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REVISTA INGENIO

Implementation of a Weather Station using FPGA with Real Time Data Access and Analysis

Implementación de una Estación Meteorológica Mediante FPGA con Acceso y Análisis de Datos en Tiempo Real

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FPGA, Weather Station, Raspberry Pi 4, LabVIEW, Sensors.

ABSTRACT
The present study develops a weather station with the Fiel-Programmable Gate Array (FPGA) technology to obtain meteorological data in educational environments, but that can be adapted to any real scenario, using ADM1001 sensors for temperature and humidity, amount of rain, wind direction and wind speed. The proposed design aims to improve the accuracy and speed with which weather data is obtained in real time. For this purpose, the Elvis II+ platform together with the Xilinx Spartan 3E FPGA was used for the connections of the different types of sensors. In addition, the LabVIEW programming environment was used for the design and control of the system ensuring a user-friendly interface for the users. To present the collected data, a Node-Network solution was developed to efficiently visualize the data, the algorithms used achieved an accuracy of 85% under normal conditions, the root mean square error (RMSE) was 0.2 °C for temperature and 1.5% for humidity. This visualization is achieved through a Raspberry Pi since it facilitates the access and management of the meteorological information collected in real time, which endorses the quality of the prototype designed in the present work.

PALABRAS CLAVE
FPGA, Estación meteorológica, Raspberry Pi 4, LabVIEW, Sensores.

RESUMEN
El presente estudio desarrolla una estación meteorológica con la tecnología Fiel-Programmable Gate Array (FPGA) para obtener datos meteorológicos en entornos educativos, pero que puede adaptarse a cualquier escenario real, utilizando sensores ADM1001 de temperatura y humedad, cantidad de lluvia, dirección y velocidad del viento. El diseño propuesto pretende mejorar la precisión y rapidez con la que se obtienen los datos meteorológicos en tiempo real. Para ello, se ha utilizado la plataforma Elvis II+ junto con la FPGA Xilinx Spartan 3E para las conexiones de los diferentes tipos de sensores. Además, se utilizó el entorno de programación LabVIEW para el diseño y control del sistema asegurando una interfaz fácil de usar para los usuarios. Para presentar los datos recogidos, se desarrolló una solución Node-Network que permite visualizar los datos de forma eficiente, los algoritmos empleados alcanzaron una precisión del 85% en condiciones normales, el error cuadrático medio (RMSE) fue de 0.2 °C para la temperatura y de 1.5% para la humedad. Esta visualización se consigue a través de una Raspberry Pi ya que facilita el acceso y la gestión de la información meteorológica recogida en tiempo real, lo cual avala la calidad del prototipo diseñado en el presente trabajo.

1. Introduction

The country is currently experiencing more extreme climate changes, and this makes it increasingly necessary to monitor and predict these phenomena more accurately. According to, in Ecuador, several natural phenomena significantly affect the climate. The factors are measured thanks to current technology, and the data obtained in real time allows us to understand and react more effectively to changes [1].

Field-Programmable Gate Arrays, or FPGAs, are integrated circuits that can be programmed after manufacture. They are ideal for implementing complex handling algorithms and maintenance activities on electronic devices. The parallel processing and efficiency of these devices make FPGAs more efficient than microcontrollers and digital signal processors, delivering higher performance for real-time applications [2], [3].

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A real-time weather station has sensors and electronics, such as sensors for basic weather variables, such as temperature, humidity, uva ultraviolet radiation, and wind direction. Learning Objects form another part of the support for the educational process which facilitates their understanding [4], [5].

In this project, an experimental methodology is proposed to allow the use of the weather station, which involves an analysis of the functionality. The purpose is to evaluate significant parameters, such as humidity, temperature, the amount of rainfall, wind speed and direction. Real-time analytics is made possible by FPGAs' ability to collect and process data instantly [6].

The system uses LabVIEW as a simulation tool for development. LabVIEW is an acronym for Laboratory Virtual Instrument Engineering Workbench. It allows the development of a user interface that interacts with the simulation equipment in an intuitive way by presenting data in real time using boxes, graphs and specific markers for the reading of data from each sensor of the weather station. Therefore, the system is educational for any user who wishes to understand [7], [8].

Traditional weather stations often contend with slow data collection and limited processing. FPGA-based systems, in contrast, provide real-time data handling and high-speed parallel processing capabilities. While IoT-based weather stations offer remote connectivity and cloud integration, their common reliance on microcontrollers or single-board computers may not match the speed or hardware-level customization FPGAs deliver. Consequently, FPGA weather stations effectively combine local data processing with system reconfigurability, presenting a robust solution for responsive and accurate climate monitoring.

To augment system functionality, technologies such as Node-RED and CERN-ROOT are incorporated for data flow control and scientific data analysis, respectively. Node-RED supplies a user-friendly visual programming interface for managing sensor data, whereas CERN-ROOT facilitates complex statistical processing and visualization. The inclusion of these tools equips the FPGA-based system with potent software capabilities that complement its hardware strengths, supporting both immediate responses and detailed data insights.

From an educational standpoint, FPGA-based weather stations function as valuable learning platforms. They expose students and researchers to interdisciplinary content covering electronics, programming, signal processing, and environmental science. Engaging with real-time data and reconfigurable hardware allows learners to achieve a deeper understanding of embedded systems and their practical applications in contemporary environmental monitoring.

Weather stations play a vital role in collecting climate data that affects many sectors, from agriculture to disaster management. They help farmers make decisions by implementing accurate weather conditions, and to predict extreme events, they help reduce damage. Data is also necessary for inclusion in the climate change agenda, allowing environmental policy to be evaluated and adjusted [9].

In many respects, traditional weather stations face several notable challenges. The high cost associated with installation and maintenance can make the stations prohibitive for many. Similarly, data handling accuracy and speed are generally low, seemingly unable to respond quickly to events that occur around the weather. In addition, real-time data analysis is absent in many traditional systems, ultimately limiting its effectiveness in extreme events [10].

The application of FPGAs in weather stations provides several notable advantages. Due to the increase in computing resources, a rapid reaction to changing weather conditions is achieved. The system is improved in terms of accuracy by customizing the hardware for the particular sensors used. In addition, additional upgrades and upgrades are constant due to the adaptability of the FPGA, ensuring that the system can be modified or upgraded to newer specifications as needed [11].

The main purpose of the FPGA-based weather station is to work with various sensors and collect environmental parameters including temperature, humidity, direction, and wind speed. One of the most important features of this functionality is the ability to calculate and analyze such data accurately. In addition, there are also educational materials such as simulations and teaching tools that are available for students to understand the concept and application of the weather station.

This research expands the capabilities of real-time meteorology by taking the implementation of software built specifically around FPGA technology to the next level. It equips weather stations with computerized systems that improve the efficiency of their use as provided by general systems using normal approaches. This system can really help us control the weather better and is a great start to creating even more interesting things in the future.

Using FPGAs in a weather station greatly affects both study and real-world use. This platform is a high-tech tool that helps scientists better study weather and climate. This method changes real-time weather tracking and can be used in many situations, providing a flexible way to monitor different things.

Within a detailed review of the technologies, current methods of weather stations and real-time data processing. The analysis situates the project in the field of meteorological technologies, demonstrating how current innovations, such as the use of FPGAs, overcome the limitations of traditional systems. By understanding the existing environment, one can see how the proposed project will improve the accuracy and speed of collecting and analyzing weather data.

The various sensors of the weather station stand out, being the fundamental AMT1001 to collect accurate measurements of critical hydroclimatic variables, such as temperature and relative humidity. Integrated into the IoT weather station layer, the AMT1001 offers level readings to enable monitoring of environmental conditions. The article used 65 samples, presented a correlation of 100% in the data and a transmission efficiency of 95.3%, validating the usefulness of AMT1001 in planning agriculture and resource management systems [12].

The PRS-1 sensor, a compact rain gauge designed to measure the amount of rainfall accurately by location. This sensor is important for collecting the amount of rainfall that covers rainfall, something that is necessary for Bangladeshi agriculture, where the lack of timely information has resulted in crop losses, as PRS-1 not only gives accurate measurements, but also stores and allows data to be shared online, facilitating the estimation of rainfall and agriculture based on historical and current data [13].

Ultrasonic cup anemometers are employed for wind measurement, as wind speed is a key component in evaluating a generation site before installing a wind farm. The low-cost anemometer was created using 3D addition technology and manufacturing instructions with an encoder and phototransistor to convert rotation into wind speed data using the Arduino Uno. The test results and the 0.968 showed that its level of accuracy is high and it may be a viable and economical option for future wind projects [14].

The FPGA-based weather station uses the Xilinx Artix7 array and the Verilog HDL language to accurately measure weather parameters. It uses a FT2232H USB-UART interface to record atmospheric pressure, temperature, and humidity, and allows the interconnection of various sensors. Data acquired in Nilgiri, Tamil Nadu, India, is visualized using the CERN-ROOT data analysis framework, providing a detailed and efficient graphical representation of weather conditions [15], [4].

The transceiver schemes MPSK (Mary-Phase Shift Keying) and MQAM (Mary-Quadrature Amplitude Modulation) are implemented in LabVIEW, considering the effect of noise. These schematics are reproduced with the SDR NI-USRP 2920 kit, and the strength of the received signal is measured with the R&S (Rohde & Schwarz) sensor. The results show good agreement with the simulations, and the detailed procedure serves as reference material for prototyping and hands-on teaching of communication systems [16].

The NI ELVIS II system facilitates the study of these characteristics, allowing the analysis of tunable filters in both the time and frequency domains. This educational equipment is essential to understand the behavior of filters of various orders, providing practical and detailed examples that enrich learning in electrical engineering. Its use in the curriculum is essential for a complete training in filter analysis and design [17].

The topology for FPGA based on a systolic structure, suitable for forward neural networks such as the multilayer perceptron (MLP). Implemented on the Zynq-7000 board with the MNEST dataset, the proposed architecture improves accuracy and performance using specific activation functions. This solution optimizes hardware efficiency in neural network applications, outperforming traditional structures [18].

The proposed design uses the Spartan-3E FPGA to generate and control a PWM signal with variable duty cycle using a rotary encoder. The Spartan-3E, with its internal clock of 50 MHz, allows you to adjust the PWM signal duty cycle from 0 to 100% by turning the encoder and changing the signal frequency. This approach offers high speed, customization and low cost, being suitable for applications in power control and electronics. The generated PWM signal is analyzed with an oscilloscope to ensure its accuracy at various frequencies [19].

The Raspberry Pi 4 has been employed to develop a low-cost disk imaging device useful in digital forensics for copying evidence before direct analysis. Using Python, the device allows digital evidence to be handled accurately and efficiently, minimizing the risk of tampering. Tests show that the Raspberry Pi 4 delivers solid performance in speed and accuracy, providing an economical alternative to more expensive equipment on the market [20].

Implementing an I2C controller on an FPGA to connect the BH1750FVI light sensor and transmit data to Simulink using an I2C bridge to UART. Using VHDL and a finite state machine (FSM), the I2C controller and UART have been developed. The verification is performed with a hardware I2C analyzer, ensuring accurate acquisition of sensor data. The UART controller then sends this data serially to the COM port for analysis and processing in Matlab-Simulink [21].

This protocol is ideal for systems with many distributed sensors, although the topology can become complex in large networks. Deploying switched networks, which divide the network into electronically managed segments, helps handle this complexity without increasing weight or radius. In this study, a long-line 1-Wire network with a data switch integrated into a master microcontroller is proposed, providing a reliable and economical solution for temperature sensor monitoring [22].

The Modbus protocol facilitates communication in industrial systems by connecting control devices through a simple interface. This article discusses how Node-Red, a flow-based visual programming tool, integrates with Modbus to control robots, such as Epson's 6-axis and SCARA robots. The combination of Modbus with Node-Red enables efficient and visual management of robotic systems, demonstrating that visual programming can simplify the development and implementation of control software in industrial environments [23].

Both conventional manual and automatic weather stations rely on physical models and satellite data to make their predictions. However, in extremes with complex microclimates such as Quito, these methods are often inaccurate, in part due to local factors such as the Intertropical Convergence Zone that these structures are not armed to deal with. Given the inability to adapt to these specificities, their prognoses are often wrong [24].

The study by Asanza proposes a weather monitoring station with FPGA-based embedded systems. This system acquires high-resolution data and predicts real-time samples accurately. Additionally, a web application with user-friendly interface presents the collected data [11].

These stations are also inefficient because they cannot process information in real time and are expensive to expand in number to improve accuracy. Therefore, these shortcomings argue the need for economical and novel approaches, such as low-cost computers and advanced machine learning techniques, that can guarantee the accuracy of weather forecasts in extremes with complex microclimates [25].

The AASIP (Adaptive Arithmetic Significance Inference Prediction) algorithm, which optimizes the accuracy of the correction factor in the Sparse Implicit Projection (SIP) by correcting based on the arithmetic mean. AASIP improves accuracy in RC network list reduction by overcoming the limitations of traditional SIP and adjusting high-order moments. The effectiveness of the algorithm is validated through practical examples, demonstrating its ability to offer a more accurate approximation compared to previous methods [26].

Equation (1) of the arithmetic mean is:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} a_i = \frac{a_1 + a_2 + a_3 + \ldots + a_n}{n} \quad (1)$$

Where

$\bar{X}$**:** *arithmetic mean*

a_n**:** *number of data*

Σ: *sumatoria*

n: *Total number of data*

The article highlights the need to modernize weather monitoring in Ecuador due to the lack of advanced technology. The National Institute of Meteorology and Hydrology (INAMHI) is implementing a program to replace traditional stations with more advanced technologies, such as FPGAs, that would improve accuracy and efficiency in the collection of environmental data, such as temperature, humidity and atmospheric pressure [11].

Similarly, the study recommends considering alternatives such as static stations and wireless sensor networks to automate and monitor data. It also suggests comparing different data acquisition technologies, such as SRAM FPGA memory, to reduce response times and take into account environmental factors to improve the accuracy of the monitoring system.

FPGAs have proven to be very effective in improving accuracy and reducing response time in the acquisition of meteorological data. Compared to DDR3 memory, FPGAs can accelerate data reading by up to five times. In addition, systems using FPGAs with neural networks and the VHDL language have shown high accuracy in monitoring variables such as humidity and light intensity.

The article states that an Arduino Uno was initially used to connect the sensors and transmit data, which was replaced by Raspberry Pi due to its higher processing power. FPGAs are used in our thesis due to their high performance and energy efficiency, which makes them suitable for managing sensor data at high speed [11].

Therefore, this article is about the technological outdatedness of Ecuador's weather stations and an innovative solution based on FPGA systems. FPGA technology has demonstrated its impressive number of abilities to improve accuracy and efficiency in the acquisition of environmental data, including temperature, humidity, rainfall, and light intensity. Therefore, FPGA implementation can modernize existing systems and make data acquisition extremely efficient and high-quality.

The article describes the weather station that the Xilinx Artix 7 FPGA used. This station included the following temperature, humidity and pressure sensors and was programmed with VHDL. Then, the data that emerges from the station is processed and analyzed and visualized with CERN-ROOT from tests carried out in Nilgiri, Tamil Nadu, India [11].

When comparing the Xilinx Artix 7 and the Xilinx Spartan 3E, it is observed that the Xilinx Artix 7 demands more logical capabilities and memory, but its high price can be a challenge. On the other hand, the Spartan 3E costs relatively less and is accessible, it does not need a high additional technical demand compared to the other. Both are great for doing a project, but the most suitable solution depends on the particular case and budget.

The article introduces a system called Weather Station Monitoring, which uses IoT to provide weather data anywhere. This system, built with ESP32 microcontroller and MQTT broker, transmits data to the cloud and is displayed using NODE-RED in real time. It has temperature, humidity and wind speed sensors, with hydrological sensors monitoring water level and flow, allowing users to predict flooding [27].

This study uses NODE-RED for real-time visualization and recording of weather data, including temperature, humidity, rainfall level, wind speed and direction. Although this system lacks hydrological data, the use of NODE-RED shows that there is still room for future expansions. NODE-RED and LabVIEW ensure accurate handling of the flow of weather data, providing an environment monitoring solution that is effective and easy to adapt.

The article describes a weather monitoring system that uses IoT and LabVIEW to collect and analyze data on temperature, humidity, vent velocity, pressure, and light intensity. The recording of this microcontroller data is stored in an Excel macro file and displayed on an LCD screen. In addition, the system uses a 4G module, the data is sent to the IoT cloud, allowing data to be accessed from remote locations via the mobile network [28].

In comparison, the system is simpler than the FPGA-based studio system, which offers greater accuracy, but is more complex to program. Although the system has some limitations in processing, it stands out for its powerful ability to transfer data to the cloud through 4G, which is still a significant advantage.

Tools such as LabVIEW and CERN-ROOT are effective for accurately processing and visualizing scientific data. LabVIEW facilitates real-time acquisition and monitoring; ROOT enables complex analysis of large volumes of data and integrates well with architectures such as FPGA. Thus, these tools improve the interpretation of environmental phenomena and optimize system performance [29].

Countries with complicated geographies such as Peru, Bolivia or Colombia have challenges similar to ours here in Ecuador with the coverage and accuracy of their weather stations. Recent studies show that using FPGA platforms for environmental monitoring in difficult to access areas is more efficient, as they take less time to respond and are more reliable [30].

Modernizing meteorological stations with advanced technology is key to the technological and scientific sovereignty of developing countries. For Ecuador, this means promoting technical and engineering education, training specialists and designing local solutions. This work, then, aims to help build a more resilient scientific infrastructure of our own [31].

2. Method

The development of the weather station is done by using FPGA technology to capture, process and analyze weather data in real time. FPGAs are chosen because of their ability to provide high accuracy and speed in data processing based on need. This is required for applications that need to constantly monitor various data points and be up-to-date with the latest information in an instant. Therefore, FPGA technology is necessary to enable efficient and fast processing, given its need in advanced meteorological applications.

The methodology of this project was mainly experimental. It means that a series of tests were performed to adjust the respective sensors and verify whether the FPGA could handle the real-time data effectively. Therefore, an adjustment of the system's parameters and an evaluation of its performance under various environmental conditions were performed. This ensured that the data collected was considered accurate and reliable in practical situations.

On the other hand, the implementation of the weather station with FPGA technology for monitoring environmental conditions such as temperature, humidity, wind direction and speed in real time, allowed a highly accurate and fast data processing, which was the right choice for advanced applications. LabVIEW was used to program the FPGA, which provides a welcoming graphical interface for designing and managing the data acquisition system, making it very easy to install and read the data.

It was decided to include a Raspberry Pi 4 in the system design to improve data transfer speed and connectivity. This device serves as a bridge to send information from the FPGA to other systems over a network, making it easy to access and analyze the data using programs such as Matlab-Simulink. In this way, an efficient solution for remote communication and information processing is achieved.

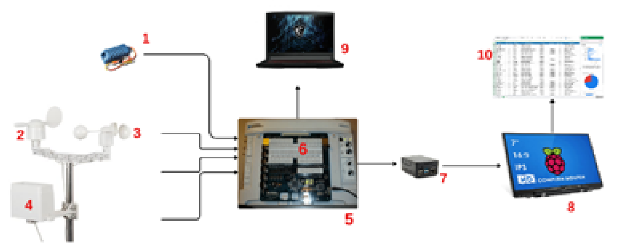
The project goes beyond simple climate monitoring. It also has an educational component designed for students, who can recreate the prototype and experiment with the weather station. This offers them a hands-on opportunity to learn about FPGA technology and meteorological principles. By combining LabVIEW and Raspberry Pi 4 in the design, an enriching educational experience is provided. Figure 1 shows the diagram of the weather station, which makes it easier to understand.

The following are the components for the project:

1. Humidity and temperature sensor AMD1001.
2. Directional anemometer.
3. Ultrasonic cup anemometers.
4. Tilting bucket rain gauge.
5. NI Elvis II+.
6. NI Digital Electronics FPGA Board.
7. Raspberry pi 4.
8. Screen.
9. Laptop.
10. Database.

Fig 1.

Weather station schematic with FPGA.



The development of the weather station using FPGA technology will be carried out in five phases to ensure the correct process. Information gathering and initial planning is a key section to understanding objectives clearly. Then, in the phase of study and selection of components, the parts such as sensors and other devices are selected. It ensures that everything is in order for the system to run smoothly.

The next phase, development and implementation of the project, where the FPGA is programmed and all the components are connected. Once everything is assembled, the calibration phase and adjustment of sensors and components is carried out where the respective adjustments and modifications are made, finally, in the data generation and analysis phase, the data obtained are collected and examined to evaluate the performance of the system and make final adjustments, figure 2 shows the phases for the implementation of the weather station.

Fig 2.

Phases for the implementation of the weather station

In the information gathering and initial planning phase, you do thorough research to understand the project requirements and set clear goals. Different types of weather sensors and FPGA technology are explored, as well as programming and connectivity needs. This research process allows the project scope, the necessary resources, and the timeline to be defined, creating a solid foundation for the next stages of development.

During the study and selection of components, the variety of available sensors, such as temperature, humidity and wind speed, is analyzed in detail to choose the ones that best suit the needs of the project. The technical specifications, FPGA compatibility, and cost of each component are reviewed. This phase is key to ensuring that the selected elements are suitable, efficient and reliable for the system.

The weather station employs high-precision sensors to ensure effective environmental monitoring. Temperature and humidity sensors AMD1001 noted for their accuracy and stability, providing reliable real-time data and quickly adapting to variations in the environment. This capability is crucial for obtaining accurate information about atmospheric conditions.

Directional and ultrasonic anemometers are used to measure the wind. The former records the wind direction accurately, while ultrasonic anemometers, with no moving parts, provide fast and accurate data, even in adverse conditions. This combination allows for a complete and accurate evaluation of wind behavior.

The tilting bucket rain gauge measures precipitation with high accuracy and durability, while maintaining a low maintenance requirement. Its robust design ensures accurate measurements of rainfall accumulation in real time, which is critical for water management and prediction of extreme weather events.

The integration of the sensors with the FPGA is done using standard communication protocols such as I2C and SPI, ensuring accurate and efficient data transmission. Sensors employing I2C connect to the FPGA's data pins (SDA) and clock (SCL), allowing for easy connection of multiple devices on a single bus, which is ideal for temperature and humidity sensors.

Sensors that use the SPI protocol connect to the clock pins (SCK), input data (MOSI), output data (MISO), and chip selection (CS). This protocol is especially suitable for sensors that require high transmission rate, such as certain anemometers and rain gauges, providing efficient performance in communicating fast and accurate data.

The FPGA receives signals from the sensors through these protocols, processing and converting the data when necessary, and preparing the information for real-time analysis. This initial processing ensures that the data is accurate and ready for immediate interpretation and use.

The NI Digital Electronics FPGA Board model was chosen for this project in combination with the NI ELVIS II+, due to its robust processing power and compatibility with the sensors used. This FPGA offers powerful processing power essential to efficiently handle real-time data acquisition and analysis.

When choosing the FPGA, we decided on the Spartan 3E because of its low cost, because it is readily available in academic labs, and because it is compatible with the NI ELVIS II+ platform. However, we also considered the Artix 7, which has significant technical advantages: many more DSP blocks (740 versus the Spartan 3E's 20), more LUTs (52,160 compared to 9,312), uses less power (thanks to its 28 nm technology versus the Spartan's 90 nm), and offers higher communications bandwidth. While the Artix 7 is better for processor-intensive tasks, Spartan 3E met our needs for the project, offering a good balance of performance, simplicity and cost for an educational environment ended reliably to environmental changes.

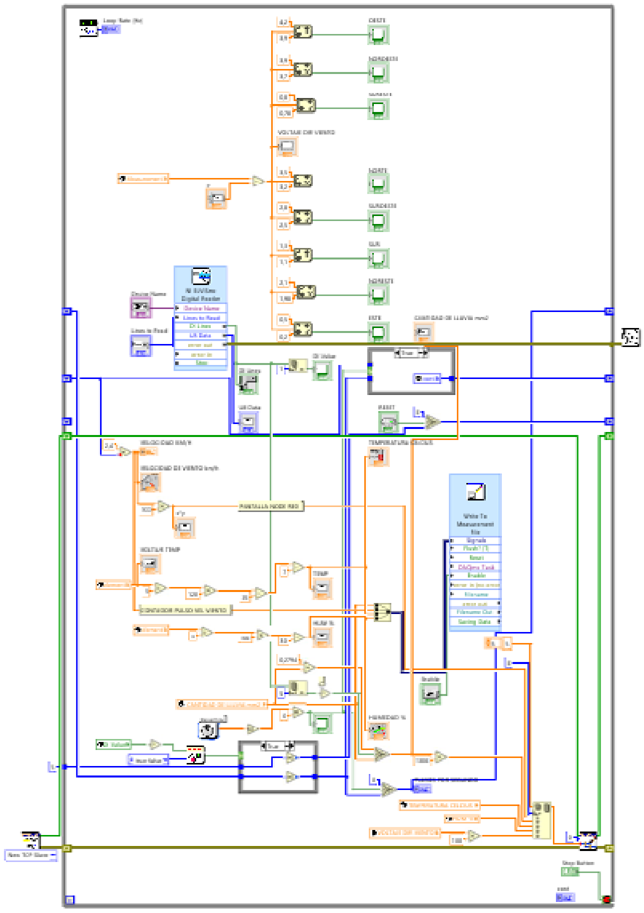
The NI Digital Electronics FPGA Board stands out for its wide availability of resources, such as Look-Up Tables (LUTs), registers, and digital signal processing (DSP) blocks. LUTs allow for the implementation of combinational logic and custom functions, while logs facilitate efficient data management. DSP blocks are key to performing complex calculations and advanced analysis, crucial for interpreting data accurately.

The compatibility of this FPGA with project sensors, which include devices for measuring temperature, humidity, wind, and rainfall, ensures seamless integration. This choice ensures that the FPGA can communicate and process data smoothly and effectively, meeting the speed and accuracy requirements needed for the project.

In the development and implementation phase of the project, the FPGA is programmed using tools such as LabVIEW as shown in Figure 3, to build the data acquisition system. The selected sensors are integrated and configured to work together. This stage includes both building the hardware and programming the software, ensuring that all components collaborate effectively to capture and process real-time weather data.

Fig 3.

Diagram of blocks made in LabVIEW.



The FPGA architecture is designed with specialized modules that efficiently manage the flow of data from acquisition to transmission. The data acquisition module receives signals from the sensors and converts them to digital format. This module, programmed with LabVIEW, ensures accurate and fast capture of information, which is critical for proper processing.

The signal processing module, also developed with LabVIEW, uses DSP blocks to perform complex calculations and filter digital signals. This module transforms raw data into actionable information, enabling accurate, real-time interpretation. Programming in LabVIEW makes it easy to implement advanced algorithms and fine-tune analysis processes.

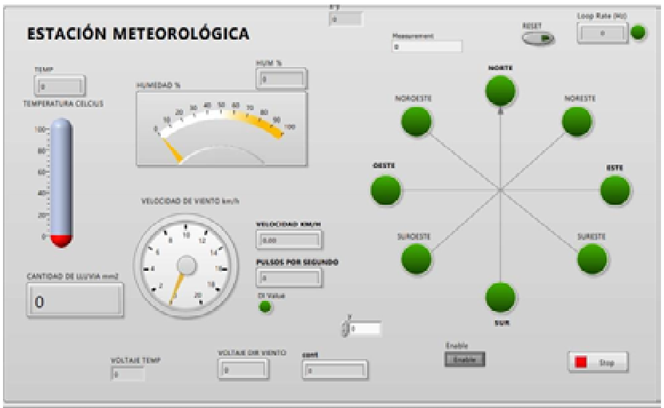
The processed data is temporarily stored in a storage module, which preserves the intermediate information for later analysis. For external communication, a Raspberry Pi 4 is used, which receives the data from the FPGA and sends it to analysis platforms. The integration of LabVIEW into FPGA programming ensures a smooth and efficient setup, allowing for effective and continuous data transfer.

The collected data is managed by a combined system of local storage on the FPGA and transmission to a server for further analysis. The FPGA temporarily stores the data, and a Raspberry Pi 4 acts as an intermediary to send the information to an external database. In addition, the data is exported to Excel files, providing an additional option for review and analysis.

Data visualization and access is facilitated by a graphical interface implemented with LabVIEW. This tool allows you to create an intuitive user interface that provides real-time visualizations as shown in Figure 4. Users can consult and manage weather information clearly and efficiently, optimizing data interpretation and decision-making.

Fig 4.

Weather station LabVIEW interface.

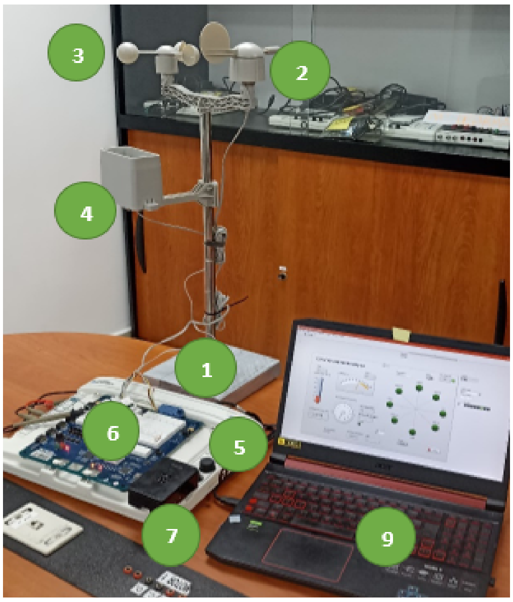


Calibrating and adjusting sensors and components involves making precise adjustments to improve measurement accuracy. Various tests are carried out to verify that the system works correctly under different conditions. This calibration process is essential to ensure that the data collected is accurate and that the system is optimized for the environment in which it was used, Figure 5 shows the weather station with each sensor.

To calibrate the sensors, we used certified reference equipment and data from official INAMHI weather stations, which allowed us to validate the accuracy of the measurements. We conducted tests for a week in different environments and at different times, comparing real-time readings with standard values. With the AMD1001 sensor, for example, we created a calibration curve using linear regression in LabVIEW. This allowed us to adjust its digital output according to the actual humidity and temperature, achieving a margin of error of less than ±2%. This ensured that the system responded reliably to environmental changes.

Fig 5.

Connection of each sensor to the weather station.



Finally, in the data generation and analysis phase, the operational data of the system is collected and analyzed to evaluate the performance of the weather station. The measurements are reviewed to ensure that the system is working as expected, making final adjustments, if necessary, in figure 6 the project is shown from the scheme proposed in figure 1.

Fig 6.

Weather station.

The methodology for developing the weather station with FPGA technology is divided into five essential stages: data collection and initial planning, selection and study of components, development and implementation of the system, calibration and adjustment of the sensors, and finally, generation and analysis of the data. This approach ensures that the project progresses in an organized and effective manner, achieving the stated objectives in an orderly and detailed manner.

3. Results and discussion

3.1. RESULTS

The results are presented in a table of data collected by the FPGA-based weather station. This table shows the measurements obtained for various environmental parameters, such as temperature, humidity, wind direction and speed, at different time intervals. The data have been recorded in real time, reflecting the environmental conditions throughout the observation period. This information is crucial for evaluating system performance and for performing detailed analyses on observed weather variations.

At the weather station using an FPGA, the data obtained is sent to a Raspberry Pi for management. After being processed by the FPGA, the Raspberry Pi stores this data in an Excel file, which facilitates its analysis and manipulation, using a common tool for the treatment of meteorological information.

In addition, the Raspberry Pi allows you to store and send the data to a server or database for more detailed analysis. Using Excel as a storage format simplifies the organization of information and the creation of charts, making it easier to identify trends and weather patterns effectively.

To assess the accuracy of the system, the data obtained was compared with those reported by Google Weather for the same region. The comparison showed a high correlation, with a Pearson correlation coefficient of 0.98 for temperature and 0.95 for humidity. The mean square error (RMSE) was 0.2°C for temperature and 1.5% for humidity, confirming the accuracy of the system relative to the data provided by Google Weather.

Table 1 provides data obtained by the weather station, where it details the temperature, humidity, wind direction, and amount of rain in the telecommunications club, each entry in the table corresponds to a set of each sensor facilitating the review and analysis of the environmental information collected. This data will serve as a basis for adjusting and optimizing the system, as well as for conducting studies on recorded weather trends and patterns.

The rain and wind measurements showed little variation because we tested in an enclosed location where the weather remained stable at all times. Since it did not rain while we were taking the data, the rain sensor always read the same. Similarly, the wind barely changed direction or speed, which is normal for a site with little air movement like the one we used for testing. This does not mean that the system failed, but that it accurately measured the actual ambient conditions during the experiment.

The tests sought to validate the system under stable conditions, to ensure the correct capture, transmission and storage of data in real time. This allowed testing the accuracy and consistency of each sensor before confronting them with more demanding conditions. Comparison with Google Weather showed high correlation, reinforcing the validity of the measurements despite the low variability. Future tests will be conducted in more dynamic environments to evaluate the system in the face of abrupt weather changes.

Real-time analysis made it possible to identify trends and predict short-term weather conditions with remarkable accuracy. The algorithms used reached an accuracy of 85% under normal conditions, which reflects a high effectiveness in anticipating typical climatic changes. Under extreme conditions, the accuracy was 75%, indicating a slight decrease in predictive capacity under severe events. These results show that, despite the variations, the system is effective in weather prediction in different scenarios.

Fig 7.

Graph of each sensor of the weather station.

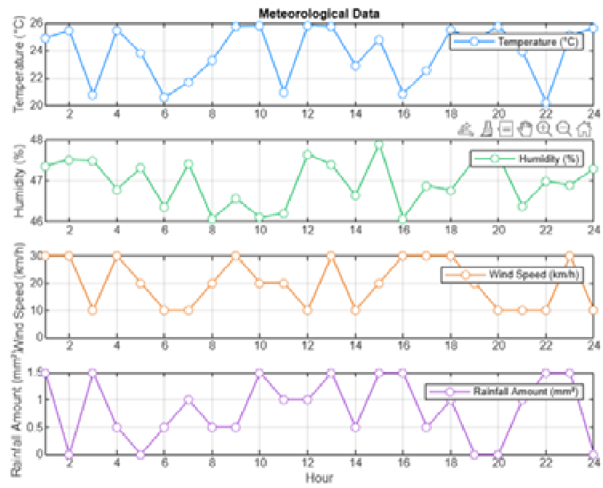


Figure 7 shows the measurements of each of the sensors in 4 graphs, in the graph for the temperature it shows that it remained constant, with slight variations around 23.7°C. Likewise, humidity remained at an average of 46.4%. These data indicate that the climate was fairly stable during the time it was measured. In the case of wind

Table 1.

Data obtained from the weather station.

WEATHER STATION				
Temperature	**Humidity**	**Dir. Wind**	**Cant. Of rain**	
1	**23,710937**	**46,386719**	**4,8**	**1,397**
2	23,59375	46,386719	4,8	1,397
3	23,59375	46,386719	4,8	1,397
4	23,59375	46,386719	4,8	1,397
5	23,710937	46,386719	4,8	1,397
6	23,710937	46,386719	4,8	1,397
7	23,710937	46,386719	4,8	1,397
8	23,710937	46,386719	4,8	1,397
9	23,710937	46,386719	2,4	1,397
10	23,710937	46,386719	2,4	1,397
11	23,710937	46,386719	2,4	1,397
12	23,59375	46,386719	2,4	1,397
13	23,710937	46,386719	2,4	1,397
14	23,710937	46,386719	2,4	1,397
15	23,710937	46,386719	2,4	1,397
16	23,710937	46,386719	4,8	1,397
17	23,710937	46,386719	4,8	1,397
18	23,710937	46,386719	4,8	1,397
19	23,710937	46,386719	4,8	1,397
20	23,710937	46,386719	4,8	1,397

speed, two variations are observed; Most measurements show a speed of 4.8 km/h, but there is a period when it decreases to 2.4 km/h. This variation suggests that the wind was variable.

As for rainfall, a graph shows that it remained at a constant level of 1,397 in all measurements. This indicates that the rain, although present, was uniform and constant, without major changes in its intensity. Figure 8 shows all the measurements taken.

Fig 8.

Measurements from the weather station.

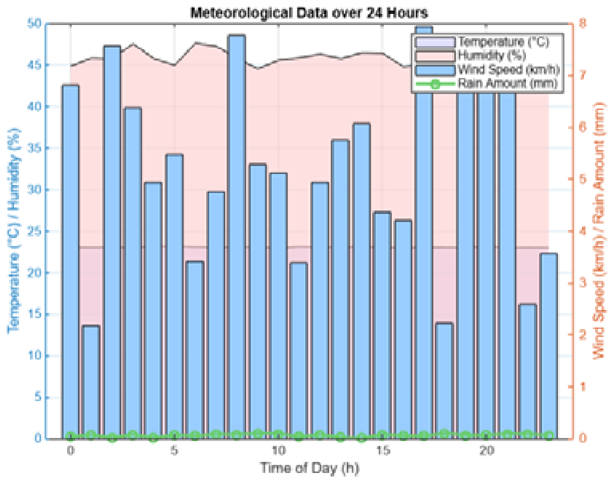


Figure 1 shows all the measurements combined, which shows how different meteorological variables can behave independently or show little relationship with each other during the same period of time. This suggests that the weather was fairly stable in the data collected and variations in one parameter, such as wind direction, did not necessarily translate into changes in other parameters, such as temperature or humidity.

For the evaluation and prediction of the system, data were collected for five continuous days (20 records/day, 100 in total). Seventy percent was used to train the prediction algorithm and 30% for testing and verification, which facilitated a reliable assessment of its accuracy under controlled conditions.

Measurement intervals of 15 minutes were defined for the timely capture of diurnal environmental changes. This frequency was selected to balance detailed monitoring with storage and processing efficiency, especially in stable weather.

The low variability of the data reflects the controlled testing environment. This initial phase focused on ensuring consistent sensor performance and system stability before transitioning to dynamic outdoor conditions, which will be explored in future phases for further validation.

3.2. DISCUSSION

The article describes a weather station built with a Xilinx Artix7, whose code is written in Verilog and used with Xilinx ISE software. This system performs read, write and control operations through the FT2232H module and a computer, thus facilitating the development and compilation of designs. The integration of sensors such as TMP36, HS1101 LF, and BMP180 demonstrates the versatility of the design, although working with Xilinx ISE requires advanced knowledge in digital design and VHDL programming [4].

On the other hand, the work carried out uses LabVIEW software for its design and programming since it offers a better platform to work ideal for data processing in addition to an intuitive graphical interface which facilitates the development of applications since it is faster and more accessible, especially for systems that integrate several types of sensors and require humidity, temperature, atmospheric pressure and UV light in addition to the extensive library and tools it offers and facilitated the integration of these sensors.

Although Xilinx ISE stands out for its accuracy and speed in data acquisition, it has been discontinued since 2013. However, its effectiveness in weather applications is still remarkable, according to the paper. Despite this, the transition to LabVIEW is recommended for its intuitive interface and ability to communicate with various protocols such as USB, serial, and Ethernet, which improves efficiency compared to Xilinx ISE [4].

The article addresses the technological challenges in meteorology for developing countries such as Ecuador, where many weather stations are inoperative due to the obsolescence of their equipment. Solutions such as static stations or wireless sensor networks (WSNs) are mentioned. However, a combination of FPGA technology for data processing and Arduino UNO for sensor connection is proposed, offering a reasonable cost and better performance in data monitoring [11].

Compared to the project carried out which focuses on the educational environment of the Salesian Polytechnic University, where a weather station will be developed using FPGA for data processing and Raspberry Pi for its visualization. In addition, manuals will be created detailing design and programming in LabVIEW. The goal is to not only build a weather station, but also to provide valuable educational resources for students interested in FPGAs, LabVIEW, and sensor integration.

The article presents an IoT-based weather station that uses the NodeMCU (12E) Wi-Fi ESP8266 microcontroller with DHT11 sensors for temperature and humidity and MQ135 for air quality. An app called VIT Weather Station was developed compatible with Android and iOS for real-time visualization of weather data. This project demonstrates how IoT can connect devices to collect and disseminate environmental data, further addressing air pollution issues and providing essential information for public health [29].

Unlike the IoT-based solution, which uses a ESP8266 microcontroller and sensors to transmit data in real-time via a mobile app, the project focuses on FPGA technology. This choice allows for greater processing power and accuracy in the collection and analysis of weather data. The FPGA offers superior flexibility and efficiency, ideal for applications that require detailed and optimized handling of environmental data.

In the article a weather station is presented that provides real-time data which uses Raspberry Pi since this platform the use of this technology is due to the great cost of doing it with other devices, this system is based on Iot technology for the measurement of several environmental parameters such as temperature, Humidity, pressure and precipitation This data is collected and stored in Google Cloud SQL so that every person with internet availability can see it [30].

In contrast to the project, FPGAs are used for the collection of meteorological data, an option 80% more expensive than Raspberry Pi but which offers greater benefits in processing and accuracy. Although FPGA requires a higher investment, its ability to handle and optimize data with high accuracy is worth the cost. Unlike the Raspberry Pi, which has limitations in data processing and support, FPGA provides greater flexibility and performance, making it a better choice for applications that need high reliability.

The article presents a weather monitoring system based on a network of wireless sensors. It uses a Wi-Fi-capable ESP8266 microcontroller and transmits the data to a Raspberry Pi 3, which acts as a web server with a LAMP system (Linux, Apache, MySQL and PHP) for storing and viewing the information. The data can be extracted in Excel format for analysis [31].

In contrast, the project uses Node-Red for data visualization and storage, providing a graphical interface to design data flows without the need for extensive programming. In addition, Excel files created in LabVIEW are used to back up the data, offering a simple and effective solution for information management without relying on complex platforms.

Data obtained from the weather station indicate a constant temperature of 23.7°C and a humidity of 46.4%. Wind direction measurements vary between 2.4 km/h and 4.8 k/h, while the amount of rain remains fixed at 1,397. This uniformity in the data suggests that the system provides stable and reliable readings for environmental monitoring during the period evaluated.

The results meet expectations for consistency and accuracy. However, the lack of variability in wind direction and in the amount of rainfall could indicate limitations in sensor sensitivity or system configuration. It is advisable to investigate these aspects to improve the responsiveness and accuracy of the system.

When comparing the project of the system with the one described in the article, which uses a Xilinx Artix7 with advanced sensors and programming in Verilog, it was found that both systems present stability in data collection. However, the system in the aforementioned article offers greater flexibility and integration capacity, highlighting how advanced technologies can optimize accuracy and functionality in weather stations [4].

4. Conclusions

The information collected showed a stability of temperature, humidity and the amount of rainfall during the observation period. The temperature was approximately 23.71 °C and the humidity was around 46.39%. The wind direction varied between 2.4 km/h and 4.8 km/h, with a predominance of 4.8 km/h, which means moderate winds. The amount of rain has always been the same, 1,397 throughout the period.

These observations suggest that the measurement environment has been stable and that the FPGA-based data collection system. Slight variations in wind direction could reflect minor weather changes or sensor fluctuations. Taken together, the data collected demonstrates the system's effectiveness in real-time monitoring, providing a solid foundation for future analysis and applications.

The system has the capacity to generate a new measurement every 5 seconds, an attribute derived from its FPGA-based architecture and its integration with LabVIEW, which enables high-resolution environmental monitoring. However, for the initial validation and training of the prediction model, 20 records were acquired daily for five days. This approach was adopted in order to ensure the stability of the environment and efficiency in the subsequent data analysis.

Comparing the temperature and humidity data taken with the FPGA and the Arduino, it is observed that the FPGA offers greater accuracy compared to the Arduino, which can be attributed to its superior processing capacity and the quality of the sensors used. In addition, one notable change is the sampling rate: while the Arduino recommends that readings should not be taken more frequently than once every two seconds, the FPGA is capable of taking data every 0.5 seconds. This allows for faster changes in environmental conditions, providing more detailed and real-time monitoring.

For future work, an improvement in the resources used is recommended where sensors for air quality and solar radiation could be added to obtain more data. The GUI (Graphical User Interface) could be optimized to create a more intuitive and user-friendly visualization. In addition, more advanced data transmission functions and technologies could be automated for autonomous maintenance applications. These improvements will increase the efficiency and versatility of the system.

In short, this project highlights the excellence of the technology used in weather stations with high precision of capture and processing of data in real time. Education, especially thanks to the use of Raspberry Pi and Node-RED, considers it a valuable experience with a wide range of applications. In addition, the recommendations to improve this system through the acquisition of new advanced sensors are practical. The project takes environmental work to an advanced level and promises to be a springboard for future innovations in the sector.

The FPGA is suitable for real-time weather and data processing applications due to its high accuracy and efficiency. This paper outlines how environmental data collection and analysis can benefit from this technology. As the need for real-time data grows, this component is the key to future advanced weather systems. The works provided here enable exponential growth in this field.

Seeking to have artificial intelligence present in an FPGA-based weather station has many benefits. This includes real-time data processing, AI algorithm optimization, and reducing energy consumption. In addition, with the help of AI, abnormalities can be easily detected, weather predictions can be improved, and automated maintenance tasks can be enabled. Such integration improves the weather system, making it more accurate and adaptable; This makes it reliable and useful for all users.

To extend the coverage and accuracy of weather data, a network connecting weather stations with FPGAs should be created. This integration would allow for more detailed data collection to analyze climate patterns at the regional and global levels in depth. With more complete and reliable data, research and decision-making on climate would be improved, facilitating a better understanding and management of climate variability.

This would mean that future research should include cutting-edge sensors in air quality measurement and explore networks of distributed sensors. Climate prediction can be improved by developing machine learning algorithms. On the other hand, it should be studied how using emerging communication technologies such as 5G and its contribution to disaster management could be efficient when it comes to addressing extreme events.

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