_Client. Application that captures the video signal coming from the medical devices. Health-5G_Client runs on the computational unit integrated in

the infrastructure of the emergency unit. Section III-A discusses why we adopted an approach based on raw video analysis rather than obtaining the medical data through an API.
- Health-5G_Server. Cloud server responsible for distributing the data obtained by Health-5G_Client to Health-5G_Holo and Health-5G_Desktop, respectively.

Figure 2 graphically shows the architecture of Health-5G from a high-level point of view, highlighting the connections existing between the four applications previously mentioned.

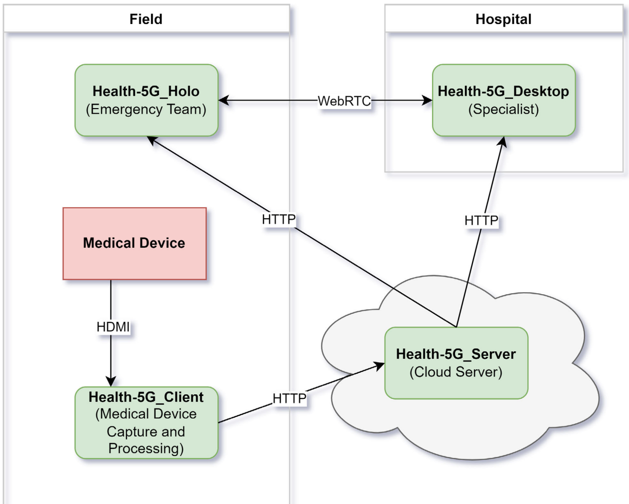


FIGURE 2. High-level overview of Health-5G architecture. The four applications that compose Health-5G are highlighted in green.

From a conceptual point of view, Health-5G structured into three major subsystems: i) medical device integration, which handles how to capture and distribute the data collected by the medical devices available in the emergency unit, ii) WebRTC-based communication, which offers low-latency audio, video and data communication between applications, and iii) human-computer interaction based on natural user interfaces, which provides the interaction capabilities to the end user. These subsystems are discussed next.

A. MEDICAL DEVICE INTEGRATION

In order to provide the ability to integrate the different medical devices used to collect data from a patient in the emergency unit, it is necessary to design a general approach that is scalable, i.e. that allows the integration of devices of different types and manufacturers. One immediate option may be to use the API exposed by the medical device manufacturer. Unfortunately, it is difficult to get access to such APIs due to the commercial nature of most existing medical devices. Health-5G proposes a different approach based on edge computing, which consists of directly capturing the video signal provided by a significant number of medical devices. This video is processed by Health-5G in a second step to obtain the medical data that the device is recording at any given moment. So, instead of getting it through the API, Health-5G uses an optical character recognition (OCR) manager to collect it. This can be combined with Health-5G's ability to send images via a video capture device connected to the PC deployed in the emergency unit. Such information is sent, in a subsequent step, to the application Health-5G_Server for viewing by the medical specialist. In particular, it is this feature of Health-5G that is used to capture ECG data. In our experience, this approach is simpler and more scalable than using existing medical device APIs in the context of our immediate healthcare environment. As discussed later on, we have validated this approach with the Philips MX450 patient monitor.

Figure 3 graphically shows the approach used to collect data from the medical devices used in the emergency room. It is important to note that the video signal is processed by a computer connected to the medical device. The video signal is then sent to the cloud to be distributed for use by video conferencing applications.

The medical device integration subsystem is divided into three parts: i) those that are designed to physically be in the ambulance (Health-5G_Client, Image Downloader Manager), ii) in the hospital (Image Downloader Manager Canvas, OCR Manager), and iii) in the cloud (Health-5G_Server).

Health-5G_Client is a key component of the subsystem because its main task is to continuously capture the video signal from the medical device (using the OpenCV library) and perform OCR on it (using the *Tesseract* text recognition software) to extract the heart rate, respiration rate, pulse and blood oxygen level of the patient. All this data is then sent to the cloud in real time.

Health-5G_Server is the part of the medical device integration subsystem that is deployed on the cloud. It provides endpoints for Health-5G_Client to upload images and data obtained through OCR analysis that can later be consumed by the videoconferencing applications with the ultimate goal of facilitating patient treatment.

Before discussing the integration with the videoconferencing applications, it is worth mentioning that HTTP requests were used as the main way to download images, instead of using a high-level approach based on WebSockets. Unfortunately, the use of WebSockets in the device Microsoft HoloLens 2 caused problems, mainly application crashes, which is unacceptable in a project designed to be used in emergency situations.

The integration with the videoconferencing applications relies on three components: ImageDownloaderManager on Health-5G_Holo, ImageDownloaderManagerCanvas on Health-5G_Desktop and OCRManager on Health-5G_Desktop. The first two components are guided by an algorithm that runs an infinite loop, which is responsible for downloading images at a rate determined by the maximum desired frame rate. These images are rendered as textures. After that, OCRManager can download JSON data and render it on the screen. This allows both the emergency unit staff and the remote medical staff to see the screen of the medical device in real-time on the Microsoft HoloLens 2 headset and

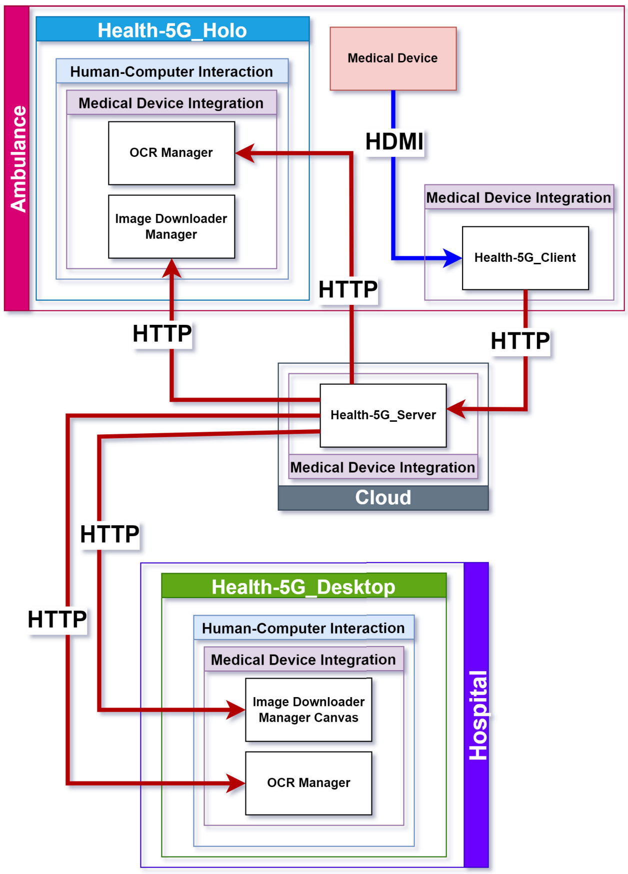


FIGURE 3. **Medical device integration diagram.**

the remote desktop computer, respectively. This is essential to provide vital information to the emergency team and the medical specialist.

B. WebRTC-BASED COMMUNICATION

Health-5G relies on Web Real-Time Communication (WebRTC) [23] to offer low-latency audio, video, and data communication between the different applications that have been designed. Before discussing in depth the components involved in the communication infrastructure, some essential aspects of this technology are introduced. In a nutshell, WebRTC allows the exchange of data streams containing audio, video, and data in a distributed way based on P2P communication. There is no need for any kind of plugin or extension as everything necessary is natively integrated in the most popular web browsers. Despite being based on a P2P paradigm, WebRTC also needs a signaling server to operate, which is not defined in the standard, in order to maintain compatibility with the established technologies and avoid potential redundancies. When transmitting data in real time, the Real-Time Transport Protocol (RTP) is used as the multimedia transport protocol for WebRTC [24]. This protocol transmits audio and video over UDP, and while it does not guarantee that data packets will arrive at their destination correctly, it achieves very low latencies due to the lack of checks.

1) WebRTC INTEGRATION

MixedReality WebRTC has been used to integrate WebRTC with the videoconference applications, which have been developed using the game engine Unity. MixedReality WebRTC is a library composed of a number of components developed by Microsoft in order to integrate real-time video and audio in MR applications designed to run on Microsoft HoloLens 2. Particularly, this library includes all the necessary functionalities for the successful development of the project, such as bidirectional transmission of audio, video, and data.

2) RELEVANT COMPONENTS OF THE COMMUNICATION INFRASTRUCTURE

In this section the most relevant aspects of the implementation of the WebRTC part of the project will be discussed in detail. Figure 4 presents a summary of the modules and components of this subsystem.

A signaling server (or signaler) is essential for WebRTC to work properly. Within this context, Health-5G relies on *node-dss signaling server*.[1]

As for the Health-5G_Holo and Health-5G_Desktop applications, the modules involved in the communication infrastructure are MixedReality WebRTC, Connection Manager and Message Manager. They are completely identical regarding functional capabilities. MixedReality WebRTC represents all the components included in the library of the same name to support the exchange of audio, video, and data over a WebRTC connection.

It is important to highlight that although MixedReality WebRTC includes most of the components necessary to create a successful P2P connection, some specific challenges have been faced to create an optimal user experience. These challenges involve that i) it is only possible to add data channels dynamically if at least one of these channels has been created before starting the call, ii) the only way to end a call is to deactivate and activate again the component that handles the connection, iii) a message cannot be sent before the data channels are opened as it will throw an exception, and iv) there is no direct way to know whether a call has been successfully started, ended or failed.

To solve this issues, the architecture of Health-5G includes the component ConnectionManager, which encapsulates, extends, and simplifies the operation of MixedReality WebRTC to allow its use in a simple way in any application. ConnectionManager exposes functionality to start a call, end a call, create data channels, and send messages. The underlying development mitigates the problems mentioned above. On the other hand, the MessageManager component extends ConnectionManager with specific functionality to create, open, close, and maintain WebRTC message channels.

[1] https://github.com/anpep/node-dss

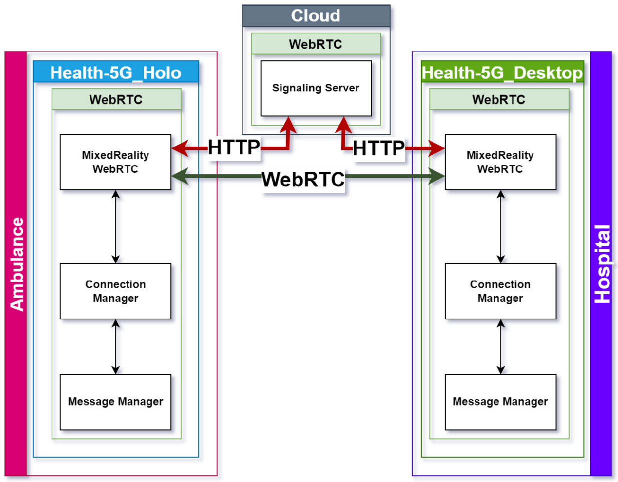


FIGURE 4. **High-level diagram of the communication infrastructure provided by Health-5G.**

This component also facilitates the redirection of these messages to the components that should receive them.

C. HUMAN-COMPUTER INTERACTION BASED ON NATURAL USER INTERFACES

From a general point of view, the interactions that the remote medical specialist performs on Health-5G_Desktop affect the visual representation that the emergency staff visualizes on Health-5G_Holo. These interactions are materialized by virtual markers, while their positioning in the real world is based on the ray tracing technique [25]. In particular, when the doctor clicks on any part of the screen represented by Health-5G_Desktop, the position of this event is sent to Health-5G_Holo so that the marker is rendered on the nearest surface following a straight line (and using ray tracing). This ray-tracing approach, chosen after evaluating other alternatives, proved to be the most practical solution among those considered.

One of the major advantages of our approach is that it allows the position of the marker in 3D space to be completely consistent with the position of the click in 2D space, which facilitates the user's interaction and makes it very easy to use the different visual and interactive components supported by Health-5G. Figure 5 shows the most relevant components of the human-computer interaction subsystem.

1) AUDIO AND VIDEO TRANSMISSION

The transmission of audio and video is another key aspect when the users are interacting with Health-5G. Within the context of the WebRTC communications infrastructure, the so-called transceiver plays a fundamental role, since it is the metaphorical pipe that connects local devices and allows audio and video to be sent through it. Each transceiver has a direction that indicates whether it is sending or receiving any media, or if it is otherwise inactive.

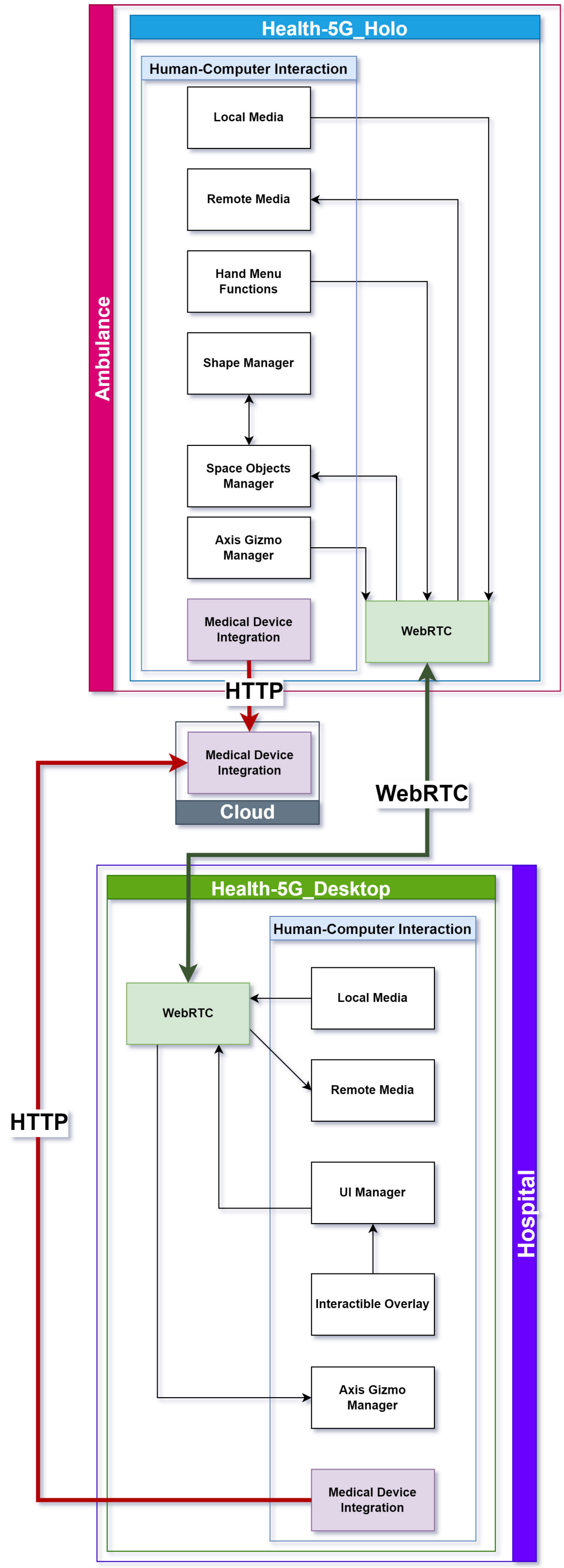


FIGURE 5. **Human-computer interaction subsystem.**

Health-5G makes use of four different transceivers. Firstly, MicrophoneSource represents a local audio source that captures frames of audio from a local device (microphones). Secondly, WebcamSource encapsulates a local video emitter that produces video frames from a local video capture device (webcams, in this case) and enables the use of Mixed Reality Capture (MRC) in Microsoft HoloLens 2. This also allows the medical specialist to receive a video stream containing the full point of view of the emergency team. Thirdly, AudioReceiver provides an endpoint for a remote audio track that can be rendered by using a component of type AudioRenderer. Fourthly, VideoReceiver provides an endpoint for a remote video track to be rendered by using a component of type VideoRenderer.

2) POSITIONING OF MARKERS IN THE 3D SPACE

The process for positioning markers in 3D space involves the following steps:

- The user of Health-5G_Desktop clicks over the video stream received from Health-5G_Holo.
- The coordinates of the click are then normalized and sent from Health-5G_Desktop to Health-5G_Holo through a WebRTC data channel where they will be interpreted by the SpaceObjectsManager sub-module in order to instantiate the corresponding marker.
- The marker is placed in 3D space as follows:
    1) First, the normalized coordinates are multiplied by the HoloLens 2 rendering resolution.
    2) The result is then converted into a ray with its origin at the Unity main camera.
    3) If the marker is an arrow, a box, or a cross, nine rays with a slight dispersion between them are generated and the intersection of these rays with the mesh representing the physical space surrounding the headset user is calculated (see Figure 6).
    4) The marker is then placed along the central ray at the average distance between the successful hits and the camera with a rotation equivalent to the average of the normals of the surfaces where the rays hit.
    5) If there are no successful hits, the marker will be placed at a distance equivalent to the average distance between the Unity main camera and the markers oriented in the same direction as the one to be placed, if they exist. If this process fails, the marker will be placed at a predetermined distance.
    6) For freehand drawing markers, the process is similar. However, due to performance reasons, only a single collision is calculated per point, and then these points are joined to render a continuous line.
- Finally, the marker is wrapped in a collision mesh allowing the user of Health-5G_Holo to interact with it by using gestures (see Figure 7).

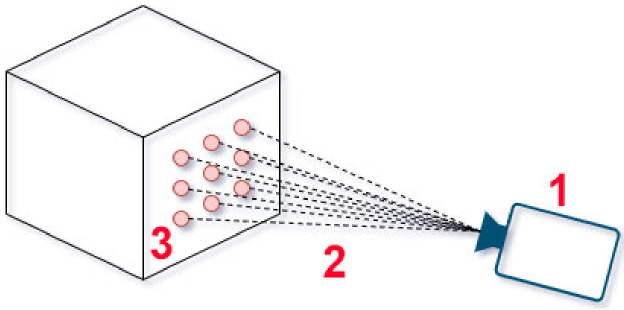


FIGURE 6. Rays being thrown towards the physical space. 1) Unity's main camera; 2) Rays thrown from the camera to the mesh representing the physical space; 3) Collision points between the rays and the mesh representing the physical space.

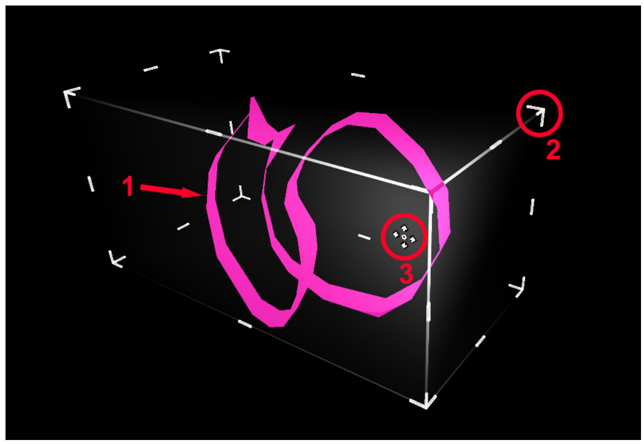


FIGURE 7. Freehand drawing enclosed in a collision box. 1) Freehand drawing marker; 2) One of the handles the user can grab to rotate, move or scale the marker. There is one handle for each corner and each edge of the collision box; 3) Pointer that shows where the user is going to perform a gesture (see Figure 11).

IV. USER INTERFACE AND USER EXPERIENCE

The design and development of agile and efficient interaction mechanisms plays a key role in Health-5G. Particularly, it is essential to keep in mind that the different applications that compose Health-5G are designed to be used in emergency situations where every second can make the difference between success and failure.

Two are the main aspects that have been especially considered when designing the user interface: i) the user experience must not be intrusive for the emergency unit staff that wears the MR headset, and ii) the medical specialist must be able to place markers in the 3D space while using a traditional 2D computer screen.

A. HEALTH-5G_DESKTOP

Figure 8 graphically shows the user's perspective when using Health-5G_Desktop.

In fact, the user interface of Health-5G_Desktop is based on the classic desktop paradigm with a small twist: the remote medical specialist must be able to place markers in the 3D space using a 2D display. Figure 9 highlights the different components of this user interface, which will be later explained in more detail.

Note that the visual component that occupies the entire background of Health-5G_Desktop is the video stream

FIGURE 8. View from the PC application during a videoconference.

FIGURE 9. Simplified design view of the user interface offered by Health-5G_Desktop.

coming from the Microsoft HoloLens 2 camera (labeled as "HoloLens 2 Video" in the diagram). This component is particularly important due to two major reasons. On the one hand, it shows the point of view of the emergency team. On the other, it represents the gateway in terms of interaction by the medical specialist, allowing the placement of markers in the 3D space through mouse clicks.

In the upper left corner of Figure 9 there is an orientation indicator ("Axis Gizmo") that shows the direction in which the user of the headset is facing. Although it may seem trivial, this component arises from the need to show the specialist the direction in which the emergency team member is facing. This makes it easier to scale and reposition the various markers.

The buttons available in Health-5G_Desktop are grouped into shape controls (Shape Controls) and call controls (Call Controls) and will be explained below, grouped according to the functionality they perform.

The shape selection buttons, which are listed in Table 1 allow the user to choose the type of marker that will be placed in the 3D space when the video coming from the headset is clicked on. The brush has no predefined shape and can be used to draw directly on the video with the computer mouse.

Health-5G_Desktop has tools to scale, move, reset, and delete the markers once they are placed in 3D space, as listed in Table 2.

On the other hand, the scale and position tools will be applied to the given axes using the axis selection buttons shown in Table 3.

Once the desired tool and axes have been selected, the corresponding transformations can be applied to the current marker. The tool application buttons, listed in Table 4, allow the user to decrease or increase the scale and position as desired.

Additionally, the marker selection buttons listed in Table 5 toggle between the markers placed in the 3D space. The status of a marker will be graphically displayed to the user by a color change: pink if it is selected, and white if it is not.

Finally, the call control buttons allows the user to start or stop the communication. They are shown in Table 6.

The last component of the interface of Health-5G_Desktop is the medical monitor. This object consists of a window, which can be modified in shape and size, in which the medical specialist can see the vital signs of the patient. The medical monitor can be appreciated in the bottom left corner of Figure 9.

TABLE 1. Shape selection buttons.

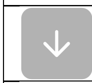
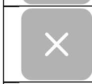
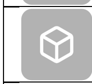
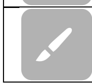
Icon	Name	Description
	Arrow	Selects the arrow shaped marker.
	Cross	Selects the cross shaped marker.
	Box	Selects the box shaped marker.
	Brush	Enables freehand drawing.

TABLE 2. Tool selection buttons.

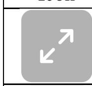
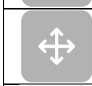
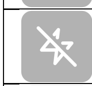
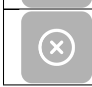
Icon	Name	Description
	Scale	Scales the selected marker.
	Position	Moves the selected marker.
	Reset	Returns the selected marker to its original position, scale and rotation.
	Delete	Deletes the selected marker.

TABLE 3. Axis selection buttons.

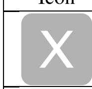
Icon	Name	Description
	X Axis	Checks or unchecks the X axis for use with the scale and position tools.
	Y Axis	Checks or unchecks the Y axis for use with the scale and position tools.
	Z Axis	Checks or unchecks the Z axis for use with the scale and position tools.

TABLE 4. Tool application buttons.

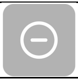
Icon	Name	Description
	Less	Decreases the scale or position on the checked axes.
	More	Increases the scale or position on the checked axes.

TABLE 5. Marker selection buttons.

Icon	Name	Description
	Previous	Selects the previous marker.
	Next	Selects the next marker.

TABLE 6. Call control buttons.

Icon	Name	Description
	Call	Allows the user to start the call.
	Calling...	The call is starting. In this state the button is not interactive.
	End call	Ends the call.

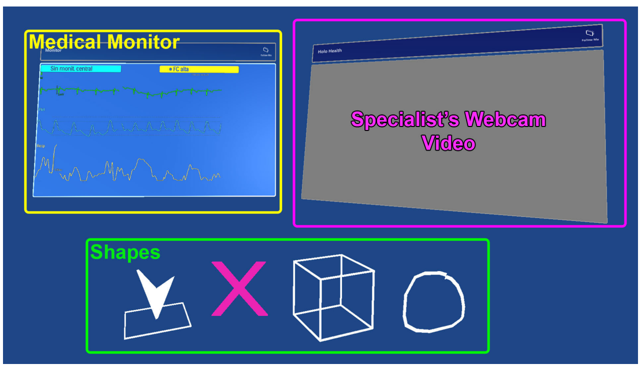
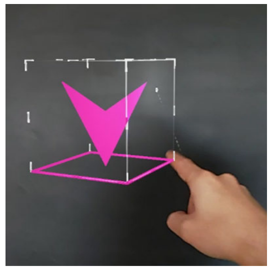


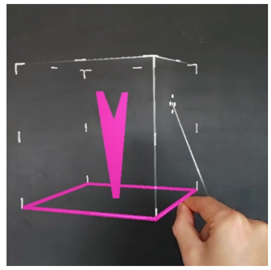
FIGURE 10. Main visual components of the user interface of Health-5G_Holo.

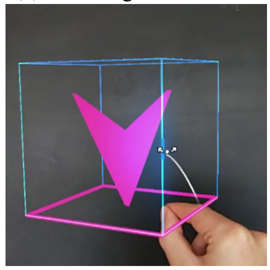
B. HEALTH-5G_HOLO

The user interface of Health-5G_Holo shows the actual potential of the MR paradigm. It is important to remark that this user interface must be as simple and non-intrusive as possible to allow the healthcare professional to perform delicate work in the most appropriate way. Figure 10 highlights the most important components of the user interface.

The component Shapes at the bottom shows the different shapes that Health-5G_Holo provides, which act as markers. These markers are highlighted in pink color when they are selected, and in white when they are not. The color selection was not trivial and previous study was made, since these shades are very visible to the user that wears the MR headset.


(a) Focusing on a marker.


(b) Moving a marker.


(c) Rotating a marker.

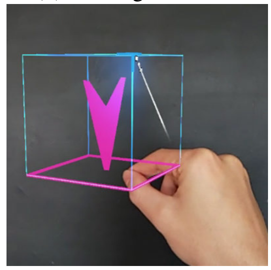

(d) Scaling a marker.

FIGURE 11. User interacting with the holographic markers provided by Health-5G_Holo.

TABLE 7. Holographic marker voice commands.

Command (English)	Command (Spanish)	Function
Delete	Borrar	Deletes the focused marker.
Reset	Reset	Returns the focused marker to its original position, scale and rotation.
Holo	Holo	Selects the focused marker.

A brief description of each of these shapes is given next: i) arrow, a marker useful for marking specific points in space, ii) cross, a marker that always looks directly into the camera, iii) box, a marker in which only the edges are visible and was designed to completely wrap around objects, iv) line, a marker that represents a line drawn freehand by the remote medical specialist and that can take any shape.

All these objects can be scaled, moved, and deleted from the application Health-5G_Holo by using the interaction mechanisms previously described. In addition, the medical staff that uses Health-5G_Holo is able to freely move these markers in 3D space by making use of the gestures which can be seen in the Figure 11.

When a marker is focused, a series of voice commands can be used on it. These are summarized in Table 7.

The application Health-5G_Holo shows two windows in which the user can see the patient's vital signs and the webcam of the specialist's computer. The particularity of these windows is that they can be freely moved around the space using gestures, as well as resized, hidden, and rotated. The holographic windows are structured as shown in Figure 12.

The major components of this holographic window are as follows. Firstly, the title bar, which shows the title of the window, contains some buttons and serves as a reference point

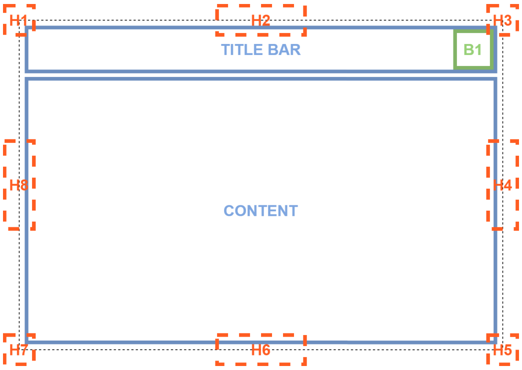


FIGURE 12. Overview of a holographic window.

TABLE 8. General voice commands.

Command (English)	Command (Spanish)	Function
Show	Mostrar	Shows all windows if they are hidden.
Hide	Ocultar	Hides all windows if they aren't hidden
Follow me	Sígueme	Makes all windows follow the user.
Stop	Stop	Using this command every window will stop following the user.
Center	Centrar	Resets the position of all windows.

when repositioning the window by using gestures. Secondly, the button "B1" toggles between following or not the user of the application. Thirdly, the "content" area represents the usable space of the window and includes all the information necessary for the user to consume at any given time. Fourthly, the handles "H1" to "H8" are needed to rotate or scale the window, depending on the gesture with which they are being manipulated.

Another interactive component of Health-5G_Holo is the hand menu, which is shown in Figure 14. The hand menu offers a number of useful buttons and appears when the user places the palm of the hand facing herself.

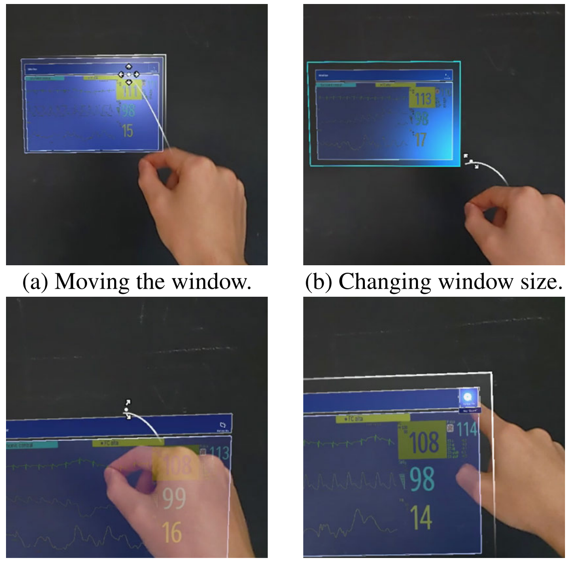
Finally, the medical staff of the emergency unit can use a series of voice commands at any time that do not require any specific holographic marker. They are listed in Table 8.

V. EXPERIMENTAL RESULTS

This section presents a case study recreating the use of Health-5G in an emergency situation coordinated by the medical staff of the General University Hospital Nuestra Señora del Prado (Talavera de la Reina, Spain) and the Emergency and Healthcare Transport Management of the Health Service of Castilla-La Mancha (Spain). Also, different tests related to latency and throughput over the 5G infrastructure that Health-5G requires to run are described.

A. CASE STUDY: EMERGENCY SITUATION

The Health-5G system, including its 4 component applications, i.e. Health-5G_Holo, Health-5G_Desktop, Health-5G_Client and Health-5G_Server, was deployed on a 5G network infrastructure to recreate an emergency situation as close to reality as possible. To this end, this activity was coordinated with the medical staff of two clinical entities. On the one hand, the General University Hospital Nuestra Señora del Prado de Talavera de la Reina (Toledo, Spain) took part in the tests by providing the specialized staff available in the hospital through the Health-5G_Desktop application. On the other hand, the Emergency and Healthcare Transport Management of the Health Service of Castilla-La Mancha (Spain) provided both the mobile emergency unit and the medical staff of this unit. The ambulance was equipped with the Philips MX450 device, which can measure heart rate, blood pressure, blood oxygen saturation, respiratory rate, and heart rate. This device was integrated into Health-5G to make this medical information accessible from both Health-5_Holo and Health-5G_Desktop.



(a) Moving the window. (b) Changing window size.

(c) Rotating the window. (d) "Follow me" mode on.

FIGURE 13. User interacting with a holographic window.

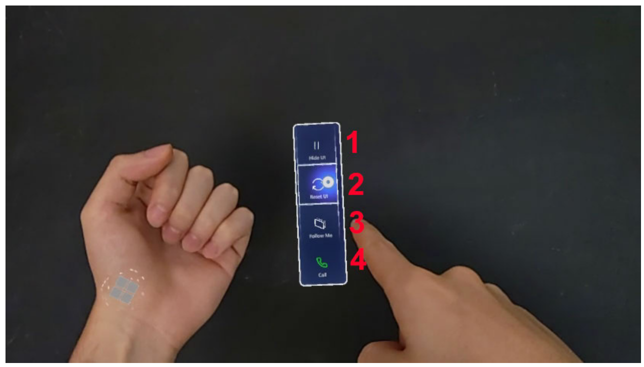


FIGURE 14. Hand menu that contains four buttons. 1) Hide UI/show UI, which shows or hides all the windows; 2) Reset UI, which resets the position of all windows (this is useful if they are too far away from the user or in an awkward position); 3) Follow me, which makes all windows follow or unfollow the user; 4) Call, which starts a call with the medical specialist.

The emergency situation simulated was the care of a patient in the street suffering from syncope due to third-degree atrioventricular block, in which a severe abnormal heart rhythm (arrhythmia) can affect the heart's ability to pump blood. In particular, when applying the medical protocol, the following situations were identified and are described below:

1) Patient care on the public road.
2) Transfer of the patient to the mobile emergency unit to start monitoring:
    a) Measurement of heart rate, measurement of blood pressure, measurement of oxygen saturation, and performance of an electrocardiogram.
    b) The emergency room staff notices that the patient is dull, pale, hypotensive and, thanks to the electrocardiogram, syncope due to third-degree block is detected.
3) Real-time connection with hospital staff via Health-5G and interactive communication:
    a) Confirmation of diagnosis by hospital staff.
    b) Venous access recommendation.
    c) Administration of intravenous medication.
    d) Placement of a transcutaneous pacemaker with sedoanalgesia.

Figure 15 shows what the medical staff in the emergency room saw directly through the Health-5_Holo application, with the exception of the lower right frame, which corresponds to the video stream from an external camera placed at the time of the experiment. At this point, the reader is referred to watch a short video (https://youtu.be/3E0P4jHm1y0) to see first-hand the interactions between the hospital's specialized medical staff and the emergency room staff.

FIGURE 15. Graphical representation of the case study discussed in this section. The figure reflects what the emergency unit clinician is seen through Health-5G_Holo. In the lower-right corner, a capture of an external camera is included.

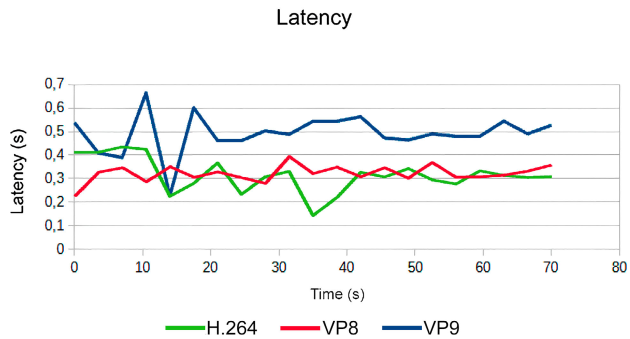


FIGURE 16. Latency results for the codecs H.264, VP8, and VP9.

B. LATENCY TESTS

One of the most useful performance metrics that WebRTC offers is the round-trip time (RTT) that measures the jitter which is the latency from one frame to another. These details are exposed in the low-level WebRTC API and are therefore not accessible from MixedReality WebRTC. This situation has led to the need to look for alternative ways to measure the time it takes from the time a video frame is sent until it reaches its destination. It has been determined that a simple and realistic way to calculate this time is to send a video from Health-5G_Desktop to Health-5G_Holo, the latter being modified to forward the frames it receives back to the source.

The images in the test video contain a series of forests and landscapes with a timestamp in the lower right corner. By subtracting the timestamp of the frame currently being sent from the one being received from HoloLens 2 and halving the result we can get an idea of the latency in milliseconds.

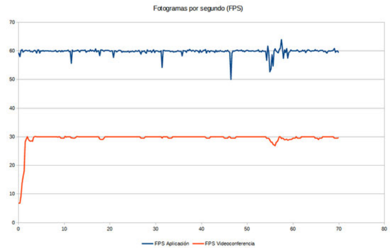
As the video codec is modifiable by the end user, experiments have been performed with H.264, VP8 and VP9 codecs using the same video at 640 $\times$ 480px resolution and then making latency measurements at regular intervals over a 70 second videoconference (see Figure 16). In every case, the audio codec was OPUS with a sampling rate of 48kHz and two channels. Final results can be seen in the next figures.

Satisfactory results have been obtained in all three cases with an average latency of about 300ms. H.264 has been chosen as the default codec for the project because of its performance in these experiments.

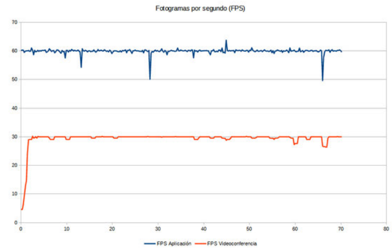
C. PERFORMANCE TESTS

Maintaining adequate performance in videoconferencing applications is a must for making the communication experience useful, especially in the case of Health-5G_Holo running on the HoloLens 2 headset, as a low number frames per second (FPS) could cause dizziness, headaches, nausea and other problems that are completely unacceptable in the context of a medical emergency.

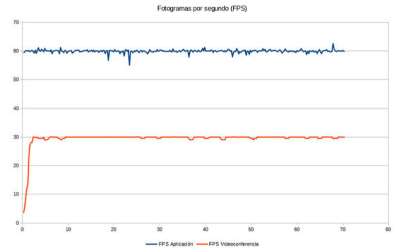
When measuring performance, three 70-second videoconferences have been performed with a different number of markers in the scene up to a maximum of 50, well above those that will be used in a real environment. Figure 17 summarizes the obtained results. For the following tests we will define an acceptable frames per second rate at around 30FPS or higher on Health-5G_Desktop, running on PC, and around 60FPS or higher on Health-5G_Holo, running on HoloLens 2. The average latencies obtained were 0.3125s for H.264, 0.3176s for VP8, and 0.4922s for VP9.



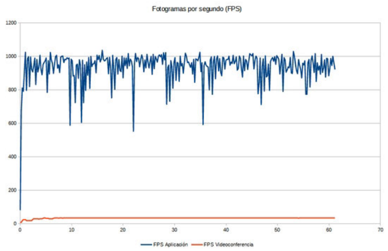
a) FPS with 15 markers
(Health-5G_Holo on HoloLens 2)



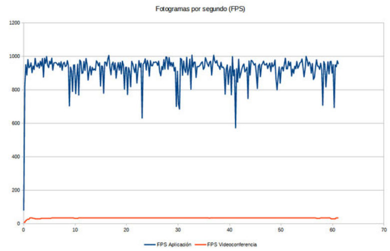
a) FPS with 30 markers
(Health-5G_Holo on HoloLens 2)



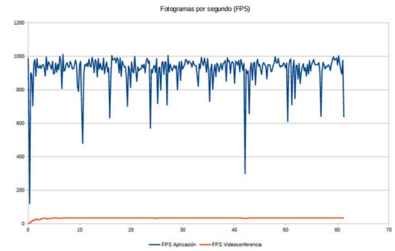
a) FPS with 50 markers
(Health-5G_Holo on HoloLens 2)



a) FPS with 15 markers
(Health-5G_Desktop on PC)



a) FPS with 30 markers
(Health-5G_Desktop on PC)



a) FPS with 50 markers
(Health-5G_Desktop on PC)

FIGURE 17. Obtained results when evaluating the performance, in FPS. The y-axis represents the FPS rate and the x-axis represents time. The first row reflects the performance of Health-5G_Holo when using the device Microsoft HoloLens 2. The second row reflects the performance of Health-5G_Desktop when using a PC.

1) PERFORMANCE WITH 15 HOLOGRAPHIC MARKERS IN THE SCENE

The first experiment involves the placement of 15 holographic markers in the scene and then measuring the performance of the application itself (blue line) and the performance of the videoconference (orange line). The results obtained on Health-5G_Holo can be seen in Figure 17.a.

The average FPS of the application was 59.81FPS, while the video coming from the PC was rendered at an average of 29.41FPS, thus meeting the required performance goals. The results obtained on Health-5G_Desktop can be seen in Figure 17.d.

The average refresh rate of the application was 936.23FPS, while the video coming from Health-5G_Holo was rendered at an average of 31.56FPS, which satisfies the expected results.

2) PERFORMANCE WITH 30 HOLOGRAPHIC MARKERS IN THE SCENE

For the following test the number of markers has been doubled, for a total of 30. The results obtained on Health-5G_Holo can be seen in Figure 17.b.

The average FPS of Health-5G_Holo was 59.84FPS, while the video coming from the Health-5G_Desktop was rendered at an average of 29.32FPS, meeting the required performance goals. The results obtained by Health-5G_Desktop can be seen in Figure 17.e.

The average refresh rate of the application was 923.6FPS, while the video coming from Health-5G_Holo was rendered at an average of 31.93FPS, which satisfies the expected results.

3) PERFORMANCE WITH 50 HOLOGRAPHIC MARKERS IN THE SCENE

For the final test, the number of markers has been increased to 50, more than would be used in a real production environment. The results obtained on Health-5G_Holo can be seen in Figure 17.c.

The average FPS of the application was 59.95FPS, while the video coming from Health-5G_Desktop was rendered at an average of 29.47FPS, meeting the required performance goals. The results obtained on Health-5G_Desktop can be seen in Figure 17.f.

The average refresh rate of the application was 920.4FPS, while the video coming from Health-5G_Holo was rendered at an average of 31.69FPS, which satisfies the expected results.

After the experiments we have come to the conclusion that Health-5G_Desktop meets (and even exceeds) the performance goals, although of course these figures depend exclusively on the hardware specifications of the PC where Health-5G_Desktop is running which is a highly variable and unpredictable factor.

On the other hand, Health-5G_Holo has maintained excellent performance in every experiment, with frame rates hovering around 60FPS for the application and 30FPS while rendering the video coming from the medical specialist's webcam. In addition, HoloLens 2 includes a closed, standard hardware across all devices so it's guaranteed that the user immersed in AR will not have any problems related to dizziness, headaches or disorientation as a result of the use of Health-5G_Holo.

VI. DISCUSSION

The feedback from the medical staff involved in the case study described in Section V-A was positive, both in terms of the functionality offered by Health-5G and in terms of its potential use as a pilot project in the coming years. The disruptive nature of the comprehensive approach presented in this article pleasantly surprised both the mobile emergency unit staff and the hospital specialists, who were familiar with the use of telemedicine tools but less familiar with such immersive and highly interactive environments as Health-5G. In this context, we believe that the use of innovative solutions must be combined with a prior training process for the medical personnel who will use them. In the video summarizing the case study, it is easy to see that the person wearing the MR device is constantly and rapidly moving his head, indicating that he is not used to using this type of immersive system. Obviously, this limitation is easily mitigated when the system is used continuously over time.

Another potential barrier that could pose a challenge is the integration with the medical devices in the mobile emergency unit. Using a solution based on transmitting the video output from the medical device to Health-5G for OCR-based processing reduces the reliance on closed APIs typically offered by device manufacturers. It is transparent to the medical staff who are only interested in visualizing the data related to patient monitoring. However, this solution requires the use of an additional mini-PC in the emergency room to deploy the Health-5G_Client application. We believe that this approach is feasible due to the low cost of adding this hardware component and the increased flexibility of the overall system.

Moreover, the results of the stress tests carried out to measure such crucial aspects as latency and throughput when using Health-5G_Holo guarantee the solvent use of Health-5G, establishing as a premise the existence of a quality communications infrastructure. In this sense, the evolution in the deployment of 5G networks and the appearance on the horizon of 6G technology will facilitate the adoption of solutions such as Health-5G. On the other hand, we can say that the graphical performance of the Health-5G_Holo application on the Microsoft HoloLens 2 MR device is more than satisfactory. Even when the number of markers is significantly increased, far beyond what could be necessary in an emergency situation, the application guarantees a high and stable frame rate per second.

VII. LIMITATIONS OF THE STUDY

The practical experiment conducted in coordination with the medical staff of two clinical entities (a hospital and an emergency department) has served as a starting point for an initial evaluation of the functional capabilities of Health-5G and to obtain positive feedback from the medical staff. This first step is essential before conducting a clinical evaluation to assess the usefulness of Health-5G.

A. HARDWARE CONSTRAINTS

In this context, a potential limitation comes from the hardware used. In particular, the Microsoft HoloLens 2 MR device. Although this device is the most advanced currently available, its size and ergonomics are aspects to be considered for use in the daily life of a mobile emergency unit. On the other hand, we have noticed that the use of gloves by the user of the Health-5G_Holo application can affect the tracking performed by the MR device under certain lighting conditions.

B. LATENCY AND BANDWIDTH

In addition, the latency and bandwidth requirements demanded by Health-5G could be a limitation if a 5G connection is not available from the mobile emergency unit. In this sense, an underlying network infrastructure is needed to ensure adequate connection quality.

C. INTEGRATION WITH MEDICAL DEVICES

Integration with medical devices is also an aspect to be considered in this section. Currently, Health-5G uses a generic OCR-based solution to collect data from medical devices by analyzing the video signal received from them. While this approach is practical and scalable, for certain devices it may be desirable to directly access the API exposed by these devices. Unfortunately, commercial medical device manufacturers often do not provide open and accessible solutions that facilitate querying of the collected medical data.

D. DATA PRIVACY

Finally, the potential use of Health-5G in the commercial environment requires a detailed study of personal data protection issues. Although the Health-5G architecture has been designed with security aspects in mind with regard to data transmission, it is necessary to delve deeper into the scope of existing regulations in the medical field.

VIII. CONCLUSIONS AND FUTURE WORK

In this work, we have presented Health-5G, a scalable system based on MR, designed to provide remote support by specialised medical personnel to the staff of mobile emergency units. The use of MR allows the integration of 3D virtual objects in the real world in real time, increasing the functional capabilities of emergency personnel thanks to the indications provided by specialists. Health-5G has been designed taking into account the capabilities of 5G networks, including latency and bandwidth, to ensure a smooth and efficient user experience.

Health-5G relies on a distributed architecture with four interconnected applications: (i) Health-5G_Holo, an application used by the emergency unit staff and deployed on the Microsoft HoloLens 2 device, (ii) Health-5G_Desktop, a desktop application used by remote staff to interact with the emergency unit staff, (iii) Health-5G_Client, an application deployed in the emergency unit to receive data from the medical devices in the emergency unit, and (iv) Health-5G_Server, an application deployed in the cloud that acts as a nexus between the other applications to send and receive information. It is important to emphasize that the authors of this paper, after a state of the art study of related work, have not identified a comprehensive solution that offers all the interaction and information visualization possibilities that Health-5G has in the context of emergency medical care.

The pilot test, carried out in collaboration with the medical staff of a hospital and with an emergency, rescue and medical transport service, served to demonstrate the technical and functional capabilities of Health-5G in a simulated situation with the same characteristics that could be encountered in the daily operation of an emergency unit. On the other hand, latency and throughput tests on a 5G network served to validate the communication infrastructure requirements and computational capacity of Health-5G, taking into account the use of the real-time interaction mechanisms based on MR discussed above.

On the other hand, there are several lines of research that can be addressed at this point, which are briefly described below. First, although the results of the use case discussed were satisfactory in terms of the capabilities offered by Health-5G, according to the feedback provided by the medical staff, a rigorous and sustained clinical evaluation is needed to ensure that Health-5G can become an effective and useful solution in a real-world environment. This clinical evaluation should include aspects of usability, security and privacy of information, and robustness in terms of continuous use of the used hardware. In this sense, the use of hardware that is more accessible in terms of economic cost must be evaluated. On the other hand, a scenario is considered where the emergency unit cannot reach the physical location where the accident or emergency has occurred. This impossibility may be due to physical constraints, such as a rural environment that an ambulance cannot access, or to time constraints, such as when an emergency unit is not available or is too far away. In such a scenario, the possibility of using a drone or other unmanned aerial vehicle to deliver the MR device running Health-5G_Holo is considered, so that anyone without advanced medical knowledge can use it with the remote support of the medical specialist. Finally, we are also considering the possibility of reusing the proposed architecture to provide solutions that support an operator's decision-making process by specialized personnel, beyond the medical field. For example, we believe it would be feasible to address remote support problems in industrial environments.

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REFERENCES

[1] T. J. Brigham, "Reality check: Basics of augmented, virtual, and mixed reality," *Med. Reference Services Quart.*, vol. 36, no. 2, pp. 171–178, Apr. 2017, doi: 10.1080/02763869.2017.1293987.

[2] T. Alelyani, A. Shaikh, A. Sulaiman, Y. Asiri, H. Alshahrani, and S. Almakdi, "Research challenges and opportunities towards a holistic view of telemedicine systems: A systematic review," in *Enhanced Telemedicine and e-Health: Advanced IoT Enabled Soft Computing Framework*. Berlin, Germany: Springer, 2021, pp. 3–26, doi: 10.1016/j.amjsurg.2019.07.018.

[3] H.-Z. Hu, X.-B. Feng, Z.-W. Shao, M. Xie, S. Xu, X.-H. Wu, and Z.-W. Ye, "Application and prospect of mixed reality technology in medical field," *Current Med. Sci.*, vol. 39, no. 1, pp. 1–6, Feb. 2019, doi: 10.1007/s11596-019-1992-8.

[4] B. W. Munzer, M. M. Khan, B. Shipman, and P. Mahajan, "Augmented reality in emergency medicine: A scoping review," *J. Med. Internet Res.*, vol. 21, no. 4, Apr. 2019, Art. no. e12368, doi: 10.2196/12368.

[5] L. Li, J. Yang, Y. Chu, W. Wu, J. Xue, P. Liang, and L. Chen, "A novel augmented reality navigation system for endoscopic sinus and skull base surgery: A feasibility study," *PLoS ONE*, vol. 11, no. 1, Jan. 2016, Art. no. e0146996, doi: 10.1371/journal.pone.0146996.

[6] L. Lu, H. Wang, P. Liu, R. Liu, J. Zhang, Y. Xie, S. Liu, T. Huo, M. Xie, X. Wu, and Z. Ye, "Applications of mixed reality technology in orthopedics surgery: A pilot study," *Frontiers Bioeng. Biotechnol.*, vol. 10, Feb. 2022, Art. no. 740507, doi: 10.3389/fbioe.2022.740507.

[7] S. Mitani, E. Sato, N. Kawaguchi, S. Sawada, K. Sakamoto, T. Kitani, T. Sanada, H. Yamada, and N. Hato, "Case-specific three-dimensional hologram with a mixed reality technique for tumor resection in otolaryngology," *Laryngoscope Investigative Otolaryngol.*, vol. 6, no. 3, pp. 432–437, Jun. 2021, doi: 10.1002/lio2.581.

[8] V. M. Ivanov, A. M. Krivtsov, S. V. Strelkov, N. V. Kalakutskiy, A. I. Yaremenko, M. Y. Petropavlovskaya, M. N. Portnova, O. V. Lukina, and A. P. Litvinov, "Intraoperative use of mixed reality technology in median neck and branchial cyst excision," *Future Internet*, vol. 13, no. 8, p. 214, Aug. 2021, doi: 10.3390/fi13080214.

[9] S. Wang, M. Parsons, J. Stone-McLean, P. Rogers, S. Boyd, K. Hoover, O. Meruvia-Pastor, M. Gong, and A. Smith, "Augmented reality as a telemedicine platform for remote procedural training," *Sensors*, vol. 17, no. 10, p. 2294, Oct. 2017, doi: 10.3390/s17102294.

[10] D. Andersen, V. Popescu, M. E. Cabrera, A. Shanghavi, G. Gomez, S. Marley, B. Mullis, and J. P. Wachs, "Avoiding focus shifts in surgical telementoring using an augmented reality transparent display," *Med. Meets Virtual Reality*, vol. 22, pp. 9–14, Jan. 2016.

[11] M. C. Davis, D. D. Can, J. Pindrik, B. G. Rocque, and J. M. Johnston, "Virtual interactive presence in global surgical education: International collaboration through augmented reality," *World Neurosurgery*, vol. 86, pp. 103–111, Feb. 2016, doi: 10.1016/j.wneu.2015.08.053.

[12] S. Zhang, F. Li, Y. Zhao, R. Xiong, J. Wang, Z. Gan, X. Xu, Q. Wang, H. Zhang, J. Zhang, and X. Chen, "Mobile internet-based mixed-reality interactive telecollaboration system for neurosurgical procedures: Technical feasibility and clinical implementation," *Neurosurgical Focus*, vol. 52, no. 6, p. E3, Jun. 2022, doi: 10.3171/2022.3.FOCUS2249.

[13] M. D. Tadlock, E. J. Olson, D. Gasques, R. Champagne, M. J. Krzyzaniak, S. A. Belverud, V. Ravindra, J. Kerns, P. M. Choi, J. Deveraux, J. Johnson, T. Sharkey, M. Yip, N. Weibel, and K. Davis, "Mixed reality surgical mentoring of combat casualty care related procedures in a perfused cadaver model: Initial results of a randomized feasibility study," *Surgery*, vol. 172, no. 5, pp. 1337–1345, Nov. 2022, doi: 10.1016/j.surg.2022.06.034.

[14] A. Follmann, M. Ohligs, N. Hochhausen, S. K. Beckers, R. Rossaint, and M. Czaplik, "Technical support by smart glasses during a mass casualty incident: A randomized controlled simulation trial on technically assisted triage and telemedical app use in disaster medicine," *J. Med. Internet Res.*, vol. 21, no. 1, Jan. 2019, Art. no. e11939, doi: 10.2196/11939.

[15] J. Jang-Jaccard, S. Nepal, B. Celler, and B. Yan, "WebRTC-based video conferencing service for telehealth," *Computing*, vol. 98, nos. 1–2, pp. 169–193, Jan. 2016, doi: 10.1007/s00607-014-0429-2.

[16] D. Antón, G. Kurillo, A. Goñi, A. Illarramendi, and R. Bajcsy, "Real-time communication for Kinect-based telerehabilitation," *Future Gener. Comput. Syst.*, vol. 75, pp. 72–81, Oct. 2017, doi: 10.1016/j.future.2017.05.006.

[17] C.-C. Teng, N. Jensen, T. Smith, T. Forbush, K. Fletcher, and M. Hoover, "Interactive augmented live virtual reality streaming," in *Proc. 2nd Int. Conf. Med. Health Informat.*, Jun. 2018, pp. 143–147, doi: 10.1145/3239438.3239456.

[18] Y. Liu, "Intelligent stereo video monitoring system for paramedic helmet," Ph.D. dissertation, Fac. Graduate Postdoctoral Stud., Univ. Ottawa, Ottawa, ON, Canada, 2017, doi: 10.20381/ruor-20932.

[19] S. Ahmadi, "Chapter 1—5G network architecture," *5G NR—Architecture, Technology, Implementation, and Operation of 3GPP New Radio Standards*. Cambridge, MA, USA: Academic Press, 2019, pp. 1–194, doi: 10.1016/B978-0-08-102267-2.00001-4.

[20] A. Ahad, M. Tahir, and K. A. Yau, "5G-based smart healthcare network: Architecture, taxonomy, challenges and future research directions," *IEEE Access*, vol. 7, pp. 100747–100762, 2019, doi: 10.1109/ACCESS.2019.2930628.

[21] S. Dananjayan and G. M. Raj, "5G in healthcare: How fast will be the transformation?" *Irish J. Med. Sci.*, vol. 190, no. 2, pp. 497–501, May 2021, doi: 10.1007/s11845-020-02329-w.

[22] H. Zhu, Y. Li, G. Gong, M.-X. Zhao, L. Liu, S.-Y. Yao, C. Wang, X. Li, and Y.-D. Chen, "A world's first attempt of mixed-reality system guided inferior vena cava filter implantation under remote guidance of 5G communication," *J. Geriatric Cardiol.*, vol. 18, no. 3, pp. 233–237, 2021, doi: 10.11909/j.issn.1671-5411.2021.03.008.

[23] B. Sredojev, D. Samardzija, and D. Posarac, "WebRTC technology overview and signaling solution design and implementation," in *Proc. 38th Int. Conv. Inf. Commun. Technol., Electron. Microelectron. (MIPRO)*, May 2015, pp. 1006–1009, doi: 10.1109/MIPRO.2015.7160422.

[24] C. Perkins, M. Westerlund, and J. Ott, *Media Transport and Use of RTP in WebRTC*, Standard RFC 8834, Internet Engineering Task Force (IETF), Jan. 2021, doi: 10.17487/RFC8834.

[25] A. S. Glassner, *An Introduction to Ray Tracing*. Burlington, MA, USA: Morgan Kaufmann, 1989.

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