CheckING: An IoT Device for COVID-19 Monitoring and Prevention

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***Abstract*—The COVID-19 pandemic has spread rapidly around the world forcing people to isolate at home and collapsing hospitals causing millions of deaths. The continuous and efficient monitoring of those who showed symptoms jointly with the analysis of the environment conditions to avoid the spread of the virus gave rise to the development of different technological alternatives. In the present work, a comprehensive device with multi-parameter sensing has been designed, emphasizing the integration of physiological and environmental parameters with remote monitoring, of the interest in the current pandemic context.**

Keywords—COVID-19, Monitoring; Sensing; Internet of Things; Early Warning Score; Wireless Sensor Network;

I. INTRODUCTION

As a result of the emergence of a type of coronavirus (CoV) which causes a severe acute respiratory syndrome (SARS-CoV-2), The World Health Organization (WHO) has classified that respiratory disease, commonly known as COVID-19, as a 'pandemic' due to the evidence of its high transferability rate. Since then, there have been more than 194 million cases and more than 4 million deaths reported around the world [1]. That condition produces an elevated infection rate in a short time, and in some occasions does not allow proper medical attention because of the saturation of hospitals' infrastructure or the shortage of human resources [2].

Related to the abovementioned, the monitoring of both physiological and environmental parameters has taken on great relevance in the last few years, especially in relation to the development of portable and wireless devices which provide the possibility of local and remote monitoring [3]. As a result, the application of the latter to the effective testing of the environment and people within the COVID-19 pandemic context allows the implementation of actions that would help to decrease the consequent impact on health systems in terms of infection rates (because of the preventive actions) or enable the remote evaluation of individuals at home (due to the isolation requirements) [3]. In a more specific way, the Internet of Things (IoT) concept is based on the development of a physical comprehensive network of devices, equipped with embedded software, sensors and wireless connection, which share information with a central server or from one device to another. These features make IoT an ideal structure for monitoring applications in healthcare [4]. According to this, increase of body temperature, blood oxygen saturation (SpO2) and heart rate [5] can be mentioned as physiological parameters of interest for the early detection of individuals who could be suffering from COVID-19. Regarding the environmental issues, carbon dioxide concentration (CO2) and room temperature can be considered to prevent indoor propagation [6]. Measuring CO2 concentration in the air has become crucial, since it is one of the most important means of propagation. Consequently, a right amount of airflow is required to prevent a sick person from infecting others when exhaling or coughing, thus causing an increased risk of airborne spread [7]. As a result, a device capable of integrating all these parameters is extremely useful for remote monitoring of individuals who present symptoms of the disease as well as for the prevention of possible future infections linked to the concentration of individuals in closed areas.

In this work, a design and development of a monitoring device for both environmental and physiological parameters is presented (named 'CheckING'), which comprises the use of multiple sensors and IoT technology. It has the capability to be connected either individually or as part of a network, analyzing areas or places where people need to interact. The obtained measurements and reports, which are continuously evaluated by a cloud server, can be visualized online by a mobile application.

II. MATERIALS & METHODS

CheckING is a monitoring device that allows the continuous and remote evaluation of individuals, as well as the specific environments where there are different degrees of people circulation. It consists of a standalone module with WiFi connectivity and directly connected to the AC power supply. The result of each parameter evaluation (i.e. body temperature, SpO2, heart rate and CO2) is luminically communicated to the user for easy interpretation and automatically sent to a cloud server for storage and continuous monitoring. The exchange of information is performed by means of the message queue transport protocol by telemetry (MQTT), which is commonly known for its lightweight data-interchange format and low power consumption, which make it ideal in IoT embedded systems [8]. A cloud server is in charge of data storage, which is transmitted from each independent device. A complementary mobile application was developed for Android OS which manages online data for continuous visualization. To make it quicker to read, the application receives raw data from the cloud server and displays it in different plot graphs and labels. Furthermore, the CheckING mobile application will notify and give alerts when predefined threshold boundaries are crossed.

A. CO2 Measurement

The CO2 values were measured in internal areas with a NDIR technology (non-dispersive infrared rays) sensor using the MHZ19 electronic module (Winsen-Sensors, Zhengzhou, China). The location of the sensor was according to the design of the printed circuit, in order to have the greatest exposure to ambient air, and close to the control system for receiving the resulting signal. According to current regulations, a precision of at least 50 ppm is needed [9]. The correction for the sensor was carried out by placing it outdoors and following the expressed instructions specified by the manufacturer in the corresponding data sheet [6].

B. SpO2 and Heart Rate Measurement

The integrated circuit MAX30100 (Maxim Integrated, California, USA) was used for SpO2 measurements, containing a complete system of optimized optical sensors and programmable sigma delta analog-digital converter with a 16-bit resolution. To estimate SpO2 and heart rate, this sensor uses light sources of different wavelengths that are reflected in the cutaneous tissue and are detected by the receiver which is on the same surface as the emitter. [10].

C. Temperature Measurement

Both body and environmental temperature measurements were carried out with an MLX90614DAA sensor (Melexis, Ypres, Belgium), which is specific for medical applications. The sensor has a digital output via I2C bus and integrates, into the same capsule, an infrared detector that receives proportional radiation to the object's temperature under measurement and includes the required hardware to digitally process the infrared detector's signal.

D. Communication & Processing

The ESP32 (Espressif Systems, Shanghai, China) microcontroller communicates with the sensors through an I2C bus and sends the measurements of the required sensors to the MQTT server (Figs. 1 and 2).

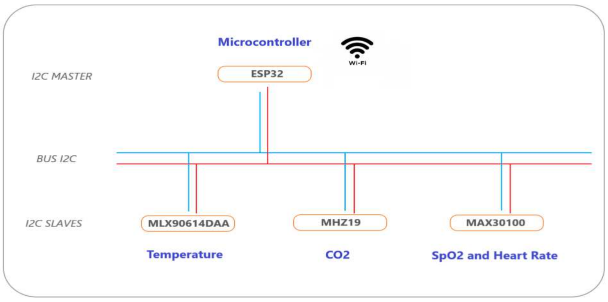

Fig. 1 Scheme corresponding to the connection of the microcontroller and the different sensors using the same I2C bus.

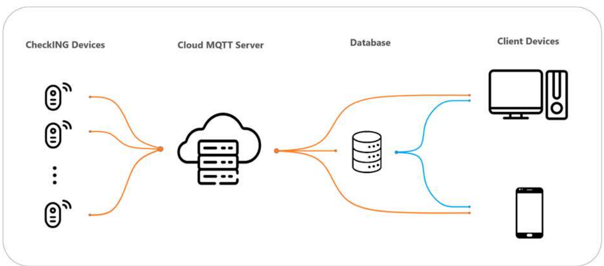

Fig. 2 Scheme corresponding to the connection of the CheckING devices and the client devices, passing through the MQTT Server and storing data in the database.

E. Case design

The device case cover design was developed using SolidWorks(R) (Dassault Systems SolidWorks Corp. Massachusetts, USA), a parametric tool which allows the manipulation and modification of the design in an efficient manner by the edition of a few parameters. A series of critical points were considered to define the best functionality conditions:

1. Optimizing the device's ability to alert users of any parameter outside the acceptable margins, defining under this premise the location of the light indicators and a general alarm button. This point was taken as a priority since the light alert is easy to understand.

2. Enabling air circulation for a correct environmental measurement, for which small openings were arranged to avoid contamination and contact with internal circuits.

3. Minimizing the device dimensions which generally works while connected to a wall power plug, thus allowing a correct temperature measurement on the wrist.

4. Integrating the power supply with the chassis, in order to allow a connection without external cables thus making it easier to fix it mechanically to the wall.

Subsequently, the resulting prototype was implemented with fused deposition modeling technology (FDM) by using a bioplastic material based on lactic acid, which allows agile manufacturing and more endurance of the final product.

F. Operating mode

To perform the temperature measurement, the user places his wrist at the bottom of the device, which will trigger a blue led on, indicating the beginning of the measurement. For the SpO2 acquisition, the user places his finger on the lateral opening of the equipment that contains the corresponding sensor. In both cases, the indicator led will blink reporting the final result, allowing a fast assessment based on thresholds. A green indicator means that the parameter is within an acceptable range, a yellow indicator means it is near the threshold and a red indicator means parameters are out of boundaries.

If no specific measurement of the physiological parameters was carried out, the indicator light informs the status of the CO2 measurement, progressively changing its color from green (for low concentration values) to red (for high risk concentration values). Likewise, room temperature is internally sent to the cloud server for control and calibration purposes.

G. Mobile Application

A mobile application was developed in Android Studio 4.1.1, API 30, with compatibility up to version 23 (Google Inc., San Diego, USA). The latter is directly connected to the cloud server (in charge of managing the CheckING devices and the processing of the collected data), making the request for the specific data that the user needs to evaluate. As a result, users can visualize all the information in an easily interpretable way, either graphically or in warning mode.

H. Usage modes

The application's main menu allows the user to choose, in the first instance, between those devices aimed at monitoring venues and those that specifically monitor individuals, as follows:

a) Busy Environment Monitoring

This operation mode is oriented to the monitoring of areas through a massive control of each person who enters the enclosure. In this operating mode, although all the parameters are important for proper monitoring, both the CO2 concentration and the ambient temperature have special preponderance, since they provide information related to room ventilation, thus preventing the COVID-19 from spreading indoors [11]. Essentially, the focus is on arranging a series of devices in different rooms (network mode), which allows monitoring work areas, with the complement of additional physiological parameters to traditional body temperature evaluation.

b) Isolated People Monitoring

This operation mode exclusively monitors a person who has been isolated in a private room, either because they are suffering from COVID-19 or because they have compatible symptoms with the disease. In this case, body temperature, SpO2 and heart rate measurements are more relevant because these parameters are specific indicators of the patient's current state. Periodic monitoring of these 3 parameters can detect, for example, low oxygen saturation, a condition that requires immediate medical attention [12].

As can be seen, the isolated people monitoring mode conceives each measurement as corresponding to the same individual, in order to develop a specific monitoring of their condition. On the other hand, the other mode is focused on busy environments, some measurements particularly relating to the environment (room temperature and CO2 concentration) and others corresponding to people who enter the place (body temperature, SpO2 and heart rate).

By accessing any of the devices from the application, graphs can be viewed as a time function for each of the measured parameters. Additionally, the isolated people mode provides an extra menu that allows the user to view the last evaluation values along with the time at which it was performed. In this way, each individual can be more easily monitored prior to viewing the graphical history.

I. Calibration mode

All devices can be calibrated on the scale of a certified measuring instrument. In order to calibrate a device, the mobile application and an appropriate standard meter are needed. In this mode, the device is requested to sample a specific parameter. Once the measurement is completed, the same action must be repeated using the certified device, so the user is asked to enter the result. Finally, both values are sent to the server, which is in charge of storing them and, based on repeated measurements, obtaining the correction factor that must be applied to the specific device.

In order to perform an accurate calibration, the recommendation is to use a measuring instrument with precision of at least ±2% for SpO2, ± 0.1°C for body temperature, ±2bpm for heart rate, and ± 50 ppm for CO2 [9]. These values were taken as a reference based on devices approved under international biomedical standards.

In order to facilitate visualization of the evolution graphs, certain limit values have been adopted for each parameter, to quickly identify those samples that indicate a potential alarm. The values adopted as reference were: body temperature greater than 37.5° C, SpO2 less than 94%, heart rate greater than 90 beats per minute, and CO2 concentration greater than 2000 parts per million [13]. In those cases, where a parameter is detected outside of the established limits, the application starts an alert state, emitting a notification for its fast detection.

J. Server

As was mentioned in previous paragraphs, a cloud server is in charge of the CheckING network, having the corresponding redundancies to ensure its reliability in case of failures, staying operational 24 hours a day. The MQTT broker to which the monitoring devices are connected is installed on it. The mobile application, however, does not interact with the server via MQTT because this protocol is optimal for low-power embedded systems, but not for cell phones. For this reason, the server stores all measurements in their corresponding databases and implements an Application Programming Interface based on Representational State Transfer (REST API) to which the various mobile devices request the information in order to make them graphically visible as needed. The mentioned REST API and the database implementation are developed in Django 3.2.25 (DSF, Django Software Foundation).

The information transfer format between the server and mobile devices was JSON (JavaScript Object Notation) due to its lightness and portability, and because it is easily read by both users and devices. However, for data transfer between the measurement devices and the server, a proprietary format has been developed, which is lighter than JSON and more specific for the design, with the aim of making communication faster, more reliable and requiring less processing time by the embedded system.

KEY	VALUE	KEY	VALUE	KEY	VALUE	KEY	VALUE	KEY	VALUE
TA	22.49	TO	38.97	C	504,26	S	96.69	HR	79.14

Fig. 3 Generic communication dataframe (top) and a complete diagram example with real values (bottom).

The developed communication format consists of predefined key-value pairs, with a key for each parameter. Therefore, the dataframe can contain data from all the parameters or just from those sensed in the last measurement, taking processing away from the device and leaving this responsibility to the server that manages the data. The defined keys are: TA (environmental temperature), TO (body temperature), C (CO_2), S (SpO_2) and HR (heart rate) (Fig. 3).

III. Results

The proposed design for the device is visualized in Fig. 4 by virtue of the conditions imposed in previous paragraphs. Air circulation holes, integrated power line connection, and general alarm button can be observed.

Fig. 4 Rendered design of the CheckING device on SolidWorks platform under the given operating conditions.

Fig. 5 shows the developed working prototype of the device based on the design described above. As a matter of fact, CheckING plugs to the power line directly and wirelessly to the cloud server under MQTT protocol. In particular, the CO_2 monitoring mode can be seen, where light indicating color changes from green to yellow/red, thus showing an increase in CO_2 concentration and a visual alert for individuals within the room.

Fig. 5 Functional device during a CO_2 measurement. The change in color from green to red, shows the presence of alarming concentrations.

In Fig 6 (left), the body temperature measurement is shown. The individual places his arm under the device obtaining a light signal in the gradient from green to yellow, which indicates a temperature within the range considered "not alarming". Likewise, the right panel displays the evaluation of SpO_2 and heart rate, with a similar determination of its condition within the normal threshold.

Fig. 6 Functional device during a temperature and SpO_2 measurement. The blinking together with the color change are indicative of the presence (or not) of alarming situations.

Fig. 7 shows the application's main menu. Four different main options can be seen: Rooms, People, Map and Settings. 'Rooms' selection gives access to the list of all the devices monitoring busy environments, being able to visualize the history of measurements of any of them. The same functionality is obtained through the 'People' option, where the user accesses the list of devices dedicated to track individuals' parameters.

In turn, the 'Map' option generates a graph with all the operating devices current status, allowing the user to have a general network overview. If any of the devices detects that a specific parameter is exceeding its considered threshold value, it will be shown in yellow/red. Finally, in the 'Settings' section the user can access the network, calibration mode and server settings.

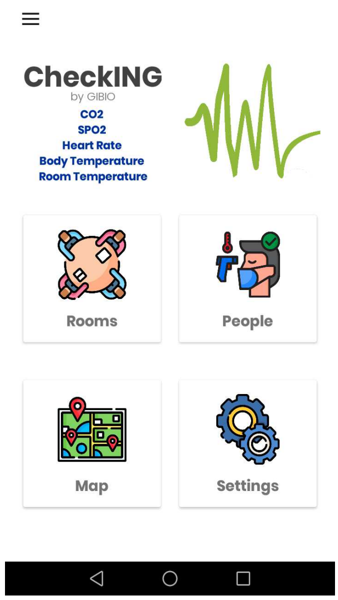

Fig. 7 Screen image corresponding to the mobile application's main menu, with its 4 main options: Rooms, People, Map and Settings.

The application section developed to monitor the different CheckING modules is shown in Fig. 8. As a particular case, the SpO2 is plotted (left panel, for an individual dedicated device) while the right panel displays the person's last measurement's general status. In addition to the indication of the time when the last measurement was made, the color of each panel is changed according to the sensed value. If any of the samples exceeds (or approaches) the risk range, it will turn yellow/red, emitting an alarm to indicate this situation.

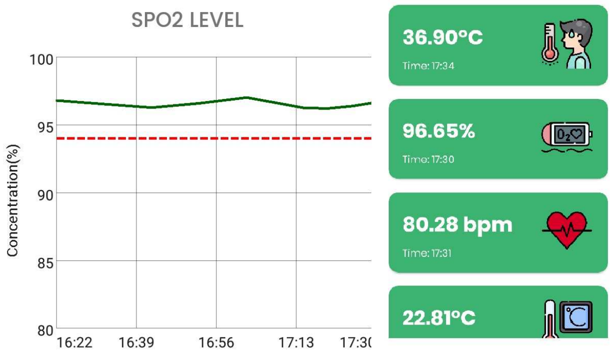

Fig. 8 Screen image corresponding to the mobile application monitoring a person's SpO2 (left panel) next to a person's last measurement monitoring (right panel).

Finally, Fig. 9 details the graph generated by the CheckING application in calibration mode, showing the relationship between measurements obtained using the certified instrument and those corresponding to the monitoring device (left panel, for a body temperature case, right panel for a heart rate case). In both cases, the sampled values obtained by the reference meter are plotted in a green continuous line. Instead, the values measured by the device are represented in red. By applying the correction factor, the calibrated values are obtained (shown in blue). This correction and calibration process can be carried out for all network devices and for each monitored parameter.

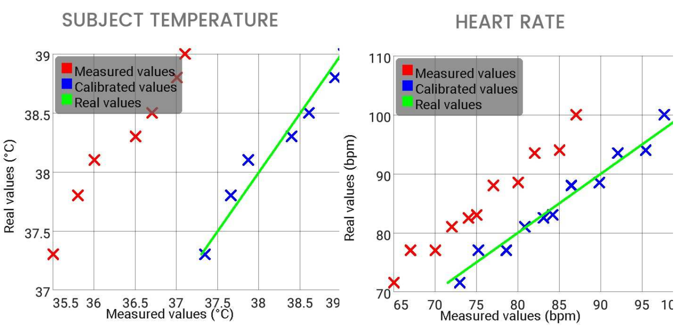

Fig. 9 Screen image corresponding to the mobile application plotting the relation between the measurement device and the reference meter for a body temperature case (left panel) and for a heart rate case (right panel).

IV. Discussion

In this work, an IoT device for monitoring both physiological and environmental parameters was designed and developed, giving rise to a comprehensive network for preventing COVID-19 infections. Additionally, CheckING can be used in a monitoring mode for isolated individuals, for remote healthcare in real time.

Indeed, such a network can play an extremely useful role in the early detection of COVID-19 cases. Multiple studies [13], [14], [15] have shown that the presence of low SpO2 values constitutes one of the most relevant indicators prior to the need for hospitalization. Early detection of these cases can be essential when assessing the priority of those patients with critical conditions. In addition, heart rate plays an important role in monitoring respiratory capacity. Respiration causes variations in blood circulation, allowing the respiratory rhythm to be monitored through heart rate and the correlation that links both parameters [16]. Finally, fever or high body temperature constitutes one of the most common symptoms of the disease. However, it is not always present in all potential COVID-19 infections (or, if it is, people could end up manifesting another condition), being not so efficient as a screening method. As a result, additional physiological parameters should be considered to overcome this issue. Moreover, since temperature usually depends on the body area (in this particular case, the user's wrist), this factor has to be taken into account when defining the threshold [17]. Therefore, the calibration mode can be a substantial contribution to avoid false alarms.

Likewise, this device is in line with other remote monitoring platforms implemented in previous works during pandemics such as SARS-CoV, MERS-CoV and Ebola. These include the use of IoT devices for temperature measurement, the development of wearable modules and the use of mobile applications for monitoring and control [4]. In this sense, one of the main benefits of the CheckING device is its ability to integrate the measurement of various parameters which are carried out simultaneously in users and in their environment. This highlights its usability with regard to the prevention of infections, since keeping shared environments with the proper air flow is one of the main recommendations to avoid the transmission [11].

On the other hand, it should be noted that optical sensors were used to isolate users from electrical risk. The circuits inside the housing are powered by a 5v certified commercial power source, so the user is only exposed to safe voltages. Additionally, CheckING uses a double cabinet to reduce the risk of failure.

To summarize, future evaluations are required so that the device can be submitted to the corresponding validation and certification processes. As future developments, the possibility of incorporating the determination of the user's respiratory rate (as an additional physiological parameter) is proposed, jointly with the tracking of infected people through the use of RFID cards, biometric identification sensors or signals from their mobile phones.

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