AR-based monitoring of instrumentation in the operating room

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***Abstract* – This paper proposes an augmented reality (AR)-based system for monitoring patient's vitals in the operating room (OR) is proposed. An optical see-through (OST) headset, worn by the anesthetist or by the OR nurses, shows in real-time the patient's vitals acquired from the electromedical equipment available in the OR. A dedicated application was developed to allow a hands-free fruition of the AR content. Experimental tests were carried out acquiring the vital parameters from two pieces of equipment typically available in the OR, namely a ventilator and a monitor. The experimental assessment of the transmission error rate and of latency demonstrated the reliability of the proposed AR-based monitoring system.**

I. INTRODUCTION

The vision and concepts of Industry 4.0 [1, 2] have extended also to other application contexts, such as Public Administration, agriculture [3, 4], bringing significant changes even in healthcare [5]. In the digital transformation of healthcare, one of the major goals is to deliver the most effective, patient-centered care [6], Starting with the introduction of robotic surgery in the 1980s healthcare has come to use technologies such as the internet of things (IoT), artificial intelligence, machine learning, cloud computing, 3D printing, and augmented reality (AR) [7]. In particular, AR and virtual reality (VR) have been pervading the healthcare field [8], with systems designed to increase the effectiveness of medical procedures: for example, for the accurate preoperative surgical planning and also for an image-guided surgery [9]; for allowing the surgeon to improve the accuracy in placing the surgical instrument within the lesion in radio-frequency ablation of liver tumors [10]; for reducing the risk of damaging anatomical structures by means of a combination of visual and audio cues [11]; for providing guidance to the surgeon within the endoscopic image [12]. Also, AR and VR have been used for the simultaneous visualization of both the "traditional" patient information (the image dataset) and a 3D model of the patient's anatomy [13]; to improve the surgeon's action and perception in open visceral surgery by displaying 3D anatomical models close to the surgical site [14] and to help the surgeon also when a clear and wide filed of view is not available [15].

Considering the aforementioned literature, it follows how AR represents a promising enabling technology in a number of medical applications, and especially in the operating room (OR). Indeed, one of the most important aspects in the OR is to ensure that the medical team has prompt access to a complete set of information about the patient and the surgical procedure. The relevant information must be readily available to the members of the surgical team so that, when necessary, immediate action can be taken.

In such a context, the authors have designed an AR-based automatic measurement system for surgery instrumentation monitoring [16]. The proposed system acquires the vitals of the patient undergoing a surgical procedure and makes them available on an optical see-through (OST) headset worn by the anesthetist or nurses involved in the surgical procedure. In this way, the proposed system allows surgical assistant to monitor in real time the patient's health. Through the AR headset, the operator can see the surrounding reality (i.e. the operating room), enriched with the vital parameters coming from the electro-medical devices. As a result, the operator does not have to continuously turn to look at the instrumental equipment; on the contrary, the patient's vitals are constantly available in front of the operator (clearly, without obstructing his view).
As detailed in the following, experimental tests were carried out acquiring the vital parameters from two pieces of equipment typically available in the OR (namely a

ventilator and a monitor) and making them available on an AR application. The experimental assessment of the transmission error rate and of latency demonstrated the reliability of the proposed AR-based monitoring system.

The present paper is organized as follows. In Section ii., the architecture of the proposed AR-based monitoring system is described in detail. Section iii. summarizes the preliminary experimental tests that were carried out for verifying the functionalities of the developed platform and for demonstrating its reliability in providing correct results in real-time. Finally, in Section iv., conclusions are drawn.

II. DESIGN OF THE SYSTEM

The architecture of the proposed system is shown in Figure 1. The patient's vitals are acquired from a ventilator and from a monitor (typically available in the OR in in an intensive care unit, ICU). A laptop is in charge of collecting the patient's vitals acquired from the OR instruments and sending them to a OST headset.
The use of AR as a fruition tool for all the information can facilitate the work of the operator, as he/she can keep the attention on the patient for a longer time, not having to turn around and look at the instrumentation [17]. In the following, the implementation of the proposed system is described in detail.

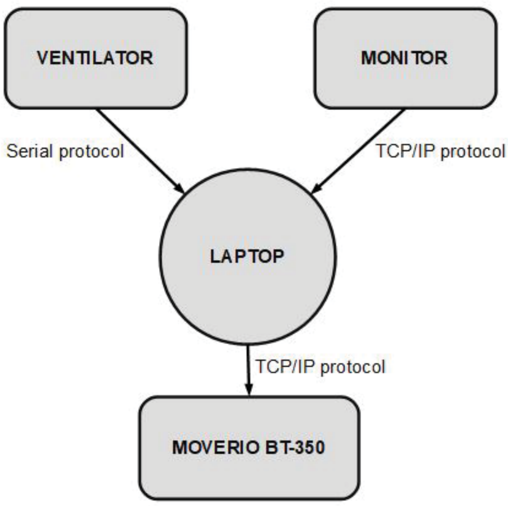

Fig. 1. Network architecture of the system.

A Ventilator

The used ventilator is the Drager Infinity V500 shown in Fig. 2(a). Ventilators are used to administer an adequate and controlled amount of O_2 to the patient and to eliminate the produced CO_2, thus helping lung function. Moreover, ventilators allow to monitor and/or control a number of indicators, some of which are summarized in Table 1.
The Infinity V500 ventilator is equipped with a LAN

(a) (b)

Fig. 2. Pictures of the medical instrumentation used in the experimental tests: a) ventilator and b) monitor.

Table 1. List of parameters of the Drager Infinity V500.

Parameter	**Symbol**	**Unit**
Compliance	Cdyn	l/bar
Resistance	R	mbar·/l
CO_2 Production	CO_2	ml/min
Minimum Airway Pressure	Pmin	mbar
Mean Airway Pressure	Pmean	mbar
Peak Airway Pressure	PIP	mbar
Occlusion Pressure	P0	mbar
Insp. Mandatory Tidal Volume	VTmand	ml
Spontaneous expired Tidal Volume	VTespon	ml
Tidal Volume	VT	ml
Minute Volume	MV	ml
Entidal CO_2	$etCO_2$	mm·Hg
Expiratory Tidal Volume	VTe	ml
Inspiratory Tidal Volume	Vti	ml
Respiratory Cycle Lenght	Tlow	s
Expiratory Minute Volume	MVe	ml/

interface and three serial Interfaces, using the MEDIBUS protocol at different Baud Rates.

B Monitor

The monitor used in this work is the Philips IntelliVue MP90, shown in Fig. 2(b). This monitor provides information on a number of patient's vitals: some of the most relevant vital parameters are summarized in Table 2. It is possible to monitor such parameters by connecting separate "plug-and-play" modules (i.e. ECG, Blood Pressure, Heart Rate). This monitor comes with a proprietary software, MediCollector software, which allows to retrieve the quantities of interest.

Table 2. Philips IntelliVue MP90 Parameters.

Parameter	Unit
Pulmunary Artery Wedge Pressure	Not Declared
Perfusion Indicator	Not Declared
Premature Ventricular Contraction	Not Declared
Respiration Rate	Not Declared
Arterial Oxigen Saturation	Not Declared
Systemic Vascular Resistance	Not Declared
ECG Lead I,II,III	mV
Compound ECG	mV

C OST Headset

The OST headset is the Moverio BT-350 AR smart glasses [18]. The perceived screen size of the glasses is 2 m at 5 m projected distance, with a refresh rate of 30 Hz. The cost of these glasses is relatively low (in the order of 500 Euros); hence, it anticipates the possibility of a large-scale use.

A dedicated Android application (running on the Moverio BT-350) was specifically developed by the Authors, aiming to receive the vital parameters from the instrumentation via TCP/IP protocol.

D Communication

A MatLab algorithm was developed to acquire the data from the instrumentation and to guarantee the communication with the laptop. This algorithm consists in two sections: the first section is dedicated to the communication between the laptop and the ventilator over serial port (by means of an RS232-USB adapter) and MEDIBUS communication protocol; instead, the second section oversees the communication between the laptop and the monitor over TCP/IP protocol (by means of the MediCollector adapter) after the MediCollector software is initiated.

The parameters received from the instrumentation are sent from the laptop, acting as TCP Server, to the headset at a fixed refresh frequency. The headset acts as TCP Client by means of the developed Android Application.

III. EXPERIMENTAL RESULTS

To verify the functionalities of the AR-based monitoring system and in particular its reliability in terms of communication and real-time operations, experimental tests were carried out with the monitor and the ventilator available at the University Hospital Federico II.

The ventilator was used with a non-self-inflating bag, which allows to emulate the patient's lung. The vitals acquired from the device were: the Compliance ($Cdyn$); the Spontaneous expired total Volume (VT_{espon}); the Mean Airway Pressure (P_{mean}); the Minimum Airway Pressure (P_{min}); the Peak Airway Pressure (PIP); and the Minute Volume (MV).

Table 3. Vitals Monitored During the Experimental Test.

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
O2 Sat	–	mV	Monitor

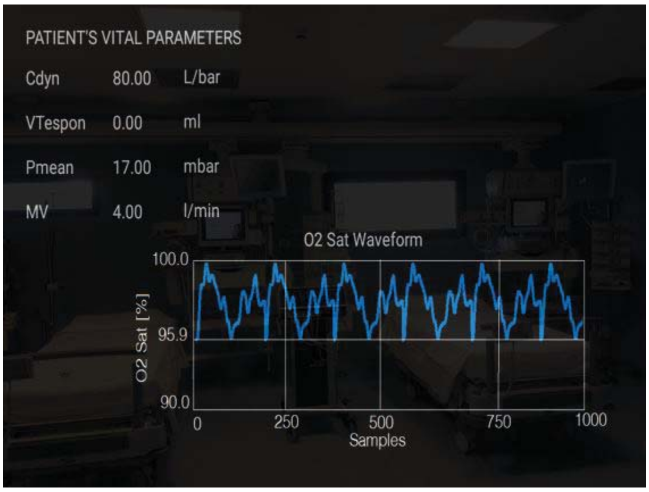

Fig. 3. View of the AR content.

The Baud Rate was set to 38400 bit/s, the Data Bits were equal to 8, the Stop Bit was equal to 1, and no Parity bit was foreseen.

As for the monitor, it was used on a healthy volunteer to monitor his Oxigen Saturation Waveform (O2 Sat).

The monitored vitals are summarized in Table 3. A capture of what the user sees is shown in Fig. 3.

The experimental activity consisted of two sessions, each consisting of five measurement runs.

In the first session, the $Cdyn$, P_{min}, P_{mean}, PIP parameters were acquired from the ventilator, while the O2 Saturation was acquired from the monitor.

In the second experimental session, the parameter acquired from the ventilator were $Cdyn$, P_{mean}, $VTespon$, and MV; once again, the O2 saturation was acquired from the ventilator. The details of the experimental activity are summarized in Table 4.

Table 4. Experimental test details.

Session	Drager Parameters	Philips Parameters	#Run
#1	Cdyn, P_{min}, P_{mean}, PIP	O2 Sat	5
#2	Cdyn, P_{mean}, MV, VTespon	O2 Sat	5

For each measurement run, in each session, the transmission accuracy was evaluated through (1) and the 3-sigma uncertainty was evaluated taking into account the total number of the run:

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

where:

- A (%) is the accuracy of the transmission;
- $N_{packets}$ is the number of packets sent; and
- E is the error count when a packets is not decoded.

The system's refresh time, defined as the time interval necessary to refresh the data coming from the devices, was measured. For each session, the pooled mean and the pooled standard deviation were evaluated, and then the 3-sigma uncertainty was assessed.
In particular, the pooled mean (μ_{t}) was evaluated through the following equation:

$$\mu_{\mathrm{t}} = \frac{\sum_{i=1}^{N} \mu_{ti} \cdot l_i}{\sum_{i=1}^{N} l_i} \tag{2}$$

where:

- μ_t (s) is the pooled mean of the refresh time;
- μ_{ti} (s) is the mean of the refresh time evaluated for each run; and
- l_i is the number of packets for each run.

The pooled standard deviation (σ_{t}) was evaluated as follows:

$$\sigma_{\mathrm{t}} = \sqrt{\frac{\sum_{i=1}^{N} {\sigma_{ti}}^2 \cdot (l_i - 1) + \sum_{i=1}^{N} l_i \cdot (\mu_{ti} - \mu_t)^2}{\sum_{i=1}^{N} l_i - 1}} \tag{3}$$

Where:

- σ_i (s) is the pooled standard deviation of the refresh time; and
- σ_{ti} (s) is the standard deviation of the refresh time evaluated for each run.

Table 5 and Table 6 summarize the experimental results for the two sessions. The duration of the experimental test was 30 minutes for each session. The refresh time was measured by means of the MatLab stopwatch timer command *tic*.

The transmission errors were determined by faults in the MEDIBUS Protocol. While receiving vitals from the ventilator, it sends, in an unpredictable manner, an unidentified string: decoding of vitals is not done correctly and the MEDIBUS protocol fails.
It is worth mentioning that the number of packets received is variable because, due to the limitations of the free demo of the MediCollector software, it was necessary to stop the software before the time-out (approximately 3 minutes).
In this application, no relevant additional time delay caused by the Moverio was observed, as the acquisition of the parameters was done through the laptop, and the Moverio is only in charge of receiving these parameters via TCP/IP. Results of the experimental activity are summarized in Table 7.

Table 5. Details for each run of the first experimental session.

#Packets	Mean Refresh Time [s]	Std Refresh Time [s]	Accuracy [%]
149	0.48	0.05	99.3
148	0.53	0.07	99.3
152	0.45	0.04	98.7
155	0.47	0.07	98.7
147	0.48	0.10	99.3
	Pooled Mean [s]	**Pooled Std [s]**	**Mean [%]**
	0.48	0.07	99.1

Table 6. Details for each run of the second experimental session.

#Packets	Mean Refresh Time [s]	Std Refresh Time [s]	Accuracy [%]
152	0.47	0.06	98.7
144	0.48	0.10	99.3
155	0.47	0.05	98.1
151	0.50	0.04	99.3
148	0.48	0.05	99.3
	Pooled Mean [s]	**Pooled Std [s]**	**Mean [%]**
	0.47	0.06	98.9

Table 7. Measure at 3σ.

Session	Refresh Time [s]	Accuracy [%]
#1	0.48 ± 0.09	99.1 ± 0.5
#2	0.47 ± 0.08	98.9 ± 0.7
Pooled	0.48 ± 0.06	99.0 ± 0.4

The results of the experimental tests confirmed the correct communication between the electromedical instrumentation and the laptop. After receiving the parameters, they are sent, at a fixed refresh rate, to the AR headset. In particular, accuracy and refresh time have been calculated, obtaining an accuracy equal to 99.0 ± 0.4 % and a refresh time equal to 0.48 ± 0.06 s.

IV. CONCLUSIONS

In this work, the development and implementation of the real-time acquisition and visualization of the patient's vitals through AR was presented.
In the envisaged practical application, the surgeon's assistant (or any other member of the medical team) wears a AR headset, which displays a real-time visualization of vitals acquired from the OR equipment, without having to look directly on the instruments.
Experimental tests were carried out acquiring the vital parameters from two pieces of equipment typically available in the OR, namely a ventilator and a monitor. The experimental assessment of the transmission error rate and of latency demonstrated the reliability of the

proposed AR-based monitoring system. The obtained results confirm the large potential of AR as an enabling technology for improving the effectiveness of medical procedures of healthcare sector.

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