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Design and Laboratory Validation of a Gas Analyzer Prototype Based on ESP32 for Mechanical Ventilation Assessment

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***Abstract*—This study presents the design, implementation, and validation of a low-cost gas analyzer prototype for measuring flow and pressure in mechanical ventilators. Built with an ESP32 microcontroller and digital sensors (SFM3000 for flow and MPXV5010 for pressure), the system offers a practical and accessible alternative for educational and experimental applications in biomedical engineering.**

The prototype was evaluated in a controlled laboratory setting using a commercial reference device (Fluke VT650) under nine ventilatory conditions, combining different tidal volumes and peak pressures. Data were collected during the inspiratory phase and analyzed using quantile–quantile plots, coefficients of variation, and confidence intervals to assess consistency and signal behavior.

Results showed a mean difference below 0.70 L/min for flow and 0.35 cmH_2O for pressure, with variation coefficients under 3.5% in all cases. The analog output through DAC pins enabled real-time waveform visualization on an oscilloscope, reinforcing the system's utility in teaching and prototype validation.

The findings demonstrate that the proposed system is stable, reproducible, and suitable for non-clinical environments. Its open-source, low-cost design supports the development of local solutions in resource-limited settings and contributes to technical training in biomedical instrumentation.

Keywords*—*Mechanical ventilation, gas analyzer, flow measurement, pressure sensor, ESP32, DAC output, biomedical instrumentation, educational prototype, equipment validation.

I. Introduction

Mechanical ventilator is a vital life support system used in intensive care units to ensure proper gas exchange and support respiratory function in critically ill patients [1], [2]. The effectiveness of mechanical ventilators depends not only on their internal hardware and control mechanisms but also on their ability to consistently deliver accurate flow and pressure values. In this context, external gas analyzers have become essential tools for performance verification, safety assurance, and equipment calibration.

Commercial systems such as the Fluke VT650 offer highly accurate flow and pressure measurement capabilities. These devices are typically used in clinical engineering environments and are considered reference standards. However, their high cost, limited accessibility, and reliance on specialized technical support make them unsuitable for widespread use in educational settings or in regions with constrained resources [12], [13]. The COVID 19 pandemic further exposed this technological gap, especially in Latin America, where many hospitals lacked the capacity to verify and calibrate their ventilation equipment properly [13].

As a response, biomedical engineers and academic institutions have explored the development of accessible and affordable alternatives. The emergence of microcontroller platforms such as the ESP32 has enabled the design of custom analyzers with features such as analog-to-digital conversion, WiFi communication, digital-to-analog signal output, and multithreaded processing [3], [4]. When integrated with compact and precise sensors like the SFM3000 for flow and the MPXV5010 for pressure, these systems can achieve acceptable levels of accuracy for non-clinical applications [6], [7].

Validating a prototype may be accomplished by a commercial gold standard, when both are connected to a commercial ventilator programmed with appropriate parameters during the experimental stage. Therefore, experimental errors can be determined, and further tests can be conducted to figure out global performance. These approaches help establish whether a prototype can serve as a functional alternative to commercial reference equipment, at least within specific conditions or use cases.

In previous studies, several authors have demonstrated that with proper calibration and design, prototypes based on low price components can deliver results comparable to commercial systems in scenarios such as technical training, biomedical education, and non critical research [14], [15]. These solutions not only reduce dependency on imported devices but also promote local innovation and knowledge generation.

This paper presents the design, implementation, and validation of a gas analyzer prototype for monitoring the flow and pressure parameters of mechanical ventilators. The system was built using an ESP32 microcontroller and digital sensors, and includes a Python-based graphical interface for visualization and analysis on a PC. Using a PC to display signals and data enhances parameter visualization.

The main objective is to evaluate whether the prototype delivers comparable results to a commercial analyzer under controlled laboratory conditions. The system's precision, repeatability, and agreement with the Fluke VT650 are analyzed using established statistical methods. The broader aim is to provide a technically sound and accessible alternative for resource-constrained environments, and to contribute to the development of biomedical instrumentation that supports both education and operational safety in healthcare.

II. Methodology

The prototype was developed in stages, beginning with an experimental version on a protoboard and later transitioned to a custom printed circuit board. It was built around an ESP32 microcontroller programmed in MicroPython to acquire and transmit flow and pressure data. The sensors used were the SFM3000 digital flow sensor, which communicated via I2C, and the MPXV5010 analog pressure sensor, connected through the ESP32's internal analog-to-digital converter.

The initial test bench is shown in Figure 1, which illustrates the connections between the sensors, microcontroller, ventilator system, and measuring equipment. The ESP32 was responsible for collecting measurements, transmitting data through USB or WiFi, to the PC. The final circuit was implemented on a custom-printed PCB, designed and fabricated to ensure compact layout and signal stability. The assembled board is shown in Figure 2**.**

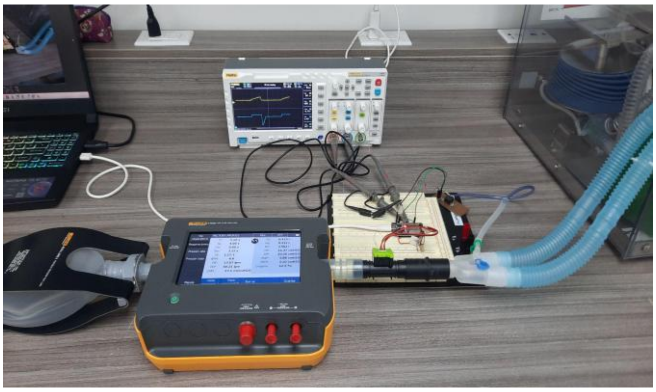

Fig. 1. Prototype test bench using protoboard, sensors, ventilator, and measurement instruments.

Fig. 2**.** Final printed circuit board (PCB) developed for the gas analyzer prototype. The board integrates an ESP32 microcontroller, a digital flow sensor (SFM3000), and an analog pressure sensor (MPXV5010). Custom design includes labeled input ports, USB communication, and a compact layout for stable signal acquisition and educational use.

A Python-based graphical interface was developed to manage real-time signal visualization and data processing. It allowed users to monitor signal behavior, adjust communication parameters, and store collected values in CSV format. The system established serial or WiFi communication with the ESP32, continuously receiving flow and pressure data for both real-time display and offline analysis.

Figure 3 presents the flow diagram of this interface logic. On the left side, the system reads and processes incoming serial data to calculate accumulated volume and identify respiratory phases. On the right side, the interface dynamically updates graphical outputs and, upon reaching configured time intervals, it triggers basic statistical analysis. This modular architecture facilitated rapid inspection of signal trends during testing and proved useful for teaching purposes.

For system validation, the prototype was tested in parallel with a Fluke VT650 gas analyzer and a Maquet Servo I mechanical ventilator. The devices were connected using custom 3D-printed splitters to ensure symmetrical airflow distribution between both measuring systems. A Fluke Accu Lung simulator was attached at the output to replicate realistic ventilation scenarios, allowing adjustments to airway resistance and lung compliance.

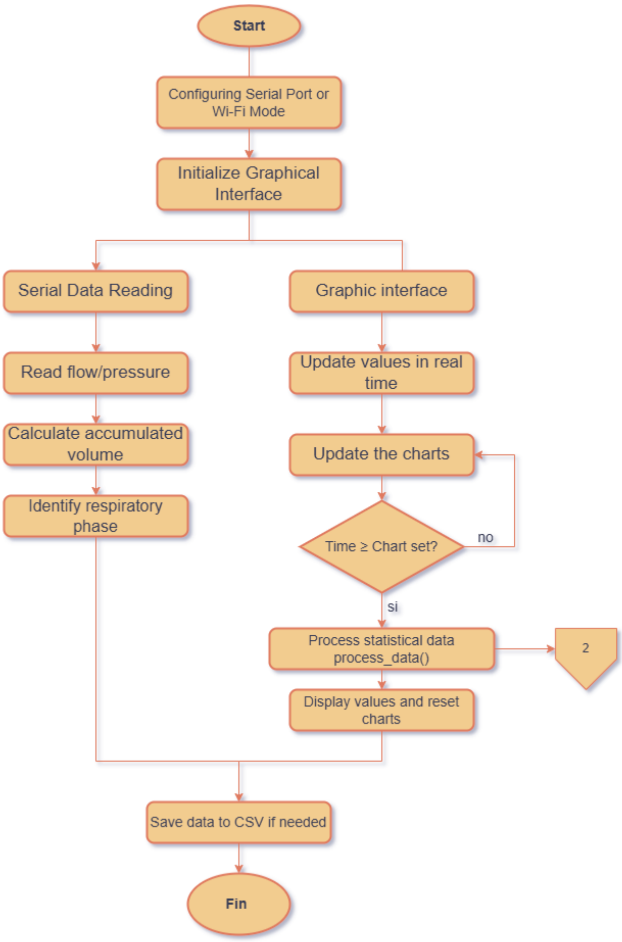

Figure 3. Flowchart of the user interface code developed in Python for the gas analyzer prototype. The diagram illustrates the dual processes of data acquisition and real-time visualization.

Testing involved two ventilator modalities: volume control and pressure control. At volume control, three tidal volumes were used: 500, 700, and 900 milliliters. Besides at pressure control, three peak pressures were used: 10, 20, and 30 centimeters of water. Data were collected during the inspiratory phase in a controlled laboratory environment. The primary objective was to assess whether the prototype could provide stable and repeatable flow and pressure readings that followed the same patterns observed in the commercial reference device.

All tests were conducted using hospital-grade air compressor and standard patient circuit tubing. Calibration procedures were performed before testing and verified using standard test loads. Emphasis was placed on verifying the functional integrity of the system rather than clinical certification.

III. RESULTS

The prototype was evaluated for each experimental condition, where the ESP32-based monitoring system acquired pressure and flow signals, which were then compared against reference measurements from the Fluke VT650 gas analyzer.

Across all test cycles, the system performed reliably, maintaining uninterrupted data acquisition and transmission. The recorded signals closely followed the expected mechanical ventilation patterns: pressure waveforms showed regular peaks and return-to-baseline transitions, while flow signals exhibited the characteristic biphasic profile with distinct inspiratory and expiratory phases. These observations confirm that the prototype accurately captured the dynamic behavior of respiratory cycles. Figure 4 presents an oscilloscope capture of the synchronized pressure and flow signals acquired in real time from the analog outputs available at the prototype, demonstrating the system's responsiveness and stability. Table 1 summarizes the comparative results with the commercial reference device, presenting mean values, absolute errors, and relative errors for flow (L/min) and pressure (cmH_2O) across the evaluated tidal volumes and pressures. All relative errors remained below 3%, confirming high measurement agreement between the prototype and the reference standard.

As an example, Figure 5 shows a screenshot from the Fluke VT650, displaying pressure, flow, and volume values for each respiratory cycle. This output served as the reference standard for comparative analysis, enabling confirmation of the trends recorded by the prototype during data collection. Ultimately, these readings were used to determine the prototype's accuracy across the range of ventilatory scenarios evaluated.

The results confirm the reliability of the ESP32-based acquisition module and its analog signal conditioning circuitry. The prototype consistently replicated pressure–volume trends with minimal deviation, demonstrating both the accuracy of the selected sensors and the robustness of the implemented signal processing architecture.

Increases in tidal volume were reflected proportionally in the corresponding variations of pressure and flow, confirming the system's ability to dynamically detect ventilatory changes. Additionally, the Python-based graphical interface enabled real-time signal monitoring, which supported the rapid identification of trends and ensured proper system performance throughout testing.

Taken together, the findings validate the system's ability to accurately acquire and represent clinically relevant ventilatory parameters with the resolution and consistency required for academic and training applications. Its low cost and reliance on readily available components make it a compelling option for integration into educational laboratories and experimental setups, particularly in resource-constrained settings.

Table 1. Comparative error analysis between the prototype and the Fluke VT650 analyzer under six representative ventilatory conditions.

Variables		Prototype/Fluke	Media	Absolute Error	Relative Error (%)
Flujo (lpm)	500mL	Prototipo	20.768	0.371	1.82
		Flukeh	20.397		
	700mL	Prototipo	29.189	0.765	2.69
		Fluke	28.424		
	900mL	Prototipo	36.206	0.532	1.49
		Fluke	35.674		
Presión (cmH_2O)	10 cmH_2O	Prototipo	15.516	0.121	0.79
		Fluke	15.395		
	20 cmH_2O	Prototipo	25.726	0.341	1.34
		Fluke	25.385		
	30 cmH_2O	Prototipo	35.605	0.103	0.29
		Fluke	35.502		

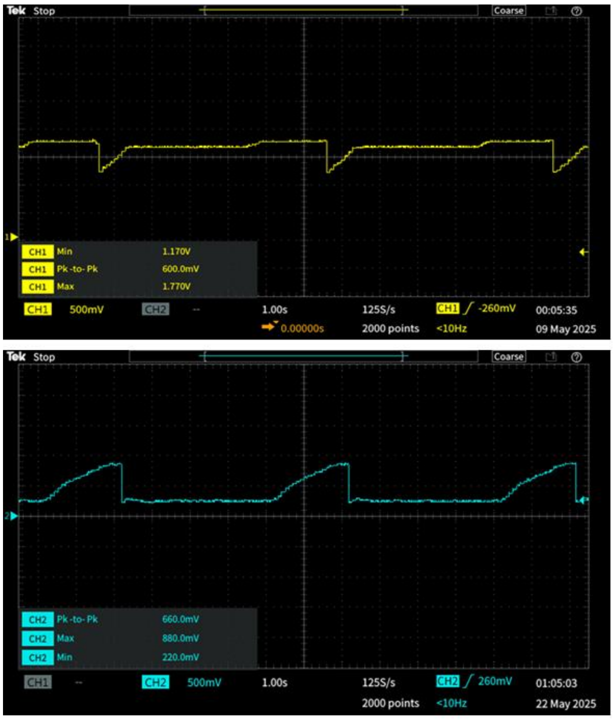

Fig 4. *Oscilloscope visualization of simultaneous flow (yellow) and pressure (blue) waveforms acquired by the prototype system.*

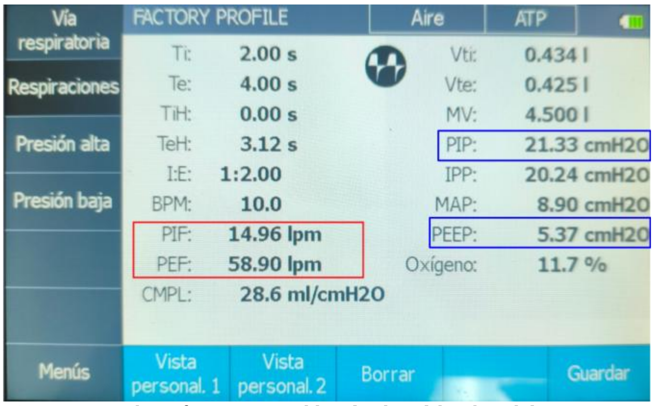

Fig 5. *Screenshot of output variables displayed by the Fluke VT650 gas analyzer under ventilatory test conditions.*

IV. Discussion

The results of this study highlight the potential of a low-cost, ESP32-based monitoring system to accurately capture and visualize key ventilatory parameters such as pressure and flow. The observed signal stability, synchronization, and waveform fidelity under various test conditions suggest that this prototype can serve as a functional alternative for basic respiratory monitoring tasks in academic or training settings.

One particularly valuable aspect of this system is its flexibility. Changes in tidal volume and inspiratory pressure were reflected in real time by both the waveforms and numerical outputs, suggesting adequate sensitivity and responsiveness. Moreover, the integration of a Python-based interface enhanced the user experience by providing real-time signal visualization, which is essential not only for validation purposes but also for educational demonstrations or development of new control strategies.

While the system was not intended to replace clinical-grade devices, its performance during testing shows that it meets basic requirements for experimental use. The cost-effectiveness, programmability, and modular design of the prototype also open the door for future enhancements, including wireless data logging, alarm systems, and the incorporation of other physiological sensors such as oxygen saturation or temperature.

Nevertheless, some limitations must be acknowledged. The prototype was evaluated under controlled laboratory conditions using artificial ventilation parameters, and its performance in real-world clinical scenarios remains untested. Additionally, the current configuration does not include calibrated flow-volume loops or integrated error analysis between devices. These elements, although excluded here to maintain the preliminary and transferable nature of the results, would be necessary in future full-scale validation studies.

Despite these limitations, the prototype succeeded in capturing clinically meaningful signals and providing a clear, synchronized representation of respiratory dynamics. This supports its continued development as a teaching or prototyping platform and demonstrates the relevance of open-source, low-cost technologies in biomedical innovation.

V. Conclusions

This work presents the successful development and validation of a low-cost respiratory monitoring prototype based on the ESP32 platform. The system was capable of acquiring and displaying real-time pressure and flow signals with behavior consistent with a reference gas analyzer.

The prototype demonstrated stability, synchronicity, and adequate sensitivity under six ventilatory test conditions. Its open-source design and low-cost components make it a practical option for educational use, experimental setups, or the development of custom biomedical applications.

Although the current prototype is not intended for clinical deployment, it proved reliable for basic monitoring, validating its use in academic contexts and as a foundation for future upgrades that could lead to a fully fledged clinical device.

Acknowledgment

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