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***Abstract*—In this work, an innovative system architecture for enhancing patient's health monitoring during surgical procedure is proposed. The proposed integrated system consists of a video see-through (VST) headset (worn by anesthetist or nurses or other member of the surgical team involved in the procedure), which shows in real-time a comprehensive set of information on the patient's health status.**

In particular, the operator can visualize in real-time the patient's vitals acquired from the operating room (OR) equipment and access the electronic medical records. The proposed system was designed in view of robotic surgery; therefore, an additional function is that the VST will display the real-time view of what the surgeon is looking at on his console. Finally, the system will also include a machine-learning algorithm which, starting from the medical records and from the monitored vitals, will predict possible aggravating conditions of the patient's health and provide a timely alert.

The present work focuses on creating the implementation framework of the whole system, and on real-time monitoring of the patient's vitals.

***Index Terms*—Augmented reality, health monitoring, Health 4.0, Vitals monitoring, patient, surgery**

I. Introduction

While people have become familiar with the concept of Industry 4.0 [1], the principles and driving forces of this new paradigm have started permeating other application contexts. Healthcare is certainly one of these, since nowadays hospitals and medical facilities can be effectively considered as *smart factories*. As a matter of fact, the introduction of robotic surgery in the late 80s can be considered as one of the earliest indicators of a trend that has been growing ever since. Health. 4.0 now leverages not only Robotics, but also other cutting edge technologies such as the internet of things (IoT); artificial intelligence (AI); machine learning; cloud computing; 3D printing; and augmented reality (AR), just to name a few. [2].

In particular, the use of AR and virtual reality (VR) have been gaining momentum in the medical field [3], for rehabilitation [4]–[7]; medical training [8], [9], and for assistance in the operating room. Indeed, systems based on AR and/or VR have established themselves as a valid support for enhancing the effectiveness of surgical procedures, contributing to increasing the location and accuracy of the invasive action [10]; obtaining a more accurate preoperative surgical planning and also for an image-guided surgery [11]; allowing the surgeon to improving the accuracy in placing the surgical instrument within the lesion [12]; reducing the risk of damaging anatomical structures [13]; providing relevant guidance to the surgeon within the endoscopic image [14]; visualizing both the traditional patient information (the image dataset) and a 3D model of the patient's anatomy [15]; improving the surgeon's action and perception in open visceral surgery by displaying 3D anatomical models close to the surgical site [16] and helping the surgeon also when a clear and wide filed of view is not available [17]. However, bringing AR in front of the surgeon's eyes by means of a head-mounted display is a complex matter that should be faced [18], [19] AR is also used to help monitoring the operating room (OR); for example, to display directly in the user's view information related to radiation safety [20].

One of the most important aspects in the OR is to guarantee that the medical team have prompt and direct access to a comprehensive set of information regarding the patient and the surgical procedure. The relevant information must be readily available to the medical team members, so that the consequent immediate action can be taken. In the literature, there are some applications in which the operator wears optical see-through (OTR) displays, so to be able to monitor the vital parameters of the patient that appear on the display overlay [21]. Other applications resort to VST for the streaming of video or images, in the field of assisted surgery, anaesthesia, dermatology, ophthalmology, neurosurgery, urology, oncology, plastic surgery [22]–[25]. In particular, in [26], it was observed that one obstacle to safety in the OR is the possible distraction of the anesthesiologist, who has to shift attention back and forth from the patient to the vital sign monitor while carrying out either routine or emergency procedures.

Starting from these considerations, the authors have designed an integrated system that, by employing AR/VR as a fruition tool, collects all the relevant information on the health conditions of the patient undergoing a surgical procedure and makes it available on a VST headset.

Differently from state-of-the-art solutions, the proposed system combines different technologies to allow members of the surgical team to monitor in real-time the patient's health and the ongoing surgical procedure as it is being carried out.

More specifically, through the VST headset, the operator can have the real-time visualization of vitals acquired from the OR equipment and can also have direct access to the electronic medical records. The proposed system was designed in view of robotic surgery; therefore, an additional function is that the VST headset will display in real-time the video streaming of what the surgeon is looking at on his console. Finally, the envisaged system will also include a machine-learning algorithm that, by processing the medical records and the monitored vitals, can predict possible aggravating conditions of the patient's health and timely provide an alert. Also this information will be available through the VST.

The operator will also see reality in front of him/her, through a dedicated camera.

It is important to point out that the operator will navigate hands-free through the informative content made available.

The present paper is organized as follows. In Section II, the architecture of the proposed integrated system is described in detail. Section III describes all the components of the system, and addresses the system section dedicated to the real-time monitoring and visualization of the patient's vitals. Section IV describes the implementation of the vitals monitoring system. Section V summarizes the preliminary experimental tests that were carried out for verifying the functionalities of the developed platform. Finally, in Section VI, conclusions are drawn.

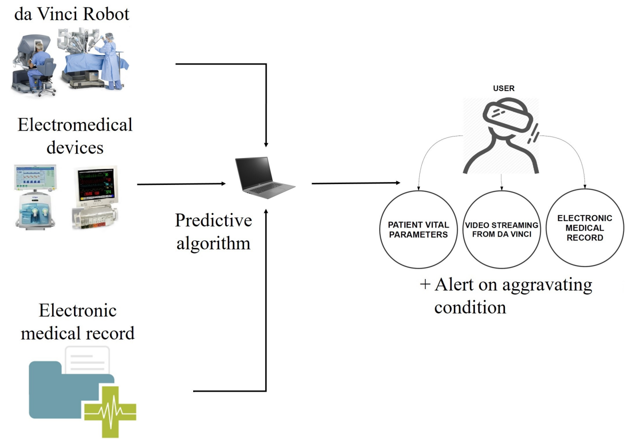

Fig. 1. Schematization of the architecture of the overall system.

II. Design of the System Architecture

Figure 1 shows a sketch of the architecture of the overall system. Basically, there are three major sections:

- the video streaming from a surgical robot;
- the monitoring of the patient's vitals acquired from the OR instruments; and
- the patient's electronic medical record.

All this content is collected by a laptop, processed as needed, and sent to the VST.

To this content, also the actual reality in front the operator will be shown through cameras, so that the operator is always in contact with reality. The system also includes an additional section, namely an algorithm that predicts in real time possible short-term aggravating conditions of the patient. By processing data from the patient's record and the data acquired from the instrumentation during the surgical procedure, the algorithm will provide a short-term prediction on possible aggravating conditions of the patient. The development and implementation of this model involves the use of AI algorithms, in particular of machine learning. Also this information will be displayed for the operator on the VST.

As a result, the VST shows in real-time a comprehensive set of information on the patient's health status. The use of augmented and mixed reality as a fruition tool can facilitate the work of the operator, as he/she can keep the attention on the patient, not having to turn around and look at the instrumentation [27].

In the following section, the details on the implementation of the system section dedicated to monitor the patient's vitals are provided.

III. Materials and Methods

In this section, the used instrumentation and the chosen communication methods are illustrated.

As detailed later in this section, the vitals of interest were retrieved from two instruments that are typically available in the OR and/or in an intensive care unit (ICU), namely a ventilator and a monitor.

A. Ventilator

The used ventilator is the Dräger Infinity V500 shown in Fig. 2(a). Ventilators allow to help lung function, as they are generally used to administer an adequate and controlled amount of O_2 to the patient and to eliminate the produced CO_2. Also, ventilators allow to monitor and/or control a number of indicators (such as CO_2 production; airway pressure; respiratory rate; compliance and several other parameters). The Infinity V500 ventilator is equipped with:

- a LAN interface, with the possibility to enable or disable the DHCP functionality; and
- three serial Interfaces, with the possibility to choose between MEDIBUS or MEDIBUSX, and the possibility to set Baud Rate, Parity Bits, Stop Bits, and Terminator Character.

B. Monitor

The used monitor is the Philips IntelliVue MP90, shown in Fig. 2(b). This monitor is largely used in the operating room, as it provides information on a number of patient's vitals (such as blood pressure, heart rate, respiratory rate, etc.)
This operating room instrument allows multi-parametric monitoring by connecting separate "plug-and-play" modules. This monitor runs with a proprietary software, MediCollector software, which allows to retrieve from the monitor the quantities of interest. In particular, for the experimental tests, the free version of the Medicollector software was used; this version of the software comes with some limitations on the duration of each session.

(a) (b)

Fig. 2. Medical instrumentation used in this work: a) Drager Infinity V500 Ventilator; and b) Philips IntelliVue MP90 Monitor.

C. VST Headset

The VST headset chosen in this work is the Oculus Rift S (Oculus VR company). The Oculus Rift S is a head-mounted display based on OLED technology. It has a low-latency tracking system to give a lifelike experience to the wearer.
The Oculus Rift S, which is largely used, offers more than 90 horizontal degrees field of view (nominal) and has a 90 Hz refresh rate, and its weight is approximately 560 g. Additionally, this headset is very ergonomic and its weight is better distributed than previous similar platform from the same manufacturer; thus reducing stress caused to the neck of the user.
For the overall integrated system, a spherical menu will be provided, so as to limit effects such as VR sickness [28] when the user turns their head to navigate between the possible menu choices. Furthermore, the background is dark, to make the experience more comfortable.

IV. Implementation of the Monitoring System

The first aspect that was addressed was to guarantee communication between the instruments and the laptop. To acquire the data from the ventilator, a MatLab algorithm was specifically developed. This algorithm consists of two sections:

- one section where the ventilator communicates with the laptop over serial port (by means of an RS232-USB adapter) and MEDIBUS communication protocol; and
- a section where the monitor communicates with the laptop over TCP/IP protocol (by means of a dedicated MediCollector adapter) after running the MediCollector software.

After the parameters are received from the ventilator and from the monitor, these data are sent to the VST Headset at a fixed refresh frequency. An Android Application receiving data from the laptop via TCP/IP was implemented on the VST Headset, which acts as Wi-Fi Client, while the laptop acts as Wi-Fi Server. Fig. 3 shows the flowchart of the implemented MatLab code.
In the implemented demo, the MatLab code can be launched through the controller touchpad. After inserting the laptop IP address and the port, it is possible to connect the VST headset to the laptop and start the acquisition of the vital signs.

V. Experimental Results

To test the developed monitoring system, dedicated experimental tests were carried out at the University Hospital Federico II. Because it is not possible to use the Ventilator on a healthy individual, a so-called *Ambu bag* was used to emulate the presence of a patient. In this condition, the application was set in order to monitor and display the following quantities: the Compliance ($Cdyn$); the Minimum Airway Pressure (P_{min}); the Mean Airway Pressure (P_{mean}); and the Peak Airway Pressure (PIP).
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.

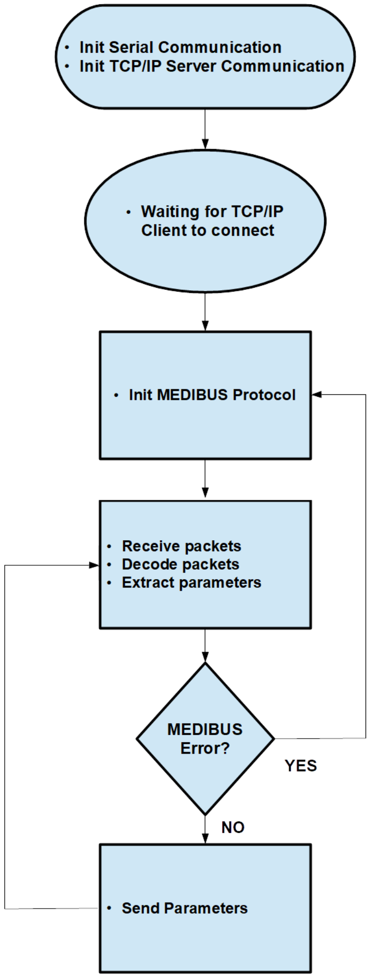

Fig. 3. Flowchart of the implemented MatLab code.

TABLE I
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 Pressur	PIP	mbar	Ventilator
ECG Lead I	–	mV	Monitor
ECG Lead II	–	mV	Monitor

As for the monitor, the electrocardiogram (ECG) signal was monitored on a healthy volunteer, by applying three electrodes according to the Lead aVR, aVL, aVF (Unipolar Goldberger Leads). The Lead I and the Lead II were extracted. The monitored vitals are summarized in Table I.

The experimental activity consisted of two sessions, each consisting of ten measurement runs. In the first session, three parameters were acquired from the ventilator (Cdyn, Pmin, Pmean) and the Lead I from the monitor. In the second experimental session, four parameter were acquired from the ventilator ($Cdyn$, P_{min}, P_{mean}, PIP) and the Lead II from the monitor.

TABLE II
EXPERIMENTAL TEST DETAILS

Session	Drager Parameters	Philips Parameters	#Run
#1	Cdyn, P$_{min}$, P$_{mean}$	Lead I	10
#2	Cdyn, P$_{min}$, P$_{mean}$, PIP	Lead II	10

For each measurement run, in each session, the transmission accuracy was evaluated through the following equation:

$$A = \frac{N_{packets} - E}{N_{packets}} \qquad [\%] \tag{1}$$

where:

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

and the 3-sigma uncertainty was evaluated taking into account the total number of the run.
Then, the system's refresh time, defined as the time interval necessary to refresh the data coming from the instrumentation, was measured. For each session, the pooled mean and the pooled standard deviation, defined by (2) and (3), were evaluated. from which the 3-sigma uncertainty was assessed.

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

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.

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

where:

- σ_i (s) is the pooled standard deviation of the refresh time;
- $\sigma_t i$ (s) is the standard deviation of the refresh time evaluated for each run;
- μ_t (s) is the pooled mean of the refresh time, as stated in (2);
- $\mu_t i$ (s) is the mean of the refresh time evaluated for each run, as stated in 2; and
- l_i is the number of packets for each run, as stated in (2).

Table II, Table III and Table IV summarize the details of the experimental sessions.

The duration of the experimental test was approximately 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, as the Ventilator, after a certain number of commands, sent an *Initialize Communication Command* and

TABLE III
DETAILS FOR EACH RUN OF EXPERIMENTAL SESSION #1

#Packets	Mean Refresh Time [s]	Std Refresh Time [s]	Accuracy [%]
204	0.72	0.16	97.6
227	0.69	0.12	99.1
223	0.69	0.13	99.1
232	0.70	0.13	99.6
232	0.70	0.13	100.0
216	0.73	0.12	99.6
224	0.73	0.12	98.2
206	0.72	0.12	99.0
130	0.69	0.14	97.7
209	0.70	0.10	98.6
	Pooled Mean [s]	**Pooled Std [s]**	**Mean [%]**
	0.71	0.14	98.8

TABLE IV
DETAILS FOR EACH RUN OF EXPERIMENTAL SESSION #2

#Packets	Mean Refresh Time [s]	Std Refresh Time [s]	Accuracy [%]
160	0.70	0.17	98.1
192	0.71	0.10	98.4
221	0.70	0.13	97.3
183	0.68	0.12	100.0
237	0.68	0.12	97.9
187	0.73	0.12	99.5
191	0.72	0.13	99.5
186	0.63	0.12	99.5
156	0.81	0.22	99.4
200	0.71	0.12	98.0
	Pooled Mean [s]	**Pooled Std [s]**	**Mean [%]**
	0.70	0.14	98.8

the MEDIBUS Protocol had to be re-initialized.
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).
Results are summarized in Table V. In this application, no relevant additional time delay caused by the Oculus Rift S was observed, as the acquisition of the parameters is done by the laptop, and the Oculus is only in charge of receiving these parameters via TCP/IP.

Fig. 4 shows the patient's vitals as displayed on the VST. In the final implementation of this system, this information will be shown to the User when he/she turns the head to his/her right or left side. Moreover, it is foreseen that the user, turning the head on the left side, will be able to see the patienatient Electronic Medical Record. Otherwise, the user will see the streaming video from the Da Vinci, as illustrated in Fig. 1.

VI. CONCLUSIONS AND FUTURE WORKS

An integrated system for augmenting patient's monitoring during surgical procedures was presented. In the overall system, the anesthetist or any other member of the medical team wears a VR HMD, which displays a set of information on the patient's status: the real-time view of what the surgeon is looking at on his console; direct access to the electronic medical records; direct real-time visualization of vitals acquired from the OR equipment; and, finally, an alert predicting possible aggravating conditions of the patient's health.
The focus of this work, in particular, was on the development and implementation of the part of the system dedicated to the real-time acquisition and visualization of the patient's

TABLE V
MEASURE AT 3σ

Session	Refresh Time [s]	Accuracy [%]
#1	0.71 ± 0.01	98.8 ± 0.06
#2	0.70 ± 0.01	98.8 ± 0.07
Pooled	0.71 ± 0.01	98.8 ± 0.06

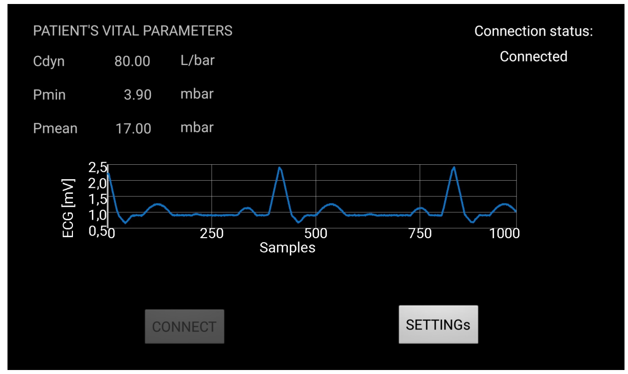

Fig. 4. Patient's vital parameters Layout.

vitals. Preliminary experimental tests allowed to validate the monitoring system. Further work is currently being dedicated to the implementation of the other sections of the integrated monitoring system, the electronic medical record and the streaming from the Da Vinci robot. Moreover, techniques to avoid the VR sickness and improve the ergonomicity will be investigated, aiming to mitigate possible stress caused to the neck of the operator, nausea, disorientation.

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