Evaluation of the HoloLens for Medical Applications Using 5G-connected Mobile Devices

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Abstract—**The updated range of models of smart glasses has expanded the availability of augmented reality (AR) technology in a way that opens them up to several applications. The first prototypes have been replaced by new models and vendors offer off-the-shelf solutions. E-health and medical applications have been in focus from the start. Furthermore, the roll-out of 5G technology would enable almost real-time, high-speed and low- latency communication, which would expand the potential uses and ideas. This paper gives a short overview of the current state, focusing on medical applications using smart glasses. The HoloLens glasses were evaluated regarding latency and data rates by using WiFi and the 5G campus network of the university. Results show that the HoloLens may be used in education, training and teleassistance; however, assisting latency-sensitive tasks that require a reliable network connection, ergonomic design, and privacy issues still remain a problem.**

Index Terms—**5G, HoloLens, Telemedicine, Augmented Reality, Smart glasses**

I. Introduction

Google presented their AR smart glasses in 2014, where computer generated information (text or graphics) could be superimposed on physical objects in the field of view. This application was considered a human computer interaction (HCI) issue that focused on the multimodal interaction methods and problems (i.e., touch, touchless and hand-held), and design challenges of input and information manipulation. Touch input can be further divided into on-device and on-body, while touchless input can be classified into hands-free and freehand [1]. The user interface plays a significant role in usability, and thus, in the adaptation of new technology [2].

Technology assisted solutions for healthcare ecosystems could address patient-specific needs, but adaptation to it requires time, especially from the patient side [3]–[5]. A 2016 study revealed the importance of different drivers for acceptance, such as usability, functional benefits, branding/fashion issues, individual differences, social norms, and privacy concerns [6], [7]. Results showed that the greater concern is of other people's privacy rather than their own.

A. Clinical Applications

The main goals of introducing smart glasses in clinical applications are: improving patient care, increasing efficiency, and decreasing healthcare costs [8], [9]. Web-connected smart glasses can present data, record images, and videos that are accompanied by audio communication. A 2015 article reviewed 71 cases using smart glasses in health care, highlighting their limitations [10]. The first applications included hands-free documentation; telemedicine meetings and diagnostics; live broadcasting (educational purposes); electronic record storage; and updates. Qualitative evaluation of applications is needed after adjusting to the special needs of the subsections of medicine. Further problems need to be addressed, such as social interactions, physiological and psychological problems, and legal issues [11]. Communication with the patients is a key driver of passive trust in technology and of trust in caregivers [12], [13].

In neurology, smart glasses were tested during ward rounds on 103 neurocritical care patients. Both human supervision and telepresence assistance were available. In 90% of the cases, excellent overall reliability was observed. There was a wide user acceptance and high satisfaction rate for virtual ward rounds [14].

Another study investigated the applicability and accuracy of smart glasses for an AR-based neurosurgical navigation. 3D MRI computer graphics were projected on to the smart glasses, using markers, which allowed for accurate navigation. The test involved two patients with brain tumors located on the surface of the brain. Hands-free neuronavigation inside the operative field was maintained and computer graphics of brain tumors were clearly visualized during surgery [15].

In anatomic pathology the HoloLens was tested for virtual annotation during autopsies, viewing 3D various pathology specimens, navigating slide images, telepathology, as well as real-time pathology-radiology correlation [16]. Residents performing autopsies were remotely instructed. The device was found to be comfortable to wear, easy to use, it provided sufficient computing power, and supported high-resolution imaging.

The HoloLens was compared to a mobile handheld tablet used in anatomy education of medical students. Both methods were beneficial; however, in the case of HoloLens, 25% more subjects reported dizziness [17]. In general, AR/VR-based head-mounted device technology was seen as a key solution in the future in medical education [18].

Another study evaluated the HoloLens as a potential alternative to conventional monitors in endoscopic surgery and minimally invasive surgery. Performance by novice surgeons was improved. The device was widely accepted as a surgical visual aid, specifically as a feasible alternative to the conventional setups with the possibility of aligning the surgeon's visual-motor axis [19].

Promotion of the integration of VR, AR and MR is im-

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portant for comprehensive rehabilitation training, as well as concise extremity rehabilitation and telemedicine (i.e., training of motor skills, individual training programs with automated correction mechanisms) [5].

Furthermore, patient safety in intensive care units may be enhanced by smart glasses. Based on interviews, smart glasses can enhance current monitoring and routines, but not replace human supervision [20], [21].

Integrating data of patients, such as information of the patient in the health care system and devices connected to the patient, can be successful using fast and reliable automated patient recognition based on face recognition using the cameras of smart glasses [22]. Smart glasses can be used to assist visually impaired in their mobility tasks, especially for obstacle detection above waist level [23]. Infrared and position sensors together with noise filters and an Android app resulted in 93% sensitivity and 95% specificity. However, there is a problem with the ergonomic design, which is of great importance, as they need to wear the device for an extended period.

Simulator sickness or cybersickness is a common problem using VR and AR simulators [24]–[26]. It is due to distorted sensation, where the information from the visual modality (often supported by the hearing modality) differs from those of the body (body posture, movement in alignment with vision). It is more common in the case of fully immersive VR scenarios, but can also happen during augmented and mixed realities using head mounted devices.

B. 5G

5G technology offers low latency, high data rate and a large number of connected devices (IoT) in mobile communications and opens new business opportunities [27]. Medical applications can be latency-sensitive, where response times as low as 1 ms are required to create real-time communication. Seeking health care services, getting individual diagnosis and treatment, and avoiding imbalanced resource management (logistics) open the way to new services and applications [5], [28]–[30].

Surgical training and telesurgery (as a future perspective) are the most important areas where low-latency is a prerequisite [31]–[33]. Nevertheless, real telesurgery is still underdeveloped due to lack of confidence from both the patient and surgeon side. Furthermore, during teleoperation, an expert surgeon must be present on-site in the operating room in case of an emergency, this raises the question of whether this is procedure is really necessary or not, as it requires two surgeons to do the job of the one that is present.

Robotic-assisted surgery can be the technological solution to bridge the gap between traditional surgery and future telesurgery (i.e., DaVinci, Hugo RAS System, Fig. 1) [34], [35]. Minimally invasive surgery can be brought to more patients with increased safety, if high operational costs can be reduced [36]. The main advantage is here to have flexible arms during operation compared to the rigid manipulators used today (i.e., in laparoscopy) [37]. On the other hand, the feeling of touch and depth perception is lost. Laparoscopes provide depth perception by looking at a 2D screen and moving the arms back and forth, thus maintaining the eye-hand coordination. 3D imaging techniques, implementation of deep learning procedures, augmented reality, and the development of force feedback robots can lead the way to resolve these problems [38]–[41].

Fig. 1. The DaVinci model Generation 4. It contains a surgeon console for HD images in 3D, a patient cart for the instruments and a vision cart for communication [34]

5G also contributes to the development of related fields in personal medicine, such as big data, artificial intelligence, smart decision making, and diagnosis assistance. The risks of a communication breakdown, and drop in instantaneous data speed or latency have to be solved in order to have a reliable system. Network slicing can help enhance safety, optimize QoS and network load for health care solutions [42], [43].

This is especially true in sparsely inhabited rural areas, which face challenges that can partly be assisted or even solved using e-health solutions based on 5G networks. The full potential of 5G can be exploited for AR solutions as well [44]–[47].

Although not a direct medical approach, multiple HoloLens devices were used for communication with an Unmanned Aerial Vehicle (UAV) that provided multiple video streaming. This allowed the user to switch among multiple perspectives that were provided by the UAVs. A 5G connection was used to compensate for the range limit of the flying device (thus independent of a WiFi connection) [48]. Using drones in the transportation of medicine, medical equipment, samples and supplies can contribute to e-health services. The HoloLens can be also used with mobile devices that share a 5G internet connection [49]–[51]. 5G edge computing enables the distribution of computation-intensive AR tasks to edge servers through 5G networks, thus, increasing quality in latency-sensitive tasks.

An alternative solution to AR glasses is that human supervision can be broadened, simplified or even replaced by automated supervision of patients in rehabilitation. In this case, a device for home usage is installed and connected to the internet (XBox 360 Kinect), which has a camera that records the patient movements, and via automatic analysis, feedback and instructions are given for corrections. Applications can be

Fig. 2. First generation Microsoft HoloLens

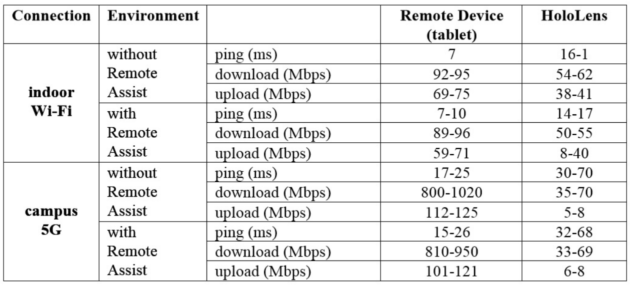
Fig. 3. System block diagram. The HoloLens communicates via 2.4 GHz WiFi with a 5G enabled cellphone. Both cellphone and remote device (tablet) connect to the same 5G base station.

developed to meet individual needs of patients and the elderly or for treatment of certain diseases, such as stroke, MS and Parkinson's, where extensive movements would be restricted by smart glasses [52]–[56].

II. SETUP AND RESULTS

The HoloLens is supported by the Dynamics 365 Remote Assist application, originally developed for Teams. It can be downloaded and installed on the Android platform. The glasses run on a Windows 10 operating system, both the glasses and remote device(s) have to install the application, and be connected to the internet. The real-time video captured by the camera of the HoloLens is streamed to the remote device and simultaneously it is displayed as an overlay in the HoloLens. Both users can edit the video, e.g., by placing pointers, drawings, and text information on it; additionally the communication is enhanced by bidirectional audio connection. The picture of the camera of the remote device cannot be shared and displayed on the HoloLens. Figure 2 shows the first generation HoloLens device.

In our test of the HoloLens, we first set up the connectivity of the devices using the university public indoor WiFi. For measuring the uplink and downlink speed, as well as the response time (ping), a "speedtest" was used in a browser window [57]. Both devices ran the Remote Access application for shared communication. A call can be only initialized from the HoloLens to the tablet, at which point the picture of the HoloLens will be streamed and displayed. Figure 3 shows the system setup in a simplified form in the case of a 5G-based connection. Both devices were connected to the same base station and communication involved the non-stand alone core network.



Connection	Environment		Remote Device (tablet)	HoloLens
indoor Wi-Fi	without Remote Assist	ping (ms)	7	16-1
		download (Mbps)	92-95	54-62
		upload (Mbps)	69-75	38-41
	with Remote Assist	ping (ms)	7-10	14-17
		download (Mbps)	89-96	50-55
		upload (Mbps)	59-71	8-40
campus 5G	without Remote Assist	ping (ms)	17-25	30-70
		download (Mbps)	800-1020	35-70
		upload (Mbps)	112-125	5-8
	with Remote Assist	ping (ms)	15-26	32-68
		download (Mbps)	810-950	33-69
		upload (Mbps)	101-121	6-8

Fig. 4. Measurement results (max-min values) based on ten measurements for latency, download and upload speeds. The tablet connected to the 5G network directly. The HoloLens connected to the 5G network via the cellphone's 5G module.

Using WiFi, the tablet had a 7 ms latency, 92-95 Mbps download, 69-75 Mbps upload speed compared to the HoloLens that had a 16-18 ms latency, 54-62 Mbps upload speed, and 38-41 Mbps download speed (these were measured based on ten measurements). During an established connection between the devices, the speedtest reported 14-17 ms ping, 50-55 Mbps download and most importantly 8-40 Mbps upload rate from the HoloLens side.

Moving outside the buildings, the campus 5G network was used to repeat the tests. A cellphone shared the internet connection with the HoloLens, and the same tablet served as the remote device. Both connected to the same base station operated by a national service provider. The HoloLens used the 2.4 GHz WiFi to connect to the cellphone. The tablet delivered ping results of 17-25 ms, 800-1000 Mbps download and 125 Mbps upload speed. However, the HoloLens had 30-70 ms ping, 35-70 Mbps download and only 5-8 Mbps upload speed independent of being connected or disconnected via Remote Assist (again, based on ten measurements).

Figure 4 shows a summary of the measurement results. Furthermore, a subjective evaluation was made with nine individuals after 30-minute test runs. Five surgeons and four physiotherapists experimented with the device and reported on ergonomics, usability and potential uses in their field of interest.

III. DISCUSSION

A. Latency and Data Speed

A ping, in regard to software, measures the latency time of a round-trip of messages sent from the source to a destination computer and back. Latency issues are clearly problematic in the case of HoloLens if low-latency is required. WiFi outperformed 5G not just in the actual ping measurements, but the difference was clearly detectable by the users experiencing perceptible lags between glasses and the remote device. Results of 30-70 ms from the HoloLens side seem to be far from the promised values of 5G (as low as 1 ms). A limiting factor is the HoloLens itself; newer models may deliver better results. Using the 5G network, there was no significant difference is latency and speed rates with or without running the Remote Assist application.

Although the remote device connected to the 5G base station performed well both in download and upload speed, the HoloLens upload data rate of several Mbps would be insufficient for applications that have high data rate video streams.

Testing in an outdoor scenario on a sunny day, the HoloLens was almost unusable with very limited picture visibility. This can be also problematic for other devices as well, and also true for bright indoor environments, i.e., in an operating room.

B. Ergonomics

The glasses were tested by subjects of the target group, mostly for ergonomics and comfort. Even when individually adjusted to the head, users were not satisfied with the comfort: the device is quite large and heavy (580 grams), the nose strip is uncomfortable, after head movements it has to be replaced, and tilting of the head can cause it to slip off of the nose and head. Test persons did not support the idea of using it in the operating rooms or while making extended, large-scale movements. However, the subjects stated that in the future they would be interested in testing the device for training and educational purposes. Additionally, six out of the nine subjects reported simulator sickness and mild dizziness.

The HoloLens and its wireless control device can be charged via the micro USB port. After a full charge, about 2 hours of operation is guaranteed, but users did not prefer sessions longer than 20-30 minutes.

C. Other Models

Other vendors also offer solutions. First of all, the follow-up model of the HoloLens, called HoloLens 2 offers a Research Mode, API and methods to access the raw sensor data using open-source tools [58], [59]. Furthermore, using the USB-C connector, an external 5G device can be connected for a direct 5G connection. Size and weight are almost the same, but balance is shifted for a more comfortable wear, the visor can be flipped and regular glasses can be worn inside the helmet. Some additional functionality improvements were added, such as eye-tracking, HD video, two-hands and gesture tracking, and an increase in the field-of-view from 30 to 52 degrees.

Google Glass Enterprise Edition 2 is the latest update from the company running on the Android platform [60]. It is lightweight, only 46 grams without frames (glass pod and titanium band). To mirror the device or remotely operate it, any standard Android 8.1-compatible casting application, i.e., *Vysor* or *scrcpy* can be used. WiFi is the basic connection and there is no information about a direct 5G connection. Due to its special design and light-weight, it can be worn as long as you would a normal set of glasses, so they are much more comfortable than the HoloLens. If the user is already wearing regular glasses or safety frames, the needed parts are detachable and can be attached to them. However, the small display in front of the left eye results in the eye constantly focusing on it, causing the user to suffer from eye strain after some time. It is comfortable if the user only needs the small screen once in a while. This can be a limitation in use and can lead to "after-effects" after finishing the procedure. It does not have a controller or hand-tracking, only a touchpad-like part of the frame (speech-command apps should be developed for the system).

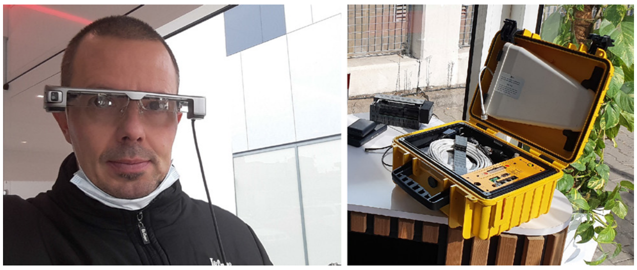


Fig. 5. AR Remote Trouble Shooting case with Epson's Moverio glasses

The Epson Moverio family offers different glasses for different applications [61]. Headsets are always tethered to a controller and the battery is separated from the headset; both of these features allow for comfort and to keep the weight low. Although this has two displays that show the same image in order to avoid conflicting images between the two eyes, this may cause fatigue. Some models offer SIM connectivity. There is a stand-alone Android Smart Glass model where apps can be installed directly to the controller. Another model includes an interface box to display content from an existing external device to the glasses. Using the Moverio, Huawei presented the AR Remote Trouble Shooting assistance system that enables untrained mechanics to operate complex systems easily (Fig. 5). The system contains a 5G antenna set in an integrated case as an all-in-one solution. A recent survey analyzed 82 publications in the field of logistics and supply chain management. Potential benefits were identified for the latter include visualization, interaction, user convenience, and navigation. For logistics, technical, organizational, and ergonomic considerations were the most important aspects [62].

In an experiment on solving logistic tasks, the Altered Vuxiz glasses were tested for comfort. Even though the "side weighted" arrangement was the most comfortable, participants still found the device uncomfortable [63].

In manufacturing engineering, the Technological Readiness Level (TRL) of some of the components is still low (displays of TRL7 and the tracking part of TRL5) [64]. Acceptance in engineering tasks and medical applications is relatively low, mostly due to ergonomics. Users can find updated information about current virtual and augmented headsets in the online database called VRcompare [65].

D. SDK and API

HoloLens comes with a pre-installed operating system and the Remote Assist application can be used as an off-the-shelf solution in various cases. However, Microsoft offers lots of documents for HoloLens developers as well [66], [67]. There is no separate SDK for Windows Mixed Reality development. The Visual Studio with the Windows 10 SDK can be used instead. Tutorials are available for starting simple projects and also for users with no technological background.

Windows 10 is required to install Unity Personal as the engine. Optionally, Vuforia Augmented Reality Support can be added, if users want to use markers on real-world objects with the HoloLens. Furthermore, Visual Studio can be installed with the option ”Game Development with Unity”. The Mixed Reality Toolkit for Unity is a collection of scripts and components to accelerate development. The HoloLens should be in Developer Mode, but if there is no device on hand, the HoloLens can be emulated as well.

Unity is a real-time development platform with runtime code written in C++ and development scripting in C Sharp. The open source Unreal Engine 4.25 can be also used for development in C++ with full HoloLens support [68]. Optimized SDK for other models such as the Moverio and Vuzix smart glasses can be downloaded and installed based on Wikitude's JavaScript API [67]. Google Glass needs Android Studio and Android SDK 8.1 (API 27) to develop applications. All models offer open-source development environments.

E. Applications in Telemedicine and Telerehabilitation

Telerehabilitation, as part of telemedicine, has been among the first areas of applications for smart glasses. Supervision of stroke patients, children and elderly persons with disabilities, subjects that have sleep disorders or neurocognitive problems, as well as remote assistance and consultation for physical therapist has opened the way for the first tests and implementation [69]–[74].

Smart glasses and VR devices offer immersive experience and entertainment. Gamification or serious gaming can be an entertaining way of maintaining motivation during execution of tasks [75]–[77]. Especially children and patients needing sustained rehabilitation process can benefit from such technology. Connected simulations and virtual realities in sport, training or while exercising can enhance the experience and maintain motivation.

Legal and ethical considerations are of great importance, as telerehabilitation solutions usually assume a patient is supervised from a distance, where the patient may not see the other end of the connection, specifically who is watching, or even recording [78]. The environment can be intimate, where supervising personnel observe the patient getting undressed, sleeping or doing physical activities. Trust, together with data and personal security, is and will be a key factor in accepting this technology.

IV. CONCLUSIONS

This paper presented results about the evaluation of the Microsoft HoloLens glasses with a focus on possible medical applications. Using 5G mobile network connection and handheld devices, latency and uplink/downlink speed were measured between the device and remote supervision. Results showed that latency-sensitive tasks are still problematic, where response time is critical and connection breakdowns are not acceptable (e.g., telesurgery). Furthermore, privacy issues and design considerations have to be addressed in order to increase acceptance by the medical personnel, patients, and society. Nevertheless, AR/MR solutions based on smart glasses are suitable for extending telemedicine services in remote consultation and assistance. Furthermore, this technology could be used in medical education and training (e.g., autopsy, anatomy, neurology, stroke treatment). Some headset models are lighter in weight and have a more ergonomic design, which allow for longer use. 5G will offer speed, reduced latency and increased throughput for medical IoT solutions, real-time audio and video streaming, but connected devices have to be fitted in order to utilize all possibilities. The communication module of smart glasses can be enhanced with SIM-slots and 5G antennas along with WiFi terminals. Future work includes exploring further application areas, especially in telemedicine, nursing, rehabilitation, and home care. Currently, an updated measurement setup is being tested using CT and MRI scans of real patients that are displayed, manipulated (rotation, zooming) with an external controller and validated by radiologist. Different wireless solutions will be tested for latency and data rates. Furthermore, other areas, i.e., telemaintenance, e-learning, e-commerce (marketing) and tourism offer additional possibilities for smart glasses [79]–[84]. Involvement and testing of other AR glasses need to be explored in the future.

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