Design and Implementation of a Low-cost CO_2 Monitoring and Control System Prototype to Optimize Ventilation Levels in Closed Spaces

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***Abstract*—High concentrations of CO_2 levels are significantly present in closed environments that do not have proper ventilation. Such high concentrations generate negative health consequences such as dizziness, headaches and various respiratory problems. For this reason, the design and implementation of a low-cost CO_2 monitoring and control prototype is proposed to optimize ventilation levels in closed spaces. The parameters that the proposed device measures are concentration of carbon dioxide, humidity and temperature. A digital PID controller was implemented, with the use of C++ programming language and an exhaust fan to stabilize carbon dioxide levels within a closed space. The aforementioned parameters can be viewed in two ways: The first way is locally through a LCD screen and LED indicators, and the second one, remotely using the free Arduino IoT Cloud platform. The closed environment was emulated using a cardboard box and in the tests it was obtained that the prototype manages to keep the CO_2 concentration levels below the established limit. However, this can be further improved by using more precise sensors for more accurate results. It is expected that this model can be successfully scaled to closed spaces such as classrooms and offices.**

Keywords—CO_2 Monitoring; IoT; Low-cost Indoor Ventilation System; NodeMCU; Open Source Software

I. INTRODUCTION

Currently, outdoor air pollution has increased in all countries due to the growth of automotive fleets and industrial companies. This affects indoor environments with a significant increase in CO_2 levels in a proportion between 2 to 5 times more than outdoors [1]. An example of this is reflected inside different environments such as classrooms, offices, bedrooms, etc; where the CO_2 concentration has values that exceed the maximum levels recommended by international standards. These places do not have an adequate mechanical ventilation system to dissipate the polluting gases that are generated inside, and even in many cases the doors and windows are kept closed. Likewise, despite the fact that they have been designed to accommodate a limited number of people, the maximum capacity allowed is exceeded on a daily basis.

Different CO_2monitoring systems have been developed for closed spaces that do not directly control this parameter. A CO_2 prediction model has been developed based on the history of measurements [2]. A user alert system has been also proposed by means of text messages to the cell phone and an email notification [3]. The information obtained is even shown through an LCD screen and warns us with an audible alarm when the maximum levels established are exceeded [4]. The aforementioned studies [2], [3], [4] defend the importance of monitoring the levels of polluting gases, such as CO_2, existing inside a closed space. This, with the aim of analyzing indicators that allow reducing the spread of diseases in the short and long term. The tendency of the authors in this regard is to develop portable prototypes that determine the concentration of harmful agents to health within the environment using low-cost sensors that provide information in real time, which seeks to maintain adequate ventilation levels below the recommended limit.

CO_2 is a gas that is released by human respiration and this is adequate to measure ventilation levels [5]. Because people exhale predictable levels of CO_2, a direct connection to air pollution can be made [3]. This parameter is extremely important, since high concentrations of CO_2 have very harmful effects on health [6]. On the other hand, the measurement of other parameters of air quality, such as particulate matter, relative humidity and temperature, are very important as well. Environmental parameters, temperature and humidity, also influence people's well-being [7], [8] and these are necessary to have a correct indoor air quality index [2].

Some devices that has been previously designed to measure different parameters from air quality have shown data in real time through the uses of displays. For example, an open source web platform was developed to display the information provided by the sensors using a MySQL server for data storage [7]. ThingSpeak was also used, which is a free web platform for the collection and representation of the measured variables [3]. On the other hand, a mobile phone application called Dataplicity was used to remotely access the pollutant indicators [9], whereas in another study only a 16x2 LCD screen was used to fulfill the same purpose [10].

When considering the methodology used by some studies to develop devices that measure air quality, diverse ones were followed. For instance, a quantitative experimental investigation was applied in 10 schools and in 2 training centers for 8 days and between 5 to 10 hours a day taking measurements from different air quality sensors [11]. A similar methodological approach is applied using pollutant weighted calculation tools and the test is performed in 2 environments. The first is a laboratory at the University of Warwick (England) during 1 hour of classes with a number of 100 students. The second environment is a kitchen of the same school, with a single person preparing the food for 1 hour [1]. On the other hand, in one study [8] a qualitative methodology based on surveys was used as an instrument to understand the experience of discomfort and evaluate the environment from the participants own point of view. Then, a statistical analysis was performed based on census data for 8 hours a day in 4 scenarios. Similarly, in another study [12] a systemic perspective of the model designed with a smoothing algorithm to reduce sensor errors caused by power failures and a data aggregation algorithm that minimizes network traffic and saves time was developed. In a research carried out in India [10], empirical methods were used to know the level of gases harmful to health using the designed prototype, but they did not specify the place or conditions where it was used.

A research carried out in Spain [11], presents as a result a very precise device whose data had a value R^2 = 0.902 in a simple linear regression test, and S = 143 and p = 0.1348 in the Moses test comparing it with the commercial Perfect Prime CO2000 device. Similarly, researchers in Portugal [13] presented a very reliable proposal, showing sensors with R^2 values between 0.73 and 0.87, obtained from linear regression tests. Another work in India [3] explained a system with good sensitivity, which although it was not compared with another device, had a sensor which was experimentally calibrated for 24 hours.

Some studies have concluded that portable devices are reliable to measure the quality of the air inside closed environments and also confirm that the use of IoT sensors is favorable for these equipments. For example, the use of IoT technology simplifies access to the information provided by the different sensors installed in the environment in order to have a better quality of air [14]. With the information collected by sensors interconnected by means of IoT technology, it was possible to develop an anticipated model based on CO_2 concentrations to improve ventilation at any time [2]. On the other hand, Interaction with a wireless sensor network that provides real-time pollutant gas indices is also affordable for everyone. Mounting a network of wireless sensors is easier and more efficient and naturally, it reduces the amount of wiring used from the end devices to the central monitoring station [15]. Finally, the Raspberry Pi development board facilitates the connection with other IoT sensors and not only with analog or digital sensors to collect information on the contamination rates in a closed area [12].

In view of this global problem, which is detrimental to people's health, of not having an adequate CO_2 monitoring and control system, it is necessary to design and implement one that optimizes the level of ventilation in closed spaces [7].

II. METHODOLOGY

A. Electronic Components

The prototype is divided into five operating stages and uses the following electronic components, with the aim of achieving a low-cost system that can be implemented in closed environments.

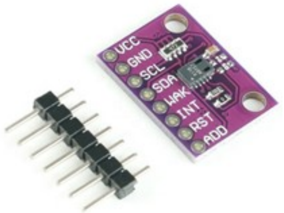

Fig. 1. CCS 811 Sensor.

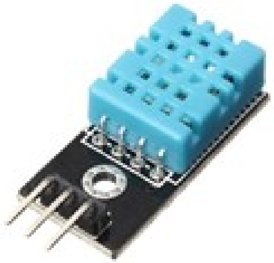

Fig. 2. DHT11 Sensor.

1) Acquisition Stage: Two types of sensors were implemented in this stage.

- CCS 811 Sensor (Fig. 1): It is an air quality sensor that allows us to obtain the equivalent concentration of CO_2 from the measurement of Total Volatile Organic Compounds (VOC) in a very precise way. This sensor was chosen as a main parameter for CO_2 measurement due to its low economic value compared to other types of air quality sensor on the market that cost up to 6 times more.
- DHT11 sensor (Fig. 2): It is a sensor that measures temperature and humidity parameters. It is a digital type that can be powered with 3.5 to 5V. Its temperature measurement range is 0 to 50° C, with an accuracy of 2° C. It allows to measure the relative humidity of 20-80% with a maximum sampling period of 1 second.

2) Control Stage: It is made up solely of the NodeMCU module.

- NodeMCU v3 module (Fig. 3): This module has an ESP8266 processor at a speed of 80 to 160 MHz. It has 1 analog port, 17 general purpose ports, 4 PWM outputs and allows I2C, UART, SPI type communication and Wifi. This device was chosen because it is a very popular and cheap module to carry out electronic projects that are synchronized with a free service in the cloud every second, due to its low consumption and high performance.

3) Communication Stage: It will be done wirelessly through the Wifi technology of the NodeMCU module. This communication was chosen because this technology is incorporated into the NodeMCU development board and that it has a free server called Arduino IoT Cloud to be able to view the

Fig. 3. NodeMCU v3 Module.

Fig. 4. 16X2 LCD + I2C Module.

KPI control indicators remotely, both on the web and on the cell phone.

4) Display Stage: It is made up of a 16X2 LCD screen with I2C module and 3 LEDs.

- 16X2 LCD Screen + I2C Module (Fig. 4): This component is a small screen that allows information to be displayed. It has 2 rows and in each row you have the possibility of observing up to 16 alphanumeric characters.
- It consists of 3 light emitting diodes of green, yellow and red respectively. They will allow to show visually based on a color of the led a range of the CO_2 sensor to indicate if the ppm values are low, medium or high, respectively.

5) Actuator Stage: It is made up of 1 pre-actuator and 1 actuator.

- AC 220V / 2A digital dimmer (Fig. 5): Provides alternating current voltage regulation in order to achieve different levels of voltages that are located within the voltage range, while varying the power delivered to the load. This is controlled by a PWM signal. : This device was chosen as a pre-actuator to gradually vary the speed of the extractor motor, due to the effect of the PID controller established to maintain the optimal CO_2 concentration at an approximate value of 1000 ppm.
- 220V Extracting fan (Fig. 6): It is that device that extracts the air through its rotating blades in a direction from inside to outside of an enclosure. It works with voltages of 220-240 VAC and at frequencies of 50 and 60 Hz. In addition, they have a protection impedance. This device was chosen to extract the concentrated gas into the environment when CO_2 levels exceed a dangerous value for human health and thus dissipate it.

A diagram of the five stages working together in the design of the prototype is show in Fig. 7.

Fig. 5. AC Digital Dimmer.

Fig. 6. 220V Air Extractor.

B. Mechanical Structure

Fig. 8 shows the design of the structure through the CAD Solidworks 2020 program, with general dimensions of 102 x 50 x 110 mm and 2 mm thick, which will contain the system components (LCD screen, sensors and plate development) so that they fit perfectly. After that, a 3D printing can be made using Acrylonitrile Butadiene Styrene (ABS) as a material, to protect the elements of the system. ABS material was chosen because it has sufficient protection against dust and splashes of water.

The front, side, rear and bottom views are seen in Fig. 9, Fig. 10, Fig. 11, and Fig. 12, respectively.

C. Software

The programming of the NodeMCU v3 module was done through the Arduino IDE platform, since the module has compatibility with that development environment. The goal is to keep the CO_2 concentration at 1000 ppm through the use of a digital PID controller. Likewise, the temperature and humidity parameters were considered in order to compensate for the variations in CO_2.

First, the readings of the temperature and humidity sensor were taken to be able to introduce them to the CO_2 sensor and improve the variation of the reading of its concentration. The PID controller is activated when the carbon dioxide concentration exceeds the value of 1500 ppm, because from this concentration it begins to be very harmful to health. With the establishment of the desired level of CO_2 and the correct tuning of the controller, the output value of the control signal is calculated. The power that will be delivered to the air extractor is the output of the PID controller, therefore a restriction of its maximum value was established at 100 and minimum at 0.

This rectified output signal will be sent to the dimmer, which will regulate the power that will be sent to the extractor. Fina1glly, when the carbon dioxide concentration is less than 900 ppm, the PID controller will stop working, since the

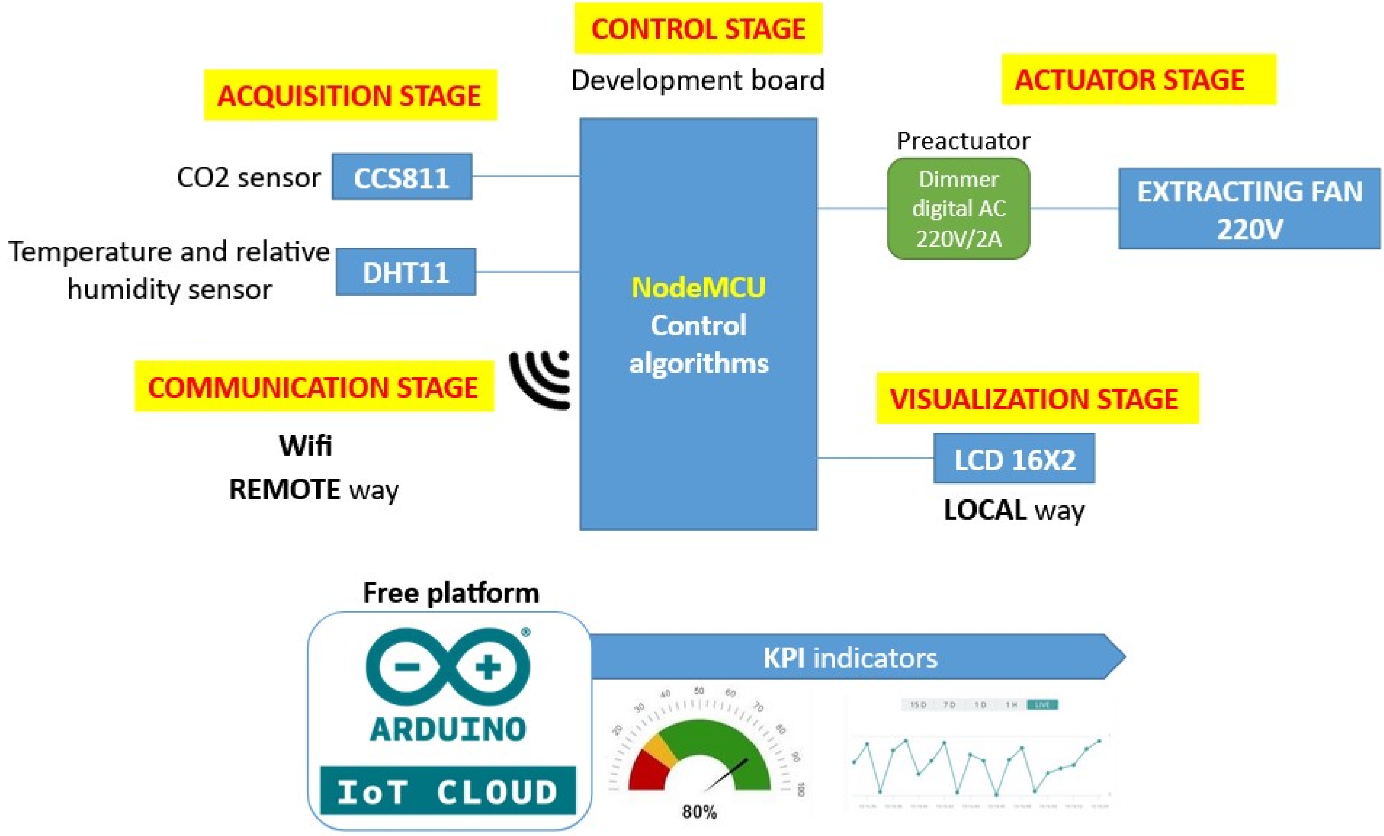

Fig. 7. Interconnection of the 5 Stages of the System.

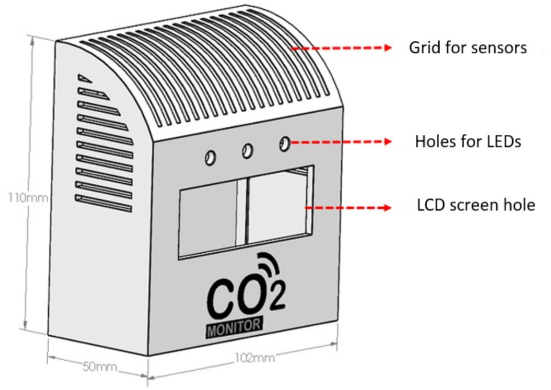

Fig. 8. Design View of the Exterior Structure.

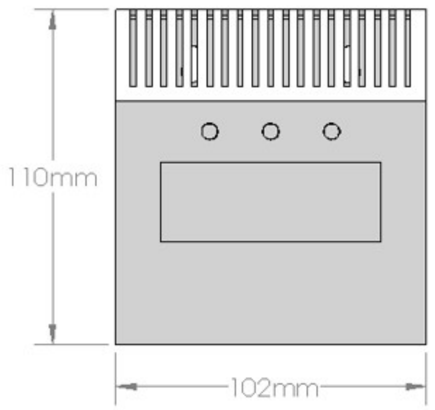

Fig. 9. Front View of the Exterior Structure.

ventilation level of the place will be safe. The values of temperature, humidity and CO_2 concentration will be sent to the cloud, displayed on the LCD screen and there will be 3 LED indicators: green when the CO_2 concentration is less than 1000 ppm, yellow when it is between the range 1000 - 1500 ppm and red when higher than 1500 ppm. Fig. 13 shows the logic used for programming the entire system.

D. Data Transmission to the Cloud

The measurements from the sensors are sent to the Arduino IoT Cloud platform. This platform is free, easy to use and all standards are open source. In addition to being compatible with all Arduino boards, it also has compatibility with the ESP8266 microcontroller, which is used by the NodeMCU module. This platform uses the MQTT protocol for data transmission and allows other interaction methods such as command line tools,

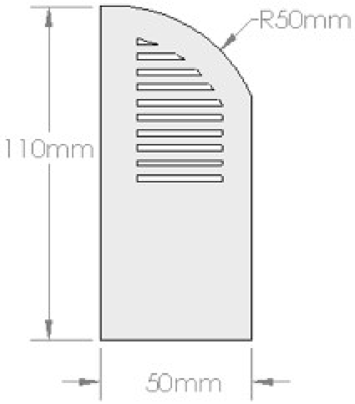

Fig. 10. Side View of the Exterior Structure.

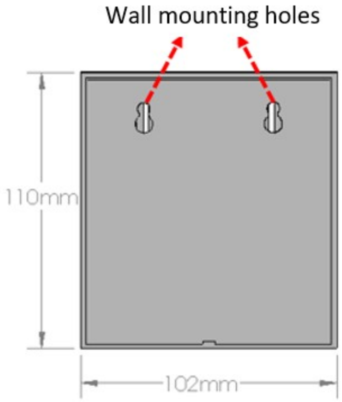

Fig. 11. Rear View of the Exterior Structure.

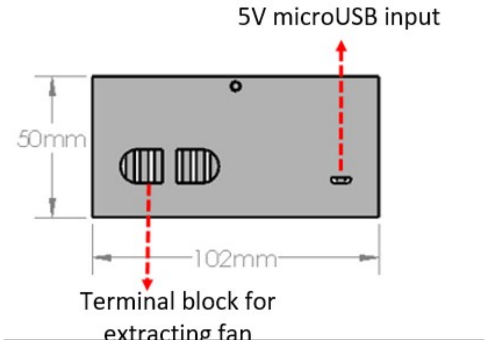

Fig. 12. Bottom View of the Exterior Structure.

JavaScript, and WebSockets. It even has a data storage of up to 2 days.

In this platform, 3 variables corresponding to each of the parameters that are obtained from the sensors were created and it was established that they are updated when their value changes. An interface called “CO_2 Monitoring and Control System” was also designed and added a percentage progress indicator for the humidity value, a nominal progress indicator for the temperature value and a trend graph for the value of CO_2 concentration in ppm, as shown in Fig. 14.

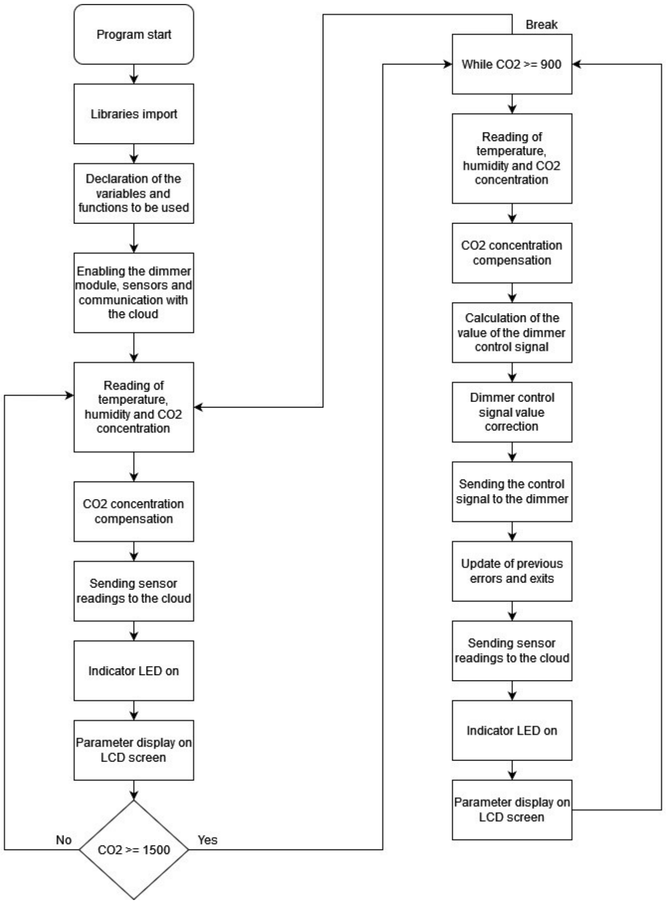

Fig. 13. Flow Diagram of System Operation.

III. RESULTS AND DISCUSSION

For the tests of the designed prototype, in Fig. 15 we have emulated a closed environment based on a cardboard box measuring 41x55x38 cm, in which 27 small holes were made, with an approximate diameter of 2 cm, on both sides and in the back of the box so that the air can circulate when the extractor is turned on, since otherwise there would not be an exchange of the flow of clean and polluted air inside the box. The cardboard box was chosen because of its low price and that it allowed to accumulate carbon dioxide in such a way as it would be done in a real closed space. However, the use of other materials such as resin or glass, as in the case of the research carried out in Algeria [16], would have allowed allow to observe the total operation of the system and to obtain a more natural behavior of the CO_2 due to a better permeability. Also, a plastic box with IP56 protection could be used to protect the system components and be the external structure of the prototype, as was done in England [17] and Indonesia [7].

As can be seen in Fig. 16, a hole with a diameter of 11.5 cm was made in the front of the box so that the air extractor can be installed outside of it. Likewise, 4 small holes were

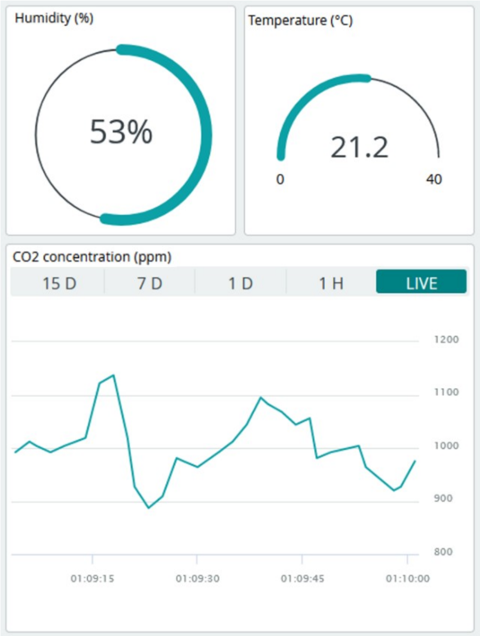

Fig. 14. KPI Indicators of the Cloud Interface.

Fig. 15. View of the Cardboard Box where the Prototype was Tested.

made in the corners to hold the extractor with screws and washers. This extractor will circulate the air from the inside to the outside of the box when the CO_2 levels are not within the allowed ranges. One type of exhaust fan that should be used in a real room is the AC180 model from the Broan brand, which works at 200 VAC 50Hz. In addition, it consumes 18W of power with an extraction capacity of 163 m3 / h and a noise level of 45 Db, being indicated for residential environments such as rooms, offices and classrooms. In a study conducted in a city in India (Durgapur), 6 conventional ”cooler” type air extractors were used to ventilate the CO_2 produced in the small environment [8]. Also, in an office space in the same country, generic mechanical ventilation was used, producing a lot of noise [18], as well as a conventional extractor that was activated when the carbon dioxide limits were exceeded [19].

Fig. 16. Hole for Extractor Installation.

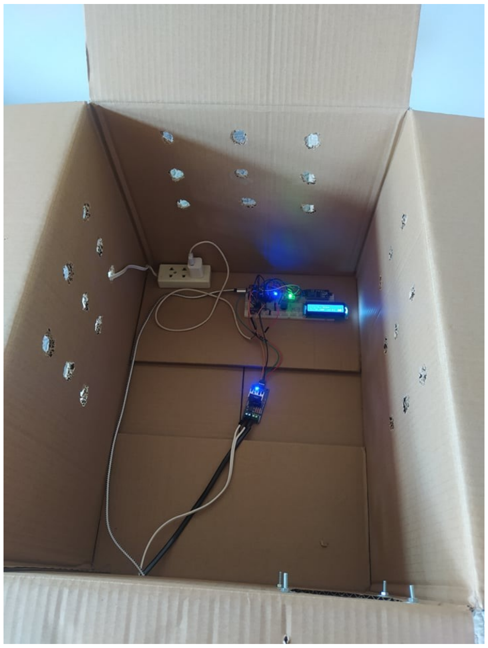

Fig. 17. Distribution of the Components within the Cardboard Box.

It can be seen in Fig. 17 that inside the box the breadboard was placed with the different components that intervene in the system, such as the NodeMCU development board, the CO_2 sensor, the temperature and humidity sensor, the LEDs and the screen. LCD coupled to its I2C module. The LCD screen and its module are powered with 5V DC through an adapted cell phone charger, the Node MCU, through a microUSB cable connected to the laptop and the other components use 3V DC provided by the development board. In the middle part of the box it can be seen the dimmer that will function as a pre-actuator, regulating the power delivered and enabling the connection between the control stage led by the NodeMCU and the power stage where the air extractor is located.

Fig. 18 shows the local display stage made up of the 16x2 LCD screen, which provides us with information about the values obtained from the CO_2 concentration through the CSS811 sensor in ppm measurements, and the temperature and relative humidity through the DHT11 sensor in ° C and % measurements, respectively.

In Fig. 19, we roughly mimic the CO_2 exhaled by people through smoke generated by burning paper in order to perform the tests. A quarter of rolled paper is set on fire and immediately placed inside the box on a metal container, to finally close it. The exhaust fan would be located in a real environment at least 2.3 meters from the ground, embedded in the wall. In the same way, the prototype that contains the CO2 sensor must be mounted on the wall with the correct orientation, because CO_2

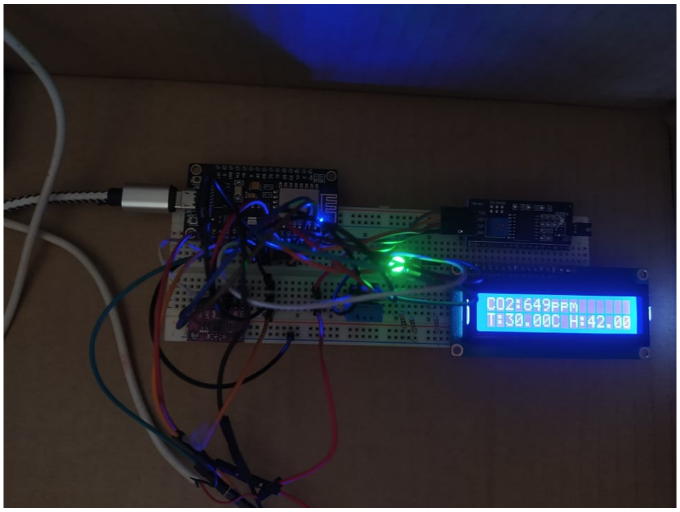

Fig. 18. Local Display Stage.

Fig. 19. CO_2 Generation within the Cardboard Box.

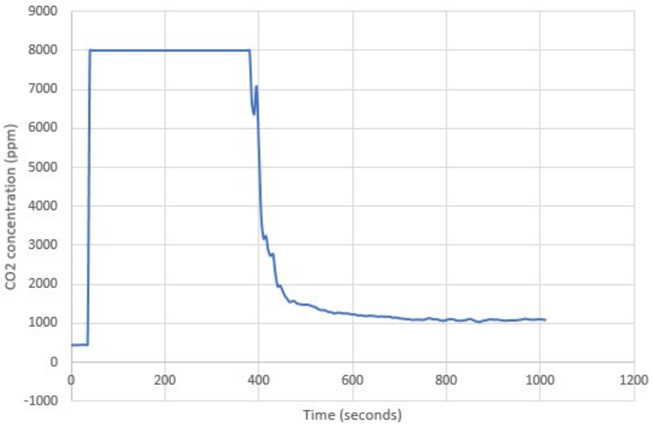

Fig. 20. Test Result 1.

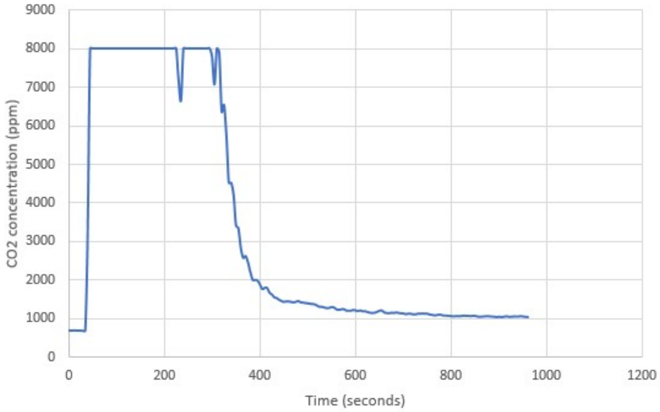

Fig. 21. Test Result 2.

is denser than air, it tends to fall to the ground and with this it would absorb the CCS 811 sensor located at the interior of the structure, which has ventilation grills that will allow the access of this gas. A research work has used the MQ135 sensor to measure the CO_2 concentration and have located this at ground level [12]. Also, in a study in India, the MQ2 gas sensor is used interconnected with Arduino and installed on top of a desk [20]. Similarly in another work, an all-in-one prototype is designed, which is installed on the wall [17].

Fig. 20 shows the result of test 1 represented with a trend graph of CO_2 concentration (ppm) vs. time (seconds), sampled in 5 second intervals. At the beginning, an establishment is observed at approximately 8000 ppm, since it was the initial moment where the smoke was generated and accumulated. Also, it should be noted that an important factor is the size of the environment since, being a small box, the smoke generates a CO_2 concentration inside the box much higher than in a natural and conventional scenario. After some time, a decrease in the CO_2 concentration occurs as a result of the action of the air extractor, thus achieving an approximate establishment of 1000 ppm after 800 seconds.

In Fig. 21 the result of test 2 is shown, in addition to the initial establishment period at 8000 ppm, some downward peaks are observed since being a non-natural environment and only simulated, the generated CO_2 conditions are not constant, as if they would be in a traditional environment. Despite this, in general a similar behavior is observed with respect to the results of test 1, stabilizing at approximately 1000 ppm after 800 seconds, thus generating a clean and safe environment. In both tests carried out, the correct extraction of carbon dioxide inside the box can be observed, through the exponential decay of its concentration seen in both graphs. This behavior is repeated in some studies carried out in Italy [21] and the United States [22] inside classrooms, varying the number of people and ventilation elements. This was also observed in an investigation conducted in two laboratories in Indonesia [23].

In Fig. 22 the remote viewing stage is shown through the free Arduino IoT Cloud platform that can be monitored through the web or its free software for Android and iOS.

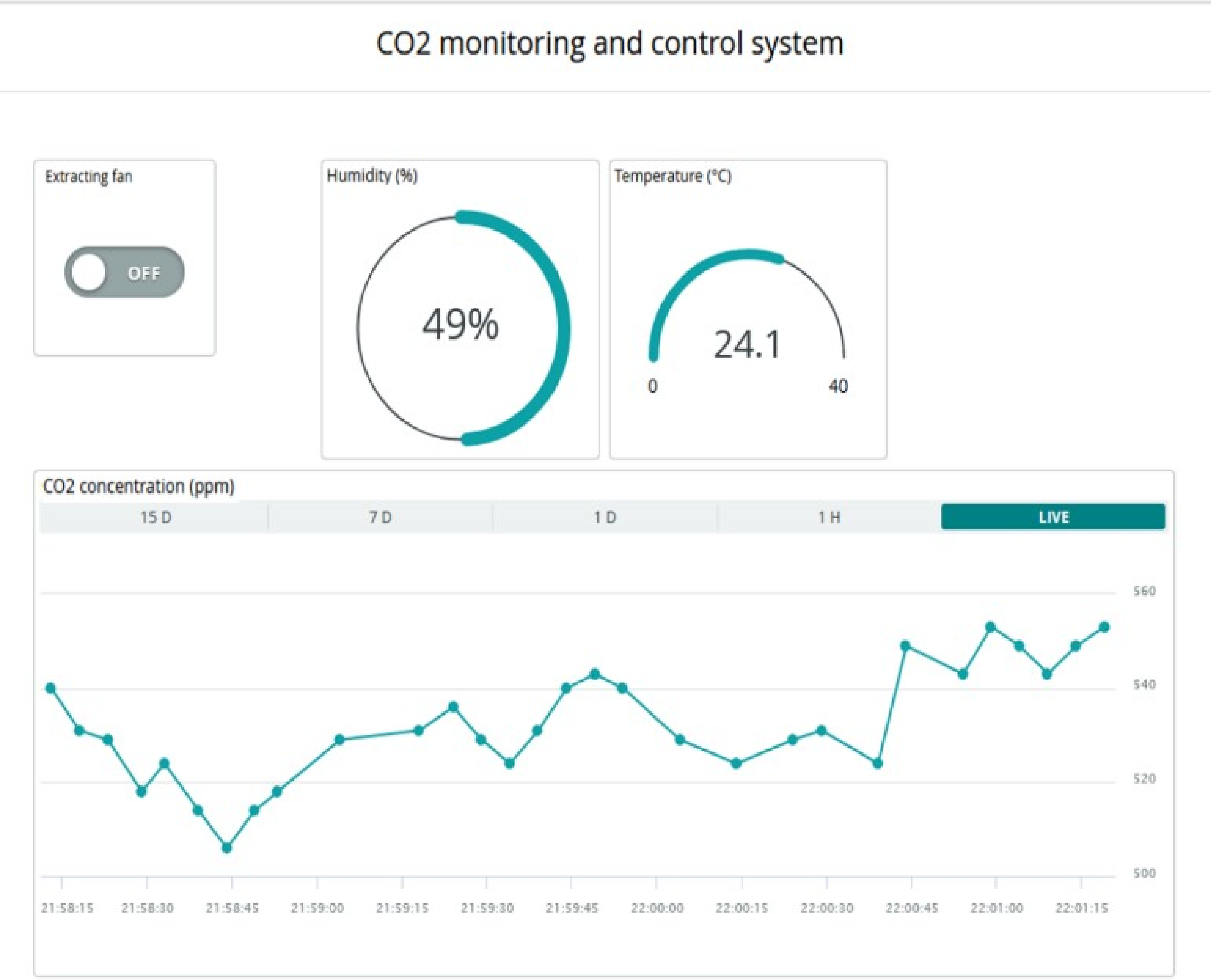

Fig. 22. Remote Viewing Stage.

In either of these two media, KPI indicators for humidity, temperature and CO_2 concentration are displayed in real time with a history of up to 2 days.

IV. CONCLUSION

In the present research work, a monitoring and control system of CO_2 concentration in closed rooms has been developed using low-cost components and a free software application to view the data remotely through smartphones, laptops and desktop computers. The results demonstrate its effectiveness compared to other studies, since after approximately 800 seconds of having detected the high levels of CO_2 concentration, it reaches adequate levels, less than 1000 ppm, thus producing a healthy area for the exchange of air of the people who inhabit it. The finished prototype would be located on the side of the room for the correct detection of the parameters described above.

As a future work, it is suggested that the development of the prototype be located within a structure with a degree of protection IP (Ingress Protection), with the aim of resisting dust and humidity found in the environment. Likewise, it is recommended to use CO_2 sensors of the NDIR (Non Dispersive Infrared Detector) type, since they are more accurate for gas detection, easier to calibrate and have minimal error percentages. Take into account the number of occupants and the volume of the room, since the precision of the sensors to be used and the number of air extractors to install depends on this. Finally, to obtain accurate measurements it is recommended to install the structure approximately 1 meter from the ground.

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