Mobile Air Quality Monitoring Device

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***Abstract*—Air pollution represents a continuously increasing environmental issue which poses significant health and ecological related risks globally. It results from a complex mixture of pollutants, including, but not limited to: particulate matter (PM), carbon dioxide (CO2), sulfur dioxide (SO2) or volatile organic compounds (VOCs) that originates from industrial activities and vehicular emissions. Exposure to surrounding pollution is almost unavoidable in today's society context, but one solution to limit its impact on one's health would be to avoid highly polluted areas as much as possible.**

We propose a new and low-cost wearable hardware solution that is able to track these harmful air pollutants in real time and send measurements and alerts. Multiple devices can track pollution over a large city-wide area and deliver air quality measurements that can be accessed by anyone. The developed device is housed in a small-sized, modular enclosure, that offers interchangeable mounting brackets for various use case scenarios: body-worn, bicycle-mounted, etc. This way, the user is able to employ these devices in daily activities and adjust one's normal route when commuting in the city to minimise the risks related to pollution exposure.

***Index Terms*—Embedded Systems, BLE, Pollution Sensors, IoT**

I. Introduction

Air pollution is considered by most scientists [1] one of the greatest problems of our era that brings significant impact on human health and well-being [2]. These papers identified 2 root problem sources that generate alarming levels of air pollutants: natural and anthropogenic sources. This second source is primarily generated by humankind: waste burning, construction sites, industry, fossil fuel combustion, agricultural runoffs. Out of the second group, car pollution is expected to be responsible for about 80% of today's pollution.

Common pollutants that can be found in the surrounding air include:

- **Ozone**; formed by a chemical reaction between VOCs and NO_x; although it plays a protective role in the stratosphere, when encountered at ground level it may pose health related problems.
- **PM_1, $PM_{2.5}$, PM_{10}**; tiny particles of dust residues of all kinds (brake dust, tyre residues, cement powder etc.) that end up in the respiratory system through inhalation.
- **CO_2**; poisonous gas that can become lethal in high concentrations, it is widely spread in exhaust gasses causing greenhouse effects.
- **Lead (Pb)**; generated by car emissions, paints, waste and coal burning or battery recycling; can lead to poisoning or intoxication when absorbed into the human body.
- **CO**; generated primarily by cars in traffic jams.

PM levels drastically increase due to braking and tyre wearing: 84% of total PM emissions come from brake wear, according to this paper [3]. This pollutant is responsible for increased health risks including heart and lung diseases, asthma and general respiratory problems as the Environmental Protection Agency concludes [4].

Studies [5] show that exposure to air pollution in congested areas during rush hours is 20 to 40% more harmful for pedestrians. Since there is no immediate way to combat this pollution source, one's best alternative is to avoid it.

Moreover, there is a shortage of fixed air quality stations that can measure particulate matter levels in Romania, as online articles [6] indicate. This kind of pollution is expected to reduce the lifespan of Romanians by nearly a year. Therefore, there is a need to expand the network of pollution sensors to combat these alarming levels, as Bucharest ranks among the 20% most polluted European cities, according to a European Environment Agency study [7].

This paper presents an affordable, energy-efficient IoT device for tracking urban pollution, which is small enough in size to be used both as a body-worn or bike-mounted device.

Deploying a network of pollution monitoring devices mounted on bicycles across the city offers the advantage of continuous pollution tracking throughout the day, with particular emphasis on identifying and analyzing sporadic hotspot areas. On the other side, utilizing the device in a body-worn manner allows users to actively monitor the pollution levels in their immediate vicinity, providing real-time data of their exposure while traveling or exercising outdoors.

The main objectives of the system are:

- Control accurate data acquisition from the sensors
- React and respond to user interactions and display live data frames with pollutants levels
- Send real-time data through a BLE server or store historical evidences of collected data
- Self adjust internal RTC clock
- Low power consumption with good battery life
- Fault tolerant system that recovers from sensor failures
- Modular and lightweight enclosure, with good air-flow

This paper is structured as follows: Section II presents similar work in this field. Section III explains the project's architecture. Section IV outlines key-points from the implementation. Section V presents the results of both field and laboratory tests conducted on the devices. Section VI summarizes our results and future work.

II. State of the Art

Extensive research has been done before defining the device architecture and binding its elements together. It was helpful to examine other existing solutions on the market, particularly in our city, Bucharest, but also in similar European capitals with comparable environments. By pointing out benefits and drawbacks on each of them, we were able to make informed decisions and maintain a simple, yet impactful design.

A. Similar Products

- **AirGradient** [8] is an open-source project in which 2 pollution tracking devices (both indoor and outdoor) were developed. They offer support for measuring temperature and humidity along with some of the most important air pollutants: CO, PM, TVOCs and NOx. One issue with these products is the sizing: 13 x 13 cm is almost the equivalent of 2 IPhone 15 placed side by side, which only makes it suitable for usage in fixed location scenarios.
- **uRADMonitor** [9] is a Romanian project that started in 2013 with a prototype and developed over the years an IoT network of interconnected pollution devices spread on several areas across multiple regions around the world. They developed a variety of hardware units, with both fixed and portable designs, that collect live data of air pollutants such as: CO and CO_2, PM, TVOCs, SO_2 and NO_2 and ambient indices: temperature, pressure, humidity or noise. In terms of pricing, these devices tend to get really expensive: for example, the A3 model which is the most similar to my pollution tracker sells for 589 dollars; other models go all the way up to 3749 dollars.
- **Sodaq Air** [10] is a similar project released in 2023, targeting the usage of sensors mounted on bicycles. It offers comparable achievements in the pollution tracking area: PM, temperature and humidity sensors, but it cannot track the harmful CO_2 levels. Moreover, it targeted simplicity in being used as a semi-passive device, but it fails to give users detailed levels of the tracked air pollution and doesn't allow user interactions.
- **Airly** [11] is another worth mentioning project, with thousands of sensors spread across the UK and Europe regions. In terms of devices, all of their proposed designs are meant to be used as stationary equipment and they mostly focus on tracking the PM pollutants. Some of their variations also track other pollutants such as ozone, CO, SO_2 and NO_2.

B. Research Studies

- **Low-Cost Air Quality System for Urban Area Monitoring** [12] proposed a pollution tracking concept, based on a "crowd sourcing" approach, with mobile sensing devices that monitor the variance of gaseous pollutants in metropolitan areas. The devices used Metal Oxide (MO) sensors to track pollutants such as CO and NO, having the advantage of low production costs, but at notable performance limitations impact, caused by different weather conditions: wind impacted the accuracy of collected data.
- **Mobile sensors in air pollution measurement** [13] introduced a mobile system designed for measuring air quality and pollution in urban environments that aims to enhance the use of existing fixed-location air sensors which can only cover a limited area. Although being classified as "mobile units" because they travel around the city, the sensors themselves were fixed units as they relied on being connected to vehicle's electrical system, being powered only when the car was running.
- **Air quality data collection and processing platform** [14] proposes a platform that utilizes both Wearable and Mobile Sensors Devices to gather large amounts of air quality data processed on a central Real-Time Data Processing System and disseminated back to users in a meaningful format. The sensors used for data collection in this paper used off the shelf components for NO, CO and PM measurements produced by AppliedSensor, all controlled by an ATMega 328 chip.

III. Project Architecture

This chapter presents the general hardware architecture of pollution sensing devices, with focus on sensors and modules and provides a high level view of the software architecture.

A. Hardware

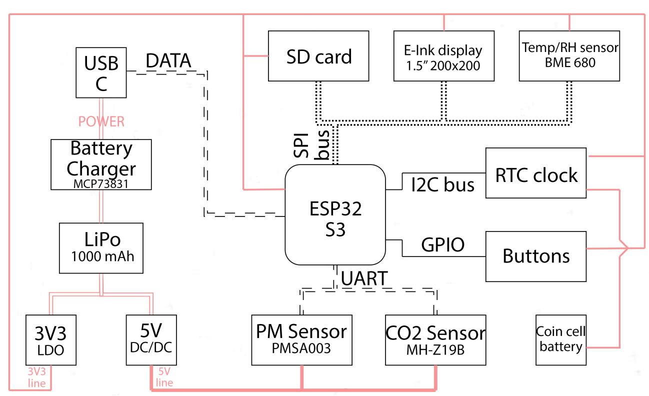

Fig. 1. Components schematic

The hardware system presented in Figure 1 combines various air monitoring sensors, all of cutting edge technology, to collect air pollution indices from the environment. A brief presentation of these sensors is the following:

- **BME 680**: gas sensor that measures humidity, barometric pressure, temperature and volatile organic compounds. It features very low power consumption values: 3.7 μA when performing reads of humidity, pressure and temperature and only up to 12 mA when also assessing the gas parameter. Works at 3V3 level and communicates on both SPI and I^2C protocols.

- **PMSA003**: particulate matter sensor. It consumes up to 100 mA in active mode and is powered by a 5V input, but compatible with interface levels of 3V3, and communicates over UART.
- **MH-Z19B**: a CO_2 sensor built on modern NDIR infrared technology. It consumes an average of 60 mA, but can go up to 150 mA during peak modes. It is powered by a 5V input, but compatible with interface levels of 3V3, and communicates over both UART and PWM. It requires a preheat time of 3 minutes for accurate results.

Apart from these sensors, the other components used in the hardware system are:

- **ESP32-S3**: microprocessor that controls and handles sensors data acquisition, coordinates the BLE communication and manages user input and output logic. It features a dual-core CPU with a frequency of 240 MHz, 45 GPIO pins and 512 KB of internal SRAM.
- **E-Ink display**: a 200 x 200 pixels display used to present pollutants values. It works over SPI protocol and uses only 10 mA of current during updates, 5 μA in standby.
- **RV-3028-C7**: the real-time clock needed to persist correct timestamps of historical data when the device runs in single mode, not paired to the mobile application. It has an integrated oscillator and consumes only 45 nA. A coin cell battery is used to power this module when the main battery loses power.
- **SD card**: used as an extension of the onboard storage where historical data is persisted.
- **MCP73831**: battery charge management controller. Supplies only 500 mA to charge the 1000 mAh battery, but has the advantage of not needing a thermistor to test battery temperature (this would have been an issue as the battery is mounted externally to the main PCB).
- **XC6220A331MR**: 3V3 low dropout voltage power source used to power a set of components that run at this level (ESP, card reader, display, BME680, RTC). It outputs up to 1A current, which is safely over the board's needs, with a low amount of voltage dropout (between 20 and 60 mV).
- **TPS63060**: buck-boost converter used to raise the input voltage from battery level to 5V in order to fulfil the needs of PM and CO_2 sensors. It outputs up to 2A current, which safely handles the 250 mA needs of these sensors.

B. Software

A high level view of the main software components is presented in Figure 2. First step when the device boots is to initialize the sensors and software modules used in the project. Subsequently, the BLE server starts advertising its services and sensors go through a heating phase to prepare for accurate readings. A cyclic phase follows when data is collected from the sensors and displayed on the screen; now, a client connected to the BLE server receives the live updates, otherwise, these readings are stored as historical data locally.

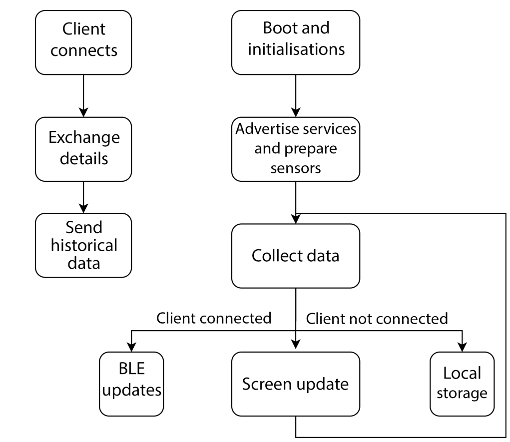

Fig. 2. Software architecture

Separated from this flow, when a client connection is established, some details are exchanged such as the current timestamp on the mobile device and afterwards batches of historical data previously stored on the sensing device are sent.

Collected data are structured under the following CSV format: [Timestamp, Voltage, Temperature, Humidity, Pressure, Gas, Altitude, CO2, PM1, PM2.5, PM10]. Apart from these labels, several others such as location, user and device identifiers are attached at the Android application level. In this final form, batches of data are later ingested into the data pipeline, processed and stored in a time series database, and retrieved for complex visualisations in the mobile application.

IV. Implementation Details

A. PCB Design

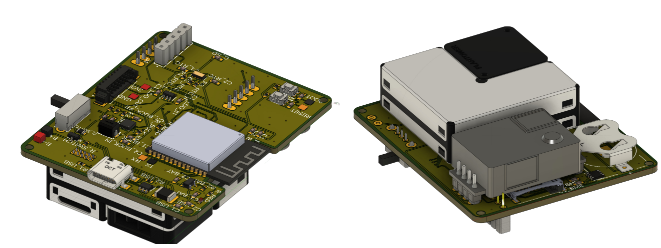

Fig. 3. Front and Bottom PCB renderings

The final version of the PCB is presented in Figure 3. All the sensors used for data acquisition are mounted on the back side, with careful consideration not to alter one another's intake openings and ensure enough air-flow for accurate readings. Also on the back, the SMD coin-battery holder is found. One smart design choice was to overlay the CO_2 sensor on top of the card reader, as its mounting points allowed for a slightly suspended position.

The battery and display were mounted external to the PCB, as another way to minimise the space used on the board itself. Wire headers were specifically fitted to ensure proper connection between the board and these external components. Moreover, the 3 GPIO buttons were mounted on an external PCB for easier access, as seen in Figure 4.

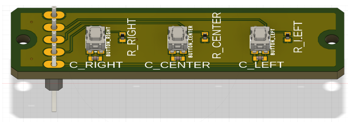

Fig. 4. Buttons PCB rendering

Overall PCB size is only 63 x 53 mm. Downsizing from this point is virtually impossible due to the physical limitation of the PM and CO_2 sensors: in terms of PCB length, the best way to mount them is across the vertical line in a horizontal position: the PM sensor is roughly a square with the side of 37 mm and the CO_2 sensor has a width of 21 mm, resulting in a total group height of 58 mm: this is only 5 mm less than the actual PCB dimension, because a small gap between components should be assured.

Routes were specifically traced to minimise the impact of viases on the power lines. The board is designed in a 2 layer fashion, using ground planes all across the 2 sides, also featuring a cutout along the antenna portion of the ESP32 chip.

B. Enclosure Design

The enclosure was designed tightly to PCB's dimensions, obtaining the smallest form-factor possible. Air vents were strategically added on the front and back bottom sides to allow a complete air flow through the case; we also placed these vents on one lateral face and on the bottom side where the sensors had openings for air intakes. Button covers were added for both better aesthetics and user interactions. The finished prototype can be seen in Figure 5.

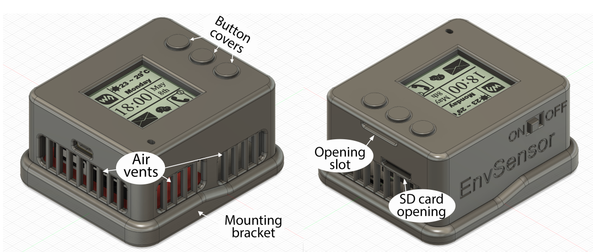

Fig. 5. Enclosure rendering

The overall design features rounded corners with no sharp edges for a more natural feeling in daily usage. Each cover for buttons and power switch has a corresponding inner groove in the enclosure that allows both a proper resting position and an unaltered moving path when actioned. For a more intuitive usage, the power switch has engraved writings for each state: "On" and "Off".

The screw-free design of both lid and mounting bracket is an extra benefit for a cleaner design and simplicity of use. This is possible thanks to the custom designed snap-fit system: the enclosure has inner cylindrical extrusions on 3 sides, on the top part for the lid and on the bottom for the mounting brackets. The other 2 enclosure parts have corresponding outer indentations that snap in place. This system can be better observed from the sectional analysis in Figure 6.

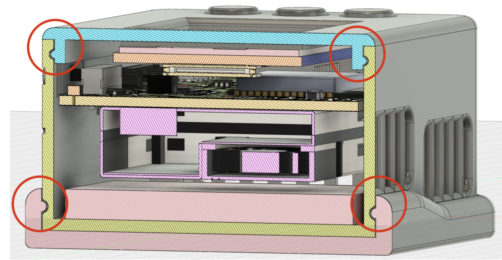

Fig. 6. Sectional analysis

C. Software Design

The general software architecture for the firmware is reflected in Figure 7. The rectangles represent modules designed as objects, while the ellipses represent extensions of code for the Main class. All sensors implement two common interfaces that play an important role in orchestrating the subsequent logic: one for data handling, another one for state and data acquisition purposes. This assures that all sensors can be accessed in an uniform manner when used as parameters of general handling functions.

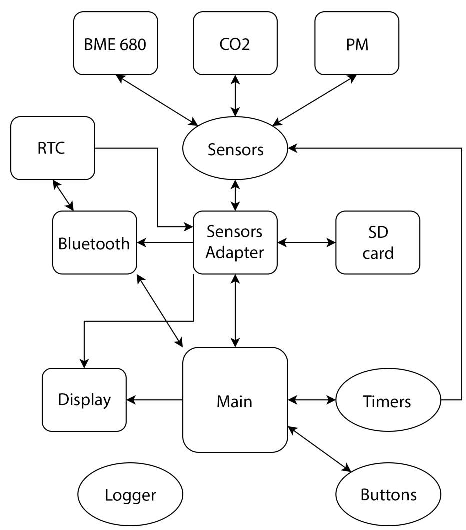

Fig. 7. Software entities

Sensors Adapter is the module that handles the main logic regarding data acquisition and handling (either storing locally or sending remotely). It coordinates in execution with both Bluetooth and SD modules to accomplish this purpose.

After a sensor performs a new reading, the freshly collected data reaches this adapter and:

- if BLE is enabled and a client is connected to the server, it updates the corresponding characteristics
- otherwise, it stores the values in a local buffer before saving them as a batch of historical data on the SD card

under CSV form; it also saves the timestamp when data collection took place

The system is fault tolerant under 3 scenarios:

- **sensor not found error**: before the initialisation step, a hardware connection must be established first. This error type suggests that a hardware issue (power issue for example) appeared.
- **sensor initialisation error**: although the physical connection to the server is established, an error may appear when trying to initialise it (might be a communication interference on the data lines)
- **sensor read error**: after successful initialisation, when readings are performed, the software system constantly checks the sensor for intermittent errors that may appear (for example a false reading given, a timeout in response or a wrong message received).

These errors are logged and a re-initialisation procedure begins.

D. Hardware Design

A simple power switching method (Figure 8) was implemented to automatically change the power input source between battery output to USB power when the latter is detected. This way, the battery is properly disconnected from the circuit while charging, assuring better circuit protection and longer life expectancy.

This system works with a PMOS transistor that is kept on via a pull-down resistor on gate (thus conducting the power from drain - battery to source - components input), until voltage is detected on the USB power line and the transistor stops conducting, completely isolating the battery. In the other case, when USB voltage is detected, power is bypassed across the transistor through a Schottky diode, assuring the lowest possible voltage drop (less than 450 mV).

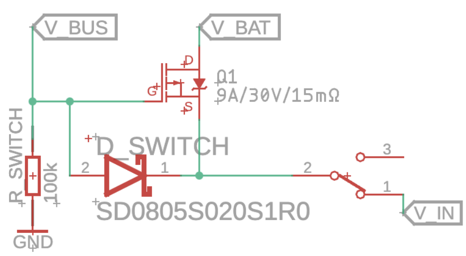

Fig. 8. Power distribution switch

V. Testing and Results

A. Power consumption

Several power consumption tests were performed under different working conditions against a power profiling tool (in particular Nordic Power Profiler Kit II) were performed in order to assess a run-time estimate of the overall system.

Initial findings, where the measured power consumption had an average of 265 mA, lead to further power optimisations: apply duty cycling procedures to the PM sensor, the biggest consumer due to its fan running continuously. It not only consumed unnecessary power to spin, but it also generated considerable voltage noise.

The chosen solution was to disable it in between cyclic readings, directly from the software side. This optimisation not only reduced the constant voltage noise, but also lowered the overall power consumption by 30%, reaching an average of only 186 mA. Test results are reflected in Figure 9.

Fig. 9. Power profiling

Marked in red rectangles there are the moments when our sensors perform sequential readings, at periodic intervals of 20 seconds (the chosen sampling rate). In these moments, there is a voltage spike of about 1.5 A for a short period, due to the fan turning on. It doesn't pose any problems as the voltage source is able to handle it and the power traces have a width of 0.3048 mm. In black rectangles there are other periodic voltage spikes that correspond to CO_2's sensor heating process.

B. Sensor calibration

Calibrating the sensors is a crucial step for providing meaningful pollution tracking results.

A detailed article [15] focuses on testing and calibrating two low-cost particulate matter sensors: the PMSA003 (also the one we are using) and Shinyei PPD42NS. Complete results are available throughout the paper, but to summarize: PMSA003 clearly offers the best results out of these two, with great out of the box calibration. The Pearson correlation between the readings of 2 different sensors had a coefficient of 0.998.

For the CO_2 sensor, there are more calibration procedures available, but some require specific equipment to perform:

- 0 point calibration: this will improve accuracy for lower range readings, typically in the range 0-400 ppm. It implies a static calibration inside an hermetic chamber filled with a known inert gas (Nitrogen - preferably or Argon). As typical CO_2 outdoor levels exceed 400 ppm, there is no need in our specific use case to improve accuracy in the lower ranges.
- rich CO_2 mixture calibration: easier to perform by exposing the sensor to a controlled chemical reaction between baking soda and vinegar, but not as efficient
- fresh air calibration: the easiest procedure is to calibrate sensors in fresh outdoor air, where CO_2 levels are a bit over 400 ppm normally, but only if low-range accuracy is not the main focus

- auto calibration: sensor's firmware offers an auto calibration procedure that will auto-correct its reference every 24 hours of use

We opted for a mix of calibrations on the MH-Z19B sensor: first exposed it to a rich CO mixture inside an hermetic container for about 30 minutes, then let it self-calibrate in fresh outdoor air for 24 hours. We also activated the software auto calibration procedure.

C. Final Prototype

Real pictures featuring the prototype of our environmental sensing device can be seen in Figure 10. For sizing reference, it is more than 2 times shorter than an IPhone 15 in length, 1.5 cm less in width, but a bit more than 3 times thicker.

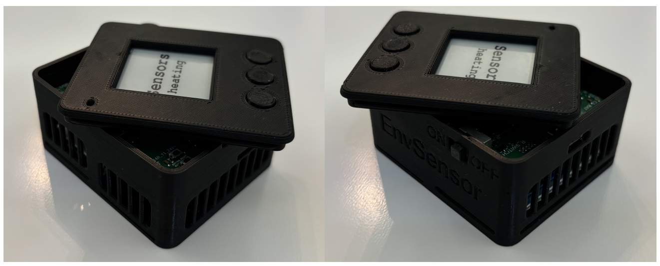

Fig. 10. Actual prototype

Associated costs for making the final prototype (only regarding components, not PCBs or enclosure) sum up to around 86 USD. A price comparison between our prototype and devices available on the market is presented in Table I.

Product	Price (USD)
CityAirQ device	86
Airly	360
Sodaq Air	250
uRADMonitor	589
AirGradient	190

TABLE I
PRICE COMPARISON

D. Field testing

While using the prototype to collect pollution data from various areas across Bucharest, we made an interesting observation: pollution levels at which pedestrians are constantly exposed on the sidewalks vary considerably with the street type. For example, in the case of a sidewalk bounded directly to the main avenue, with only the curb that separates them, measured CO_2 pollution levels were more than 35% higher compared to those on another sidewalk in the same neighbourhood, which has more than 5 meters of green space filled with grass and trees before its connection to the main road. Both data collections were performed in similar traffic conditions (moderate traffic).

VI. CONCLUSIONS

A. Contributions

We successfully designed from scratch a working version of a mobile pollution tracking device, focusing the work on 3 fundamental pillars: hardware, software and enclosure. On the hardware side, we used low-cost, but reliable components, with good energy efficiency, that are able to track key environmental pollutants levels such as $C0_2$, PM and gas levels. The software is a robust and fault tolerant system that minimises the refresh-rate overhead of e-ink displays by efficiently printing live updates on a single, yet meaningful, screen. The enclosure is minimal in sizing, with interchangeable mounting sockets supporting various use cases and a screw-free design.

B. Future development

The future work we envision for this project involves:

- **Power consumption improvements**: although it offers about 5 hours of continuous use on battery, there is still room for improvements: a more power optimized version of the CO_2 sensor (MH-Z1311A) can decrease its average power consumption from 60 to 1 mA.
- **Tracking more pollutants**: by including a sensor such as MICS-6814, which is both low-cost and small in size, we can track a set of 8 new air pollutants.
- **Battery percentage**: correlate voltage level to percentage

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