Project Report

Smart Weather Station

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1 Problem Statement

Two common ways of measuring wind and rain exist using existing technologies.

The first solution uses a vane anemometer for wind speed, a wind vane for wind direction, and a tipping bucket for rainfall measurements. This solution is simple and easy to implement, but contains moving parts that are prone to a failure.

The second solution does not contain any moving parts. The wind speed and direction are inferred by measuring Doppler shift in the ultrasonic wave between a transmitter and a receiver. Rain can be measured either optically using the amount of reflected vs refracted light, or with a microwave radar, which is a more advanced method that can also detect other types of precipitation such as hail and snow. Even though this solution is not expensive component-wise, it requires advanced analog circuitry, precise timing, mechanical rigidity, and complex algorithms to process the captured signals.

This project aims to solve disadvantages of the both aforementioned solutions.

2 Solution Proposal Summary - Overall Design

The proposed solution does not contain any moving parts, consists of only a few components, and relies on a neural network. The weather station hardware consists of a hollow cube, containing a 3-axis IMU (inertial measurement unit), and a 2-axis strain gauge. The 3-channel accelerometer signals contain information about the raindrops (size, frequency, and direction) hitting the station. The 2-channel strain gauge signals indicates the force and direction at which the incoming wind is acting against the station.

3 Electronic Design

The weather station should be able to operate in resource-constrained environments, where power might not be easily deliverable. Therefore, the electronic design has to reflect this constraint, and be as low-power as possible. The following section describes the proposal of a printed circuit board (PCB) in its "development kit" version. This means that while it provides easy and accessible prototyping/debugging experience, some components could be omitted to further optimize cost, and decrease the power consumption.

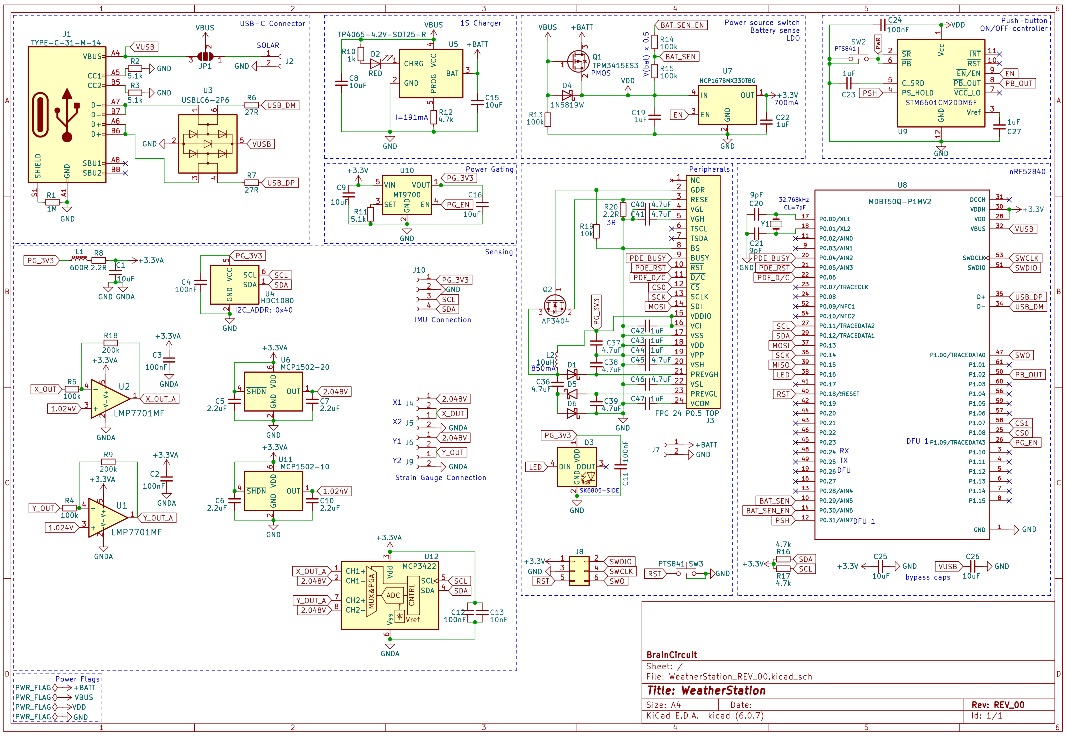

Figure 1: Weather Station Schematic

The board is based on Nordic Semiconductor's nRF52840. This System on a Chip (SoC) is built around the 32-bit Cortex M4 with FPU (floating point unit) that allows to effectively perform mathematical operations on floating-point numbers, implements support for various wireless radio protocols such as BLE (Bluetooth Low Energy) and Zigbee, and can be put into deep sleep mode to draw a very little current. To make life easier, a pre-certified MDBT50Q-U1MV2 module from Raytac was used.

The USB-C connector provides power to the circuit, but is also used as a programming and serial interface (a bootloader must be flashed through the SWD interface once in the beginning). It is used to charge a 1S 3.7V Li-ion battery using a TP4065 charger. For deployment in a field, a solar cell can be used as a power source instead. This development version is controlled through a push-button controller, which activates the NCP167, a tiny (1mm x 1mm), 3.3V LDO (low-dropout regulator) to provide power to the nRF52840, and also has a driver for EPD (epaper display) to show the current values. But again, these features can be removed in the final version to optimize the design for deployment. The PCB is divided into multiple domains (see Figure 2 and 3).

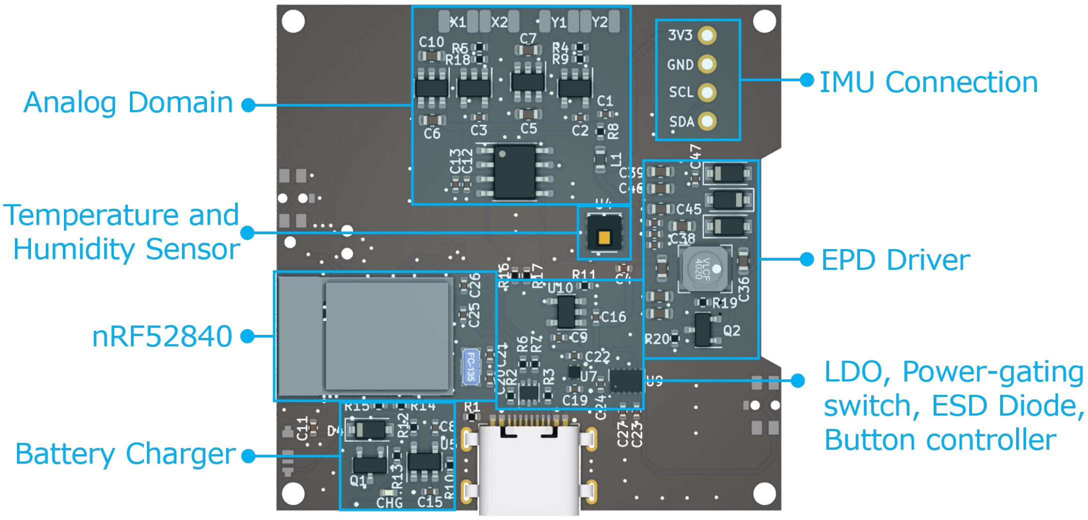

Figure 2: Weather Station Layout Front

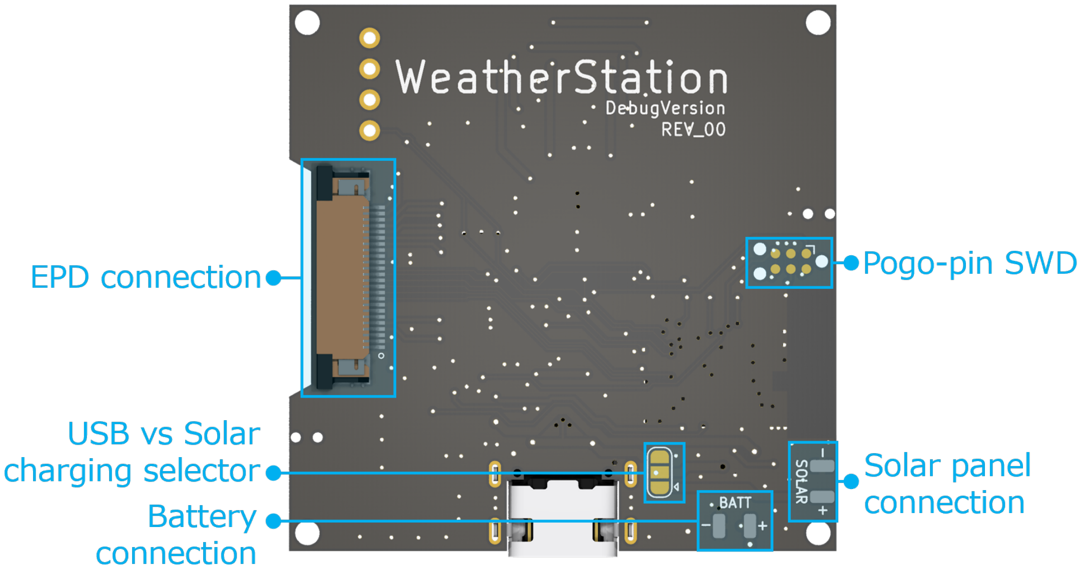

Figure 3: Weather Station Layout Back

The temperature and humidity is monitored using TI's HDC1080 (14-bit I2C sensor with ±0.2°C and ±2%RH precision). Other sensors (pressure, gas, etc.) can be easily added to the design, but this is not covered in the report, since that is not the innovative part. All of the peripherals, including the components required for the monitoring sections described below, are power-gated through a cost-effective, low voltage P-MOS switch, with less than 1µA standby current. This means that no extra power is wasted, since the unused components are completely disconnected while in the sleep phase.

3.1 Wind monitoring

The idea behind the proposed wind monitoring consists of utilizing principles commonly used in pointing stick devices. A center shaft (stick) is attached to a bendable material with strain gauges placed perpendicular to each other. This way, any movement of the shaft can be recorded in terms of a force, and angle. If an object with a known shape (e.g. a cube - Figure 4) is attached to the top of the stick at a certain distance from the bending point, it is essentially a cantilever beam, and the wind behaviour and drag can be simulated using fluid dynamics methods. The analog domain on the PCB consist of a two precise voltage references, one setting a bias for the strain gauges (forming a voltage divider), and the second one is fed into an differential op-amp together with the strain gauge output. This way, the amplification gain can be tuned to increase the peak-to-peak voltage of the full-scale beam deflection, thus increasing the resolution. The output is connected to an 18-bit differential ADC (analog to digital converter). An alternative version could use capacitive sensing instead of the resistive (strain gauge) one.

3.2 Rain monitoring

To detect rain, an IMU is mounted to the top plane of the cube (see Figure 4), and wired to the main PCB through the connecting shaft. This way, the vibrations caused by rain drops hitting the top surface can be captured, and valuable information like drop size and frequency can be inferred. An extra, outwards-facing capacitive sensing plane can be added to the assembly, to gain more information for the neural network, possibly allowing detection of other forms of precipitation.

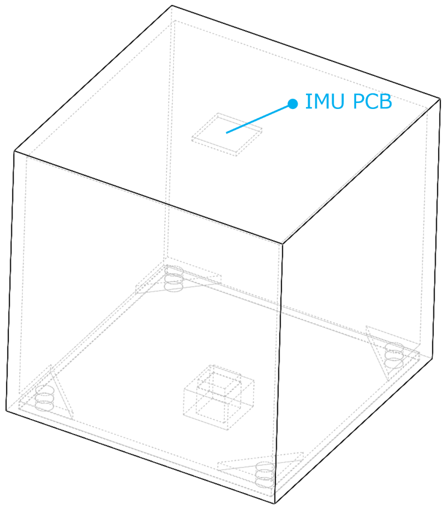

Figure 4: Weather Station Top

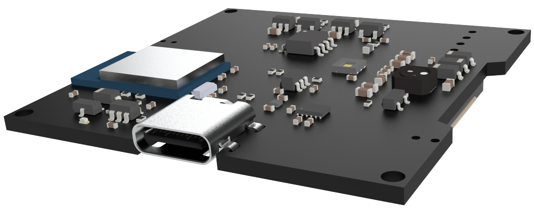

Figure 5: Weather Station PCB Render

4 Physical design

It is important that the enclosure is made out of material that can withstand harsh environmental conditions. A good candidate is polycarbonate (PC) due to its strength, durability, and good UV and weather resistance. However, the prototypes for this project are printed on an FDM (fused deposition modeling) 3D printer in PLA material.

The rectangular base of the station has to be firmly attached to a mount. It connects to the central stick through four narrowed paths, that act as a spring. Modifying the thickness of these elements influence the spring constant. For example, Figure 6 shows three different 3D-printed versions, where the spring element has 1mm, 2mm, and 3mm thickness.

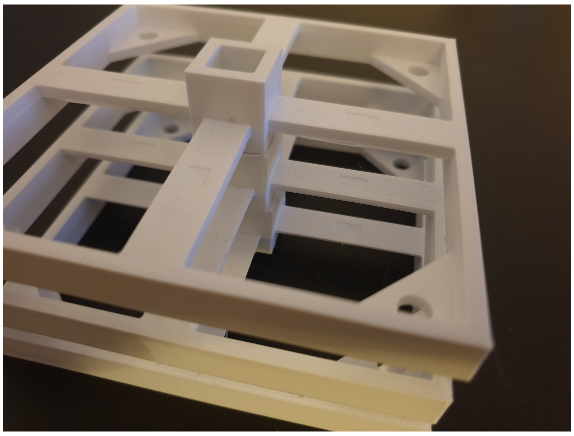

Figure 6: Base station - spring testing

The system has a few important variables to be tweaked. Length of the stick, surface area of the cube, and spring constant of the spring elements. Making the stick longer, surface area larger, or springs softer, will increase the responsiveness and bending under the same wind conditions, and vice versa. The cube shape was chosen since it provides a predictable response in all directions.

Figure 7: Prototype design - 3D print

The final shape can be seen in Figure 8. This serves as a proof of concept for the aforementioned sensing principles. For real life use, additional parts have to be designed, that cover the sensitive parts, such as the strain gauges on the spring elements, and the PCB to be hidden in the base, while still allowing unobstructed motion of the central stick.

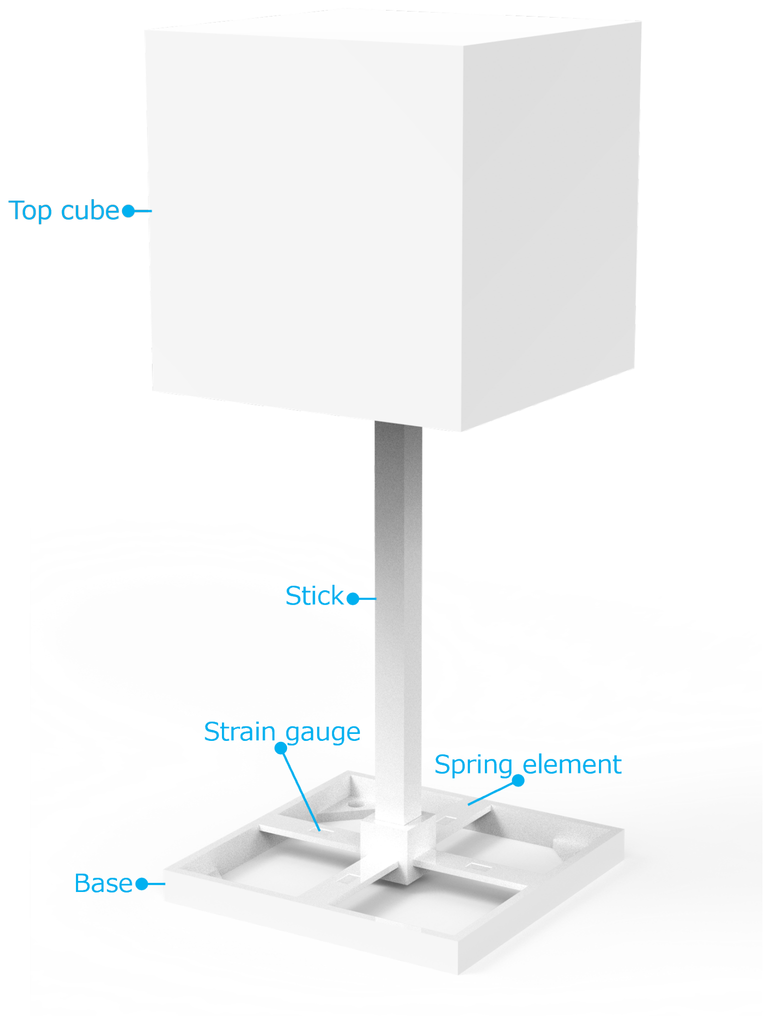

Figure 8: Prototype design - render

However, this design also have possible limitations. Since wind is not always nice and smooth, the sudden gusts from different directions at specific rates might excite unwanted oscillation modes in the assembly. This is a valid concern that can be simulated and compensated for by changing the shape, weight distribution, etc.

5 Neural Network

Two main neural network use cases were initially identified to demonstrate the capabilities of the designed weather station:

1. Determining a type of the rain.
2. Determining a wind speed and direction.

After some considerations, we decided to implement a neural network support only for the rain task, since we believe the wind speed and its direction can be calculated purely by looking at the 2 channel strain gauge data. Therefore, the text below focuses on the rain data and rain classification.

The proposed weather station currently runs a five-layer fully connected neural network (FCNN) capable of classifying four types of rain using a 3-channel accelerometer. The network is trained on our own collected dataset.

In order to collect data as close as possible to real life, we used the first 3D-printed prototype part of the weather station responsible for rain data collection as described previously and illustrated in Figure 7.

The accelerometer was interfaced through I2C using Nordic nRF52840, and set up to continuously stream 3-channel (XYZ) data at the highest precision (±2G) and a 250Hz sampling frequency. The data stream was captured over serial port on a computer and saved in a csv format. The rain types with their corresponding features are depicted in Figure 9.

The rain was simulated with a dispersed water stream at different flow rates and intensities, corresponding to four different scenarios (types of rain): 1) *no_rain*, 2) *sprinkle*, 3) *regular_rain*, and 4) *strong_rain*.

The collected data was divided into training and test subsets (∼80:20 ratio), and preprocessed using spectral analysis with 512-point FFT on 500 ms windows and a 250 ms stride (50% overlap). The training data was then fed into the five-layer FCNN model with 100, 50, 20, 10, and 4 neurons, respectively, where the last layer represent the four types of rain. The input layer has 259 features as a result of data preprocessing. *EdgeImpulse* reports accuracy of 97.7% (see Figure 10), and most misclassifications are for the *rain* category (mistaken with *strong_rain*). The inference time (without retraining) on Cortex-M4F 64MHz (used in Nordic nRF52840) that we use is ∼25 ms.

This is still an ongoing project, where more features are on the road map, such as determining size, frequency, and direction of the raindrops hitting the station. A drop size can be solved by feeding the z-axis data of the accelerometer to a DNN,

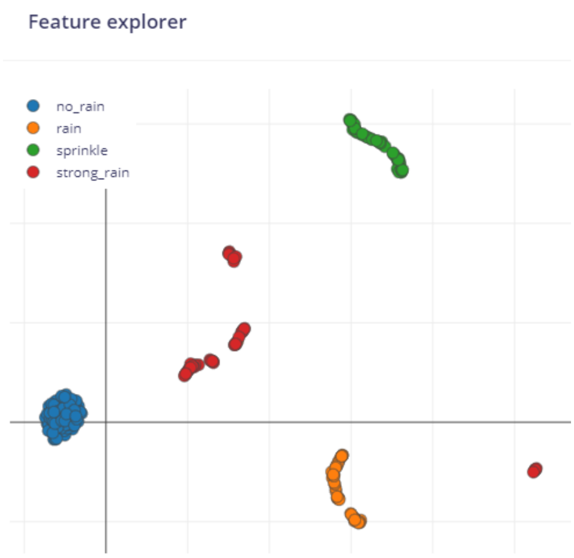

Figure 9: Feature extraction for the baseline (no_rain) and three types of classified rain.

ACCURACY
97.7%

LOSS
0.17

Confusion matrix (validation set)

	NO_RAIN	RAIN	SPRINKLE	STRONG_RAIN
NO_RAIN	100%	0%	0%	0%
RAIN	0%	85.7%	0%	14.3%
SPRINKLE	0%	0%	100%	0%
STRONG_RAIN	0%	0%	0%	100%
F1 SCORE	1.00	0.92	1.00	0.96

Figure 10: Confusion matrix obtained using validation data.

where the DNN can learn to predict the size based on the delta change of the amplitude during the impact - the bigger the amplitude deviation is, the bigger the rain drop. The frequency of the drops can be identified by analyzing the z-axis in the temporal domain. These two tasks are a good fit for a regression neural network model, while the direction of the raindrops for a classification model with 8 main output directions: North, West, South, East, and their complements North-West, South-West, North-East, and South-East. These 8 categories will be also used for determining the wind direction via the 2 channel strain gauges.