POLITECNICO DI TORINO
Repository ISTITUZIONALE

Metrology-Based Design of a Wearable Augmented Reality System for Monitoring Patient’s Vitals in Real Time

Original
Metrology-Based Design of a Wearable Augmented Reality System for Monitoring Patient’s Vitals in Real Time / Arpaia, Pasquale; De Benedetto, Egidio; Dodaro, Concetta Anna; Duraccio, Luigi; Servillo, Giuseppe. - In: IEEE SENSORS JOURNAL. - ISSN 1530-437X. - ELETTRONICO. - 21:9(2021), pp. 11176-11183. [10.1109/JSEN.2021.3059636]

Availability:
This version is available at: 11583/2943252 since: 2021-12-15T14:18:58Z

Publisher:
IEEE

Published
DOI:10.1109/JSEN.2021.3059636

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
IOP postprint/Author's Accepted Manuscript

“This is the accepted manuscript version of an article accepted for publication in IEEE SENSORS JOURNAL. IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at http://dx.doi.org/10.1109/JSEN.2021.3059636

(Article begins on next page)

23 April 2024

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

Metrology-based Design of a Wearable Augmented Reality System for Monitoring Patient's Vitals in Real Time

Pasquale Arpaia, *Senior Member, IEEE,* Egidio De Benedetto, *Senior Member, IEEE,* Concetta Anna Dodaro, Luigi Duraccio, and Giuseppe Servillo

***Abstract*—In this work, an augmented-reality (AR) system for monitoring patient's vitals in real time during surgical procedures is proposed and metrologically characterized in terms of transmission error rates and latency. These specifications, in fact, are crucial to ensure real-time response which is a critical requirement for Health applications. The proposed system automatically acquires the vitals from the operating room instrumentation, and shows them in real time directly on a set of wearable AR glasses.In this way, the surgical team has a real-time visualization of a comprehensive set of patient's information, without constantly looking at the instrumentation. The system was designed to ensure modularity, flexibility, ease of use and, most importantly, a reliable communication. The system was designed, implemented and validated experimentally through on-field tests carried out at the Academic Hospital of Federico II University, using instrumentation typically available in the operating room: namely, a respiratory ventilator and a patient monitor. Results of the experimental validation highlight the need for the metrological approach in conceiving advanced monitoring surgical procedures in operating room.**

***Index Terms*—Augmented reality, health 4.0, latency, measurement system, monitoring system, operating room, patient's vitals, real-time monitoring, smart glasses, ventilator, wearable.**

I. Introduction

INFORMATION and Communication Technologies (ICTs) in healthcare are bringing new opportunities and disclosing novel market scenarios [1]. In particular, the Health sector is benefiting from several 4.0 technologies [2], such as the internet of things (IoT) [3]–[5]; artificial intelligence [6]; machine and deep learning [7]–[9]; cloud computing [10]; additive manufacturing [11]; wearable sensors [12]–[17]; and augmented and virtual reality (AR and VR) [18]–[20]. With regard to AR, relevant applications in healthcare can be found in medical training [21], but also for surgical procedures [22]–[24]. In surgery, one important application of AR is the overlay of digital medical images on the patients while the surgical procedure is being carried out [25]. Another important AR application is the monitoring of patient's vitals in the operating room (OR). Patient's vitals, along with additional information on the electronic medical records, may be displayed directly on wearable AR glasses worn by the nurses or by the anesthetist. The idea is to use AR smart glasses to allow the surgical team to monitor the patient's health status in real time, even at a distance from the electromedical equipment. The final goal is to improve the efficiency of the procedures by relieving the burden of constantly looking at the OR equipment; in this way, the surgical team can focus their attention on the patient and on the task at hand.

Previous works have addressed the possibility of using AR to display patient's vitals [26]–[30]. In [26], the authors focused on the number of times the anesthetist had to shift attention from the patient to the equipment, by achieving a significant decrease of more than a third through an AR head-mounted display (HMD). The use of AR HMD was also investigated

This work was carried out as part of the "ICT for Health" project, which was financially supported by the Italian Ministry of Education, University and Research (MIUR), under the initiative 'Departments of Excellence' (Italian Budget Law no. 232/2016), through an excellence grant awarded to the Department of Information Technology and Electrical Engineering of the University of Naples Federico II, Naples, Italy.

P. Arpaia is with the University of Naples Federico II - Interdepartmental Research Center in Health Management and Innovation in Healthcare (CIRMIS), Naples, Italy.

E. De Benedetto is with the University of Naples Federico II - Dept. of Information Technology and Electrical Engineering, Naples, Italy, e-mail: egidio.debenedetto@unina.it

L. Duraccio is with the Polytechnic University of Turin - Department of Electronics and Telecommunications, Turin, Italy.

C. A. Dodaro is with the University of Naples Federico II - Dept. of Advanced Biomedical Science General Surgery and Transplant Unit, Naples, Italy,

G. Servillo is with the University of Naples Federico II - Dept. of Neurosciences, Reproductive and Odontostomatological Sciences, Section of Anesthesia and Intensive care, Naples, Italy.

Manuscript received Month XX, 2020; revised Month Day, Year.

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

in [27], along with auditory display to avoid distractions to the anesthetist in the OR. More recently, in [28], a bio-monitoring platform for supervising personnel operating in critical infrastructures was developed. The platform collects a set of signals in order to determine the optimal physiological profile of the personnel. A mixed-reality system for real-time, hands-free, measurement and visualization of blood flow and vital signs was also implemented in [29].
However, in the aforementioned AR-based works, the attention was generally focused on the usability of the system, without measuring its performance. On the other hand, for medical applications, guaranteeing the dependability of an AR-based system for monitoring patients' vitals is crucial. In particular, for a remote monitoring system in surgical procedures, it is of the utmost importance the warranty that the information is transmitted correctly, timely, and virtually, without latency.
For example, in previous works related to health monitoring systems [31], [32] the main challenges and requirements involving real-time wireless data transmission were explored. Namely, the transmission bandwidth, the number of interruptions per time unit, the mean duration of the stops, the monitoring delay, the energy efficiency, and the reliability were taken into account. In particular, it results that any video/audio delay over 300 ms should be avoided, to guarantee a proper interaction between the user and the system. Furthermore, to avoid network failures (which can range from minor disruptions to major life-threatening scenarios), fault-tolerant techniques are generally included into the network.

On the basis of these considerations, in this work, a metrology-oriented design of an automatic monitoring system based on AR is proposed to support the medical team during surgical procedures. The system acquires the vital parameters from the electromedical instruments in the OR (e.g, a respiratory ventilator and a patient monitor) and display them in real time on a set of AR glasses [33]. The proposed system was implemented and experimentally validated with the aim (i) to verify the proper functionalities of the system, and (ii) to assess its data transmission dependability, in terms of real-time communication. The latter was done by assessing the system's accuracy and latency, and verifying their compatibility with the stringent requirements of the OR.

The paper is organized as follows. In Section II, the concept design of the proposed system is presented, along with the general architecture, the operation and the software. Section III addresses the implementation of the customized system in a specific application context, considered as a case study. After the description of the experimental setup and of the function validation, Section IV summarizes the experimental tests of the metrological characterization carried out at the Hospital facilities of the University of Naples Federico II. Finally, in Section V, conclusions are drawn.

II. Design

This section addresses the conceptual design of the proposed AR-based, real-time monitoring system, with focus on (i) the *architecture*, (ii) the *software*, and (iii) the *metrological characterization module* in terms of the requirements of real-time, wearable healthcare applications [31], [32].

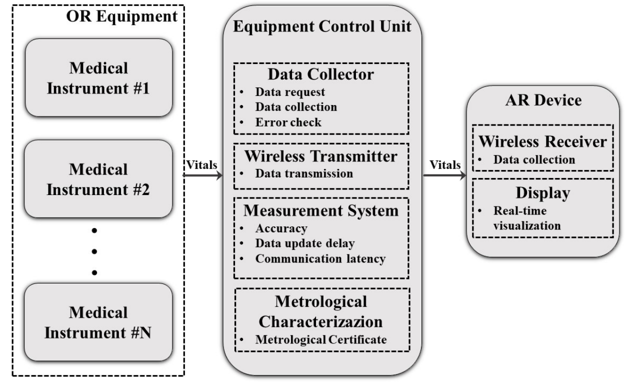

Fig. 1. Architecture of the proposed monitoring system.

Overall, the design choices were made to adhere to the stringent requirements of the health sector. Basically, the system was conceived for nurses and anesthetists, who are the ones in charge of monitoring patients' vitals in the OR (while the surgeon is focused on the procedure). Based on the authors' experience, the proposed system would allow nurses and anesthetists to monitor the patient vitals directly through the AR glasses, without having to turn their head to the monitoring equipment, thus being ready to to promptly act in case of aggravating conditions. The medical team involved in this work also gave suggestions on what it is needed to be displayed on the AR glasses and on how it is better to have these data displayed (for example, giving priorities to specific vitals and presence of alerts). Finally, the surgeons advised on the data communication requirements, and on the maximum latency acceptable during surgical procedures (lower than 2 s). Thanks to these preliminary considerations, the design an AR-based monitoring system was tailored to suit the basic requirements of the considered application field.

A. Architecture

The concept architecture of the system is shown in Fig. 1. An *Equipment Control Unit (ECU)* collects the vital parameters from the *OR Equipment*, which includes a number N of *Medical Instruments*. Once the data are requested and collected, the *Data Collector* checks for possible errors, to ensure the accuracy of the communication.
A *Wireless Transmitter*, integrated with the *ECU*, transmits in real-time the data to the *AR Device*: this acquires the vital parameters and displays them in AR, overlaid to the view of the physical world [34]. The *ECU* is also equipped with a *Measurement System*, for analyzing the *accuracy*, the *data-update delay*, and the *communication latency*.
Accuracy (expressed as a percentage), is defined as the number of packets correctly decoded, divided by the total number of received packets. The *data-update delay* is the time needed for the system to refresh the values of the acquired vital parameters, while the *communication latency* is the delay in the wireless transmission.
In addition, upon user request, the *ECU* processes the results of the *Measurement System*, to carry out a *Metrological Characterization* of the monitoring system as a whole.

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

As a result, a *Metrological Certificate* summarizing the system's performance is generated.

The overall architecture was conceived in order to maximize wearability and ease of use: in fact, the user has just to wear the AR device and start the application. The architecture guarantees modularity and flexibility, as the number and typology of medical instruments can be modified according to the specific conditions at hand. Also, the application was developed to allow the user to easily select different parameters to be shown on the AR glasses.

The presence of the *ECU* provides two major advantages. First, it allows to generalize the application; in fact, the system can be interfaced with different AR devices and/or with different OR equipment. Additionally, the *ECU* allows to include possible processing strategies, such as the visualization of alert if the vitals exceeds pre-established thresholds, or display the results of predictive algorithm forecasting possible aggravating trends of the patient.

B. Metrological Characterization

The AR-based system includes an off-line feature of self-metrological characterization. On user demand, the *Metrological Characterization* shown in Fig. 1 computes (i) the transmission accuracy (related to both the equipment and the communication protocol); (ii) the data-update delay (related to the equipment); and (iii) the communication latency (related to the communication protocol). To this aim, when the user wants to assess the metrological performance, different experimental sessions, each consisting of several runs, are carried out automatically. For each run, the transmission accuracy, A (%), is assessed as:

$$A = \frac{N_{packets} - E}{N_{packets}} \cdot 100 \tag{1}$$

where $N_{packets}$ is the number of packets sent; and E is the error count when a packets is not correctly decoded.

Then, for each session, the accuracy mean value μ_A and the standard deviation σ_A are assessed. Hence, the 3-sigma uncertainty is computed by taking into account the total number of runs, according to:

$$u_{\mathrm{A}} = \frac{k \cdot \sigma_{\mathrm{A}}}{\sqrt{N}} \tag{2}$$

where k = 3 is the coverage factor, corresponding to 99.7% confidence interval, and N is the total number of runs.

Finally, the time interval necessary to refresh the data coming from the devices is measured. In particular, for each packet within a run, the time related to data-update and to wireless communication is assessed. At the end of each run, the mean value and the standard deviation of these quantities are evaluated.

When the test session is completed, the pooled mean and the pooled uncertainty are assessed, taking into account the different number of packets sent for each run. The pooled mean of the update time μ_{t} is evaluated through the following equation:

$$\mu_{\mathrm{t}} = \frac{\sum_{i=1}^{N} \mu_{ti} \cdot l_i}{\sum_{i=1}^{N} l_i} \tag{3}$$

where μ_{ti} is the mean of the update time evaluated for each run; and l_i is the number of packets for each run.

The pooled uncertainty (u_{t}) is assessed as follows:

$$u_{\mathrm{tpo}} = \sqrt{\frac{\sum_{i=1}^{N} {u_{ti}}^2 \cdot (l_i - 1) + \sum_{i=1}^{N} l_i \cdot (\mu_{ti} - \mu_t)^2}{\sum_{i=1}^{N} l_i - 1}} \tag{4}$$

where u_{tpo} is the pooled uncertainty of the update time; u_{ti} is the 3-sigma uncertainty (assessed through (2)) of the update time evaluated for each run; μ_t is the pooled mean of the update time: μ_{ti} is the mean of the update time evaluated for each run; and l_i is the number of packets for each run (according to (3)). A further evaluation of the uncertainty is carried out, taking into account the law of propagation of uncertainty. Assuming μ_t as the weighted mean among the runs, as expressed by (3), the 3-sigma uncertainty is also evaluated through the following equation:

$$u_{\mathrm{tpr}} = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial \mu_t}{\partial \mu_{ti}} \cdot u_{ti} \right)^2} \tag{5}$$

where u_{tpr} is the uncertainty of the update time evaluated with the law of propagation of uncertainty, assuming the independence between each run.

When the metrological self-characterization of the system is completed, a metrological report summarizing the (i) transmission accuracy; (ii) data-update delay; and (iii) communication latency, is produced for the user.

C. Software

At operation level, the system software was designed (i) to acquire the parameters from the *OR Equipment* and send them to the *ECU*; (ii) to transmit the data to the the *AR Device*; (iii) to make the AR receive the vital signals from the *ECU*; and (iv) display them in real time on the *AR Device*. Moreover, through the AR device, the user can select the parameters to be displayed, with complete control over the entire incoming set of information. A flow diagram of the overall system operation is shown in Fig. 2.

After the initialization of the medical protocols related to the *OR Equipment*, the *ECU* establishes the connection with the devices and configures the parameters to collect. Then, the parameters are collected, decoded, and extracted, while also possible errors are checked for the functional verification of the system. If no errors have occurred, the parameters are sent to the *AR Device*. Otherwise, the system generates an alert and waits for the new packet. In the unlikely event that also the new packet is not correctly extracted, the protocols are immediately re-initialized. In this way, the maximum interval time when the operator could have missing data is restricted to two packets. Finally, the *AR glasses* display in real-time the incoming information.

III. Prototype

In this section, the *Equipment*, the *ECU* and the *AR Glasses* employed for the prototype are presented. Also, the dedicated software and the implemented communication are described.

As a case study, the *OR Equipment* includes a respiratory

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

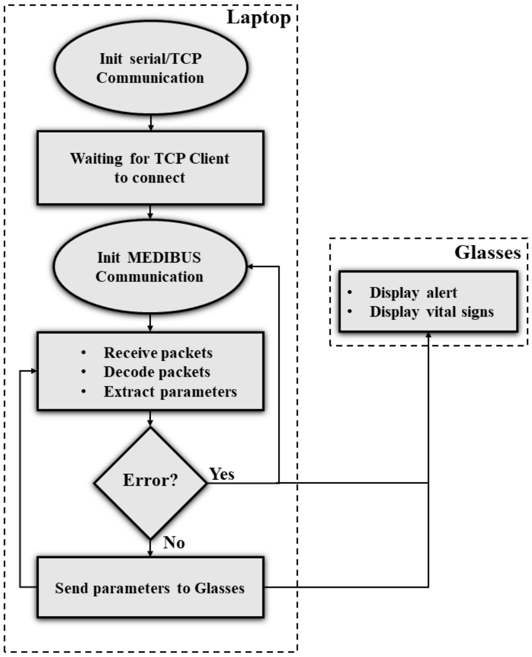

Fig. 2. Flowchart of the system operation.

(a) (b)

Fig. 3. OR equipment employed for the proposed monitoring system: (a) Drager Ventilator; and (b) Philips Patient Monitor.

ventilator for intensive care and a patient monitor. The parameters acquired from the two medical instruments are sent to a laptop, which acts as the *ECU*. It receives the values of the patient's vitals, and sends them to the AR glasses, by means of a wireless communication. After the communication between the laptop and the electromedical instrumentation is established, the user wears the *AR Glasses* and connects the wireless device to the laptop. The patient's vitals are finally displayed on the AR glasses.

A. Equipment

The equipment includes the following four major elements:

- *Respiratory ventilator:* The ventilator used in this work is the Dräger Infinity V500 [35], shown in Fig. 3(a). Ventilators for intensive care are used to help lungs to administer an adequate and controlled amount of O_2 to the patient, to eliminate the produced CO_2 and to reduce the respiratory effort of a patient due to an excessive work of the lungs. A complete list of all the vital parameters that can be monitorred through this instrument can be found in [35]. The Infinity V500 ventilator is equipped with a LAN (Local Area Network) interface, with the possibility to enable or disable the DHCP (Dynamic Host Configuration Protocol) functionality, and with three serial Interfaces, with the possibility to choose between MEDIBUS or MEDIBUSX protocol. Moreover, it is possible to set Baud Rate, Parity Bits, Stop Bits, and Terminator Character.
- *Patient monitor:* The Philips IntelliVue MP90 [36] patient monitor was used [36]. This piece of equipment, shown in Fig. 3(b), allows to monitor more than 50 different vitals, such as oxygen saturation; compound ECG; respiration rate; perfusion indicator; etc. It is possible to monitor the aforementioned parameters after connecting separate 'plug-and-play' modules (i.e. ECG, blood pressure, heart rate).
- *ECU:* The used *ECU* is a laptop, equipped with an AMD A10-9600P Processor, 16 GB RAM, and two USB 2.0 ports, used to connect the electromedical devices. A WiFi *IEEE 802.11a/b/g/n* module is used for a wireless communication with the AR Smart Glasses.
- *AR Glasses:* The Epson Moverio BT-350 AR glasses were used as an AR device. These are OST (Optical See-Through) glasses, which allow the user to see the digital images overlaid to the real world environment. OST technology guarantees that the user always has view of the (real) surrounding environment. The Moverio BT-350 is relatively inexpensive (in the order of 700 Euros), and this makes it suitable for possible large-scale applications. The Moverio BT-350 also satisfy the operating requirements in the Health sector. In particular, these AR Glasses have proven much more powerful, in terms of CPU and RAM, and more ergonomic than previous versions (e.g, the Epson BT-200 previously used in AR industry-oriented applications [37]).

B. Software

A code running in MATLAB environment was implemented for the acquisition from the medical instruments and the transmission of the data.

a) Acquisition from ventilator: The relevant subsection of the MATLAB code implemented the MEDIBUS protocol. This is a software protocol intended to be used for exchanging data between a Dräger medical device and external medical or non-medical devices via RS-232 interfaces. After the initialization of the protocol, the code asks and decodes the vitals to be acquired.

b) Acquisition from the monitor: the code related to the patient monitor is in charge of exchanging data with a proprietary software, *Medicollector*, able to acquire the waveform from the monitor. After starting Medicollector on the laptop, the MATLAB code acquires the desired patient monitor's waveforms over TCP/IP via LAN cable.

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

Fig. 4. Picture of the experimental validation.

c) Transmission to the glasses: For the laptop, a TCP/IP Server was implemented in MATLAB environment, and integrated with the code related to the acquisition of the parameters from the ventilator and the monitor. Once the connection with the the AR Glasses (acting as a Client) is established, the Server can send the parameters to the user.

d) Development of smart glasses software: Finally, also the software necessary for the AR Smart Glasses to receive data coming from the laptop was developed. In this case, an Android application, developed in Android Studio environment and installed on the Glasses, receives and displays the data. The Android application developed on the AR Glasses (acting as TCP/IP Client) is in charge of establishing the connection with the laptop (TCP/IP Server); of receiving the parameters; and of showing them on the AR glasses. The user can select which waveform from the patient monitor and which parameters from the Ventilator he/she wants to be displayed on the AR glasses.

A crucial part of the work is represented by the the communication between the instruments:

- *Ventilator-Laptop:* the serial communication between the laptop and the ventilator is performed at a Baud rate of 38400 bit/s and no parity bit and stop bit were considered. Because the used laptop had no serial port, an RS-232 to USB (Universal Serial Bus) adapter was used.
- *Patient monitor-laptop:* the TCP/IP communication between the laptop and the patient monitor is performed by means of the Medicollector adapter, a particular LAN to RS-232 adapter, and of a RS-232 to USB adapter, aiming to successfully connect the monitor (with a LAN port) to the laptop (with a USB port).
- *Laptop-AR Glasses:* the TCP/IP communication between the laptop and the AR glasses is wireless. The laptop receives the parameters from the OR equipment, and sends to the Moverio BT-350 the data to be displayed in AR.

It should be mentioned that, although a wireless connection could be a more practical solution, the use of such a series of converters was mandatory because the electromedical equipment used for the validation did not support any wireless connections.

IV. Experimental Case Study

The AR-based monitoring system was validated and metrologically characterized through experimental tests carried out at the Academic Hospital of Federico II University. Figure 4 shows a picture taken during the experiments. First, it was verified that the performance of the system would satisfy the requirements of the health sector, such as functionality, transmission speed and accuracy, and wearability. To this purpose, a preliminary validation and a consequent metrological characterization were carried out, by measuring the system accuracy and latency.

A. Experimental Setup

A non-self-inflating bag was plugged to the ventilator to emulate the patient's lung. The Baud Rate was set to 38400 bit/s, 8 Data Bits, 1 Stop Bit, and no Parity bit were foreseen. As for the patient monitor, it was used to monitor the vitals of a healthy volunteer.

Figure 5 shows a picture of what the user sees through the AR glasses. The user sees the major parameters from the ventilator; also, at the bottom, the real-time variation of oxygen saturation is displayed. By pressing a button, it is possible to switch between different waveforms coming from the Monitor. This information is superimposed to the user's vision. It should be mentioned that if the user is not wearing the AR glasses, the patient's health status can only be monitored by looking directly at the medical equipment. On the other hand, by wearing the AR glasses, the OR operator can monitor the patient's condition (avoiding distractions) directly as digital AR content overlaid to the real world. In this way, the user has complete control over the information.

Thanks to the modularity of the system architecture, each subsystem can be adapted to suit the specific context at hand.

B. Validation

Table I summarizes the list of vitals that were monitored through the ventilator and through the patient monitor. Once the monitor and ventilator are connected to the laptop by means of the aforementioned adapters, the MATLAB code is started for initializing the MEDIBUS and TCP/IP protocols. Then, the user wears the AR glasses and launches the Android application, setting the IP address and the port to communicate with the laptop. After the connection between the glasses and the laptop is established, the data coming from the instrumentation are collected and sent to the user's display.

Each block of the system was tested to guarantee that it worked properly without any degradations during data transmission, in particular: the equipment RS-232 and LAN ports, along with the laptop USB ports and the adapters; the MEDIBUS and TCP/IP protocol implemented on the laptop to fetch data from the instrumentation; and, finally, the TCP/IP protocol on the AR glasses to collect the vital parameters from the laptop with high accuracy and low latency.

Another important aspect of the research was also to make the user feel comfortable during the entire tests, by avoiding issues such as motion sickness. Nurses and anesthetists who tested

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

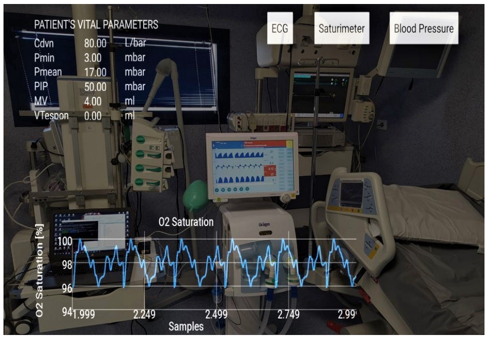

Fig. 5. Image of the user's view through the AR glasses.

TABLE I
LIST OF MONITORED VITALS

Parameter	Symbol	Unit	Ventilator/Monitor
Compliance	Cdyn	l/bar	Ventilator
Minimum Airway Pressure	Pmin	mbar	Ventilator
Mean Airway Pressure	Pmean	mbar	Ventilator
Peak Airway Pressure	PIP	mbar	Ventilator
Minute Volume	MV	l/min	Ventilator
Spontaneous expired total volume	VTespon	ml	Ventilator
O_2 Saturation	SpO2	%	Monitor
Compound ECG	ECG	mV	Monitor

the system during the experiments did not report dizziness or particular discomfort during the tests. The good usability of the AR-based system was the result both of the design choices for the AR application and of the specifications of the Moverio BT-350 (in terms of field of view and frame-rate stability), which proved adequate for a good user experience.

C. Metrological Characterization

After verifying that the data were correctly received, decoded and displayed, the metrological characterization of the system in terms of transmission latency and accuracy was conducted. Three major causes that contribute to the latency of the system were measured, namely:

- The delay related to the Monitor waveforms to be updated (*Monitor Latency*);
- The delay related to the update of the Ventilator parameters (*Ventilator Latency*); and
- The latency needed for the system to send a packet via TCP/IP (*TCP/IP Latency*).

Then, to metrologically characterize the signal, two experimental sessions were carried out, each consisting of five measurement runs (because the Medicollector Software was used in free-trial mode, each run had a maximum duration of 180 s.) For each run, the measurement of the transmission accuracy (related both to the communication between equipment and the laptop and to that from the laptop to the glasses) was carried out, through (1). Then, for each session, the accuracy mean value and the standard deviation were evaluated. Hence, the 3-sigma uncertainty was evaluated taking into account the total number of runs, according to (2). Finally, the system's latency was measured.

As aforementioned, three different contributions to latency were considered. In particular, for each packet within a run, it was possible to evaluate the latency related to: (i) ventilator update, (ii) monitor update, and (iii) TCP/IP communication. At the end of each run, the mean value and the standard deviation of these quantities were evaluated. At the end of the session, the assessment of the pooled mean μ_t and 3-sigma uncertainty σ_{tpo} was carried out, taking into account the different number of packets sent for each run, according to (3) and (4).

The uncertainty was also evaluated through the law of propagation of uncertainty. Assuming μ_t as the weighted mean among the runs, as explained in (3), the 3-sigma uncertainty u_{tpr} can be evaluated through (5). Table II and Table III summarize the details of the two sessions. The duration of the experimental test was about 30 minutes for each session. The

TABLE II
DETAILS FOR EACH RUN OF THE FIRST EXPERIMENTAL SESSION

#Packets	Type	Mean Update [s]	Std Update [s]	Accuracy [%]
117	(i)	1.05	0.15	97.5
”	(ii)	1.17	0.19	100.0
”	(iii)	$9\cdot10^{-4}$	$3\cdot10^{-4}$	100.0
122	(i)	1.06	0.15	99.2
”	(ii)	1.19	0.19	100.0
”	(iii)	$9\cdot10^{-4}$	$2\cdot10^{-4}$	100.0
118	(i)	0.99	0.15	96.7
”	(ii)	1.10	0.25	100.0
”	(iii)	$8\cdot10^{-4}$	$2\cdot10^{-4}$	100.0
118	(i)	1.02	0.15	96.7
”	(ii)	1.13	0.19	100.0
”	(iii)	$9\cdot10^{-4}$	$3\cdot10^{-4}$	100.0
41	(i)	0.99	0.21	97.1
”	(ii)	1.25	1.01	100.0
”	(iii)	$8\cdot10^{-4}$	$3\cdot10^{-4}$	100.0
Total	**Type**	**Pooled Mean [s]**	**Pooled Unc [s]**	**Mean ± Unc [%]**
514	(i)	1.02	0.05	97.4 ± 1.4
”	(ii)	1.16	0.16	100.0 ± 0.0
”	(iii)	$9\cdot10^{-4}$	$8\cdot10^{-5}$	100.0 ± 0.0
Total	**Type**	**Weighted Mean [s]**	**Propagated Unc [s]**	**Mean ± Unc [%]**
514	(i)	1.02	0.02	97.4 ± 1.4
”	(ii)	1.16	0.05	100.0 ± 0.0
”	(iii)	$9\cdot10^{-4}$	$3\cdot10^{-5}$	100.0 ± 0.0

Legend:
(i) Drager update; (ii) Philips update; (iii) TCP/IP latency

TABLE III
DETAILS FOR EACH RUN OF THE SECOND EXPERIMENTAL SESSION

#Packets	Type	Mean Update [s]	Std Update [s]	Accuracy [%]
111	(i)	1.06	0.16	98.2
”	(ii)	1.19	0.17	100.0
”	(iii)	$9\cdot10^{-4}$	$4\cdot10^{-4}$	100.0
102	(i)	1.07	0.17	100.0
”	(ii)	1.18	0.26	100.0
”	(iii)	$8\cdot10^{-4}$	$2\cdot10^{-4}$	100.0
113	(i)	1.02	0.17	96.0
”	(ii)	1.17	0.18	100.0
”	(iii)	$17\cdot10^{-4}$	$6\cdot10^{-4}$	100.0
35	(i)	1.09	0.17	97.4
”	(ii)	1.15	0.18	100.0
”	(iii)	$7\cdot10^{-4}$	$2\cdot10^{-4}$	100.0
117	(i)	1.05	0.17	97.5
”	(ii)	1.17	0.18	100.0
”	(iii)	$9\cdot10^{-4}$	$3\cdot10^{-4}$	100.0
Total	**Type**	**Pooled Mean [s]**	**Pooled Unc [s]**	**Mean ± Unc [%]**
478	(i)	1.06	0.05	97.8 ± 1.5
”	(ii)	1.17	0.06	100.0 ± 0.0
”	(iii)	$11\cdot10^{-4}$	$4\cdot10^{-4}$	100.0 ± 0.0
Total	**Type**	**Weighted Mean [s]**	**Propagated Unc [s]**	**Mean ± Unc [%]**
478	(i)	1.06	0.02	97.8 ± 1.5
”	(ii)	1.17	0.03	100.0 ± 0.0
”	(iii)	$11\cdot10^{-4}$	$6\cdot10^{-5}$	100.0 ± 0.0

Legend:
(i) Drager update; (ii) Philips update; (iii) TCP/IP latency

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

TABLE IV
MEASURE AT 3σ

Session	Refresh Time [s]	Accuracy [%]
1	(i) 1.02 ± 0.05	97.4 ± 1.4
"	(ii) 1.16 ± 0.16	100.0 ± 0.0
"	(iii) $9 \cdot 10^{-4} \pm 8 \cdot 10^{-5}$	100.0 ± 0.0
2	(i) 1.06 ± 0.05	97.8 ± 1.5
"	(ii) 1.17 ± 0.06	100.0 ± 0.0
"	(iii) $11 \cdot 10^{-4} \pm 4 \cdot 10^{-4}$	100.0 ± 0.0
Results	(i) 1.04 ± 0.05	97.6 ± 1.5
"	(ii) 1.16 ± 0.12	100.0 ± 0.0
"	(iii) $10 \cdot 10^{-4} \pm 3 \cdot 10^{-4}$	100.0 ± 0.0

Legend:
(i) Drager update; (ii) Philips update; (iii) TCP/IP latency.

latencies were measured by means of the MATLAB stopwatch timer command *tic*.
Due to issues in MEDIBUS protocol, the ventilator may send, in an unpredictable manner, an unidentified string: therefore, decoding of vitals cannot be performed and the MEDIBUS protocol fails. A certificate reporting the results of the metrological characterization was issued to the user after the end of the experimental sessions. Results of the experimental activity are also summarized in Table IV, where the considered uncertainty was the greater among the two different evaluations.

Overall, the two approaches for evaluating the measurement uncertainty led to compatible results. In particular, in most cases, the values obtained through the pooled uncertainty was slightly greater than those obtained by means of the propagation uncertainty. The approach that resorts to the evaluation of the pooled uncertainty can be applied only if the output quantity is a mean (weighted, or arithmetical) of different quantities having their own mean value and standard deviation. On the other hand, the evaluation by means of the propagation of uncertainty is more general, although in (5) the correlation between the different runs was neglected, assuming the independence of each run.

The results of the experimental tests confirmed the quality of the communication between the electromedical instrumentation and the laptop. In particular, as shown in Table IV, the transmission accuracy related to the communication between the ventilator and the laptop over MEDIBUS protocol was equal to $(97.6 \pm 1.5)\%$ at $(3 - \sigma)$, while the accuracy related to the TCP/IP protocol were always equal to 100 % (no errors occurred during the whole session). The latency due to the TCP/IP communication between the laptop and the AR smart glasses was in the order of milliseconds, a value considered negligible if compared to the update of the parameters from monitor and ventilator, in the order of seconds (an intrinsic feature of the available equipment). After an error occurred in decoding a packet, the system was always able to successfully decode the next incoming set of data. An alert to the operator was also provided. In this way, the maximum time with absence of data was about 1 s (the update of a single packet).

V. CONCLUSION

A system for the real-time acquisition and visualization of the patient's vitals through AR, designed focusing on the metrological performance, was presented. This implementation focused on a practical application for members of the surgical team in OR. The surgeon's assistant and/or the anesthetist wears the AR glasses, which display in real-time the vitals parameters acquired from the OR equipment. This allows the user to have the vitals constantly available without the need to look directly on the electromedical instrumentation. Moreover, on the user demand, the system assesses automatically its metrological performance in terms of transmission accuracy, data-update delay, and communication latency. The system was designed, implemented and experimentally validated through measurements using equipment available in the OR. The design an AR-based monitoring system was tailored to suit the requirements of the considered application field, thus paving the way for the future practical implementation of the system. After the preliminary functional validation of the system, the metrological characterization was carried out with focus on the transmission error rate, on the display refresh time, and on the latency induced by the communication, demonstrating the effectiveness of the proposed system.
It was observed that the measured accuracy is higher than 97%, and the latency introduced by the Android application to receive the parameters ranges in the order of milliseconds, a value that fully satisfies the aforementioned healthcare requirements. This is an important step aiming to improve by AR the effectiveness of medical procedures in the Health 4.0 framework, still preserving the real-time requirements of the application context. The system can be improved by adding vocal commands, and the use of noninvasive, wearable Brain Computer Interface (BCI). This will be investigated to provide an innovative alternative for hands-free navigation, through the acquisition and processing of the user's electroencephalographic (EEG) signal [37] using off-the-shelf components such as Emotiv Epoc or Olimex EEG-SMT.

REFERENCES

[1] G. Aceto, V. Persico, and A. Pescapé, "The role of information and communication technologies in healthcare: taxonomies, perspectives, and challenges," *Journal of Network and Computer Applications*, vol. 107, pp. 125–154, 2018.
[2] H. Qiu, M. Qiu, M. Liu, and G. Memmi, "Secure health data sharing for medical cyber-physical systems for the healthcare 4.0," *IEEE Journal of Biomedical and Health Informatics*, vol. 24, no. 9, pp. 2499–2505, 2020.
[3] L. Angrisani, P. Arpaia, A. Esposito, and N. Moccaldi, "A wearable brain-computer interface instrument for augmented reality-based inspection in industry 4.0," *IEEE Transactions on Instrumentation and Measurement*, 2019.
[4] R. Schiavoni, G. Monti, E. Piuzzi, L. Tarricone, A. Tedesco, E. De Benedetto, and A. Cataldo, "Feasibility of a wearable reflectometric system for sensing skin hydration," *Sensors*, vol. 20, no. 10, 2020.
[5] L. Corchia, G. Monti, E. De Benedetto, A. Cataldo, L. Angrisani, P. Arpaia, and L. Tarricone, "Fully-textile, wearable chipless tags for identification and tracking applications," *Sensors*, vol. 20, no. 2, 2020.
[6] B. Alotaibi, "Utilizing blockchain to overcome cyber security concerns in the internet of things: A review," *IEEE Sensors Journal*, vol. 19, no. 23, pp. 10953–10971, 2019.
[7] P. Arpaia, R. Cuocolo, F. Donnarumma, A. Esposito, N. Moccaldi, A. Natalizio, and R. Prevete, "Conceptual design of a machine learning-based wearable soft sensor for non-invasive cardiovascular risk assessment," *Measurement*, vol. 169, 2021.
[8] A. S. Alharthi, S. U. Yunas, and K. B. Ozanyan, "Deep learning for monitoring of human gait: A review," *IEEE Sensors Journal*, vol. 19, no. 21, pp. 9575–9591, 2019.

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/JSEN.2021.3059636

[9] B. Zhang, X. Hong, and Y. Liu, "Multi-task deep transfer learning method for guided wave-based integrated health monitoring using piezoelectric transducers," *IEEE Sensors Journal*, vol. 20, no. 23, pp. 14 391–14 400, 2020.

[10] P. Pace, G. Aloi, R. Gravina, G. Caliciuri, G. Fortino, and A. Liotta, "An edge-based architecture to support efficient applications for healthcare industry 4.0," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 1, pp. 481–489, 2019.

[11] R. Bernasconi, D. Meroni, A. Aliverti, and L. Magagnin, "Fabrication of a bioimpedance sensor via inkjet printing and selective metallization," *IEEE Sensors Journal*, vol. 20, no. 23, pp. 14 024–14 031, 2020.

[12] C. N. Teague, J. A. Heller, B. N. Nevius, A. M. Carek, S. Mabrouk, F. Garcia-Vicente, O. T. Inan, and M. Etemadi, "A wearable, multimodal sensing system to monitor knee joint health," *IEEE Sensors Journal*, vol. 20, no. 18, pp. 10 323–10 334, 2020.

[13] L. Corchia, G. Monti, E. De Benedetto, and L. Tarricone, "Low-cost chipless sensor tags for wearable user interfaces," *IEEE Sensors Journal*, vol. 19, no. 21, pp. 10 046–10 053, 2019.

[14] J. Wannenburg, R. Malekian, and G. P. Hancke, "Wireless capacitive-based ecg sensing for feature extraction and mobile health monitoring," *IEEE Sensors Journal*, vol. 18, no. 14, pp. 6023–6032, 2018.

[15] E. Spanò, S. Di Pascoli, and G. Iannaccone, "Low-power wearable ecg monitoring system for multiple-patient remote monitoring," *IEEE Sensors Journal*, vol. 16, no. 13, pp. 5452–5462, 2016.

[16] P. Alinia, R. Fallahzadeh, C. P. Connolly, and H. Ghasemzadeh, "Paralabel: Autonomous parameter learning for cross-domain step counting in wearable sensors," *IEEE Sensors Journal*, vol. 20, no. 23, pp. 13 867–13 879, 2020.

[17] R. A. Bloomfield, M. G. Teeter, and K. A. McIsaac, "A convolutional neural network approach to classifying activities using knee instrumented wearable sensors," *IEEE Sensors Journal*, 2020.

[18] M. Wehde, "Healthcare 4.0," *IEEE Engineering Management Review*, vol. 47, no. 3, pp. 24–28, 2019.

[19] F. Cutolo, B. Fida, N. Cattari, and V. Ferrari, "Software framework for customized augmented reality headsets in medicine," *IEEE Access*, vol. 8, pp. 706–720, 2020.

[20] J. Meyer, T. Schlebusch, W. Fuhl, and E. Kasneci, "A novel camera-free eye tracking sensor for augmented reality based on laser scanning," *IEEE Sensors Journal*, 2020.

[21] A. Alamri, J. Cha, and A. El Saddik, "Ar-rehab: An augmented reality framework for poststroke-patient rehabilitation," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 10, pp. 2554–2563, 2010.

[22] V. Mamone, S. Condino, F. Cutolo, I. Tamadon, A. Menciassi, M. Murzi, M. Ferrari, and V. Ferrari, "Low-computational cost stitching method in a three-eyed endoscope," *Journal of Healthcare Engineering*, vol. 2019, 2019.

[23] M. Kersten-Oertel, P. Jannin, and D. Collins, "Dvv: A taxonomy for mixed reality visualization in image guided surgery," *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 2, pp. 332–352, 2012.

[24] I. Sauer, M. Queisner, P. Tang, S. Moosburner, O. Hoepfner, R. Horner, R. Lohmann, and J. Pratschke, "Mixed reality in visceral surgery," *Annals of Surgery*, vol. 266, no. 5, pp. 706–712, 2017.

[25] C. He, Y. Liu, and Y. Wang, "Sensor-fusion based augmented-reality surgical navigation system," in *2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings*, May 2016, pp. 1–5.

[26] D. Ormerod, B. Ross, and A. Naluai-Cecchini, "Use of an augmented reality display of patient monitoring data to enhance anesthesiologists' response to abnormal clinical events," *Studies in Health Technology and Informatics*, vol. 94, pp. 248–250, 2003.

[27] P. M. Sanderson, M. O. Watson, W. J. Russell, S. Jenkins, D. Liu, N. Green, K. Llewelyn, P. Cole, V. Shek, and S. S. Krupenia, "Advanced auditory displays and head-mounted displays: advantages and disadvantages for monitoring by the distracted anesthesiologist," *Anesthesia & Analgesia*, vol. 106, no. 6, pp. 1787–1797, 2008.

[28] C. Cepisca, F. C. Adochiei, S. Potlog, C. K. Banica, and G. C. Seritan, "Platform for bio-monitoring of vital parameters in critical infrastructures operation," in *2015 7th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*. IEEE, 2015, pp. E–7.

[29] D. McDuff, C. Hurter, and M. Gonzalez-Franco, "Pulse and vital sign measurement in mixed reality using a hololens," in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, 2017, pp. 1–9.

[30] J. Y. C. Chang, L. Y. Tsui, K. S. K. Yeung, S. W. Y. Yip, and G. K. K. Leung, "Surgical vision: Google glass and surgery," *Surgical innovation*, vol. 23, no. 4, pp. 422–426, 2016.

[31] A. Alesanco and J. García, "Clinical assessment of wireless ECG transmission in real-time cardiac telemonitoring," *IEEE Transactions on Information Technology in Biomedicine*, vol. 14, no. 5, pp. 1144–1152, 2010.

[32] T. Muhammed, R. Mehmood, A. Albeshri, and I. Katib, "Ubehealth: a personalized ubiquitous cloud and edge-enabled networked healthcare system for smart cities," *IEEE Access*, vol. 6, pp. 32 258–32 285, 2018.

[33] P. Arpaia, M. Cicatiello, E. De Benedetto, C. Anna Dodaro, L. Duraccio, G. Servillo, and M. Vargas, "A health 4.0 integrated system for monitoring and predicting patient's health during surgical procedures," in *2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2020, pp. 1–6.

[34] P. A. Rauschnabel and Y. K. Ro, "Augmented reality smart glasses: An investigation of technology acceptance drivers," *International Journal of Technology Marketing*, vol. 11, no. 2, pp. 123–148, 2016.

[35] (2020) Ventilator Drager Infinity V500. [Online]. Available: https://cardomedical.com/product/drager-evita-infinity-v500-ventilator/

[36] (2020) Philips IntelliVue MP-90. [Online]. Available: https://avantehs.com/p/philips-intellivue-mp90-patient-monitor/1511

[37] P. Arpaia, L. Duraccio, N. Moccaldi, and S. Rossi, "Wearable brain-computer interface instrumentation for robot-based rehabilitation by augmented reality," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 9, 2020.

Pasquale Arpaia (SM'14) received the M.S. and Ph.D. degrees in electrical engineering from the University of Naples Federico II, Naples, Italy, in 1987 and 1992, respectively. He was a Professor with the University of Sannio, Benevento, Italy. He is currently a Full Professor of instrumentation and measurements with the University of Naples Federico II, and a Team Leader with Conseil Européen pour la Recherche Nucléaire (CERN), Geneva, Switzerland.

Egidio De Benedetto (M'14, SM'16) received the M.S. degree in materials engineering and the Ph.D. degree in information engineering from the University of Salento, Lecce, Italy, in 2006 and 2010, respectively. Since 2019, Egidio De Benedetto is an Associate Professor with the Department of Electrical Engineering and Information Technology of the University of Naples Federico II (Naples, Italy).

Concetta Anna Dodaro is Professor of General, Clinical and Pediatric Nursing Sciences at the Federico II University of Naples. She has coauthored more than 150 scientific publications, which include numerous reports from national and international conferences. The scientific sector of interest is the oncological-genetic one. Her scientific production is mainly oriented towards new educational goals and new nursing models.

Luigi Duraccio received the M.S. degree (cum laude) in electronic engineering in 2018. He developed his master thesis at CERN, Geneva, Switzerland, in the field of radiation measurement for electronics. His current research interests include biomedical instrumentation and measurement, electroencephalographic data acquisition and processing, augmented reality, and brain–computer interfaces.

Giuseppe Servillo is a Full Professor of Anesthesiology at the Federico II University of Naples. He has coauthored 49 scientific publications for national and international journals. His scientific sector of interest is related to clinical aspects of acute and chronic respiratory failures, neurological problems in pregnancy, and ethical issues of the dying patient in intensive care.

Copyright (c) 2021 IEEE. Personal use is permitted. For any other purposes, permission must be obtained from the IEEE by emailing pubs-permissions@ieee.org.