Design and Implementation of a Georeferenced Multi-Sensor System for Monitoring Volcanic Gases

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***Abstract*—This paper presents the development and evaluation of a low-cost multisensor system to monitor volcanic gas emissions, focusing on CO_2, SO_2, and H_2S. The performance of the system was validated through field tests conducted at critical sites, including the crater rim of the Santa Ana volcano and the thermal area of Los Infiernillos on the slopes of the San Vicente volcano. Comparison with commercial equipment from the Ministry of Natural Resources (MARN) of El Salvador revealed minor deviations from the measurements, demonstrating the system's ability to provide reliable data while capturing rapid fluctuations and peak concentrations. This work aims to serve as a low-cost technological tool to achieve effective volcanic risk management and environmental monitoring efforts.**

***Index Terms*—CO_2, SO_2, H_2S, multisensor, volcanic monitoring.**

I. Introduction

The monitoring of volcanic gases represents a fundamental instrument for the observation and assessment of volcanic phenomena. The gases released during magmatic processes offer crucial insight into the internal dynamics of the volcano and potential associated hazards. Of particular interest are the gases carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S), given their environmental impact and correlation with volcanic activity [1].

The primary challenge in this field is to develop measurement systems that are accurate and reliable, portable, inexpensive, and capable of operating in extreme environments [2] [3]. This is particularly relevant in highly active volcanoes, where direct measurement may be dangerous or unfeasible. Although effective, traditional technologies often rely on fixed stations, limiting their ability to provide georeferenced data in real time. These limitations prevent a more dynamic and effective monitoring of volcanic emissions, especially in countries with limited resources [4] [5].

El Salvador is part of the Volcanic Disaster Assistance Program (VDAP) of the United States Geological Survey (USGS), under which the Ministry of Natural Resources received in 2019 the donation of a portable commercial multigas instrument manufactured by NOVAC to measure volcanic emissions. This equipment is the only one for all measurement campaigns carried out in the country's territory and is already seven years old.

In this context, the present work addresses the necessity of developing a georeferenced volcanic activity monitoring system. A multisensor system was designed and implemented, comprising an infrared analyzer for CO_2 and electrochemical sensors for SO_2 and H_2S. The system incorporates a datalogger for data recording and a GPS module for georeferencing, allowing the acquisition of precise and location-specific information in real time.

The principal contributions of this work are as follows.

- The provision of a compact and efficient system that facilitates the collection of georeferenced data in volcanic environments.
- the device enhances operator safety and enables comprehensive analysis of emission patterns in critical areas
- its modular and scalable design allows for adaptation to diverse environmental monitoring contexts

This paper presents the system's design, construction, and implementation and the results obtained during field tests in various volcanoes in El Salvador.

The document is organized into the following sections: Sections II and III present related studies and the proposed system, respectively. Section IV details the implementation process. Finally, Section V summarizes the key points.

II. Related Work

Monitoring volcanic gases has been the subject of extensive research due to its significance in predicting eruptions and assessing environmental risks [6]. Traditionally, this monitoring is carried out using fixed stations [7] [8], laboratory sample analysis [9], and remote sensing techniques [10], such as the application of differential absorption ultraviolet spectrometry (DOAS) and infrared systems for the measurement of CO_2, SO_2 and H_2S [11] [12]. Although these methodologies are accurate, their reliance on stationary equipment and the need for post-processing analysis can restrict their ability to operate in dynamic environments.

The use of electrochemical sensors and portable analyzers has increased as a cost-effective and flexible alternative. Systems that employ electrochemical sensors for SO_2 and H_2S, in conjunction with non-dispersive infrared (NDIR) analyzers for CO_2, have shown efficacy in spot monitoring [13] [14] [15] [16]. However, these devices often lack sophisticated integrations such as real-time georeferencing or comprehensive field data storage and analysis capabilities.

Recent research has concentrated on integrated systems for volcanic monitoring, including creating drones equipped with gas sensors. These drones provide a remote solution for challenging regions. However, these innovative solutions have limitations, particularly in terms of flight autonomy and implementation costs [17] [18].

In Central America, where volcanic activity is considerable, considerable efforts have been made to improve monitoring technology. For example, recent research in El Salvador proposed the use of a portable sensor system to quantify volcanic gas concentrations [19]. The system exhibited enhanced portability and precision in measurements within volcanic regions. Although the approach showed promise, it was limited to the documentation of the CO_2 gas.

The proposal presented in this work differs from existing solutions in that it integrates a compact and portable multisensor system with real-time georeferencing and storage capabilities. In contrast to the solutions mentioned above, this system integrates electrochemical sensors and NDIR analyzers with a standalone datalogger, eliminating the need for intricate post-processing and enhancing portability for field deployment. This work addresses fixed-station limitations while simultaneously improving operational safety by facilitating rapid and precise measurements in regions characterized by elevated volcanic activity. The low cost and flexibility of the system make it a viable alternative for regions with limited technical resources, thus advancing the democratization of access to advanced environmental monitoring technologies.

III. Methodology

Developing the georeferenced multisensor system for the monitoring of volcanic gases was carried out using a structured methodological approach comprising three main phases: design, construction and implementation. These stages facilitated the integration of multiple electronic components and software, creating a robust, portable, and functional device suitable for use in volcanic environments.

A. Functional System Requirements.

The development of the multisensor system for the monitoring of volcanic gases was started by identifying essential functional requirements, which were established to ensure its operational efficacy in field conditions. These requirements were defined considering the project objectives, the characteristics of the volcanic environments, and the technical and economic constraints.

The system must be capable of accurately and sensitively measuring concentrations of carbon dioxide (CO_2), sulfur dioxide (SO_2) and hydrogen sulfide (H_2S). These gases were selected for their relevance to the monitoring of volcanic activity and their role as indicators of magmatic processes. It is imperative that the system incorporates a global positioning module (GPS) to correlate each gas reading with geographic coordinates. This enables spatial analysis and determination of emission patterns. A data logger is necessary for the automatic and autonomous storage of measurements, which eliminates the need for a continuous computer connection. This guarantees data availability for further analysis, even under conditions of limited connectivity.

The system should be compact and robust enough to easily transport and withstand adverse environmental conditions, such as high temperatures, humidity, and exposure to corrosive gases typical of volcanic environments. Furthermore, the system should be able to operate with portable power sources to ensure prolonged operation during field activities. Fig. 1 shows the system architecture of the proposed system.

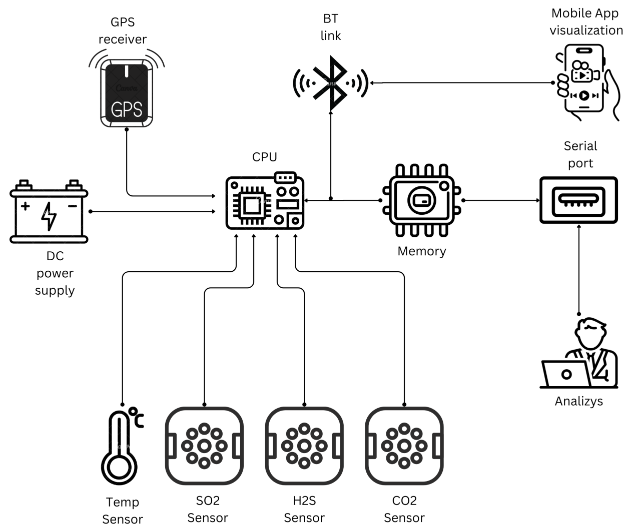


Fig. 1: Overview diagram of the system architecture.

B. Selection and specification of the hardware and sensors.

The selection of hardware and sensors for the multisensor system was based on previously defined functional requirements.

1) Gas Detection Sensors:

- SBA-5 Infrared Analyzer: This sensor was selected for carbon dioxide (CO_2) measurement due to its non-dispersive infrared absorption (NDIR) technology, which provides accurate readings with resolution in the parts per million (ppm) range.
- 3TF electrochemical sensor (SO_2): Explicitly designed to detect sulfur dioxide, this sensor combines precision with low power consumption and is protected against particle ingress.
- T3H electrochemical sensor (H_2S): This sensor is highly sensitive and allows for the detection of hydrogen sulfide, making it suitable for low concentrations and prolonged field operations.

2) Georeferencing: is defined as the process of associating geographic coordinates with a given set of data. The Garmin 18x GPS module was selected for its compact size, high accuracy in obtaining geographic coordinates, and the ability to operate in low signal conditions. The module integrates both the antenna and the electronic components, reducing the installation steps required.

3) Data Management: The datalogger CR300 centralizes the collection, storage and synchronization of data from sensors and GPS. The compatibility of the device with multiple analog and digital inputs and its capability to program in the CRBasic programming IDE. The CR300 data logger includes a USB port for downloading recorded data to a PC and a wireless Bluetooth connection to connect to a mobile phone application for real-time visualization in the field.

4) Other Components: include the TD-2NA suction pump, which guarantees uninterrupted and regulated flow of gases to the sensors, thus improving the precision of the measurements. The power system employed consisted of 12V rechargeable batteries, which ensured operational autonomy in the field.

Figure 2 presents a schematic diagram of the selected hardware components. Table I provides a detailed specification of the models and characteristics of the selected components for the proposed system.

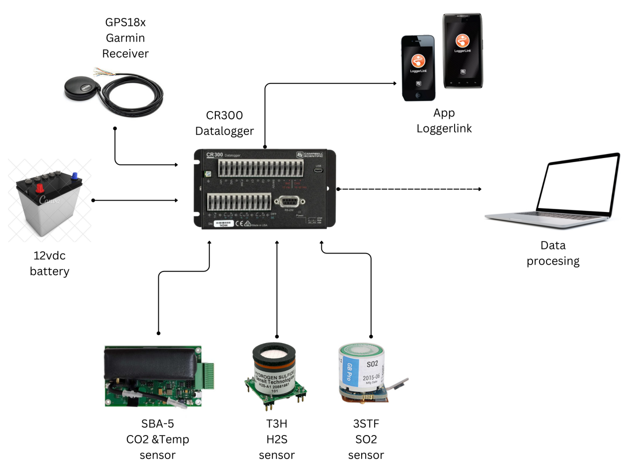


Fig. 2: Schematic of the system components.

C. Definition of the Operating Algorithm

The operating algorithm of the system was developed using the CRBasic programming language, which is specific for the CR300 datalogger. The main purpose of this algorithm is to manage the acquisition, processing, and storage of data from gas sensors and the GPS module, synchronizing the readings with time stamps and geographic coordinates.

1) Initial Configuration: The analog and digital input ports are configured for each sensor. The GPS module is initialized to receive georeferenced data. The sampling frequency is defined, and a fixed interval is set for the readings.

2) Data Acquisition: The program reads the analog signals from the gas sensors and converts them into concentrations using calibration factors. Geographic coordinates are obtained from the GPS module and are synchronized with the system time.

3) Processing and Validation: The acquired data are verified to ensure consistency and detect possible erroneous values. Basic filtering is performed to minimize noise in the input signals.

4) Data Storage: Processed data, including gas concentrations, temperature, time, and coordinates, are stored in internal flash memory in CSV format.

5) Data Export: The algorithm includes a routine for transferring data to external devices via USB or RS232 interfaces, facilitating further analysis. The algorithm 1 describes the logic of the code for the C300 datalogger.

Algorithm 1: General Algorithm for CR300 Operation

Configure inputs for CO_2, SO_2, H_2S sensors;
Initialize GPS module for georeferencing;
Set data sampling interval;
while *True* **do**
  Read analog signals from CO_2, SO_2, H_2S sensors;
  Convert raw signals to concentrations;
  Retrieve GPS coordinates and system timestamp;
  Perform data validation and noise filtering;
if *Data is valid* **then**
  Save ppm, temp, timestamp and coordinates;
if *External device connected (USB drive or PC)* **then**
  Transfer stored data in CSV format;

IV. Results and Discussion

The multisensor system for volcanic gas monitoring was implemented and evaluated in three key locations in El Salvador: autosomal vents in El Espino ecopark, the crater rim of the Santa Ana Volcano, and the geothermal zones known as Los Infiernillos in San Vicente. These areas were selected due to their volcanic activity and the need to continuously monitor gaseous emissions; see Fig. 3. The main objective was to evaluate the system's ability to measure and record CO_2, SO_2, and H_2S concentrations and georeference the collected data.

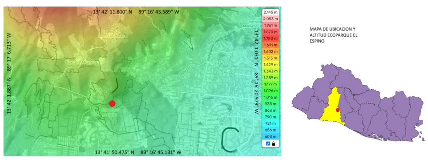
The system was assembled in a portable case for easy transport and protection; see Fig. 4. During the tests, the equipment was deployed at previously determined strategic points.

A. Procedure

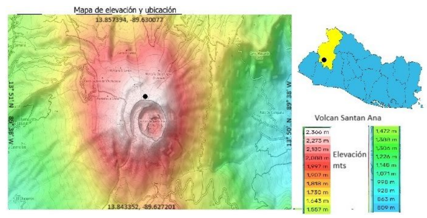
The sensors were calibrated prior to each test using standard gas mixtures. The GPS module was activated to synchronize the readings with precise geographic coordinates. The suction pump was connected to ensure a constant flow of samples to the sensors. Measurements taken in the field were verified

TABLE I: Key Specifications of System Components

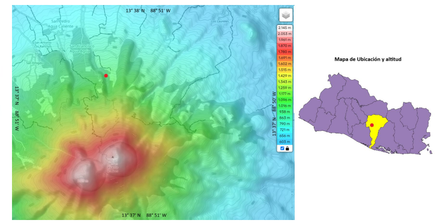
Component	Function	Key Specifications
SBA-5	CO_2 Measurement	NDIR technology, range 0 to 2000 $\pm$ 2 ppm
Sensor 3TF	SO_2 Measurement	Range 0 to 25 ppm, output 4 to 20 mA
Sensor T3H	H_2S Measurement	Range 0 to 25 ppm, output 4 to 20 mA
GPS Garmin 18x	Georeferencing	Accuracy 3-5 m, integrated antenna, RS232 output
Datalogger CR300	Data logging and storage	10 MB flash memory, analog/digital inputs, CRBasic
Pump TD-2NA	Gas flow to sensors	Flow rate 250-400 ml/min, power 9-15 V



(a) Ecoparque El Espino



(b) Volcano Santa Ana



(c) Infiernillos

Fig. 3: Test locations for the proposed portable multigas system.. .

Fig. 4: Prototype of the proposed portable multi-sensor system.

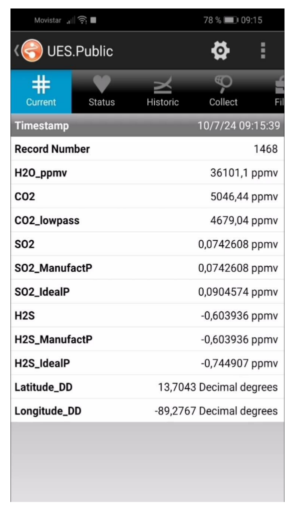


Fig. 5: Loogerlink app to monitor real-time data on C300 datalogger.

in real time using the Loggerlink mobile phone application, which is compatible with the C300 datalogger.

1) El Espino eco-park: Tests were carried out in autosoil vents, where CO_2 emissions were measured in a moderate geothermal environment.

2) Santa Ana Volcano: Measurements were made on the crater rim, recording SO_2 and H_2S concentrations in an environment of high volcanic activity.

3) Los Infiernillos: In this geothermal zone, CO_2, SO_2 and H_2S were measured simultaneously, emphasizing the correlation of emissions with terrain characteristics.

B. Results

1) El Espino eco-park: The CO_2 measurements were made with the multisensor system developed in this work. The results have been compared with those obtained with a commercial measuring device used by the Ministerio de Recuersos Naturales (MARN) of El Salvador, with a difference of 3% between the measurements, see Fig. 6. The developed system's primary sensor recorded concentrations that reached maximum values in the vicinity of 10,000 ppm, whereas the commercial meter exhibited maximum values of approximately 6,000 ppm. Furthermore, the designed system demonstrated an improved ability to register rapid fluctuations in CO_2 concentration, as evidenced by the more pronounced oscillations of the orange line of Fig. 6.

2) Santa Ana Volcano: We conducted a second test at the crater rim of the Santa Ana volcano, explicitly focusing on evaluating the performance of our SO_2 and H_2S sensors. The results of this evaluation are shown in Fig. 7, which present a detailed comparison of the readings from our proposed system against those recorded by commercial equipment utilized by

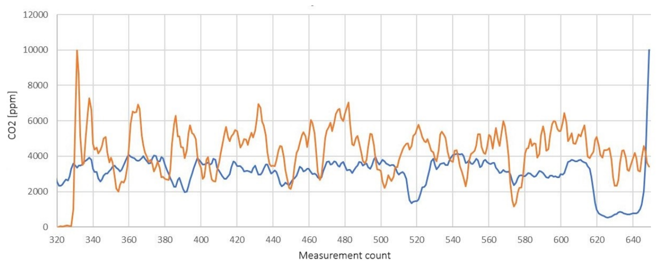
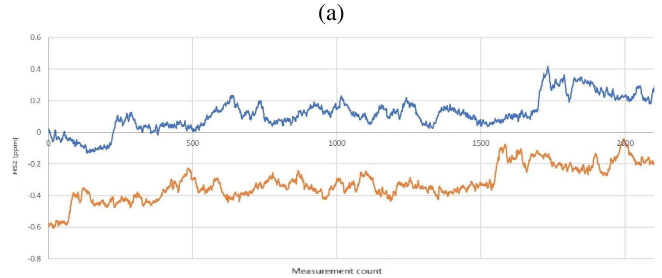


Fig. 6: Comparison of CO_2 measurements made with the proposed system (orange line) versus measurements made with MARN commercial equipment (blue line).

MARN. In our analysis of sulfur dioxide (SO_2) emissions, we calculated a mean value of 10.91% based on approximately 160 individual data points. This finding indicates a measurement deviation of 7.56% from the target value, suggesting a relatively close approximation to the expected emissions. For hydrogen sulfide (H_2S), our results revealed a backward mean value of 13.32 derived from 150 data points, with an agreement of 7.09% compared to commercial equipment measurements.

(a)



(b)

Fig. 7: Comparison of measurements made in Santa Ana Volcano with the proposed system (orange line) versus measurements made with MARN equipment (blue line), 7a for SO_2 and 7b for H_2S.

3) Los Infiernillos: A third measurement was carried out in the thermal area known as Los Infiernillos, on the slope of the San Vicente volcano. In this test, measurements were performed using the proposed system. In this test area, CO_2, SO_2, and H_2S emission samples were taken, the results of which are presented in the graphs in Fig. 8. A comparison is also shown with the readings of the commercial equipment used by MARN. Analyzing the trend and average of the data for both emissions, for CO_2, we obtained a lead of 3%, approximately 70 data and an error percentage of 20.08% 480 ppm below coincidence, for SO_2 we obtained a lead of 4.28%, approximately 100 data and an error percentage of 4.29%. For H_2S, a lead of 2.57% from 60 data with a coincidence with an error percentage of 2.67%, values that are largely due to the calibration of the sensors and the delay in the sensitivity of the response, but a significant improvement has been seen in the same, with a reduction in the error.

C. Discussion

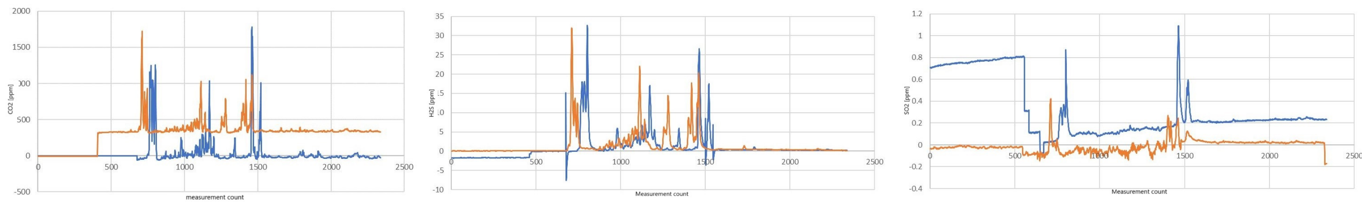
The results of this study demonstrate the effectiveness and limitations of the multisensor system developed to monitor volcanic gas emissions of CO_2, SO_2, and H_2S. Although the system exhibited promising accuracy and functionality, certain discrepancies compared to commercial measuring equipment warrant further exploration. The developed system's enhanced capacity to detect rapid changes offers a significant advantage in understanding dynamic volcanic emissions, but it also points to potential calibration differences that require refinement. In the tests, the sensors of the developed system SO_2 and H_2S showed acceptable performance compared to the commercial equipment. These deviations are small enough to validate the system for practical applications, but highlight the need for ongoing sensor optimization to ensure reliability under varying environmental conditions. In particular, the CO_2 readings showed a more significant error margin, possibly due to higher variability in gas concentrations at this site or differences in environmental conditions that affect sensor performance. These results underscore the importance of refining the sensor calibration to minimize errors and improve consistency at various monitoring sites; see table II.

TABLE II: Mean difference between measurements at test sites

Percentage diference (Commercial vs. Proposed)		
CO_2	SO_2	H_2S
44.05%	5.95%	4.9%

V. Conclusions

The development and evaluation of the multisensor system for monitoring volcanic emissions have demonstrated its potential as an efficient and economical tool compared to the commercial equipment currently used. The system demonstrated satisfactory accuracy in the measurements SO_2 and H_2S, with mean differences of 5. 95% and 4. 9%, respectively, compared to commercial equipment. Although the system demonstrated high sensitivity and the capacity to capture rapid fluctuations in CO_2 concentrations, the average difference of 44.05% in comparison with commercial equipment highlights the necessity for enhanced sensor calibration and responsiveness in extreme conditions. Tests conducted at sites including the Santa Ana volcano crater, the Los Infiernillos thermal area, and the El Espino ecopark vents corroborated the system's functionality in disparate geographic and climatic contexts, underscoring its portability and resilience as pivotal



(a) (b) (c)

Fig. 8: Comparison of measurements made in Infiernillos thermal zone with the proposed system (orange line) versus measurements made with MARN equipment (blue line), 8c for SO_2, 8b for H_2S and 8a for CO_2

advantages. Despite the discrepancies observed in the measurements, the system has demonstrated considerable advances in error reduction, particularly in the measurements SO_2 and H_2S, strengthening its capacity for practical applications in environmental monitoring.

Future research should focus on optimizing the sensors' calibration and sensitivity to reduce error margins under varying conditions. It is also proposed to extend the testing of the system to other volcanic and climatic environments and incorporate additional sensors to monitor a wider range of gases of interest. Integrating advanced technologies such as machine learning for real-time data processing and analysis could also improve the accuracy and predictive capability of the system.

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