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An IoT measurement system for a tailored monitoring of CO_2 and total volatile organic compounds inside face masks

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ABSTRACT
This paper proposes an innovative IoT-based system for monitoring air quality inside protective equipment such as FFP2 masks, which have become more widespread due to the COVID-19 pandemic. The system aims to provide diagnostic elements to specialist doctors and suggest a healthier use of the mask by monitoring the concentration of pollutants. The system aggregates data over a 15-minute window and calculates average values for each measured parameter, comparing them with reference thresholds to suggest removing the mask if necessary. An innovative aspect is personalized monitoring of exhaled breath, specifically Volatile Organic Compounds (VOCs), providing a customized and reliable information framework for doctors. This is possible thanks to the integration of removable memories, inside which the user's personal information and metrological characteristics of the system are stored in a standardized form. The proposed platform is accessible to both users and doctors, enabling early diagnosis by providing a complete picture of the patient's specific condition. This solution can have a strong impact on daily life and well-being, especially for diseases that increase the presence of certain compounds in the exhaled breath.

Section: RESEARCH PAPER

Keywords: Air quality; face mask; TVOC; COVID19

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1. INTRODUCTION

After the declaration of COVID-19 as a global pandemic, multiple scientific research publications, acknowledge that SARS-CoV-2 is mainly transmitted from human to human through close contacts, airborne respiratory droplets, aerosols and contaminated surfaces [1]-[3]. Since March 2020 several countermeasures have been taken by the national governments to limit the pandemic spread, whose impact has been devastating in terms of human lives [4]. These countermeasures include restrictive measures to limit interpersonal contacts and the use of personal protective equipment (PPE), i.e., face masks. The introduction of the new mRNA COVID-19 vaccines strongly reduced morbidity and mortality, anyhow they were not enough to prevent the spread of new Sars-Cov-2 variants and to fully protect the groups of people most at risk. For this reason, the use of face masks and social distancing are still highly recommended, mainly in those areas with high viral spread [5], [6]. In this context, the use of sensors and the integration of Internet of Things (IoT), can lead to a more efficient and smart usage of PPE, allowing a continuous monitoring of the microenvironment inside them. Several studies assess the importance of monitoring air quality in order to reduce exposure to some pollutants that, over time, can increase the risk of psycho-physical discomfort, which often leads to devastating effects on the human organism [7]-[11]. PPEs filter the air in both directions (inhaled and exhaled), creating a microenvironment which has higher temperature and humidity than the external environment [12]. Moreover, with the use of face masks, it is observed a substantial increase in inhaled CO_2 concentration, also known as CO_2 rebreathing [13]-[15]. Several studies demonstrated that CO_2 accumulation in the mask microenvironment varies in function of breath rate and intensity. It was demonstrated that the increase in CO_2 concentration ranged from 1.5 % at rest, during speech, or at low work rates, up to 3.5 % during low-intensity exercise, which is well beyond the expected in atmospheric air (~0.04 %) [11], [16]. Several studies have also analysed the impact of PPE usage during physical exercise [17]-[19]. As stated in [20]: *"even though in healthy populations, the potentially life-saving benefits of wearing facemasks seem to outweigh the documented adverse effects, there seems to be widespread* *agreement on the increased breathing resistance, CO_2 rebreathing and decreased inhaled O_2 concentration caused by the use of facemasks".* In this context, a real-time monitoring of the air quality inside the face mask can help assessing both potential risks for health [20] and the integrity of the mask itself [21]. This is possible nowadays thanks to the technological development, which has allowed the realization of new thin and light sensors used in wearable devices in many medical applications [22]-[27].

Such a solution can help in finding a good trade-off between the mitigation of infection transmission risk and minimization of potential harmful effects due to CO_2 rebreathing, in particular in those contexts, like hospitals, pharmacies, classrooms and workplaces, where face masks are usually worn for many hours.

In addition, the integration of sensors and the monitoring of the microenvironment inside the face mask may give important information on the health status of the person who wear it. In particular, a high concentration of some substances, mainly VOCs, in exhaled breath, may relate to an increase in oxidative stress and many potential health problems, such as chronic inflammation [28], hypoxia in Multi Chemical Sensitivity (MCS) [29] and even COVID-19 [30]. As said in [31] the main techniques used to detect biomarkers in exhaled breath are based either on chromatography and spectroscopy, which is used mainly in laboratory, or on bioelectric MOS sensors. Using these techniques, it is possible to detect and isolate some specific types of VOCs. Nowadays it is known that breath contains more than 3500 types of VOCs [32] and some of these are particularly related to some specific health issues, such as ammonia, which is related to renal failure, liver dysfunction and cirrhosis, Acetone and Isoprene to diabetes and hypercholesterolemia, ethane and pentane to GI diseases and asthma, aldehydes to cancer and neurological disease. Many other types of VOCs are related to specific issues, and many are still under investigation in order to find if there is a correlation with specific health diseases. In this specific context, with the work presented in this paper, the authors aim to propose a tool for monitoring the air quality within the PPE, which allows, albeit without making a diagnosis, to give information indicative of the patient's state of health, based on breath analysis. In particular, the proposed solution consists in an Internet of Things (IoT) face mask with integrated sensors for the monitoring of CO_2 and Total Volatile Organic Compounds (TVOC). The face mask is connected to a personal platform that allows to store all the information related to data monitoring over time and allows the physician to check the information relating their patients on their online medical record. Since the masks are approved for use for a few hours, typically 6-8, after which they should be changed, the proposed type of monitoring must provide for the re-configurability of the new masks. This is implemented in the proposed approach using removable memories, which contain all the information relating to the specific patient. In this way, the proposed solution relies on IoT to implement a tailored monitoring of the parameters of the patient in an Ambient Assisted Living application [33]-[35], both for prevention of possible health issues and for sharing data on his/her digital medical record.

2. METHODOLOGY

In this section the methodologies used to develop the proposed IoT face mask are explained. In detail the discussion is focused on the design of the monitoring system and the IoT tools. The proposed system relies on the integration of sensors inside the face mask to continuously monitor CO_2 and TVOC concentration in the mask microenvironment. In fact, as said in Section 1, monitoring the concentration of these two substances is important both for safety reasons, i.e., mitigation of potential harmful effects due to exposure to these substances, and for health monitoring, since TVOC concentration is related to many health issues.

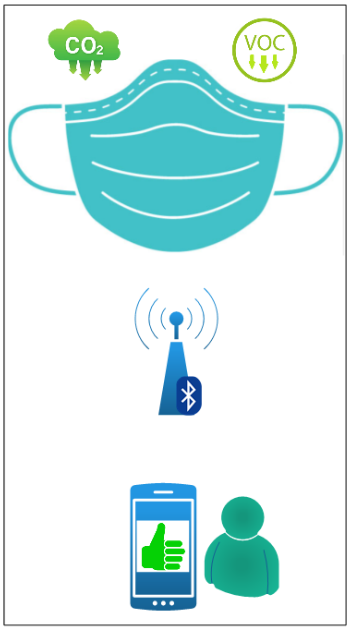

Figure 1. Project framework.

The system implements the framework shown in Figure 1, consisting of two sensors integrated into the mask, an embedded system for data processing and transmission and an application on a remote device that, together with a local LED advises the user in case of anomalies. Furthermore, the application, synchronized with a remote Smart Personal Platform, let the user to visualize the monitoring data and the trend over time.

A microcontroller (MCU) manages data acquisition phase and, using its internal ADC, samples CO_2 and TVOC sensors data over a 15-minute interval at a rate of 1 S/s (samples for second). Data acquired are stored in local memory and, after the time acquisition window has expired, the MCU averages all acquired samples, for each monitored parameter, and compares the average measured value with a reference threshold. The reference threshold is taken by the local regulations and indicates the maximum concentration of the pollutant, which is still considered safe, considering an exposure time of 15 minutes. If the result of the comparison is positive, even for one of the two substances, the microcontroller advises the user of a possible issue turning on a LED indicator and sending a warning to the software application on the remote device. After making the comparison with the threshold, the average measured value for each pollutant is sent to a remote device for data collection and visualization on the dedicated application and the internal memory of the MCU is erased and ready to store the new incoming samples.

The innovative feature of the proposed system is the monitoring of exhaled TVOC over time, which can provide valuable information about potential health issues. However, the presence of high VOC concentrations in exhaled air is not diagnostic by itself, and repeatable measurements must be taken in a controlled environment following standard protocols to compare them with reference thresholds. It is also important to consider that the normal range varies from person to person, making personalized monitoring necessary. Monitoring the trend of VOC concentration in exhaled breath over time is more important than a single comparison with a reference threshold. For daily use, replicating the measurement in standard conditions is not feasible, nor is it necessary since the objective is to monitor the user's breath parameters over the medium to long term and provide indications for further medical investigation if needed.

The personalization of the monitoring process takes place through the use of a removable memory support, that carries general information on the single user, on his/her health status, on average monitoring data over different periods of time and on normal reference range defined by the personal physician. Another removable memory support carries calibration and accuracy information on the specific measurement system, allowing to check if data are reliable or if a re-calibration of the system is necessary. Since common FFP2 face masks are approved for a use of maximum 6-8 hours, after this time of use, when the user needs to change the mask the entire system, joint with the two memory supports, are removed from the old mask and inserted in the new one to continue the monitoring with the new mask.

The microcontroller periodically performs a comparison between the average measured values stored in the memory and the reference range defined by the physician and stored in the same memory. If the measured values are out of range, it turns on a LED indicator to inform the user and give suggestion for a medical check.

For a better customization of the monitoring process, the use of memories integrates perfectly with the use of a remote smart personal platform, better described in Section 2.1, to which only the specialist doctor and the user have access. The smart personal platform is synchronized with the user software application. It is divided into two sections, one dedicated to the air quality monitoring for safety purposes and one dedicated to the automatic processing and custom visualization of exhaled breath parameters. It receives real-time data from the monitoring each 15 minutes, processes the new data, and stores them on the digital medical record of the patient.

The platform uses data to create hourly, daily, weekly and monthly statistics regarding the concentration of exhaled TVOC. These statistical data, each time they are re-processed, are sent back to the microcontroller, which stores them on the dedicated removable memory support. A block diagram of the described process is reported in Figure 2.

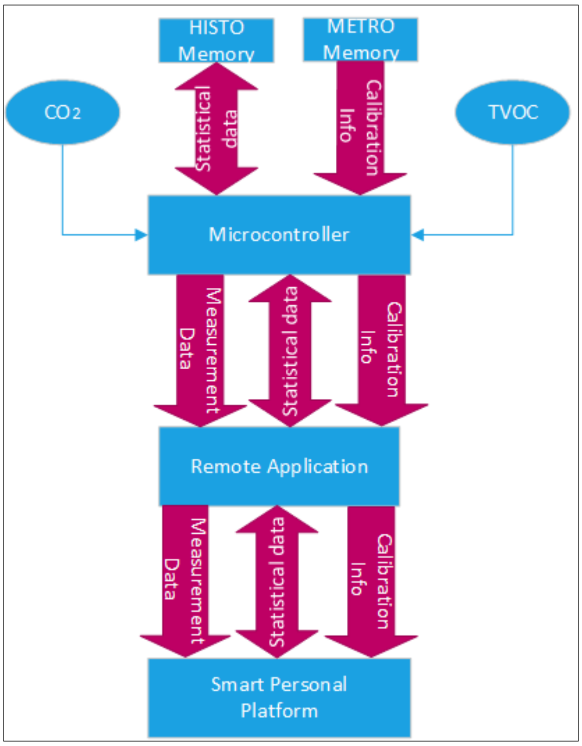

Figure 2. Data flow block diagram illustrating the flow of information in the system.

2.1. Smart Personal Platform

A key factor that has an important role in improving reliability in the detection of health risk situations, starting from the values of the parameters detected in the breath, is the knowledge of the history of the patient, i.e., what are typical values in known operating conditions. This, together with the knowledge of a reference range determined by the personal physician and fitted to the patient allows a prompt identification of any deviations from standard conditions.

Therefore, as said above, in order to customize the monitoring system, it becomes essential to integrate memory devices to save personal information useful for assessing the state of breath, the history of previous evaluations and the reference range determined by the specialist doctor.

In order to implement an automated access to this information, it was decided to implement two Transducers Electronic Data Sheets (TEDS) that are intended to allow access in a standardized format, according to the indications contained in the IEEE 1451 standard, thus facilitating the automatic configuration of the system. This reduces configuration time and allows metrological information to be integrated into data processing, reduces the possibility of error related to manual entry and improves traceability by linking all meta-information to the specific user.

TEDS can be loaded into the system at start stage or on request.

In the proposed IoT face mask, the presence of this standard data structure allows to access historical information in an easy way and to fit the monitoring system on the specific user.

The implemented Smart Personal Platform, synchronized with the software application, can access two TEDS where, as seen in Figure 3, personal data (HISTO) and sensor-related measurement uncertainty (METRO) information are stored and accessible.

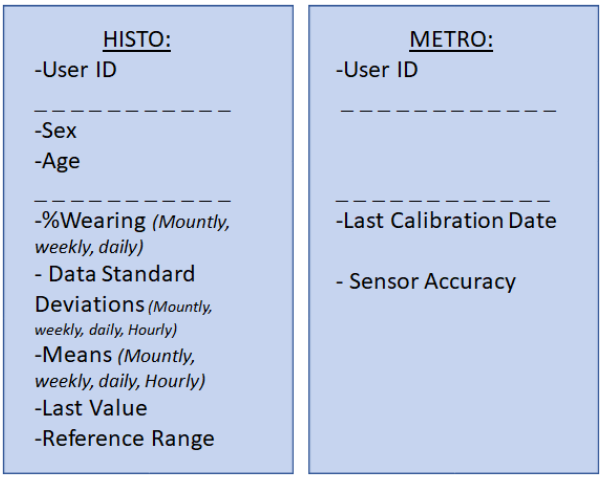

Figure 3. Parameters stored in HISTO and METRO.

HISTO allows the system to adapt the processing algorithm to the specific patient being monitored, it must be patient-specific and updated whenever a new assessment is made. Before applying the algorithm for the evaluation of breath, the platform accesses the memory to acquire the statistics of some predefined intervals (mean and standard deviation) and the reference range defined by the specialist doctor. Using non-volatile memory offers a simple solution to store patient data and to tailor the assessment made by the algorithm, by providing a comparison baseline for each new assessment. Personal information such as: User ID, age, sex, statistical data calculated on previous time frames (monthly, weekly, daily or hourly), average percentage of hours of use, presence of past specific diseases that affect breath and reference normal range for TVOC concentration in breath (assessed by the doctor), are all stored in HISTO. Using the stored information, the system facilitates the reading of the measured data. In this way, abnormal breath characteristics or patient-specific pathologies are considered during the evaluation of acquired data, allowing to reduce the occurrence of false positive detections and helping the specialist to have a complete picture of the available information.

METRO contains information related to the measurement uncertainty of the sensor, because data reliability is of primary importance when dealing with issues related to personal health and safety. The measurement system must be the most accurate and reliable possible. In order to achieve this objective, it is always necessary to consider the calibration intervals, after which the metrological characteristics of the sensor are no longer guaranteed, and a new calibration must be carried out. Once a day, the system evaluates whether or not the time suggested for the next calibration has elapsed and, if necessary, informs the user of the need for a technical intervention. The system will continue to operate, but the presence of the alert will be an element to be evaluated in presence of non-normal values, as they could be linked to a drift in sensor performance.

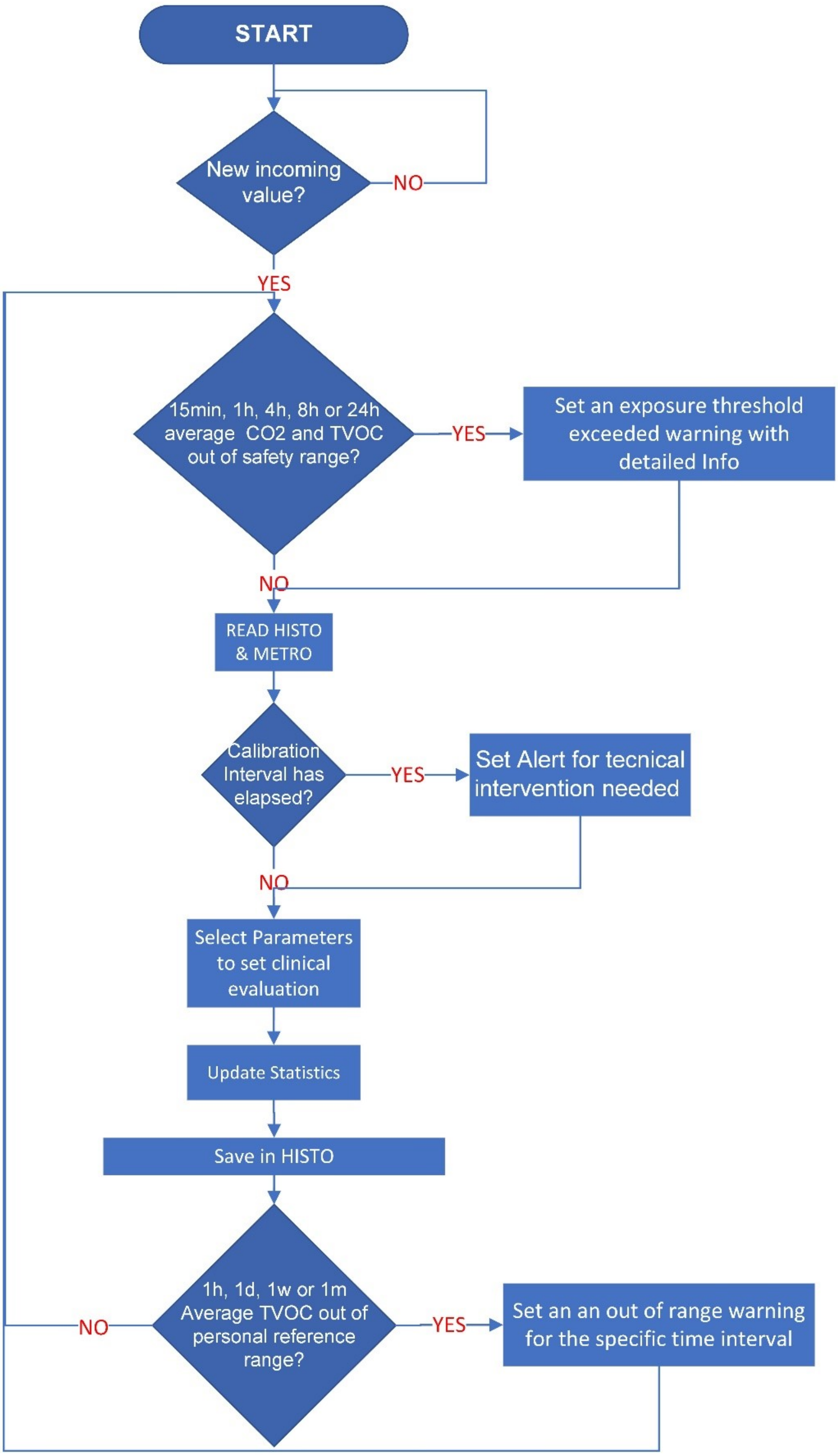

Figure 4. Smart Personal Platform Algorithm.

All data stored into TEDS are accessible from the data analysis platform, which, by combining that information, performs a tailored processing and is able to determine if the average TVOC monitored in exhaled breath, over pre-set time windows, is in or out of reference range. Furthermore, the platform allows user to plot a graphical representation of the raw data and of the trend line, obtained applying regression techniques.

Every time the platform receives a new data from the IoT mask stores it in a personal medical record, which can be accessed from the specialist. The platform algorithm, whose data flow is shown in Figure 4, processes each new received value, updating the hourly, daily, weekly and monthly statistics. After that, it verifies if the average measured TVOC in these time

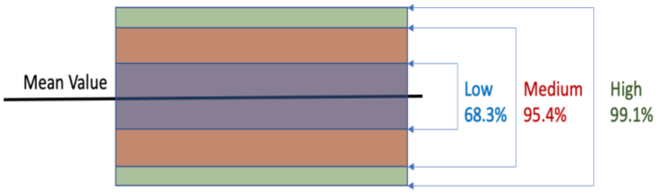

Figure 5. Impact of coverage factor on tolerance band around mean value.

intervals is within the reference range indicated by the specialist doctor and stored in the HISTO memory and, if it is not the case, turns on a LED on the platform, specific for each time interval, to advise the user that the measured values are out of range. The updated statistics, once calculated, are sent back to the IoT mask to be overwritten in the HISTO memory.

The platform allows the user and the specialist doctor, who has full access to the platform, to plot raw measurement data over a selectable time interval and to trace a regression line in order to show the trend over time.

Furthermore, the platform allows to show on the graph the reference band indicated by the doctor and the average band where the measured data of the patient fall. The last one is identified as the average measured value for the selected interval plus or minus the corresponding standard deviation multiplied for the coverage factor, that is simplified for selection with a simplified label for the user (Low, Medium, High). As shown in Figure 5, “Low” indicates the choice of a coverage factor equal to one, which identifies an interval around the average value, where there is approximately 68.3 % probability that a new measured data will fall, Medium corresponds to a coverage factor of two, equivalent to 95.4 % probability and High corresponds to a coverage factor of 3, which identifies an interval in which 99.7 % of the measured data will fall, in the absence of anomalies. The user, normally a doctor specialized in respiratory diseases, can obtain different informations by varying these parameters. In fact, based on the choice of the coverage factor, any positioning outside the so-called average range will have a different weight.

The graphical visualization of the data, in this way, let the doctor to see if the measurements, in the visualization interval, are compliant or not with the reference range, if there is a drift over time and what is the slope of the regression line and finally to determine the number of occurrences in which the measured value falls out of the average band (considering different coverage factors).

The platform is also accessible to the patient, who can see his/her monitoring data and eventual warnings that can advise for a medical check.

3. RESULTS

To test the proposed monitoring approach, a first prototype of the measurement system, described in Section 2 has been realized and tested with FFP2 face masks. The prototype, shown in Figure 6, is still a preliminary version and its aim is only to test the functionality of the proposed method. CO_2 and TVOC sensors, whose characteristics are described in Table 1, have been integrated into the face mask making a little cut on the cloth. After introducing the sensors, the cut was

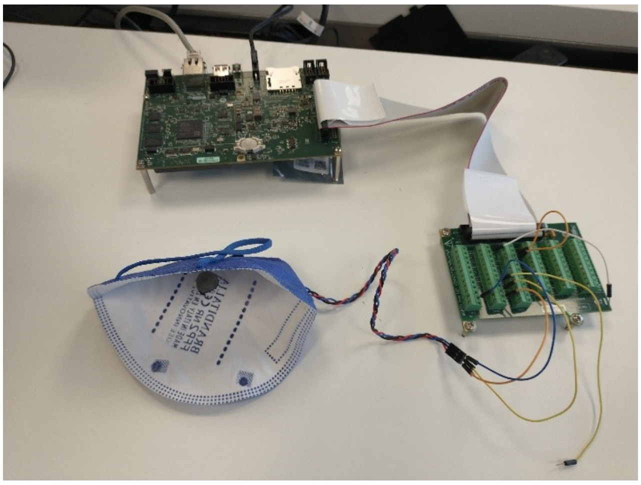

Figure 6. Prototype of the IoT face mask.

Table 1. Sensor Characteristics.

Sensor	Range	Accuracy
CO_2 in ppm	0 – 40000	± (40 + 5 % of reading)
VOC in ppb	0 – 60000	± 15 % of reading

stitched up and closed with hot glue to restore the original insulation. The sensors are externally wired to a NI RIO acquisition board, which acquires measurement data and implements, on board, the entire monitoring, and control station described in Section 2. The Smart Personal Platform, described in Section 2.1, has been realized in LabVIEW and is reachable through the web by acceding the remote application web page, as shown in Figure 7. All the monitoring data are also loaded to a personal FTP folder, which can be remotely acceded by both the user and the personal physician.

As it can be seen in Figure 7, the user interface of the web application is divided in three panels. The first panel reports the personal information of the user, taken from HISTO and METRO; the second panel shows a series of indicators that warn the user if the average TVOC measured in the last 60 minutes, 24 hours, 7 days or the last month are above a certain tolerance band defined by the physician for the specific user. Furthermore, it allows the user and the physician to graphically show the TVOC measured points over a selectable time interval and to

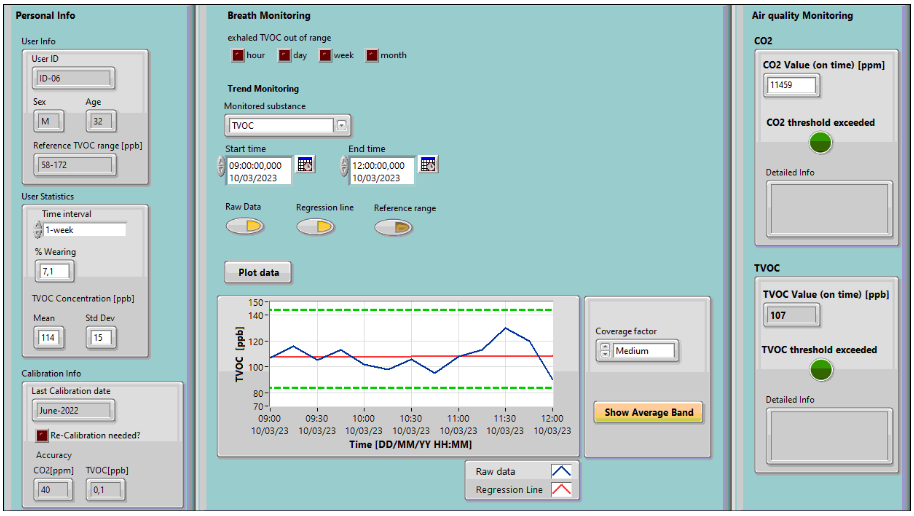

Figure 7. Graphical Interface of the Personal Smart Platform application.

trace a regression line implementing a best linear fit function. The information so obtained, in particular the slope of the regression line can give the physician important information on how the exhaled TVOC has changed over the selected time interval. In the same graph it is possible also to graphically show both the limits of the reference range defined by the doctor, and the tolerance band around the average measured value, as defined in section 2.1. In this way, the doctor observing the data can easily assess whether the parameters are out of the normal range or the usual range and, if so, to quantify their extent. Furthermore, in this last case, he/she can easily assess whether it is an isolated phenomenon or whether it is part of a process to be observed more carefully.

A third panel is dedicated to the monitoring of air quality levels for safety purposes, verifies whether the monitored values of CO_2 and TVOC are higher than the reference thresholds established by the regulations and, in that case, warns the user of the problem, suggesting, if possible, to go outdoor and remove the mask.

Ten specimens of the described prototype have been realized and the system was tested on 10 healthy volunteers, 5 males and 5 females, aged between 23 and 35 years over a period of one month. The monitoring was carried out inside the Electric and Electronic Measurement laboratory of the University “Mediterranea” of Reggio Calabria and each day included a monitoring interval of 4 hours. Since the face masks are approved for a use of 4-6 hours, at the end of each day they were substituted with new ones. The results obtained from the monitoring campaign over the period of one month are summarized in Table 2, which reports for each of the 10 volunteers the average CO_2 and TVOC measured values and their standard deviation.

As you can see in Table 2, the average value of CO_2 measured inside face masks, in all cases, is not far from the safety thresholds defined by the standard regulations in EU, which are 15.000 ppm for an exposure time of 15 minutes and 5000 ppm for an exposure time of 8h. During the monitoring campaign the 15 minutes threshold has never been reached, and the 8h threshold could not be considered, since the monitoring interval is 4 hours per day. Anyhow considering a conservative threshold of 10000 ppm for a period of 4 hours, after this time of use, in almost all cases the system turns on the low air quality warning indicator. As it can be seen CO_2 measurements present also a high standard deviation, which, as the reader can see in Figure 8, is due to a drift in CO_2 concentration inside the mask over the time of use, mainly due to the deterioration of the face mask.

Table 2. Results obtained from one month trial.

Sex	Age	Average CO2 in ppm	CO2 StdDev in ppm	Average TVOC in ppb	TVOC StdDev in ppb
F	23	9599	1156	85	22
F	23	9780	1132	82	23
M	24	10165	1125	100	23
M	23	9130	1210	115	43
F	24	10243	1154	102	23
M	32	10341	1140	115	19
M	31	9136	1132	82	20
F	35	9352	1208	82	21
F	25	9196	1176	81	20
M	28	9656	1147	81	21

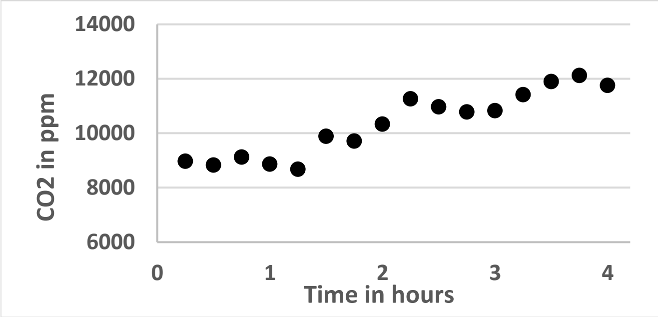

Figure 8. CO_2 trend over 4 hours of use.

For what concerns TVOC measurements no situations of particular relevance were recorded, and the data monitored was almost constant over time. In only one case, a daily variation of expired TVOC deviated from the mean value recorded up to the moment by a value greater than three times the standard deviation. However, as can be seen in Figure 9, the phenomenon was episodic and did not impact the slope of the regression line, which is 0.11 ppb/day. In this case, since the phenomenon is episodic and there is no incremental trend in exhaled TVOC, it can be traced back to temporary situations or alimentary reasons.

To prove the algorithm functioning in detecting a deviation over the time periods defined before, a Montecarlo simulation was performed, obtaining 1000 possible random TVOC paths. The simulation was set to start from a TVOC value of 115 ppb, with an increment between each step chosen randomly from a Gaussian distribution centred in zero and with a standard deviation of 10 ppb. The reference range was set, in order that the algorithm can detect a potential anomaly if the average value of the first hour, day, week or month exceeds the average reference value for the same time interval by more than 3 times the standard deviation associated. The results obtained are summarized in Table 3.

Considering one case where the simulated exhaled TVOC over one month period goes out of range, it is shown in Figure 10 how the TVOC trend deviates over time, by observing the regression line, which in this case has a slope of 12.1 ppb/day. If a case like this would arise, the personal physician after a medical check can determine if the observed trend is indicative of a possible issue or not.

4. CONCLUSIONS

In conclusion, this work presents an innovative IoT measurement system integrated into PPEs to monitor air quality in the microenvironment inside them. The proposed system aims to provide an easy-to-use tool that signals the deterioration of air quality inside the mask in the presence of a high exposure risk to two specific pollutants, CO2 and TVOC. Additionally, the system can be used to monitor the user's health, as VOC concentration in exhaled air may be related to various health issues.

Table 3. Results of algorithm test using Montecarlo simulations.

Time interval	Number of TVOC paths	Number of detections above thresholds
1st hour	1000	0
1st day	1000	3
1st week	1000	158
1st month	1000	277

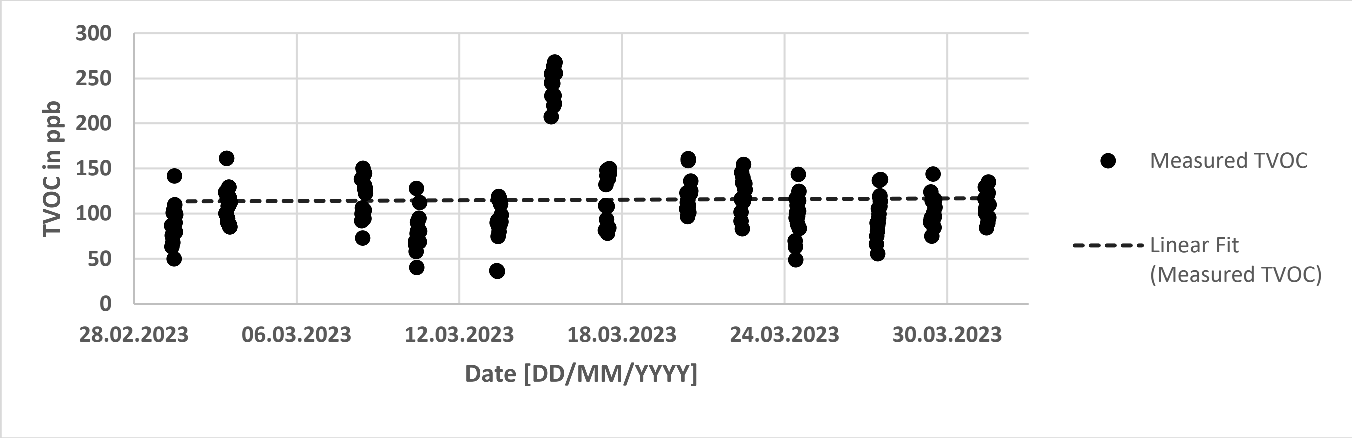

Figure 9. TVOC measurement data and regression line over one month for a 23 years old male volunteer.

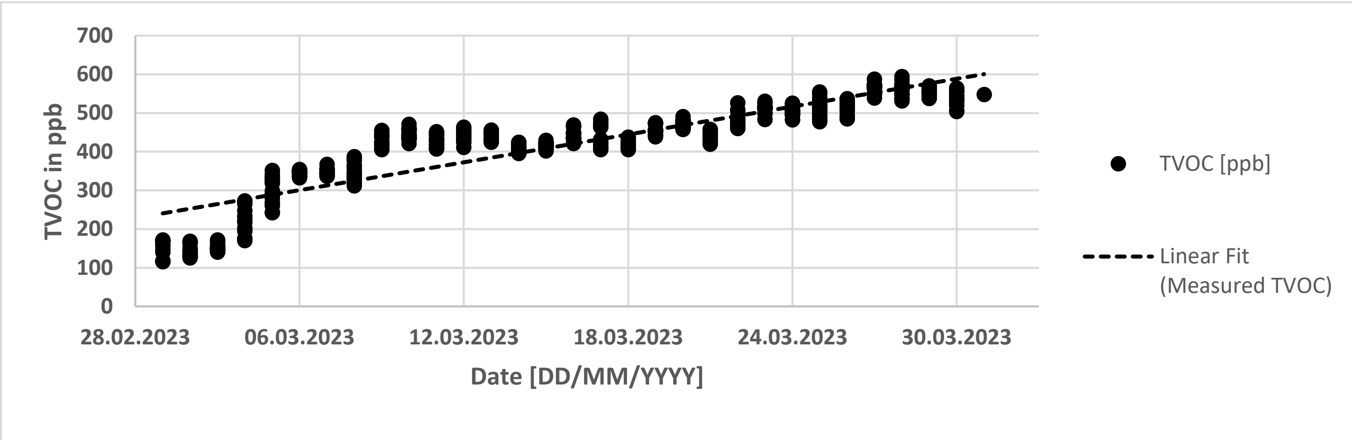

Figure 10. A TVOC path obtained from Montecarlo simulation.

The IoT mask becomes a highly personalized health-checking support tool, allowing the specialist doctor and the user to see any warnings and visualize both raw data and trends over selectable time intervals. To account for the variation in normal range among individuals, a standard format file containing personal information is used, and the sensors' calibration status is continuously checked to ensure the reliability of the collected data.

Ten prototypes were implemented using NI RIO acquisition boards and tested on 10 healthy volunteers for one month. The proposed algorithm's capability in detecting anomalies in 1000 random TVOC generated using Montecarlo simulations was also evaluated. The results show that after one hour, no detection above thresholds was reported, but after one day, three detections above thresholds were reported. After one week, 158 detections above thresholds were reported, and after one month, 277 detections above thresholds were reported.

The IoT mask proposed in this work is innovative compared to the state of the art since it becomes a personalized diagnostic support tool that can help obtain early diagnoses for disorders still difficult to identify through traditional protocols. Further developments may concern the engineering of the prototype to make it cheaper, lighter, smaller, and easily transportable from the old mask to the new one. With the level of technological advances in semiconductors and PCB printing, the proposed monitoring system can be implemented using thin film wearable and flexible sensors and chips that can be easily integrated within the mask.

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