NKUA Weather Station Network Project

General Project Description, Requirements, Objectives, Methodology

Version 2

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Contents

Purpose

The purpose of this report is to present the preliminary analysis stage for the development of a ground-based weather station network and its associated application programming interface (API) and user interface (UI). The project aims to develop and implement three ground-based weather stations that will collect real-time meteorological data in a fully automated manner. The collected data will be stored for subsequent analysis and research purposes.

This report sets the fundamental requirements and objectives of a weather monitoring network of ground-based stations. For the proposed system architecture a set of design options are defined and the design methodology to implement these options is set.

Introduction

Developing a network of ground-based weather stations offers numerous advantages across various domains. By providing a wealth of data and insights, such a network significantly contributes to scientific knowledge, enhances weather forecasting accuracy, supports climate research, and enables informed decision-making in multiple sectors. The data collected from these stations play a crucial role in comprehending weather and climate dynamics, addressing environmental challenges, and ensuring the well-being and safety of individuals. The following highlights some of the key benefits associated with a weather station network:

Improved spatial resolution: A network of ground-based weather stations allows for increased spatial resolution in weather monitoring. By distributing stations across a region, they provide localized weather data, which help capture microclimatic variations and understand weather patterns at a more granular level. This spatial resolution enhances the accuracy and reliability of weather forecasts and climate change.

Data validation and calibration: Ground-based weather stations serve as reference points for data validation and calibration. They provide accurate and reliable measurements that can be used to cross-validate data collected from other sources, such as satellite platforms. This helps to improve the quality and reliability of weather data and supports the calibration of other weather monitoring instruments.

Long term climate studies : Ground-based weather stations contribute to long-term climate studies. By collecting historical weather data over extended periods, analyzing trends, identifying climate change patterns, and modeling future climate scenarios with high accuracy is possible. These studies provide insights into climate variability, regional climate trends, and the impact of human activities on the environment.

Verification of weather models : Weather stations play a vital role in verifying and validating weather prediction models. By comparing the observed weather data from ground-based stations with the predictions generated by models, scientists can assess the accuracy and reliability of the models. This feedback loop helps refine and improve weather forecasting models, leading to more precise predictions and improved understanding of atmospheric processes.

Research and scientific investigation: A network of ground-based weather stations provides an invaluable resource for scientific investigations across various disciplines. Meteorologists, climatologists, environmental scientists, and other researchers can access the weather data to study specific phenomena, investigate the impacts of weather events, analyze atmospheric processes, and assess the effects of climate change on ecosystems. These studies contribute to our understanding of the Earth's climate system and support evidence-based decision-making in various sectors.

Emergency response and risk mitigation: Ground-based weather stations are essential for monitoring severe weather conditions and supporting emergency response efforts. Accurate and localized weather data from the network can assist in predicting and tracking severe storms, hurricanes, floods, or other hazardous weather events. This information helps in issuing timely warnings, preparing communities for potential risks, and facilitating effective disaster response and mitigation strategies.

Education and public out-search: A network of ground-based weather stations offers an excellent platform for educational initiatives and public outreach. Weather data collected from the stations can be shared with schools, educational institutions, and the public, promoting awareness and understanding of weather patterns, climate change, and environmental stewardship. Citizen science projects can also involve the public in data collection and analysis, fostering scientific engagement and empowering communities to contribute to weather research.

Requirements and objectives

Data collection: The primary objective of a weather station network is to collect accurate and reliable weather data. This includes measurements such as temperature, humidity, wind speed, wind direction, precipitation, and atmospheric pressure. The network should be designed to capture and transmit these data points from multiple weather stations thus multiple ground regions.

Data accuracy and precision: Weather data must be collected with a high degree of accuracy and precision to ensure reliable analysis and forecasting. The network should include calibration and quality control mechanisms to verify and maintain the accuracy of the collected data. Factors like sensor calibration, regular maintenance, and periodic sensor replacement to minimize errors are to be considered as good practices.

Data transmission: The network should facilitate the transmission of weather data from the individual weather stations to a central database system. The data transmission can be achieved through various communication technologies for wired and wireless transmission. Wireless communication, however, is considered the best option. Protocols such as Wi-Fi, LoRa, or cellular networks are to be considered.

Scalability: The weather station network may need to accommodate a varying number of weather stations. The network should be designed to easily scale up or down to support the addition or removal of weather stations without significant disruption or reconfiguration.

Real-time monitoring: Weather station networks require real-time monitoring capabilities, allowing users to observe current weather conditions continuously. This includes displaying live weather data on web-based interfaces or other platforms and applications facilitating timely decision-making and enabling users to respond to changing weather conditions promptly.

Data storage: The network should include mechanisms for storing and archiving historical weather data. The storage capacity, backup strategies, and data retention policies when designing the network are some of the most significant features considered. Also applications and platforms that use this data must be not dependent on the data storage mechanism, the storage location or the storage type.

Placement: The stations should be placed in an open area, away from any obstructions that could affect the sensor readings. They should be positioned at an appropriate height and orientation to ensure accurate measurements. The anemometer should be placed at a sufficient height above the ground to avoid interference from nearby objects, the temperature and humidity sensors should be positioned away from direct heat sources, possibly away from direct contact with the sun’s radiation. The precipitation measurement device must not be covered from all four sides and top.

Data visualization and analysis: The weather station network involves providing users with intuitive visualizations, charts, and graphs to interpret the collected data effectively. Analysis features like trend analysis, statistical calculations, and forecasting models also should be integrated into the network to assist users in understanding weather patterns and making informed decisions.

System reliability and redundancy: To ensure continuous operation, the network should be designed with redundancy measures. This includes backup power supply options, redundant data storage, and failover mechanisms in case of connectivity or hardware failures.

Security: This includes mainly access control to the user interface. User authentication, and intrusion detection systems are to be considered to protect the integrity and privacy of the data. The database system and the station control must not be accessible by end-users, but only by the administrator.

Integration and interoperability: The weather station network may need to integrate with other systems or platforms in the future, such as meteorological agencies, research institutions, or IoT ecosystems. Interoperability standards, API’s, and industrial data exchange formats (eg CSV) to ensure seamless integration with external systems must be taken into consideration.

Maintenance and support: The network should be designed with ease of maintenance in mind. This includes remote monitoring and diagnostics capabilities, firmware update mechanisms, and a well-defined support system to address any issues that arise during the operation of the weather station network. Tactical maintenance planning should be considered as a solution to fix possible bugs and system errors.

Testing and quality assurance: Rigorous testing and quality assurance procedures are crucial to identify and resolve potential issues or bugs in the API and the hardware system. Thorough testing, including unit testing, integration testing, and performance testing must be done in every step of the design procedure. The implementation of a debugging mode mechanism for all the components is very important. Furthermore the quality of data must be measured and the sensor integrity must be tested extensively.

Documentation: Extensive documentation about the API endpoints, data formats, integration guidelines, system architecture and design approaches are very important for the future extension and management of the project. A series of design, implementation and user manual reports make it easier for the following developers and the end users to utilize this product.

Proposed Design

The initial phase entails establishing the system requirements and objectives. This involves clearly defining the desired functionalities and goals of the weather station network. Subsequently, conducting thorough research in the open literature related to this topic is essential. This research serves as a foundation for creating a general description of the entire project, outlining the overall behavior of the system. Analyzing the set of requirements in this high-level description helps identify the various components that constitute the system, providing a higher level of abstraction thus simplifying the design process.

The proposed concept revolves around establishing initially three fully automated weather monitoring stations capable of recording various weather variables, such as air temperature, relative humidity, wind speed and direction, precipitation rate, and barometric pressure. These stations operate wirelessly in designated regions of interest and utilize solar energy as their primary power source. The collected meteorological data is transmitted in near-real time over a wireless link utilizing packet-oriented networking protocols (eg GSM, WiFi) to a central server-host, where it is stored in corresponding relational databases. Access to the central server-host is controlled and managed using a station ID field transmitted together with the station data.

To ensure the proper functionality of the stations, telemetry is required to monitor their health status. Parameters such as generated voltage from the solar panels, battery voltage level, internal temperature, network state, sensor state, and internal controller state describe the health condition of the stations. Additionally, small telecommand packets are necessary for remote control, enabling actions such as system reset, parameter configuration, and mode switching between sleep mode and active mode. It is crucial to consider the implementation of debugging mechanisms and ensure easy accessibility to the overall system and structure to facilitate firmware updates and hardware replacements.

In addition to data collection and transmission, the development of a web-based platform is necessary to handle the generated data. This platform should provide a user-friendly graphical interface with various views to display real-time graphical representations of the collected data over the designated area of interest, along with relevant statistical values. The platform should also incorporate a set of predictor algorithms that can be compared to the actual data measurements, demonstrating their ability in short-range forecasting. Access to the platform should be restricted to authorized users, requiring a password token and registration provided by the administrator. Any application view must be independent of the database system, thus hosting applications to multiple different server-hosts or a cloud based hosting system is considered a good practice for faster applications and safe transactions.

To administer the platform effectively, an administrator viewpoint should be also implemented. This viewpoint enables control over the databases, user accessibility, and allows for monitoring station telemetry and sending telecommands.

Design Options

Sensor selection options

Temperature sensor: A high-quality thermistor or platinum resistance temperature detector can provide accurate temperature measurements. Brands like Sensirion, Texas Instruments, and Maxim Integrated offer reliable temperature sensors.

Humidity sensor: Capacitive humidity sensors are commonly used for measuring humidity. Brands such as Sensirion, Honeywell, and Silicon Labs offer reliable humidity sensors known for accuracy and stability. Many times the humidity detectors are embedded together with thermistors providing temperature and humidity measurements from the same device.

Barometric pressure sensor: For barometric pressure measurements, sensors based on microelectromechanical Systems technology are widely used. Brands like Bosch, NXP Semiconductors, and Honeywell offer accurate and reliable barometric pressure sensors.

Speed and direction sensor: Cup anemometers or ultrasonic anemometers are commonly used for measuring wind speed and direction. Brands like Gill Instruments, Vector Instruments, and R.M. Young provide reliable anemometers for accurate wind measurements.

Rainfall sensor: Tipping bucket rain gauges are popular for measuring rainfall. Brands like Texas Electronics, Hydrological Services, and Onset offer reliable tipping bucket rain gauges known for their accuracy.

Structural design options:

Mounting options: The type of mounting system that will hold the weather instruments securely can vary from brackets and clamps to towers and specific buildings. Proper enclosures must be utilized to ensure stability and protection of the internal electronics from environmental factors.

Weather resistance: It's essential to select materials that can withstand various weather conditions, including rain, snow, wind, and extreme temperatures. Corrosion-resistant materials like stainless steel and polymers can help prolong the lifespan of the weather stations.

Accessibility for maintenance: The structure must be designed in a way that allows for easy access to the sensors and equipment for maintenance, firmware update and calibration purposes. Features such as removable components, hinged doors for convenient access and ports are important.

Integration of solar panels: The structural design must support the placement of solar panels in a way that can provide the required energy for the system to charge batteries and to operate through day and night in continuous manner.

Data Collection System Architecture Options

Microcontroller/ single-board computer: A microcontroller or single-board computer is responsible for the housekeeping, the data collection, and the overall system control. Popular choices include Arduino, Raspberry Pi, or ESP32. Factors that determine which board to use are the processing power, the onboard memory capacity, the overall I/O capabilities to handle the sensor inputs, data processing requirements, the cost and also the robustness of the device for outdoor applications.

Power supply: A reliable power supply for electronics is important. This can be achieved using a combination of batteries, solar panels, and AC/DC power adapter since the main energy source must be solar energy. Current and voltage regulators need to be selected carefully according to the power needs of every component in the bus.

Data storage: The storage capacity and type of data storage that best suits the project must be determined. The internal memory of the microcontroller systems is usually very small. Stations must be able to collect all the data required and then transmit these packets to the central data management system. These data are stored in a cloud-based database system. If the internal buffers of the station are not enough to temporarily store the data collected (before transmission) then an external storage device such as an SD adapter must be integrated.

Communication module: Data transmission from the weather stations to a central server is done via a network module. Options include Wi-Fi, GSM/GPRS, LoRaWAN, or cellular technologies and their corresponding communication protocols. The method employed to transfer the data is based on the coverage area, data transmission speed, and reliability requirements.

Firmware/ software: Specific purpose firmware and software is required to program the embedded computer to handle data acquisition, processing, and communication tasks. The firmware design follows the Finite State Machine (FSM) approach. For every possible state/ condition the controller must execute the related set of operations. Deadlocks are a very common challenge in this approach especially for multistate systems. For reducing the possibility of a fatal runtime error extensive testing and debugging should be considered. In addition to the firmware running on the embedded computer, testbench "lab" software are developed assuring that the approach is error free. Lastly debugging and administrator mode changeable by telecommands should be considered for system monitoring in case of error.

Development Tools, Frameworks and API's

Hardware: For the hardware development (electronics and structure), several design tools are available. Computer-Aided Design (CAD) software such as ANSYS Inventor or Fusion 360 is commonly used to create 2D and 3D models of the weather station's structural components. Tools like ANSYS APDL or Analysis are utilized for structural analysis and thermal behavior simulations. For designing the electronics and PCB layout, tools like KiCAD are popular choices, as they enable the creation of compact and robust system architectures. SPICE technologies, such as LTSpice, provide powerful simulators for analyzing the electrical and electronic behavior of various components.

Firmware: There are several Integrated Development Environments (IDE's) available that facilitate programming the onboard computer and automate complex and time-consuming tasks involved in uploading code to the target device. These IDE's often come with libraries and Board Support Packages (BSP's) that offer high-level API's for programming low-level controllers, simplifying the process significantly. Additionally, sensor providers like Adafruit provide specific libraries that effectively manage the control of sensory devices without requiring extensive coding. Among the popular IDE's, Arduino IDE and PyCharm are commonly used, depending on the specific computer platform options expressed.

Software: For the software side of the project, two approaches can be taken to develop the backend and frontend platform interfaces. The first approach involves creating applications from scratch using the trio HTML/CSS/JavaScript, or the HTML/CSS/PHP. The second approach utilizes specific frameworks and libraries like Express.js, Flask, Django, and Ruby on Rails (RoR). Express.js is a minimal and flexible Node.js framework designed for building APIs. It provides middleware for handling routing, authentication, and simplifies the creation of API endpoints. Flask and Django are Python-based frameworks for web application development. Flask is lightweight and ideal for quick and straightforward API implementation. Django, on the other hand, is a full-stack development tool that offers powerful features, enabling the rapid implementation of professional API's. Ruby on Rails (RoR) is also a full-stack web framework that includes tools for API development following the RESTful architecture. SQL scripts and DBMS like Postgres, MariaDB, Oracle, PHPMyAdmin and more may be utilized for the database schema modeling and database transactions.

Testing: Testing is conducted on both the physical units and the software components. Extensive testing of the components is a prerequisite before proceeding to the next step of the design methodology. Hardware testing tools like multimeters, logical analyzers, and prototyping components, along with specific software, help evaluate the system's behavior under various conditions. Tools such as MATLAB and Python scripts can be utilized to display the test results in each testing iteration. On the software side, testing is made easier by leveraging automated testing tools such as JUnit and pytest. These tools provide frameworks for writing and executing automated tests efficiently. However, it is also important to consider the use of custom testbenches to ensure full coverage.

Deployment: The chosen host service provides tools to support the management of the backend application. Services such as Google Cloud web hosting, topHost and others provide the storage and hosting mechanisms for databases and web applications. In addition, tools, such as ANSIBLE, Docker, or Heroku, automate the task of deploying various applications to the web developed utilizing specific frameworks and programming languages such as Python. Additionally, utilizing Git repositories can greatly assist in version control for the launched applications.

Proposed Design Flow

After defining the requirements and main objectives, the next crucial step is to plan the prototyping design process. The proposed design flow encompasses the following essential steps divided into

Stage 1.

Sensor selection, placement, drivers and calibration: The appropriate sensors are carefully chosen based on project requirements, considering factors such as accuracy, reliability, compatibility with data transmission systems, and cost-effectiveness. The sensors are placed strategically, considering the external structure of the weather stations. Statical and thermal analysis techniques may be employed to assess the stations' ability to support the selected sensors and ensure correct placement. Furthermore, an interface is established between the sensors and the embedded computer, with the necessary drivers and system functions installed for device control. Libraries and APIs provided by their provider are studied and utilized together with custom code. Calibration is performed to increase accuracy, ensuring that the sensors' measurements align with known reference values. Regular calibration intervals are established to maintain accuracy over time.

Data collection and transmission: After ensuring the operational functionality of the sensors, the next step is to design a data collection system architecture that effectively captures readings from the sensors at regular intervals. This architecture will include establishing a connection between the weather station and the backend application running on a server. Additionally, a robust data transfer mechanism over the network will be developed, taking into consideration encryption mechanisms and ensuring data integrity is maintained throughout the process.

Telemetry: After the weather data transmission functionality is established, a new channel is developed for transmitting telemetry data. Telemetry is provided by a set of custom internal (on-computer) or external (devices) system monitors that measure the internal state of the station. The voltage level of the battery, generated solar power density, internal temperature and network state are some basic telemetry packets required for system health monitoring. This step consists mostly of designing the system state monitors.

Stage 2.

Data storage and management: Once the data transmission system is successfully established, the subsequent step involves implementing a robust data storage system. The collected weather data needs to be stored in a dedicated database, which requires the utilization of a reliable database management system. The database schema is carefully developed, and a fundamental backend data management API is created. This API serves the purpose of handling new data arriving from the weather stations and facilitating end-users' queries to the database system. Moreover, data backup and archiving processes are implemented to prevent any potential data loss.

Telecommand: A third channel is added to the system for telecommands. Small packets operate as a set of runtime instructions for each station separately transmitted by the backend API as request of the administrator. These small packets contain the station ID and a series of small operation modes.

Stage 3.

Firmware verification: The code running on the onboard computer of each station is developed (FSM approach) and verified through extensive testing. Standardized communication protocols such as I2C, SPI and UART are utilized providing integrity to the hardware design. Debugging mode is a prerequisite which can also be enables either by a hard button implemented on hardware or by a software command. Controllers for sensory devices and system monitors should also be verified. Controllers for the integrated system display and user interfaces are also considered.

The hardware stack: After the basic operations of the weather station are met, for a better design specific purpose costume hardware PCBs are created providing robustness, more compact and easily manageable and maintainable structure. Testing and integration of the hardware stack into the stations will be the last step on the physical design. After the physical implementation placement of the stations on the targeted regions for the network formulation follows. Target areas are selected carefully to meet the aforementioned requirements.

Stage 4.

Data Analysis and Visualization: After the fundamental schema of the weather station network system is designed and operates normally, the next steps consist of giving life to the collected data. Algorithms for statistical analysis and visualization through charts, graphs and maps are developed to manage the collected data. Furthermore, a series of algorithms for short range prediction are developed and tested. The first application-demonstrator that utilizes the collected data will be the study of various predictors and how satellite-based weather data affect the prediction accuracy for short-range forecasts.

User Interface Development: The next step involves utilizing these data analysis and visualization tools specifically designed to create a simple and user-friendly frontend API. The interface allows users to view real-time readings and graphical representations, providing access to historical data, statistics, and weather forecasts for all the weather stations within the constructed network. Also, the results of all the predictors architectures studied are displayed along with the collected data.

Stage 5.

Deployment and Maintenance: The final step in designing the ground-based weather monitoring network involves carefully placing each station in its designated location, taking into account factors such as accessibility, safety, and environmental conditions. A comprehensive maintenance schedule is created to ensure regular sensor calibration, equipment checks, software updates, and general upkeep. This maintenance schedule includes detailed descriptions to guide the upcoming personnel in troubleshooting and performing proper maintenance tasks.