An Augmented Reality-Based Solution for Monitoring Patients Vitals in Surgical Procedures

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***Abstract*—In this work, an augmented reality (AR) system is proposed to monitor in real time the patient's vital parameters during surgical procedures. This system is characterised metrologically in terms of transmission error rates and latency. These specifications are relevant to ensuring a real-time response. The proposed system automatically collects data from the equipment in the operating room, and displays them in AR. The system was designed, implemented and validated experimentally through experimental tests carried out using AR glasses to monitor the output of a respiratory ventilator and a patient monitor, which are instruments that are generally present in an 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

The advent of the 4th industrial revolution in health care is reflected in an ever-increasing impact of digital in order to improve the service in addition to saving both economic resources and time. It starts from the most advanced technical instrumentation such as the application of robotics to surgery up to the implementation of digital interfaces for the relationship with the patient. The use of different technologies such as the internet of things (IoT) [1]–[3]; artificial intelligence [4]; machine and deep learning [5]–[7]; cloud computing [8]; additive manufacturing [9]; wearable sensors [10]–[13]; and augmented and virtual reality (AR and VR) [14]–[16]. All these technologies contribute to the dedevelopment of cyber-physical systems with an intrinsic monitoring feature [17].

In surgery, an important use of Augmented Reality consists in the superimposition of medical images on patients during the execution of the surgical procedure [18]. Another important advantage is the ability to monitor in real time the patient's vital parameters with the ability to access additional information from the electronic medical record. All this information is made available on AR glasses worn by nurses. In order to improve the efficiency of procedures, put in place in the operating room (OR) you could equip the surgical team with smart glasses AR allowing real-time monitoring of the state of health of the patient even at a distance from the electromedical equipment. In this way the surgical team can focus its attention on the patient and the task to be performed. In this way the surgical team can focus its attention on the patient and the task to be performed. Previous work addressed the possibility of using AR to visualize the patient's vital parameters [19]–[23]. In [19], the authors focused on the number of times the anesthesiologist had to shift attention from the patient to the equipment, achieving a significant reduction of more than a third through a head-mounted AR display (HMD). The use of AR HMD has also been studied in [20], along with auditory visualization to avoid distractions to the anesthesiologist in the operating room. More recently, in [21], a bio-monitoring platform has been developed for the supervision of personnel operating in critical infrastructures. The platform collects a series of signals in order to determine the optimal physiological profile of the staff. In [22] was also implemented a mixed reality system for real-time measurement and visualization, hands-free, of blood flow and vital signs.

In the above-mentioned works, attention is focused on the usability of the system without measuring its performance. On the other hand, for remote surgical procedures it is important to ensure that information is transmitted correctly, virtually and without latency. For example, in work on health monitoring systems [24], [25] the main challenges and requirements regarding real-time wireless data transmission were explored. In other words, various parameters such as the transmission bandwidth, the number of interruptions per time unit, the aver-

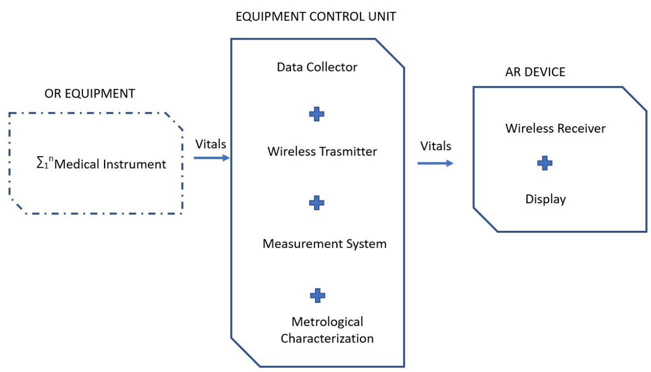

Fig. 1. Architecture of the proposed monitoring system.

age duration of stops, the monitoring delay, energy efficiency and reliability have been analysed. It is clear from these studies that any video/audio delay of more than 300 ms should be avoided in order to ensure correct interaction between the user and the system. On the basis of these considerations, a metrological design of an automatic system based on AR is presented to support the medical team during surgical procedures. The system captures vital parameters from electromedical instruments in the operating room and visualizes them in real time on a set of glasses AR [26]. The proposed system has been implemented and validated experimentally with the aim (i) of verifying the correct functionality of the system, and (ii) of assessing its reliability in the transmission of data, in terms of real-time communication. The latter was done by assessing the accuracy and latency of the system and verifying their compatibility with the strict requirements of the operating theatre.

This paper is organized as follows: Section II presents the system describing its architecture and software operation. In Section III it is considered a case of use in comparison with the experimental tests of metro-logical characterization at the hospitals of the University of Naples Federico II. Finally, in Section IV, conclusions are drawn.

II. Design

This section deals with the design of a real-time monitoring system based on AR, with focus on (i) architecture and (ii) metrological characterization module, in terms of requirements for real-time wearable healthcare applications [24], [25]. Overall, the design choices comply with the strict requirements of the health sector. The system was designed to be used by those responsible for monitoring vital signs in the operating room, such as nurses or anaesthetists. The system would allow the medical staff to view the useful information without turning to the monitoring equipment allowing them to act promptly in case of emergency situations. Finally, based on the suggestions of surgeons of the Federico II hospital, the maximum acceptable latency during surgical procedures should be lower than 2 s. Thanks to these preliminary considerations, the design of an AR-based monitoring system was adapted to the basic requirements of the scope considered.

A. Architecture

The architecture was designed to maximise wearability and ease of use. In fact, the user will only have to wear the AR viewer and start the application. Another strength lies in the modularity and flexibility, as the number and type of medical instruments can be modified according to the specific context. It can be seen that a *Wireless Transmitter*, integrated with the *ECU*, transmits in real time the data to the *AR Device*: this captures the vital parameters and displays them in AR, superimposed on the view of the physical world [27]. *ECU* is also equipped with a *Measurement System*, to analyze *accuracy*, *data-update delay* and *communication latency*. *Precision* (expressed as a percentage), is defined as the number of packets correctly decoded, divided by the total number of packets received.

The *data-update delay* is the time needed by the system to update the acquired vital parameter values, while the *communication latency* is the delay in wireless transmission. In addition, at the request of the user, the *ECU* processes the results of the *Measurement system*, to perform a *Metrological characterization* of the monitoring system as a whole. As a result, a *Metrological Certificate* is generated which summarizes the performance of the system.

The architecture has also been developed to make appreciable the ease of selecting the different parameters using the viewer. In fact the presence of the *ECU* provides two main advantages. First of all, it allows to generalize the application; the system, in fact, can be interfaced with different AR devices or with different operating room equipment. In addition, the *ECU* allows to include possible processing strategies, such as displaying alarms if vital parameters exceed pre-established thresholds, or displaying the results of the predictive algorithm that predicts possible aggravating patient trends.

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 [28]. 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.

III. Case Study

The monitoring system based on AR was validated and characterized metrologically through experimental tests carried out at the University Hospital Federico II. Fig. 2 shows a photo taken during the experiments.

The OST headset is the Moverio BT-350 AR smart glasses. 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. The used ventilator is the Drager Infinity V500, while the patient monitor was the Drager Infinity V500. Both these pieces of equipment are generally available in the operating room; hence, they represent an interesting case study.
In order to emulate the patient's lung, a non self-inflatable bag was connected to the ventilator. Fig. 3 shows what the user sees through the AR glasses. The main parameters from the ventilator are shown and in addition to this information is also reported the real-time variation of oxygen saturation.
Moreover, it is possible to alternate between the different waveforms coming from the Monitor. The advantage in using the AR is the overlapping of the parameters to the user's vision, avoiding distractions of the same allowing a prompt response in emergency situations. Thanks to the modularity of the system architecture, each subsystem can be adapted to the specific context. After establishing the connection between the glasses and the laptop (to which the monitor and ventilator are connected) the data from the instrumentation are collected and displayed. Every block of the system was implemented

Fig. 2. Picture of the experimental validation.

Fig. 3. Image of the user's view through the AR glasses.

to ensure a data transmission without degradation. Another fundamental aspect was to make the user comfortable throughout the test avoiding problems such as motion sickness. For each session the performance was evaluated in terms of average value of accuracy and the dev std. Thus, the 3-sigma uncertainty was evaluated taking into account the total number of executions, according to (2). Last parameter evaluated is the latency of the system seen as three contributions: (i) ventilator update, (ii) monitor update and (iii) TCP communication/IP. At the end of each analysis, the average value and the standard deviation of these quantities were evaluated. At the end of the session the evaluation of the aggregate average was carried out μ_{t} and uncertainty 3-sigma σ_{tpo}, taking into account the different number of packets sent each run, according to (3) and (4). Uncertainty was also been assessed through the law of propagation of uncertainty. Assuming μ_t as a weighted average between series, as explained in (3), the uncertainty 3-sigma u_{tpr} can be evaluated by (5). Overall, the two approaches to assessing measurement uncertainty led to compatible results.

IV. Conclusion

A system for real-time acquisition and visualization of vital signals using augmented reality was described. The implementation was based on both metrological performance and the users of this application or the medical team. The surgeon's assistant and/or the anesthesiologist wears the AR glasses, which visualize in real time the vital parameters acquired by the operating room equipment without having to constantly look at the medical device.

In addition, at the request of the user, the system automatically evaluates its metrological performance in terms of transmission accuracy, delay in updating data and communication latency. The system was designed, implemented and validated experimentally through measurements using equipment available in the operating room. The design of an AR-based monitoring system was adapted to the requirements of the scope considered, thus paving the way for the future practical implementation of the system. After the preliminary functional validation of the system, metrological characterization was carried out with focus on the rate of transmission error, the display refresh time, and the latency induced by the communication, to demonstrate the effectiveness of the proposed system.

It was observed that the measured accuracy is over 97%, and the latency introduced by the Android application to receive the parameters varies in the order of milliseconds, which fully meets the aforementioned health requirements. This is an important step that aims to improve through AR the effectiveness of medical procedures in the Health 4.0 framework, while preserving the real-time requirements of the application context.

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References

[1] 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.

[2] 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.

[3] 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.

[4] B. Alotaibi, "Utilizing blockchain to overcome cyber security concerns in the internet of things: A review," *IEEE Sensors Journal*, vol. 19, no. 23, pp. 10 953–10 971, 2019.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

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

[15] 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.

[16] 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.

[17] S. Grazioso, A. Tedesco, M. Selvaggio, S. Debei, and S. Chiodini, "Towards the development of cyber-physical measurement systems (CPMSs): case study of a bioinspired soft growing robot for remote measurement and monitoring applications," *ACTA IMEKO*, vol. 10, no. 2, pp. 103–109, 2021.

[18] 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.

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] 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.

[24] 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.

[25] 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.

[26] P. Arpaia, E. De Benedetto, C. A. Dodaro, L. Duraccio, and G. Servillo, "Metrology-based design of a wearable augmented reality system for monitoring patient's vitals in real time," *IEEE Sensors Journal*, vol. 21, no. 9, pp. 11 176–11 183, 2021.

[27] 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.

[28] P. Arpaia, E. De Benedetto, and L. Duraccio, "Design, implementation, and metrological characterization of a wearable, integrated ar-bci hands-free system for health 4.0 monitoring," *Measurement*, vol. 177, 2021.