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Influence Human body on Impedance of Wearable Antenna

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ABSTRACT

This paper investigates the influence of the human body on the input impedance of wearable antennas, with a focus on dipole and microstrip antenna designs operating at 0.9 GHz. Instead of directly modeling the complex human body, equivalent structures such as perfect electrical conductor (PEC) planes with various geometries (square and rectangular) and multilayer configurations are employed using CST 2011 simulation software. The study analyzes the relationship between antenna input impedance and the distance between the antenna and the approximated body models. Several configurations, including floating dipole antennas and microstrip antennas, are evaluated under different plane dimensions (3×3, 6×12, and 9×9) and multilayer materials representing human tissues. Additionally, a cylindrical model is considered to better approximate the human body shape. The results demonstrate that antenna performance, particularly input impedance, is significantly affected by nearby structures, while optimized configurations-especially the rectangular 6×12 plane-achieve desirable impedance matching around 50–70 Ω. The findings indicate that floating dipole antennas exhibit more stable and suitable performance for wearable applications compared to microstrip designs, particularly in proximity to human body-like environments.

Keywords: Wearable Antennas, Input Impedance, Body Area Networks (BAN), Floating Dipole Antenna, Microstrip Antenna, Human Body Modeling, Electromagnetic Interaction, CST Simulation, Impedance Matching, On-Body Communication

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1. Introduction

The weather situation influences airport operations and air traffic control (ATC) directly, in a decisive way, especially during aircraft departure, arrival, and taxi [1, 2]. Parameters including temperature, humidity, rain, and wind speed have a significant effect on runway condition, aircraft performance, and operational safety. Irrespective, precise real-time weather monitoring is generally considered an important disruption detection for all new aviation systems [3, 4]. The traditional airport meteorological station provides very high-quality measurements but comes at a cost of extremely expensive installation, maintenance, and operational expenses [5]. Small and regional airports, training centers, or temporary deployment may not be able to afford these systems. Furthermore, rigidity and scalability of the legacy systems also lead to consideration of embedded alternatives, which can be easily extended as well as integrated with current air traffic control equipment at low cost [6, 7]. Development in the area of embedded and microcontroller systems has resulted in some forms of environmental monitoring station systems, which are low-cost, support real-time data acquisition and processing [8, 9]. Weather monitoring systems implemented using microcontrollers are advantageous in terms of being modular in nature, low power consumption, easy setup, and varied operating requirements. Such properties render embedded systems particularly valuable for in-situ weather sensing at airports [10, 11].

In this regard, the present paper suggests a low-cost embedded weather monitoring system intended for airport air traffic control. The design has an Arduino Uno microcontroller as the core and includes various environmental sensors to measure temperature, relative humidity, rainfall, and wind speed. A special infra-red (IR) anemometer is applied to measure wind speed in the time domain with interrupt technology for high measuring precision. All sensor data is processed and graphed in real-time with an I2C-connected LCD that allows for instantaneous readout. The main contributions of the paper are as follows:

- Design of Low-Cost Embedded Weather Monitoring System for Airport Air Traffic Control: A Case Study on Affordable and Deployable Systems.
- Integration of various environmental sensors that record temperature, relative humidity, rainfall, and wind velocity is also provided with online data processing.
- Construction of a home-made IR anemometer with interrupt-based pulse counting for accurate wind speed reading.
- Development of a real-time GUI interface with an I2C-based LCD, to give prompt situational awareness to the operator.
- Experimental confirmation of the developed solutions using an operating hardware prototype with testing in real environmental conditions.

The remainder of this paper is organized as follows. Section 2 reviews related work on embedded and Arduino-based weather monitoring systems. Section 3 presents the system architecture and hardware design. Section 4 describes the implementation methodology. Section 5 discusses the experimental results and performance evaluation. Section 6 outlines future directions and open issues, and Section 7 concludes the paper.

2. Related Works

Weather monitoring has been extensively researched because it is vital for environmental observation, disaster prevention, and transportation safety [12 -14]. For example, conventional meteorological stations in an airport, such as a typical airport meteorological observatory, can offer very accurate measurements but cost a lot and are limited to being deployed at small airports or regional ones due to a complex installation process, and are less extensible than their counterparts mentioned above.

A low-cost Arduino-based mobile weather station for climate monitoring and educational purposes in Mauritius is presented by Ujoodha et al. [15]. The system reports several different environmental conditions, and increases the understanding of climate change in students by involving them in data gathering while heightening their aware- ness and decisions based on knowledge throughout their educational career. Mabrouki et al. [16] presented an IoT-based automated weather monitoring system to acquire the real-time climatic status with the help of embedded sensors and wireless communication. The temperature, humidity, and gas presence are captured by the system, with measurement data being sent to remote databases for onboard visualization (graphically or in a tabular manner) and analysis. In Michailidis et al. [17], a portable weather monitoring station developed on an Arduino platform incorporating temperature, humidity, pressure, and CO sensors, complemented with GSM communication, is presented. Through ThingSpeak, it can transmit data to the cloud for cost-effective, real-time, long-range environmental monitoring with a scalable and modular system design. Venugopalaswamy et al. [18] introduced an air quality and weather monitoring system using IoT (Internet of Things) with ANN-embedded hardware in Arduino RP2040 platform powered by TensorFlow Lite. As one can see, our system can estimate air quality based on real-time sensor information with an accuracy rate of 85.27%, which implies the achievement of machine learning–aided environmental monitoring. Stoyanov et al. [19] introduce how to build a DIY IoT-based automated weather station for real-time observation and visualization of the weather conditions. The system transmits the data collected to a website, an Android application, and the cloud plat- form ThingSpeak, enabling reliable response time as well as ubiquity and mobility at relatively low-cost based on open-source hardware and software.

Contrary to the existing works, oriented mostly toward general-purpose environ- mental monitoring or for IoT platforms, this paper addresses an embedded weather monitoring system solution, especially designed to meet the requirements of the air traffic control ecosystem in airports as a cost-effective one. The vision to fulfill is a system capable of real-time operation, easy handling, and low costs, as well as an individual IR-based anemometer with interrupt-based wind speed detection. It simplifies the system and improves response speed, making it an alternative to traditional airport meteorological systems.

3. System Architecture and Design

The system is realized through a modular embedded structure including environmental sensors, an MCU, data processing logic, and a user display interface. The architecture is aimed at achieving real-time monitoring, low power consumption, and easy deployment in an airport, as shown in Figure 1. The system works by aggregating weather data from multiple sensors scattered around the monitoring location. These sensors record data such as temperature, humidity, rainfall, and wind velocity. The readings of the sensors are directly transferred to an Arduino Uno microcontroller, where raw signals are processed, translated into meteorological values, and then visualized through an I2C-based LCD module. This structure provides a system for always-on monitoring, plus quick viewing by the airport staff of what conditions are relevant to flight operations. The hardware is designed to be inexpensive, simple, and extremely reliable, and can be installed at any airport, from small airfields upwards, or even still for educational purposes.

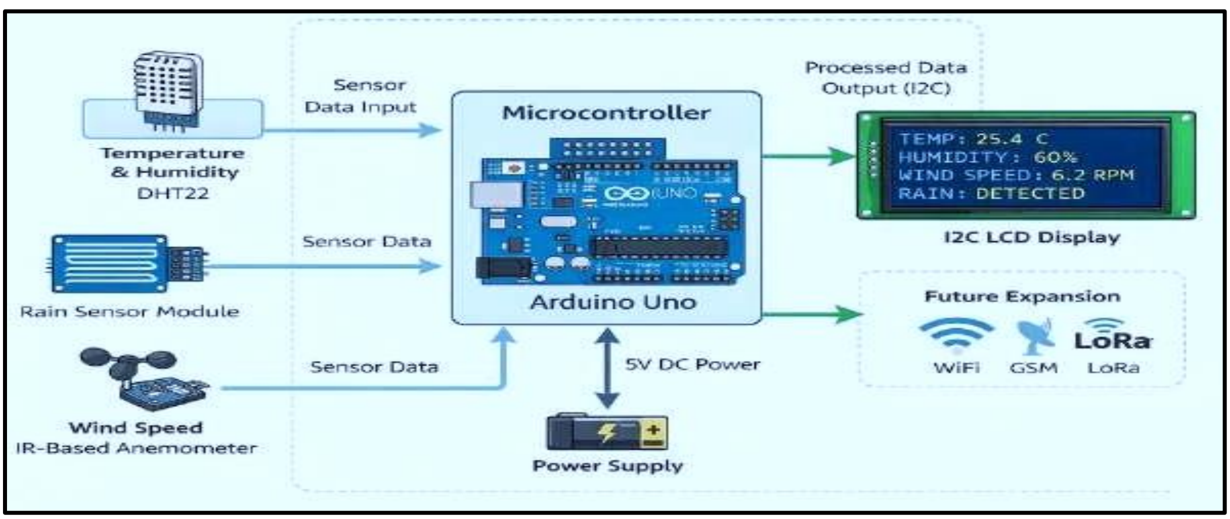

Figure 1. Overall system architecture illustrating the main components and their interactions

• Microcontroller Unit: The heart of the system is an Arduino Uno, which is powered by an ATmega328P Microcontroller. It was chosen for affordable cost, commercial availability, good programmatic interface, and computing capacity that allowed real- time signal processing of sensor data. Key features include: 14 digital input/output pins; 6 analog input pins; support for interrupting measure wind speed, and use the library function to write the program. I2C communication for LCD interfacing. Sensor interfacing, signal processing, interrupt handling, and data visualization are performed by the microcontroller.

• Environmental Sensors: In order to record meteorological data useful for the operation of an airport, various sensors are included:

– Temperature and Humidity Sensor (DHT22): It measures ambient temperature and relative humidity fairly accurately for environmental monitoring. The digital output reduces noise sensitivity and facilitates the interface.
– Rain Sensor Module: Senses the presence of rain using a Rain Sensitive Recorder Pad and comparator circuit. The digital output can be used for fast detection of rain events that could impact runway operations.
– Wind Speed Sensor (IR-Based Anemometer): A modified type of anemometer is made with a rotatable mechanical system and an IR (infrared) sensor. Wind speed is determined by counting IR pulses from rotation, with hardware interrupts used to ensure accurate measurement.

• Display and User Interface: Real-time weather parameters are displayed using I2C based 16×2 LCD module. I2C (Inter-Integrated Circuit) communications interface allows for ease of configuration with high-integration while minimizing the number of microcontroller pins needed. Displayed parameters include: Temperature (°C); Relative humidity (%); Wind speed (RPM-based calculation); and Rain status (Rain/ No Rain). The straightforward display enables airport operators or staff mem- bers to readily ascertain weather conditions without the need for extra computing equipment.

• Power Supply and Expandability: Powered by 5V DC (standard) supply for laboratory test and Permanent installation. Here you have architecture that paves the way for future extension and also: Incorporation of wireless communication mod-ules (WiFi, GSM, and LoRa). Advanced sensors added include barometric pressure, wind direction, and UV radiation. Linkage to central airport monitoring or ATC system. This modular architecture enables the proposed system to be tailored as well as scaled up or down to changing airport operation needs.

4. Implementation and Methodology

Implementation The practical implementation of the low cost embedded weather monitoring system is presented in this section through interfacing, sensor integration and software development along with anemometer construction on hardware level via Arduino platform.

4.1 Hardware implementation

Figure 2 shows hardware implementation of the proposed cost-effective embedded weather monitoring system, showing the integration of environmental sensors, Arduino Uno microcontroller, and I2C-based LCD module. Interfacing of the sensor and circuit design: On the technical side, it’s based on an Arduino Uno controller that connects to a whole collection of environmental sensors in order to pull down live weather data. All the sensors are driven by a regulated 5 V DC power supply and interfaced via suitable digital and analog pins. The DHT22 temperature and humidity sensor features a single-wire digital inter- face, which makes it possible to collect both atmospheric temperature and relative humidity measurements. The rain sensor module is produced with precision technology to simulate the field environment, and connected to the MCU as an interrupt input.

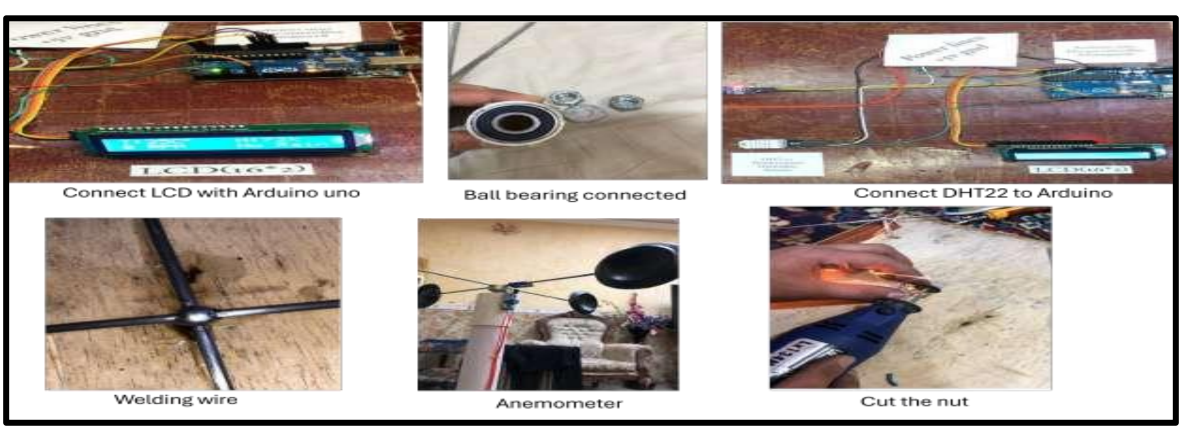

Figure 2. Hardware prototype of the proposed embedded weather monitoring system.

• Anemometer development and measurement of the wind speed: We fabricate an in- house mechanical anemometer characterized by a small mass rotational structure with a low-friction bearing system, which improves the response time of the device toward flow variations. The rotating part is created to form temporary obstacles detectable by the IR sensor. A pulse is generated for every rotation of the anemometer and counted in an ISR. The number of pulses during a fixed time duration is processed to determine the rotational speed (RPM). This method can accurately estimate the wind speed under changing airflow conditions.

• Software Implementation: The actually used development environment for the system software is Arduino Integrated Development Environment (IDE) with embedded C/C++ programming. There are also specialized libraries to help interact with the sensor and the LCD module. This program runs in an infinite loop and it does the following steps: Interpret the temperature and humidity from the DHT22 sensor; The digital rain sensor output senses if the weather is wet or dry; Use hardware interrupts to count IR pulses for wind speed; Convert raw sensor data into real-world physical values; Show and continuous write the processed weather parameters to the I2C LCD. Using an interrupt-driven wind speed measurement for accurate pulse counting without blocking the main program. The readings were revised online, and the results of estimated values on a daily basis, which allowed continuous surveillance with little apparent lag.

4.2 System Operation Flow

The working process of the developed low-cost embedded weather monitoring system has been implemented to enable the prompt, real-time measurement and timeo-graphic representation of meteorological parameters in air traffic control applications for airports. At the beginning of system startup, all sensors, the I2C LCD module, and the interrupt service routine for wind speed measurement are initialized by Arduino Uno. Once initialized, the system begins in a loop of continuous monitoring. In every cycle of the monitoring process, the temperature and humidity are taken initially from sensor DHT22. Then the rain sensor module is polled for whether it is have rain. Meanwhile, the wind speed is measured by collecting infrared pulses of each rotation from the rotating anemometer with an interrupt mode in order not to interfere with the main program execution. The obtained sensor information's are then processed in order to be transformed into physical quantities. According to the rain sensor output, the system recognizes both Rain and No Rain weather states. All the calculated weather parameters are shown in real time on the I2C-equipped LCD and can be interpreted directly by the operator. This process is being repeated every fixed time period, so that the weather monitoring outside and air ahead operation on the grostation will continue. This model uses structured flow, which offers both low overhead during computation and high responsiveness, along with stability in the task of airport application.

5. Experimental Results and Discussion

Experimental results and discussion of the proposed low-cost embedded weather monitoring system design developed for airport ATC application are presented in this section. Another tool was developed for signal generation and synchronization of the sound source in real environmental conditions to validate the system with respect to its functionality, free force response, and reliability.

5.1 Experimental Setup and Results

The experimental system is composed of an Arduino Uno–based prototype equipped with a DHT22 temperature and humidity sensor, a rain sensor module, an IR-based anemometer to measure wind speed, and an I2C LCD display, as shown in Figure 3. The system was energized by a regulated 5 VDC power supply, and it ran continuously in the testing regime. The DHT22 sensor was able to offer stable and regular ambient temperature and relative humidity readings, which were updated every few moments and shown on the LCD. The module successfully sensed the water droplet presence, which allowed easy and quick weather classification as Rain or No Rain. Wind speed was based on the infrared pulses produced by the anemometer rotation. A pulse counting mechanism based on interrupts allowed measurement that is accurate without disturbing the system responses. Calculated wind speed output was presented in real time to signify the success of the custom anemometer. On the whole, the setup worked without any communication errors or sensor malfunctions, supporting the robustness of hardware and software integration.

Figure 3. Results of This Paper

5.2 Discussion

The experimental results indicate that the developed system can be suitable for real-time measurement of important meteorological factors in airport operations. Connection of inexpensive Sensors to an onboard microcontroller with the support of software makes a practical trade-off between performance and cost. The measurement accuracy remains modest compared to commercial airport weather stations, but it provides acceptable data for situational awareness and crude decision support. The utilization of wind speed measurement with interrupts dramatically increases reliability over polling. The I2C compatible LCD interface reduces the number of required system wiring and scales design easier. From an operational point of view, the system could help air traffic controllers by offering immediate information on local weather conditions, including rainfall and wind, which are important factors in takeoff and landing. Low power consumption and modular design also make it suitable for use in small or regional airports. However, sensor calibration and encapsulation are yet long-term outdoor deployment considerations. The prototype is functionally valid, but additional improvements in performance are necessary to satisfy the very strict accuracy requirements for certified aviation meteorological systems.

6. Future Directions and Open Issues

Although the performance of the proposed low-cost embedded weather monitoring system is very attractive, there is still some room/deliverables and open research issues in future work to address to improve accuracy, scalability, and operational suitability for airport air traffic control.

6.1 Future Directions

• Integration of Additional Meteorological Sensors: Subsequent steps include the addition of a barometric pressure sensor and digital compass for wind direction, providing more complete weather coverage relevant to aviation. The addition of UV and gas sensors would allow for additional environmental monitoring and safety assessment.

• Wireless Communication and ATC Integration: The system is expandable with Wi- Fi, GSM, or LoRa modules for real-time data transfer to central ATC monitoring systems for remote access, data logging, and archive purpose.

• Calibration and Accuracy Enhancement: Establishing systematic sensor calibration processes and correction algorithms should enhance measurement accuracy, otherwise degraded in extreme outdoor environments.

• Data Logging and Analytics: Future models may have data storage and analytics capability that resides either onboard or in the cloud, so historical trends can be analyzed and early warnings of hazardous weather conditions produced.

• Robust Enclosure and Outdoor Deployment: Development of a weather-proof housing and long-term field testing will improve system ruggedness and readiness for continuous outdoor deployment at airports.

6.2 Open Issues

• Measurement Accuracy vs. Certification Standards: Although the system delivers real-time situational awareness, ICAO-certified meteorological accuracy has not yet achieved, and hence the system remains suited for supportive or follow-on applications only.

• Environmental Exposure and Sensor Degradation: Long-term exposure to excess heat, moisture, and dust may result in the degradation of sensor performance, which requires periodic maintenance and adjustment.

• Scalability and Network Management: Working in a multi-airport zone spanning environment causes difficulty in implementing network synchronization, data fusion, and latency control, particularly for wireless-based links.

• Security and Data Integrity: Future wireless extensions need to address data security, authentication, and integrity, especially when incorporated with safety-critical air traffic control infrastructure.

In this regard, the present paper suggests a low-cost embedded weather monitoring system intended for airport air traffic control. The design has an Arduino Uno microcontroller as the core and includes various environmental sensors to measure temperature, relative humidity, rainfall, and wind speed. A special infra-red (IR) anemometer is applied to measure wind speed in the time domain with interrupt technology for high measuring precision. All sensor data is processed and graphed in real-time with an I2C-connected LCD that allows for instantaneous readout. The main contributions of the paper are as follows:

7. Conclusion

This paper describes an embedded WM system offering a low-cost solution for airport ATC applications, operating in real-time and measuring the most important meteoro-logical parameters. The proposed system combines several environmental sensors with an Arduino Uno microcontroller for the easy and accurate monitoring of temperature, humidity, rainfall, and wind speed. The hardware prototype and software solution illustrate that lower-budget edge platforms can perform continuous monitoring of the weather with adequate precision for situational awareness, as well as preliminary decision support in airports. An IR anemometer with pulse counting makes for a robust wind speed monitor, and the I2C-based LCD display makes it easy to spot check the current conditions. Test results demonstrate that the system can work as expected in practical environments stably, which illustrates the feasibility, modularity, and scalability of our proposed design. The system is not a substitute for certificated aviation meteorological observation stations; it makes an economical alternative, notably where small or local airfields and educational or experimental projects are involved. Taken as a whole, the proposed scheme provides a good compromise between performance, cost, and accessibility. With additional improvements of sensor calibrations, wireless data transmission, and more advanced data analytics, the system may contribute much more to becoming an intelligent and integrated airport weather monitoring system.

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Ethics declarations
This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication
Not applicable.

Competing interests
All authors declare no competing interests.

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