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Development of a Low-Cost Device for Monitoring Ventilation Parameters (Temperature, Humidity and Pressure) in Underground Environments to Increase Operational Safety Using IoT

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Abstract: The important role of ventilation in underground mines is to ensure safety and adequate environmental conditions in all accessible areas of a mine. This research aims to develop low-cost solutions for monitoring ventilation parameters in underground mines using the Internet of Things (IoT). A comparison between standard measuring equipment and a new low-cost wearable monitoring device prototype was performed, and the variables measured in an underground mine were pressure, temperature, and relative humidity. The results in all surveys indicate that the wearable monitoring device prototype can properly be used for continuous monitoring of the underground environment. The standard measurement devices for underground mines should continuously be used by mining companies as requested by local legislation. The low-cost wearable monitoring device developed should be viewed as a redundant measurement device for operators' safety. The constant innovations in technology can support mining operators in anticipating problems, improving productivity, ensuring safety, and meeting standards at low investments.

Keywords: underground mine; wearable devices; safety; IoT; low-cost

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1. Introduction

Safety and health in underground mines are challenging issues in the mining industry [1]. The ventilation system implemented in the mine must meet the required standards and ensure the physical integrity of workers. The main circuit is responsible for bringing fresh air to the work fronts and removing contaminated air from these fronts. The secondary circuit aims to bring fresh or cooled air to the mining fronts [2–4]. No ventilation system can remain adequate indefinitely; every system requires monitoring and adjustments to continue to provide adequate ventilation [5].

Measurements related to the parameters presented are made normatively using equipment such as anemometers, thermometers, and gas detectors with the periodicity indicated in the standard. The proposed device makes it possible to obtain a greater number of data in smaller intervals, thus allowing the monitoring and control of these parameters. The determination of gas detectors is related to the material mined and the type of mining adopted, including mainly those related to oxygen and carbon dioxide. In addition to these gases, the underground atmosphere may contain small amounts of other gases such as methane (CH_4), nitrogen oxides (NO_X), non-oxidized and partially oxidized hydrocarbons, ammonia (NH_3), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), NO_X among others that must be investigated according to the mine profile to be monitored.

Technologies of production of hazardous gas sensors differ from each other both based on materials detecting concentrations of elements and chemical compounds as well as by different methods of physical quantity transduction [6]. The availability of fresh air in underground excavations stands out as the main control parameter, having a direct influence on other environmental parameters.

The cost of ventilation, the geometry of the considered mine, and the mining technology used make the ventilation process very difficult. Moreover, the local air quality may fluctuate and pose a threat to miners. Thus, portable, personal devices are required in order to inform miners about gas hazards. There are tools available on the market that meet certain requirements for that demanding environment. However, although these allow the storage of data collected during a shift, they do not allow basic analysis of the acquired data in an online mode. In addition, these solutions are extremely expensive, and it is impossible to equip all underground workers [7]. Controlling working environment conditions provides better safety conditions, contributing significantly to increasing productivity and, consequently, reducing mining operating costs. Excavations with insufficient ventilation usually carry high levels of contaminants and high temperatures.

Environmental aspects must always be analyzed and treated together, as one parameter influences the others [8]. Ventilation is the main factor controlling the conditions of an underground mine environment in terms of gas dilution and dust removal. Ventilation also contributes to the attenuation of excessive temperature and humidity, warranting a work environment that respects safety and health standards [2,3]. These atmospheric characteristics must be constantly monitored as they are continually renewed by the ventilation system [9].

The efficient monitoring of natural events that pose a safety risk to humans in underground mining environments can assist with improving the health and safety conditions in the environment. Such risks can emanate from rock movement due to stress, imbalances in temperature and ventilation, and smoke and air quality issues [10]. Therefore, the mining company must constantly analyze the variables that change the quality of the environment inside an underground mine and, thus, ensure adequate environmental conditions for human work, as well as local safety, in accordance with current regulations. Industry 4.0 has brought several new technologies and concepts to the industrial sector. The development of modern industry has had an enormous impact on technological progress in the field of sensor devices. Smart metering, big data analytics, and cloud computing can be applied in the mining industry, too. The unification of smart sensor networks and data handling for a better understanding of the environmental properties in underground conditions is now widely taken into account [11,12]. The enabling technologies for IoT (Internet of Things) have many challenges that are addressed continuously in academia and industry [13]. Consequently, new opportunities for improvement in the entire mining chain production have risen. Analysis of large amounts of data integrating different types of equipment using IoT and cloud computing are some of these new technologies explored by the mineral sector [14]. Stakeholders must manage many interconnected processes and data sets to ensure that an operation is sustainable [15].

The potential for innovations leads to a reduction in investment and operating costs associated with gains in safety and productivity. In mining, the application of IoT promises benefits such as an increase in the level of automation, improvements in production performance, and greater assertiveness in decision-making. The IoT integrates personnel positioning, dust control, gas monitoring, pressure monitoring, fan line monitoring, and other subsystems. The system automatically handles operational status and the need for safe production under the proper introduction of human factors, handles special events, and provides security for management decision support [16].

There are several IoT applications; however, service provisioning to the various IoT applications according to their demands has been quite difficult. IoT consumers typically require on-the-move applications that are continuously optimized, personalized, value-added, and autonomous. In the context of the mining industry, the mine sites are dynamic in nature, with various risks. For example, there is an alert for some accidents in the mine, so the IoT devices and systems should be flexible enough to adapt the changes according to the needs [13]. Today's availability of reliable instruments for measuring ventilation parameters, together with the increasing availability of computing resources, justifies the attention of companies in the sense of designing, in a more efficient way, their ventilation systems [17].

According to [18], a reduction in energy consumption can be achieved using Ventilation on Demand (VOD) which, in turn, demands a great deal of automation. Therefore, a substantial amount of research is needed to improve this field of knowledge to ensure better competence of the mining personnel to fulfill the requirements of ventilation. IoT manages to merge the real world and the technological world. It makes it possible to connect people, machines, and equipment, favoring interaction and making life more dynamic. In recent decades, there has been a significant increase in patent applications worldwide [19].

A company's capacity for innovation and sustainability is closely related to its investments in research and development (R&D) which play an important role in its competitive advantage [20]. The mining industry has constantly adopted new technologies and methodologies, seeking to reduce costs and increase productivity while warranting efficiency and maintaining high safety standards [21]. The research objective is to develop a low-cost device prototype to monitor ventilation parameters (temperature, relative humidity, and pressure) in underground environments. The monitoring of these parameters enables control and, therefore, greater operational safety. The specific objectives include the study of sensors and construction materials of the device, approach to invention notifications, and data analysis integrating different types of equipment using IoT and cloud computing, aiming at a better guideline for managerial decision-making. The invention notifications produced are the research contributions and show the possibility of increasing the underground mine operators' security using wearable technology with low investment.

2. Experimental

All the materials used to develop the wearable monitoring device prototype are specified. The survey and the data collected to compare its measurements with the standard measurements are detailed in the methods section. Additional information can be accessed in [17,22].

2.1. Materials

The wearable monitoring device prototype developed was mounted inside a custom plastic box produced in a 3D printer using PLA filament (biodegradable thermoplastic of natural origin and renewable sources, such as corn starch or sugar cane). The device weighs 150 g and is 77 mm wide, 96 mm long, and 32 mm high with the following components: Arduino Nano; card reader; microSD card; rechargeable battery with connector; temperature and humidity sensor (DHT11); pressure sensor (BMP280), gas sensor (MQ7); alarm sound; power button (on/off); 1 LED. According to the sensor manual, the measuring range of the DHT11 for humidity is from 20 to 95% RH and an accuracy of $\pm$ 5.0% RH. As for temperature, it measures ranges from 0 to 50 °C with an accuracy of $\pm$ 2 °C. BMP280. The pressure sensor has a measuring range of 300–1100 hPa with an accuracy of 0.06 hPa. MQ-7 for carbon monoxide gas detection, detection concentration 300–10,000 ppm, operating voltage 3–5 V, digital and analog output. Figure 1 identifies the location of sensors in the custom box.

The customized protective box can be adapted to fix the employee's outfit (wearable) with clips, elastic bands, tape, adhesive, and other options.

The advances in mobile computing and hardware designs have enabled the deployment of more efficient functionalities on mobile devices while these devices have become smaller and more compact. In underground mining environments, the low rate of mobile device usage is mainly caused by strict safety regulations [23].

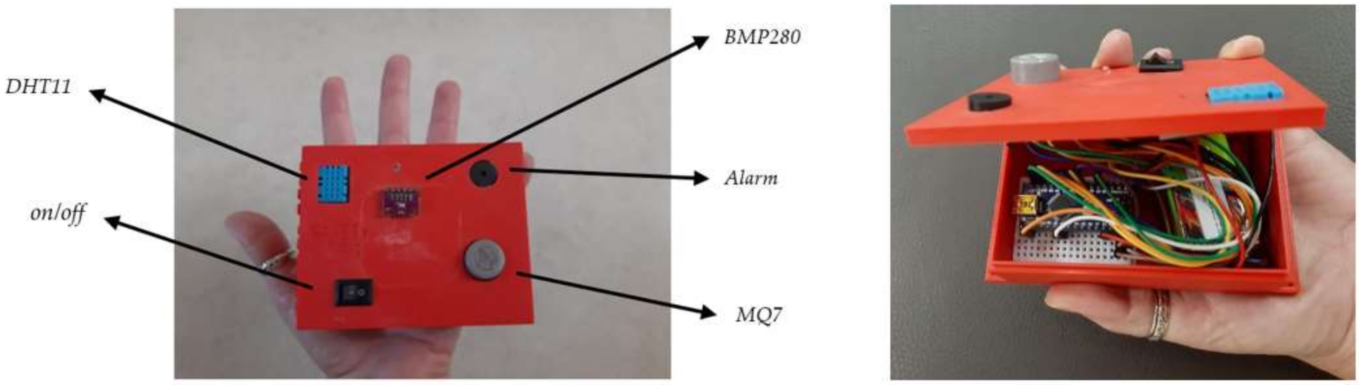

Figure 1. The wearable monitoring device prototype.

2.2. Methods

Measurements were made using a portable meteorology station (model Tesa WS1151) at five monitoring points in an underground mine to compare with the readings obtained by the low-cost wearable monitoring device prototype. The underground mining location is in Minas Gerais State, Brazil, and it has a current depth of 120 m and around 120 employees. The company's total production capacity is 80,000 tons/year of industrial minerals, destined to industries such as ceramics, paper and cellulose, paints, rubber, and plastics, among other applications. This mine operates with the chambers and pillars method, with main access by slope with slope and dimensions for the traffic of machinery and road equipment. Figure 2 shows the 3D underground mine with the location of the five monitoring points.

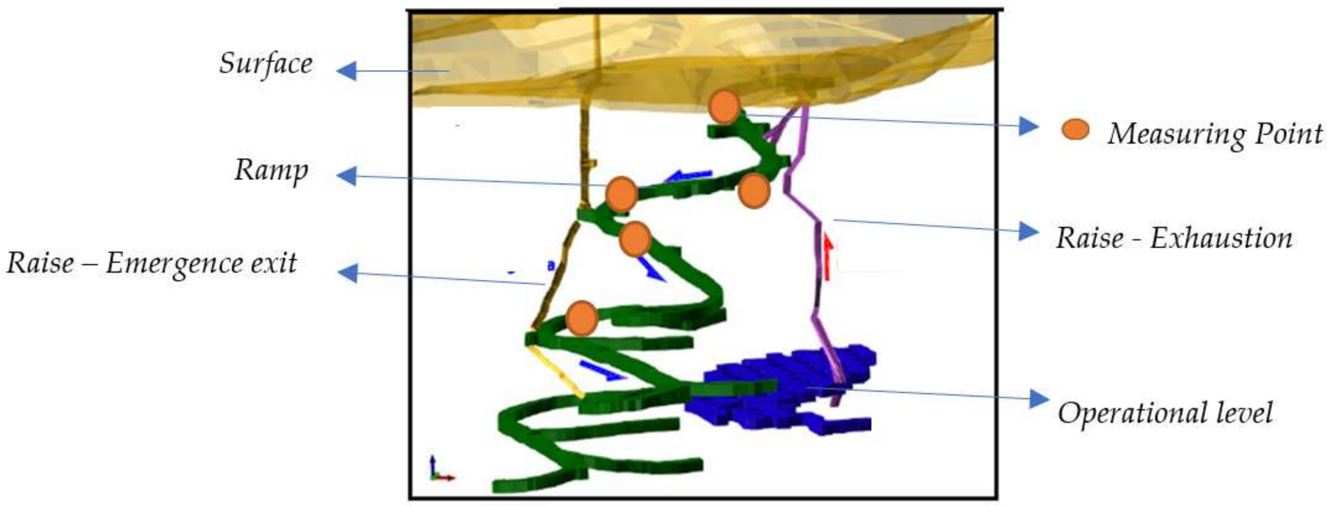

Figure 2. 3D underground mine map showing the monitoring points.

The measurement data obtained by the low-cost wearable monitoring device prototype were recorded on an SD card since there was no structure set up for the transmission of data in real time. The online transmission system in underground mines normally requires a greater investment.

A set of measures that includes continuous monitoring and recording allows, more accurately, the analysis of the ventilation system and the air quality in the underground mining environment. The Arduino is the microcontroller that receives the sensor readings and is programmed to sound an audible alarm if the parameters are outside the acceptable range defined by the company. Thus, this system allows preventive actions to ensure underground operational safety.

3. Results and Discussion

The wearable monitoring device prototype allows continuous readings and data transmission by monitoring the operating environment online. It enables better visualization of the entire ventilation process and greater control and operational safety by granting interventions at any time.

3.1. Field Measurements

Figure 3a,b shows the research team measuring ventilation parameters in the underground mine studied using standard equipment (portable meteorological station) and a low-cost wearable monitoring device prototype.

(**a**) (**b**)

Figure 3. Measurements in underground mine performed by the research team (Minas Gerais State, Brazil). (**a**) Underground mine entrance. (**b**) Inside the underground mine.

Table 1 presents the readings from the low-cost wearable device prototype and the portable meteorological station at five points along the underground mine. These measurement points are operationally routine and standardized by NR22—Brazil. Figure 2 shows the location schematically.

Table 1. Simple average of measured parameters in points 1 to 5.

Point	Meteorological Station			Wearable Monitoring Device		
	Relative Humidity	Temperature	Pressure	DTH11	BMP280	BMP280
	% RH	°C	hPa	RH%	°C	hPa
1	75	15.3	937.6	83.4	16.4	939.7
2	80	15.6	938.7	85.0	16.7	940.8
3	81	15.7	939.6	88.5	16.8	941.7
4	82	15.7	940.8	91.1	16.8	943.0
5	88	15.9	941.9	92.0	17.0	944.1

Figure 4 shows a comparison of the pressure parameter readings by the meteorological station and the BMP280 sensor installed on the low-cost wearable monitoring device prototype at points 1 to 5. The pressure increased at each point, and sensors tracked these differences. The pressure variation obtained during the entire journey was 2.1 to 2.2 hPa at the meteorological station and the sensor reading of the wearable monitoring device prototype. Once the differences between the measurements were almost constant, it was possible to apply a correction factor of 2 hPa in Arduino programming.

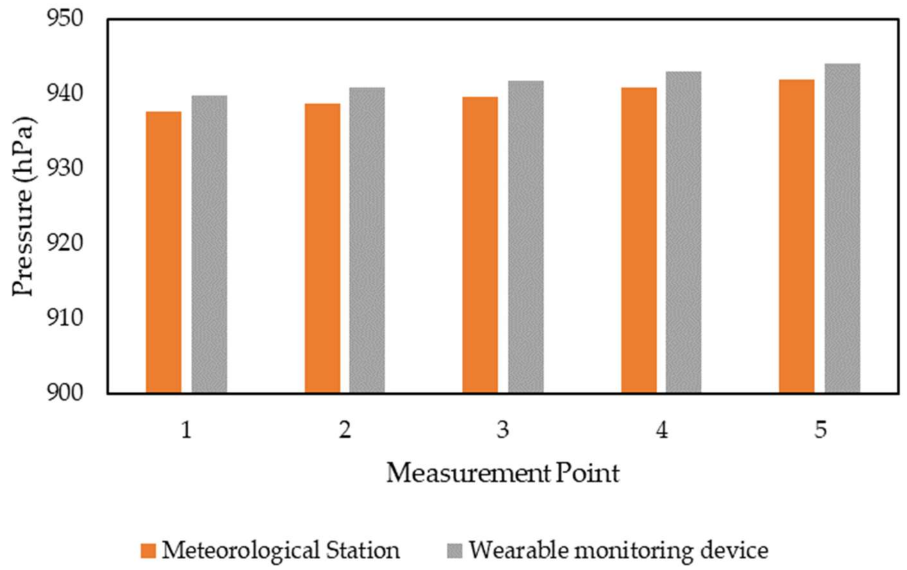

Figure 4. Pressure measurements comparison at points (1 to 5).

Figure 5 shows a comparison of the temperature parameter readings by the meteorological station and the BMP280 sensor installed on the low-cost wearable monitoring device prototype at points 1 to 5. Temperature measurements at all points in the underground mine were below 28.9 °C. The temperature in the mine studied is pleasant throughout the year, and there is no need for cooling systems, which would require high energy consumption to operate. The differences in the readings were 1.1 °C, which does not require a correction factor with programming due to the small variation. The problem of thermal comfort in underground mines involves not only heat sources but also mine conditioning, which includes relative humidity and air velocity in the excavations and accesses, and it must be analyzed.

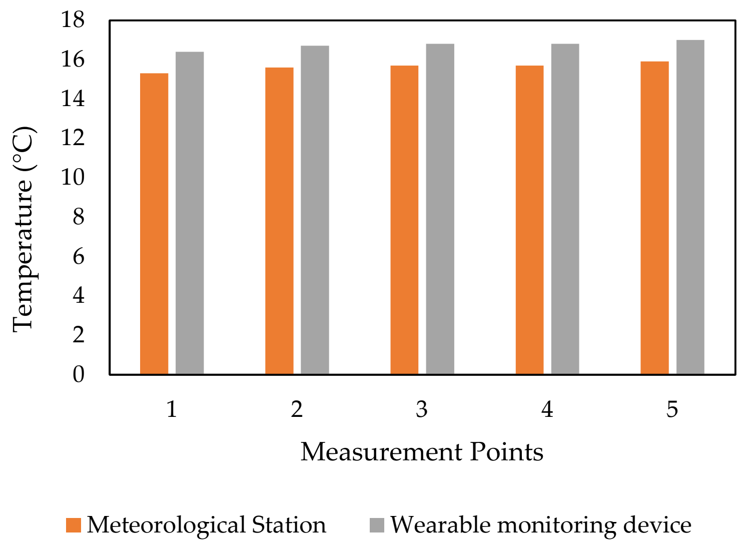

Figure 5. Temperature measurements comparison at points (1 to 5).

Figure 6 shows a comparison of the relative humidity parameter readings by the meteorological station and the DHT11 sensor installed on the low-cost wearable monitoring device prototype at points 1 to 5. There is a tendency for an increase in the relative humidity as the mine gets deeper, as evidenced by both measuring devices. The variation along the mine was around 13% at the meteorological station and 8.6% at the device sensor installed on the wearable monitoring device prototype. It is observed that the difference is greater in the first points, and the difference decreases with the deepening of the mine.

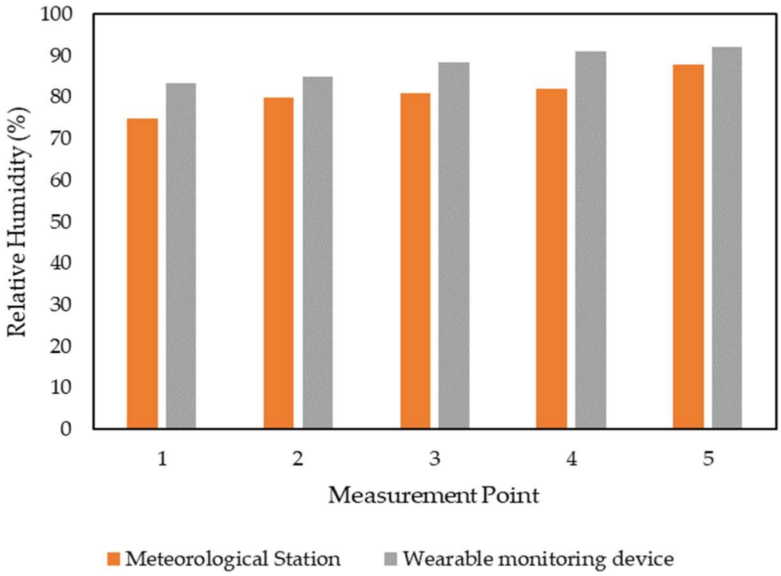

Figure 6. Relative humidity measurements comparison at points (1 to 5).

The results point to a correlation with the control data, and a correlation coefficient ϱ was, for all measurements: 0.885 (RH), 1 (temperature), 1 (for pressure). The difference in temperature recording at 1.1 °C and pressure at 2.1–2.2 hPa signals a systematic error and can be calibrated easily.

The measurements of the gas sensor (MQ7) presented inconsistent values. Other gas sensors should be tested in the future to assure reliable measurements of this important variable.

3.2. Costs

The unit cost of the devices varies according to the requirements needed. The entire wearable monitoring device prototype assembled had a cost of approximately USD 50.00.

The wearable device is light and can be worn in many variations, including on vests, belts, bracelets, or uniforms, thus providing greater versatility of installation according to individual comfort. Figure 7 presents suggestions of places for the use of wearable technology.

The customized box allows a tight seal avoiding damage to the electronic components. Its industrial design registration is found under the number BR 302021003203-1 [24].

3.3. Data Collection and Analytics

The device also uses a microSD card reader inside the case that allows recording the measured data and later downloading. It is considered an advantage as not all companies have a wi-fi network inside the mine. If the mine has a wi-fi network, the device can be connected to the existing controller for wi-fi network access, and then the data will be sent online to a control room, enabling online monitoring.

Figure 7. Fixing options for the wearable monitoring device prototype.

The microcontroller code is designed to:

- collect automatically environmental data, which can be upgraded according to sensor availability and company interest;
- transmit online to an external environment respecting the transmission technology available inside the mine and investments proposed by the company;
- store the data on a microSD card;
- schedule alarm activation if any parameter is outside the pre-established limits;
- automate the time-consuming data collection and recording of a ventilation process.

A website to display the data for further analysis was designed (Figure 8). The figure represents a web interface, viewing the readings online on any device through a responsive system. Responsive websites adapt the size of their pages (by changing the layout) to the size of the display screens, such as mobile and tablet screens. Its advantages derive from adapting to any tool that users are using to facilitate its visualization [25]. Figure 8 shows the computer screen and allows monitoring of sensors for individual and collective security depending on the location of the device. Computer programming is registered with the number N-PC-09-2021 [26]. The data can be presented in the form of tables and graphs, assisting the data analysis. This information will be used to verify if the underground environment control conditions are within the established limits and to trigger alarms if they exceed the preset values. Monitoring and assessment of underground conditions are necessary to identify potential hazards and prompt corrective measures. The fundamental basic inputs to be stored in the database are the ventilation map, the location of monitoring points, and limits required by the company for the parameters that will be monitored.

There are many possibilities for designing wearable or fixed devices according to the company's location, parameters to be read, infrastructure, and available technologies. Other adjustments can assist in the collection and analysis of online data or even the inclusion of specific sensors in each underground mine. In addition, the devices may vary to meet these company specifics:

- Mine typology: use of specific sensors whose availability and reliability must be verified in the market.
- Definition of parameter limits: the sensors may have to be switched depending on the current local legislation or even on the range requested by the company.
- Data transmission: depends on the conditions and availability of the existing, or to be installed, networks. The devices designed can adapt to any kind of data transmission, whether by broadband, wi-fi, point-to-point network, Bluetooth, or even cell phone signal. This is an essential factor of analysis to define the investment and the speed

required for data transmission from the interior of the mine to the surface. Optionally, the data can be recorded on a microSD card and not transmitted online.

- Device energy source: depending on the company's facilities, it may be connected to an on-grid power line or different types of batteries. The choice depends on the chosen frequency of the readings, the required autonomy, and the energy availability.
- Device casing: can be configured depending on the company's definition of the device's components and the installation location.
- Audible alarm: can be installed inside the mine and/or in the control room.
- Display: can be installed at each of the continuous monitoring points.
- Ventilation on Demand (VOD): if the company works with VOD, it is possible to program the microcontroller to control a fan, aiming at energy savings. For example, if the average value of the carbon monoxide concentration (indicated by one of the installed sensors) exceeds the established limit, the exhaust fan speed can be increased so that the gas concentration is diluted. In addition, energy savings can be achieved when fans supply air while preserving atmospheric conditions [18].

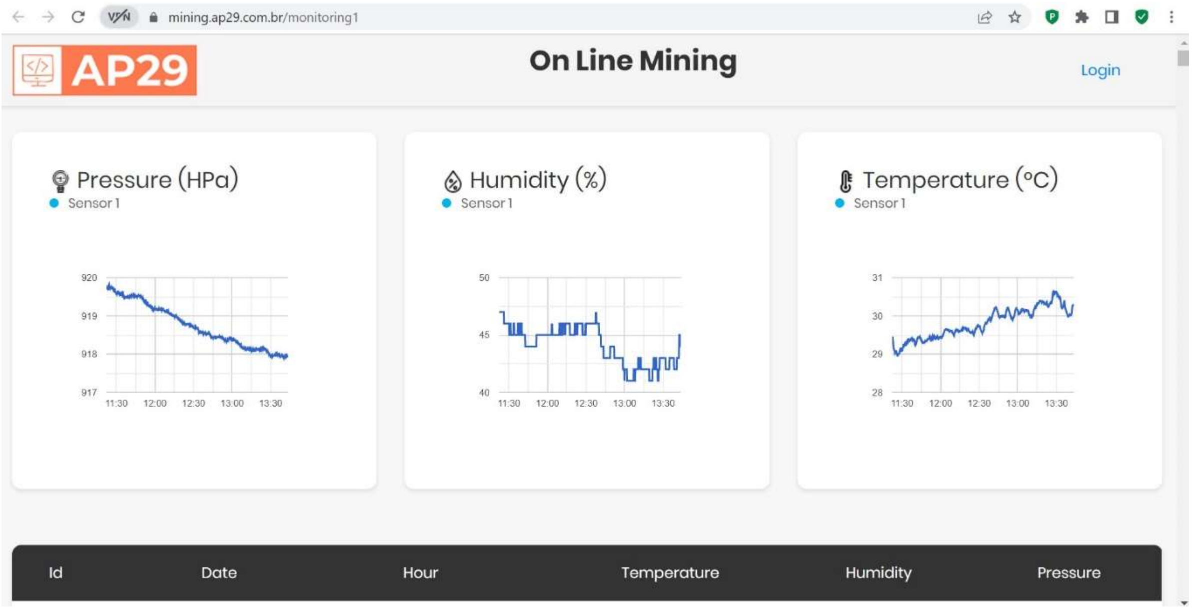

Figure 8. Website showing the measurement readings by the wearable monitoring device.

The devices must be repositioned periodically according to the mining activities' progress or a manager's determination.

4. Conclusions

The IoT is a source and enabler of industrial automation and opens possibilities for important insights applicable in several business areas. A low-cost wearable monitoring device was developed to work as a redundant measurement device for operators' safety in underground mines.

The designed low-cost wearable monitoring device prototype can be used in different configurations depending on the requirement of mining situations. Wearable technology is composed of smart devices that the user literally wears to obtain personal monitoring in the place where the user is located. Continuous monitoring increases the ability to collect and analyze the quantity and quality of data during mining activities. The low cost of the device (approximately USD 50.00) combined with the flexibility in use allows for a wider range of applications for small and large companies.

The determination of gas detectors is related to the material mined and the type of mining adopted. In addition to these gases, the underground atmosphere may contain small amounts of other gases; in accordance with the development of technology and the Internet of Things, the website and measuring system can be easily extended to test the conditions of other gases such as CO, NO_X, SO_X, and CH_4. The authors recommend future work consisting of new surveys to measure other gas concentrations and a long period of monitoring using the low-cost wearable monitoring device prototype for as many operators as possible to collect big data and improve the system functionalities.

5. Patents

Industrial design registration certificate: Configuration applied to/in mobile monitoring device, Depositor: Federal University of Minas Gerais. Registration BR 302021003203-1. Deposit: 7 August 2021. Concession: 8 October 2021. Author: Rita de Cassia Pedrosa Santos; Douglas Batista Mazzinghy; Walter Albergaria Junior.

Digital Certificate of Computer Record: Monitoring Parameters in an Underground Mine. Registration: 20210008, Depositor: Federal University of Minas Gerais Identification: N-PC-09-2021. Creation: 6 May 2019. Issued on: Mar 24 23:27:25.839 2021 GMT. Author: Rita de Cassia Pedrosa Santos; Douglas Batista Mazzinghy, D.B.; Walter Albergaria Junior.

Author Contributions: Conceptualization, R.d.C.P.S. and D.B.M.; methodology, R.d.C.P.S., M.M.O. and D.B.M.; software, W.A.J.; formal analysis, J.M.d.S. and C.L.P.; data curation, R.d.C.P.S. and W.A.J.; writing—original draft preparation, R.d.C.P.S.; writing—review and editing, J.M.d.S., C.L.P., M.M.O. and D.B.M.; supervision, M.M.O. and D.B.M. All authors have read and agreed to the published version of the manuscript.

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