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Preliminary Design:

Low-cost High-precision PM Sensor

Revisions

Revision	Author	Changes	Date
001	Zhaoqi Ma Siru Chen Zixuan Wan Xiaolei Zhang	version 1.0.0 (initial release)	2022-02-07
002	Zhaoqi Ma Xiaolei Zhang	version 1.0.1 Fixed User cases figure; Fixed system architecture figure; Finished prototype budget; Fixed minimum design.	2022-02-09
003	Zhaoqi Ma Siru Chen Zixuan Wan Xiaolei Zhang	version 1.1.0 (final release version)	2022-02-10
004	Siru Chen Zixuan Wan	version 2.0.0 (based on version 1.1.0, adding the updated SD card reader approach)	2022–03-05
005	Siru Chen Zixuan Wan	version 2.0.1 (based on version 1.1.0’s feedback, fixed previous issues)	2022–03-07
006	Xiaolei Zhang Zhaoqi Ma	version 2.0.2(update Alpha design)	2022-03-13
007	Zhaoqi Ma Siru Chen Zixuan Wan Xiaolei Zhang	version 2.1.0(final release version)	2022-03-17

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Acronyms

acronym	full description
PM	Particulate matter
BLE	Bluetooth Low Energy
RTC	Real Time Clock
MCU	MicroController Unit

References

[1] J. M. Barcelo-Ordinas, J. Garcia-Vidal, M. Doudou, S. Rodrigo-Muñoz and A. Cerezo-Llavero, "Calibrating low-cost air quality sensors using multiple arrays of sensors," *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, 2018, pp. 1-6, doi: 10.1109/WCNC.2018.8377051.

[2] Cho and Y. Baek, “Practical Particulate Matter Sensing and Accurate Calibration System Using Low-Cost Commercial Sensors,” *Sensors*, vol. 21, no. 18, p. 6162, Sep. 2021, doi: 10.3390/s21186162.

[3] Nosto. 2022. “*Ecommerce Return Rate Statistics in 2021: Causes and Best Practices*”. [Online] Available at: <https://www.nosto.com/ecommerce-statistics/return-rate/> [Accessed 18 March 2022].

1 Purpose

This document describes the preliminary design for the Low-cost High-precision Particulate Matter(PM) detector.

2 Concept of Operation

The high-level operation of the Low-cost High-precision PM detector is illustrated by the following user stories and use cases:

2.1 User Stories

- As a user, I hope that the PM detection device can continuously record the air quality of the current environment, and make the historical data searchable and traceable, preferably in the form of graphs, so that I can have a better monitoring of the current environmental situation.
- As a user, I would like the PM detection device to be able to implement different frequencies of detection. Because sometimes I want to observe the change of air quality in one hour, but sometimes I want to observe the change of air quality every minute and every second, so I want the monitoring frequency of the system to be user-controllable.
- As a researcher, I need a lot of PM detectors to measure the air quality in different areas. Due to the need for scientific research, I want sensors that are accurate, portable, and have a wide range of working conditions. Because we need to deploy such air quality monitoring devices in many places, I want air quality detectors that are affordable.
- As a researcher, I wanted to be able to use the PM sensor for a large amount of time without the need of replacing batteries or recharging.
- As a researcher, I would like the system to have enough capacity to store a large amount of data. Because of my work, I need to analyze a large amount of PM data, so I want the system to be able to store the data in csv format, so that I can easily process and analyze the data afterwards.
- As a parent, I would like this PM detector to have an “Alert Mode”, which lets the phone be able to alert the user while the PM value is detected above a certain level. (Manually Inputted before), so that I can take air purification measures to improve the air quality in my home.

Figure 1 below shows all the corresponding use cases

2.2 Use Cases

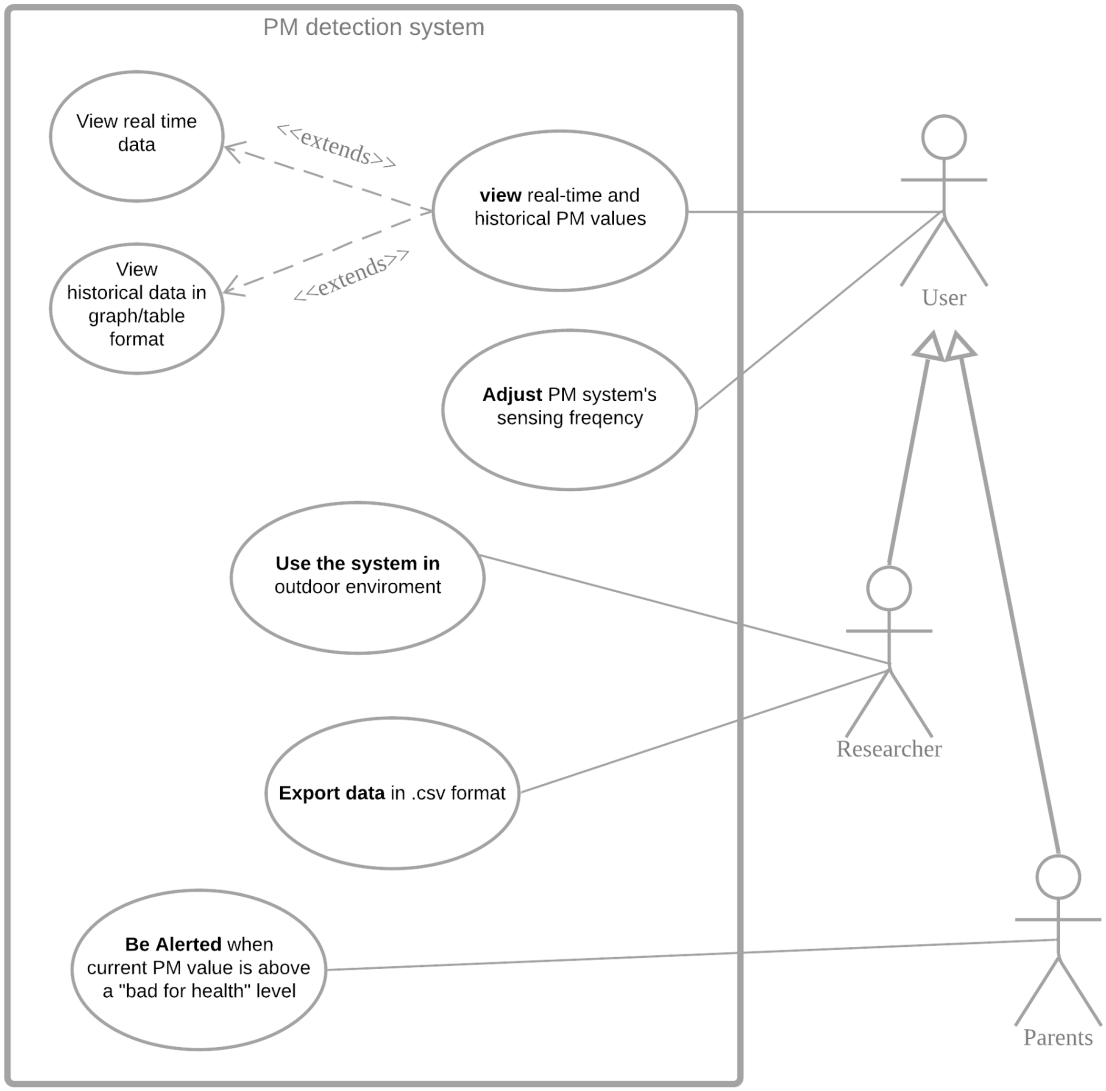

Figure 1 Use case UML diagram

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3 Functional and Performance Requirements

Table 1 Functional Requirements

FR #	Functional Requirement Description
FR-1	Sensor system should be battery powered;
FR-2	Sensor system should have a bluetooth connection to communicate with a smartphone;
FR-3	An Android App should be developed in order to communicate with the sensor;
FR-4	Sensor system should be able to store measured data;
FR-5	Android App should present the sensor system's detected value to users;
FR-6	Sensor system should have data processing and filter algorithm;
FR-7	Sensor system should be portable;
FR-8	Android phone should have access to bluetooth connection
FR-9	Android application should support an "Offline Mode" to access even without internet

Table 2 Performance Requirement

PR #	Performance Requirement Description	Related FRs
PR-1	Sensor system should be able to run for about 30 days without recharging.	FR-1, FR-7
PR-2	The Android application should be able to collect the existing data from the sensor to the phone and upload to the cloud server;	FR-2, FR-3, FR-4, FR-8
PR-3	The android application should alert the user when the sensor reports PM level is greater than 150 ug/m^3;	FR-2, FR-3
PR-4	The Android application should represent PM values in graphic or table format;	FR-4, FR-5
PR-5	The PM data processed by the system should be similar to the PM data from the accurate instrument, and the error range should be between an acceptable range;	FR-6
PR-6	The storage module should have the ability to store data from the past month with 2GB Capacity;	FR-4
PR-7	Storage method of the SD card should be circular storage.	FR-4
PR-8	The Android application should provide the function for opening .csv file	FR-5

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4 System Design

The PM detection system consists of a battery-powered particulate matter sensing unit and a smartphone application. The smartphone APP is based on Android, and is responsible for viewing data and setting some parameters for the sensing unit. The PM sensing unit is based on Arduino MKR WiFi 1010 board and uses three PM sensors, one temperature sensor, one Bluetooth low energy(BLE) module, one Real time clock (RTC) module, and one SD card module. The use of three PM sensors is to eliminate part-to-part variation, and each sensor will be calibrated using machine learning similar to the way that Barcelo-Ordinas et al. have done [1]. The use of temperature & humidity sensors is to offset the variations caused by temperature and humidity differences [1],[2]. Data processing algorithms and supporting firmware run on Arduino to realize the required sensing and data processing functionality.

4.1 System Architecture

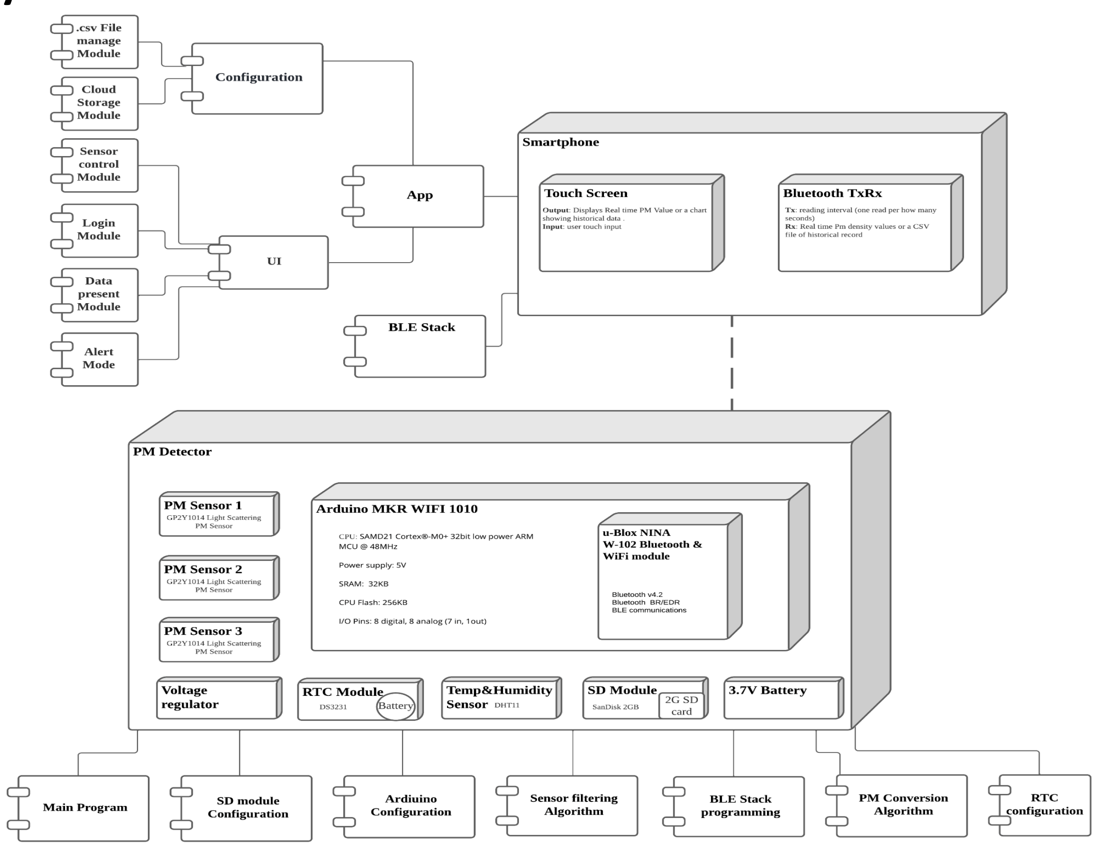

Figure 2 deployment and component diagram with annotations

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The primary software component on the Android application utilizes the BLE stack to send commands, set reading intervals, and receive data from the sensor system. The hardware PM sensor system consists of an Arduino MKR WiFi 1010 in prototype, three PM sensors, a temperature-humidity sensor, a RTC module and an SD storage module. The Arduino board has a built-in WIFI module(NINA).

4.1.1 Hardware Components

Hardware Components for Smartphone End
Smart phone running on Android with bluetooth 4.0 or above

Hardware Components for PM Sensing Unit
1x Microcontroller unit (MCU) *Should have sufficient processing power and on board storage. The MCU should have at least 3digital output, 1 digital input, and 3 analog input pins and is also capable of connecting with external SD card and BLE module.*
1x Bluetooth low power (BLE) module (incorporated into Arduino MKR WiFi 1010)
3x Light scattering PM sensor
1x Temperature humidity sensor
1x Micro SD card reader
1x 2GB Micro SD card
1x Voltage regulator
1x 3.7V 2000mAh Li battery
1x Rigid case
1x Real time Clock(RTC) module

4.1.2 Firmware Components

Firmware Components for PM Sensing Unit
Main program *Controller, Program logical execution procedures.*
Arduino configuration *Configurations of Analog-in, digital-out, GPIO ports.*
SD configuration module *Data storage, file manager.*
BLE Stack program *Communication interface.*
Sensor filtering algorithm *Filtering out noise and unwanted input data.*
PM conversion algorithm *Convert and process analog signal input to reliable PM value.*
Real time clock(RTC) configuration *Provide reliable and accurate time records to the system. Allows the system to keep track of the time when powered off*

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4.1.2 Software Components

Software Components for Android application to establish connection to PM Sensing unit
Login system *Uniquely defined user, establish bluetooth connection via device*
Sensor Control system *Operate the PM sensing unit via application; choose the frequency for the sensor to work with*
Data transmission system *Obtain real-time data.*
Data display System *Showing values of the current PM quality, provide statics over various time periods in graph*
"Alert Mode" *Set a boundary of PM values, alert via phone if the sensing PM value over the boundary*
.csv File manage Module File manager that is capable of opening and reading .csv files.
BLE stack program *communication interface between smartphone and PM sensor unit*
Cloud-uploading system *Upload the current data or locally stored data into our clouding system*

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5 System Requirements

Table 3 System Requirements

SR #	System Requirement Desc	FR#	PR#	Notes
SR-01	Sensing unit must contain a MCU with adequate processing power, RAM, and storage (32-bit 48MHz CPU, 32KB SRAM, 156KB Flash for Arduino MKR WiFi 1010).	FR-1, FR–6	PR-1	The sensing unit must have enough power to store firmware programs and process required algorithms.
SR-02	MCU must contain or connect to an external BLE module.	FR-2, FR-3	PR-4	BLE module is required to be connected with Android APP.
SR-03	Light scattering PM sensor must be able to directly output analog voltages without the need to pass through an op-amp.	FR-6	PR-5	This design does not contain an op-amp, thus the output voltage from the sensors must be tuned to be readable by the MCU without any amplification.
SR-04	Temperature & Humidity sensor must be able to output a digital signal.	FR-4 FR-6	PR-4, PR-5	Temperature & humidity sensor is connected to digital ports, so it must output sensed value in digital format.
SR-05	The Micro SD module must contain a Micro SD card reader and a 2GB SD card, and is able to communicate with MCU via SPI interface.	FR-4	PR-4, PR-6, PR-7	Since the on board flash is vulnerable to multiple writes, and is not large enough, a large enough external SD card must be used to store data.
SR-06	The 3.7V Li battery must be larger than 1024mAh.	FR-1	PR-1	Arduino MKR WiFi 1010 requires a battery to be larger than 1024mAh, a 3.7V 2000mAh secondary battery is directly power up MCU and will be boosted to 5V though a regulator to power up the PM sensors;
SR-07	Rigid cases must be minimized as much as possible.	FR-7	PR-1	Sensors must be portable.
SR-08	RTC must be able to run at least a month without running out of battery.	FR-1	PR-1	The RTC module has a coin cell backup, so the external clock should continue running even if the system is out of battery.
SR-09	Smartphones must be running on Android.	FR-3, FR-5	PR-2, PR-3, PR-4, PR-8	The APP we developed is based on Android.
SR-10	Smartphone OS must support BLE.	FR-2, FR-3, FR-8	PR-4,	The smartphone must be able to use BLE to communicate with the sensing unit.

6 Minimum Design

In this section a minimum design, the "walking skeleton" is described. The purpose is to define the functionality to be implemented in the first development iteration. The outcome is reported to the client providing an opportunity for early feedback. In the minimum design, after the PM sensing unit is turned on, the unit will automatically read signals from the PM sensor once per 30 seconds. Then, the signal will be converted into one physical density value. The restored data will be stored in the SD card as CSV format. Bluetooth advertising will begin as soon as the unit has been turned on. The user can start up the Android APP and connect to the unit via Bluetooth. If the user chooses to display real-time data, the PM sensing unit will speed up reading time and send a PM density value whenever a read is completed. The default reading interval is 3 seconds. The user can change the real-time and disconnected reading intervals by choosing a time interval from the application (the minimum reading interval is 1s). If the user decides to read historical data, Android Application provides functionality that can maped the data points into Density vs. Time chart, based on the value obtained from real-time data reading that is stored in the Firebase. Figure 3 below shows the minimum design deployment and component diagram.

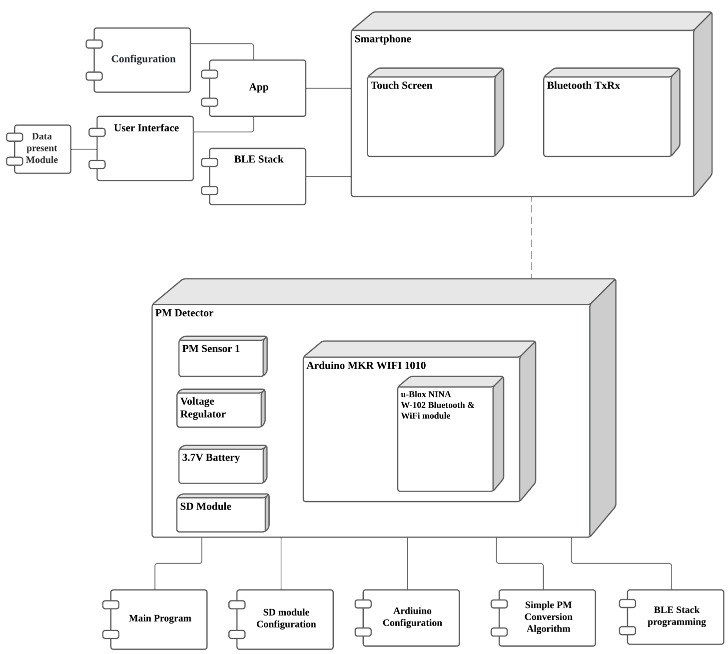

Figure 3 Minimum design deployment and component diagram

7 High-level Hardware Design

As shown in Figure 2, the primary hardware component for the smartphone application end is a smartphone running on an Android system with Bluetooth 4.0 or above, and the phone must either have an integrated Micro-SD card reader or a type-C/micro-USB port that will be connected to a Micro-SD card reader. The phone must be running on an Android system because the application in this design is based on Android. The phone must have Bluetooth 4.0 or above to establish a Bluetooth low energy connection with the PM detection unit.

The hardware components for the PM detection units are detailed in Figure.2. As shown, the controlling and processing unit of the PM detection unit is an Arduino MKR WiFi 1010 evaluation board, which is equipped with a Cortex M0+ 32bit MCU operating at a maximum 48MHz. The board is also equipped with a 32KB SRAM and 256KB onboard flash memory; however, we will not use the flash to store data sets since the flash memory will experience degradation after 10000 writes. Instead, the 1GB Micro SD card is used to keep data sets. A uBlox NINA W-102 Bluetooth and WiFi module is integrated into the Arduino development board; thus, there is no need for connecting an external Bluetooth module to the system. Temp Humidity sensor and three Particulate Matter detecting sensors are wired connected to the Arduino MKR board's Analog input port(built-in ADC). PM detection sensors' IR LED control pins are wired connected to Arduino MKR's digital output port. The SD module, including a 1GB MicroSD card, is wired connected to Arduino MKR board's digital output port via SPI protocol. A 3.7V rechargeable battery used to power Arduino is wired connected to Arduino, and the voltage regulator will boost the voltage to 5V to power sensors. A RTC module is wired connected to the Arduino via I2C protocol. Everything will be packed into a rigid case at the final design stage.

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8 High-level Software/Firmware Design

Software Design:

Software design includes 8 components. The software serves as a platform for users to send, read and interact with PM sensors. Login system uniquely identifies the user and builds bluetooth connection via device. The sensor control system is a user interface that provides researchers ability to adjust and set frequency. The BLE stack program serves as a communication interface between smartphone device and arduino. Data transmission system is to explore the functionality of BLE to receive and collect the real time data. The .csv management module reads the historically stored data directly from the SD card, so that users can then view and store them in the application. The cloud uploading system prompts users to store the data to a cloud database to obtain easy access for large amounts of data anytime with the account, while the cloud database as well as account are supplied by Google FireBase. Data display system is the rudimentary purpose of software, it displays diagrams over various time periods and current PM sensor values to users. Alert Mode serves as an additional functionality that provides an interface to monitor PM sensor value in the real time domain.

Firmware Design:

Firmware design includes 6 components. Arduino configuration is a custom software developed as a part of the project which will define the GPIO port and ADC. The main program is a custom software that will describe how the system behaves and goes through state transition. The SD module configuration is an open-source resource, providing the necessary interface to manipulate/access SD card storage space. The BLE stack is vendor-supplied, which will give essential methods to access BLE functionality. The Sensor filtering Algorithm is a necessary part of the project used to filter out unwanted data and noise [1], [2]. PM conversion Algorithm is a critical portion of the project, and it is customized to increase the accuracy and reliability of sensed PM data. RTC module configuration is needed since every PM value has a timestamp. RTC module configuration is an open-source resource that provides interfaces to access real time information.

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9 Prototype Budget

Table 4 System Budget (ROM)

Component	Mfr P/N	Mfr	Qty	Unit Price	Extended Price
Arduino	Arduino® MKR 1010 WiFi	Arduino.cc	1	$54.92	$54.92
PM sensor	GP2Y1014AU	Sharp	3	$3.55	$10.65
RTC Module	DS3231	ELECFANS	1	$2.39	$2.39
LiPo Battery	B08214DJLJ	EEMB	1	$5.81	$5.81
Temp Humidity Sensor	DHT11	ELECFANS	1	$1.12	$1.12
MicroSD Card	TF/MicroSD(2G)	Sandisk	1	$2.61	$2.61
MicroSD Module	B0793H4GPC	Robojax	1	$7.55	$7.55
				Total Cost	$85.05

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10 Alpha System Design

Introduction:

Compared to our prototype, there are several changes made for the Alpha design considering manufacturability and user experience. Considering the cost factor and manufacture purpose, our Arduino will be replaced by a customized PCB to connect the MCU, Bluetooth module and sensors. Similarly, we will change the models for sensors, Bluetooth module and MCU. Additionally, a voltage regulator will be implemented to provide two voltages (3.7V and 5V) using one battery. In the Alpha design, we will provide an extra wireless method for .csv file transmission to improve user experience.

Motivation:

In our prototype, we chose Arduino because it is off-the-shelf and would save us a great amount of time. However, the Arduino that we have chosen has extra hardware and processing power than needed. Hence we will need a deeply customized PCB board (containing the MCU and peripherals) to reduce cost, weight, and size in the production model. Furthermore, using a PCB will eliminate the need for a breadboard, greatly enhancing stability and integrity while reducing size and weight. We have used two separate batteries to provide two different voltages in our prototype, this would not be desired in the mass production design because it requires the user to handle two batteries separately, hence for better user experience and size, weight, and power + cost (SWaP+C), we will use a single battery together with a voltage regulator to provide two separate voltages. In the prototype, we have chosen to make .csv file reading purely manual by taking the SD card out from the sensor unit and placing it into a card reader because it is easier to implement and more stable than Bluetooth transmission, which is more desired in the development and testing phases. However, this would require the user to prepare an SD card reader and manually operate with the card. Hence, providing a relatively easier way of wireless file transmission is desired if the sensor is to be mass-produced.

- **Better user experience**

  We can give the user the option to transfer the .csv file via Bluetooth or manually remove the SD card from the sensor and read it using the smartphone. Considering that the SD module is the essential way to store data, circular storage is used in the design to meet the storage requirements from users, which means that if the storage space is used up, the latest data will cover the oldest data. This storage method can improve the freshness of the data.

On this basis, the system is designed to support hot-swap SD cards so that users can remove the SD card without restarting the system. When the .csv file is imported to their smartphone, the Android app will automatically upload the data to Firebase cloud storage so that users can get rid of struggling with storage space on local devices.

- **Better Size, Weight, Power, and Cost**

The changes mentioned below will mainly bring down the cost while maintaining the system's accuracy and integrity, which fits the initial goal of making a low-cost but high-precision sensor.

ATSAMD21G18A-UUT will replace Arduino MKR 1010 WIFI, an MCU from Microchip Technology; since Arduino resources are excessive, most resources are left unused. This MCU is Arm architecture, and its advantages lie in its small size, low power consumption, low cost, and high performance. If superior performance is required in subsequent product iterations, the ARM architecture has abundant chips to choose from, reducing the difficulty of porting in subsequent development. This replacement has a low power mode that will significantly save the system's power consumption. This MCU has 32KB RAM and 256KB flash memory, which is sufficient for the memory requirements in this design. The price for this MCU is $3.71USD.

ESP32-C3 from Espressif Systems will replace the NiNa Bluetooth module, ESP32-C3 is cheap and provides low power consumption with a reduction in size. The maximum output power is 21dBm, and the sensitivity is -105dBm, which is sufficient to cover the working scenario of the system. This module is based on Bluetooth 5.0 and BLE and has a low power mode. Those features exactly satisfied the low power consumption requirements in this design. The size of this Bluetooth module is tiny (5mm x 5mm), which could contribute to reducing the size of the system. This module also has a price advantage that only costs USD 1.61.

All sensors in the prototype will not be cut. If some sensors are cut, the accuracy of the PM will be sacrificed. However, in order to improve performance and accuracy, the temperature

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and humidity sensor will be updated to DTH22, which provides a broader temperature detection range (-40 to 80°C). The reason for not using separate temperature and humidity sensors is that using separate temperature and humidity sensors is more expensive than using DTH22, and DTH22 is an integrated sensor that effectively reduces manufacturing and testing efforts.

The battery choice will be changed from the previous dual battery (an alkaline battery for powering the sensor and a lithium battery for powering the MCU) to a 2000 mAh lithium battery. This would eliminate the need for the user to manage two batteries separately. This choice is based on environmental, size, and weight considerations. Although alkaline batteries are cheaper and the voltage regulator incurs additional cost, in the long term, lithium batteries are more common in modern technology.

- **Possible enhancement <NOT IMPLEMENTED DUE TO TIME LIMIT>**

The second prototype enhancement can be on the file transfer process. The research and development of large-scale data transmission through Bluetooth needs considerable effort, but there is not enough development time for this feature. Moreover, the project was developed based on Arduino, which has a single-threaded architecture, and relying on Bluetooth for a large amount of data transmission will consume a large amount of system resources, so the real-time performance of reading and processing sensor's data cannot be guaranteed.

If the time is permitted, the FreeRTOS can be ported to Arduino, which could provide a multitasking runtime environment to schedule the sensor reading task and the file transmission task. We can make the system more extensible by providing an API that allows the user/researcher to change the filtering algorithm. We can also create an API that enables the user to read the raw input from each sensor selectively. Technology improvements, such as the availability of better MCUs, can make our system better by giving us the ability to enhance machine learning. Furthermore, we can incorporate an LCD screen into the system in the future.

- **Conclusion**

In terms of user experience, the major enhancement will be that the user can now read .CSV files faster as we altered from Bluetooth file transfer to wired manual transfer or Bluetooth transfer. However, manual transfer of the SD card comes at the cost of making the user take out

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the SD card from the sensor manually and place it either into their phone or an adapter. Unfortunately, the users should prepare SD card adaptors to keep the selling price down. Other factors such as shape and SWaP factors have not changed significantly.

In terms of manufacturability, the sensor is not hard to manufacture in our prototype as it uses an off-the-shelf MCU (Arduino) with an integrated Bluetooth module and I/O interfaces. Nonetheless, to keep the mass production cost below $15, the Alpha design (and future iterations) will require the manufacturer to integrate (connect) Bluetooth module and I/O interfaces with the ATSAMD21G18A-UUT on a PCB. On the other hand, soldering everything, including sensors, battery cases, and buttons onto a single PCB, will eliminate the need for a breadboard, making manufacturing easier and more stable connections.

10.1 System Architecture

As mentioned above, the major change in our firmware architecture is that we will set the default transfer mode of the .csv file as Bluetooth. This would require our software end to incorporate an extra module, called the ".csv file management module" in Figure 3, responsible for extracting and storing the .csv file from the external SD card connected to the smartphone. We will further make the software capable of transmitting the extracted .csv file to the cloud. The major hardware changes are the swap of hardware components and the use of a voltage regulator to provide a 5V supply from a 3.7V battery so that we can use a single battery to power the whole system, as shown in Figure 3. The rest of the architecture remained the same as our prototype because this is a relatively simple sensing device. The basic sensor combination (3 PM sensors + 1 temperature & humidity sensor) should stay unchanged as this is the core of our design.

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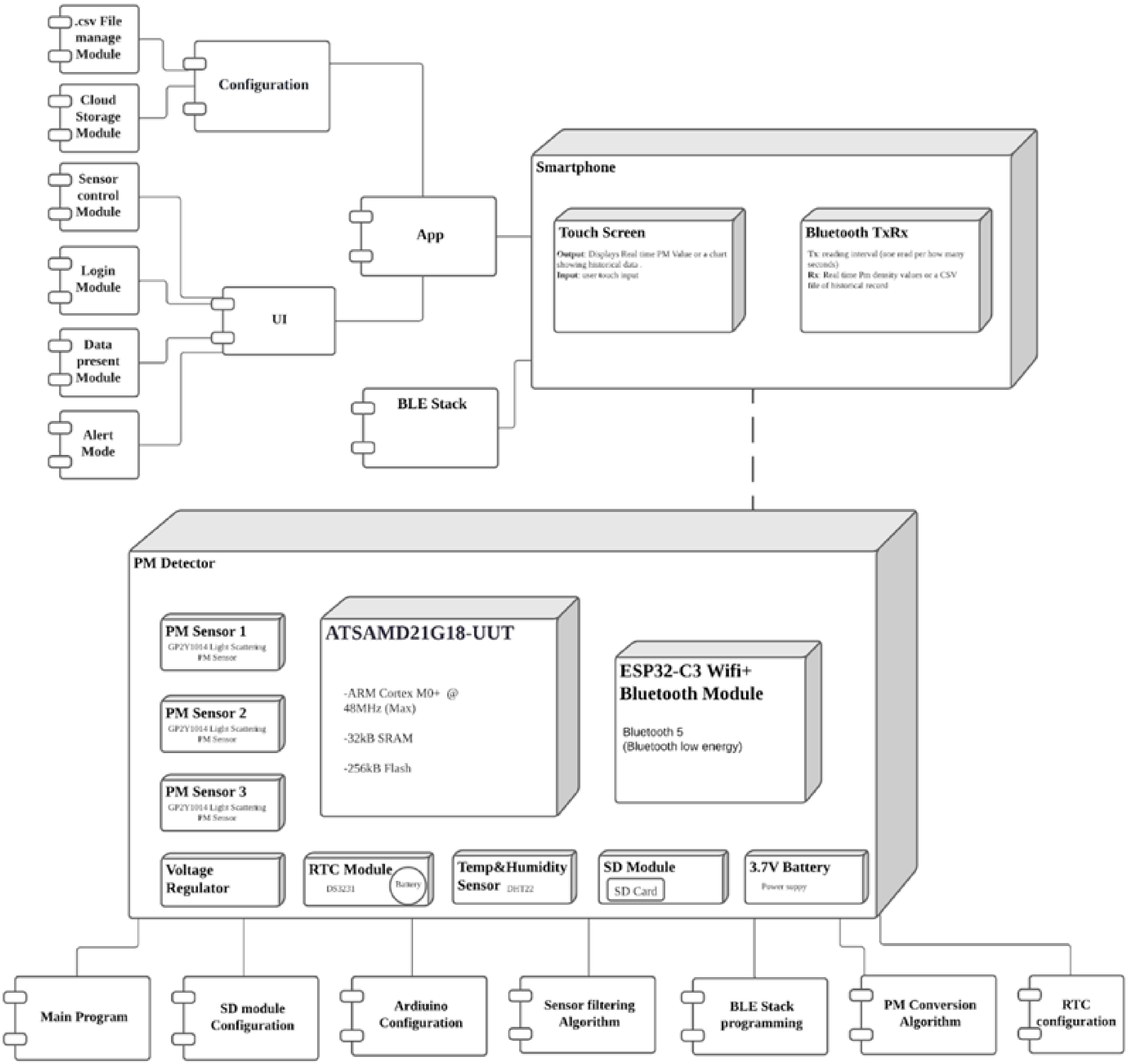

Figure 3 *Deployment and component diagram with annotations*

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10.2 Block Diagram

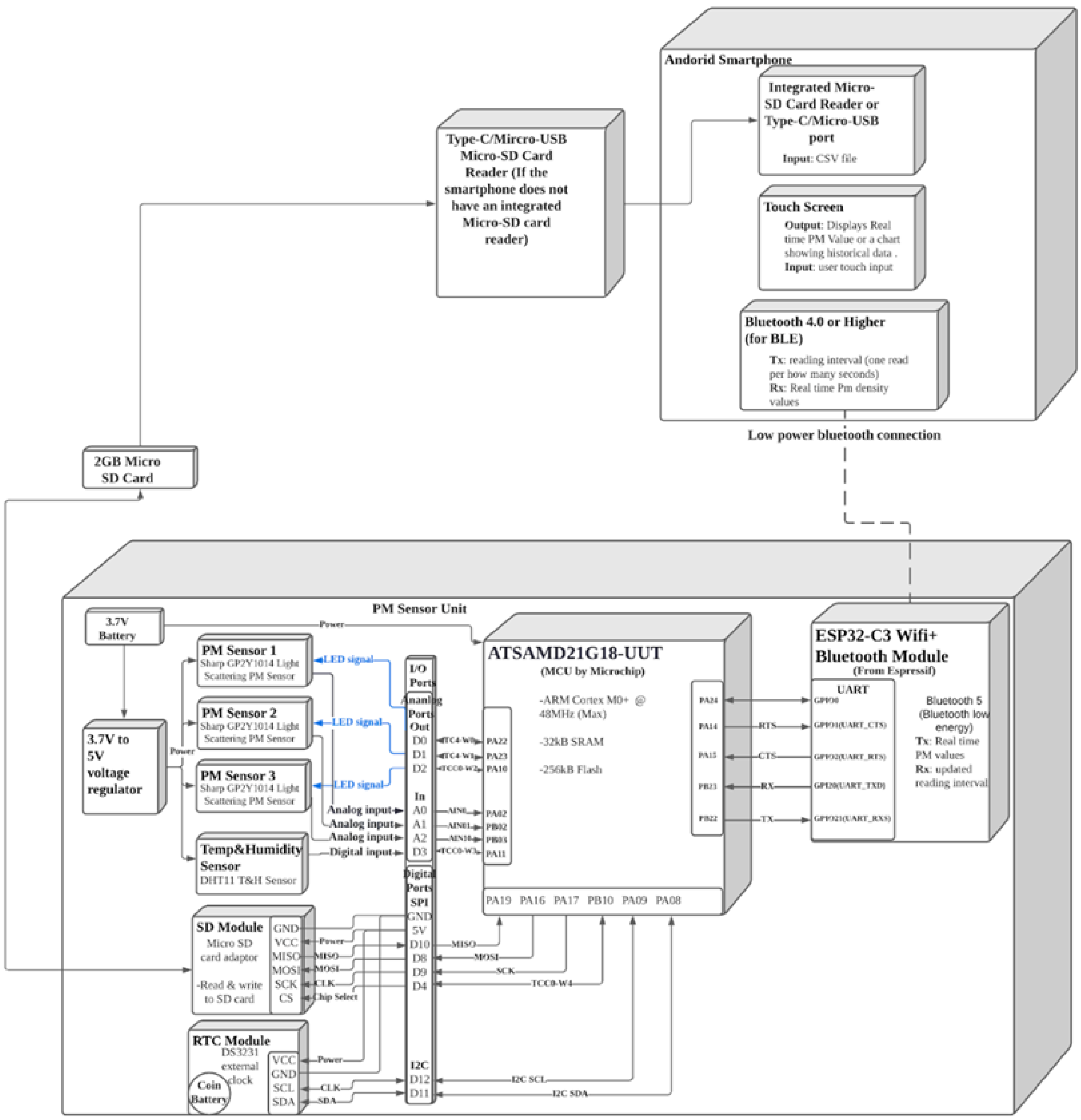

Figure 4 updated hardware block diagram for the Alpha design

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11 System Budget

Component	Mfr P/N	Mfr	Vendor	Qty	Unit Price	Extended Price	Extended cost(1000)
MCU	ATSAMD21G18A-UUT	Microchip Technology	Digikey	1	$4.45	$4.45	$3.98
PM sensor	GP2Y1014AU	Sharp	Alibaba	3	$3.19	$9.57	$7.64
RTC Module (incl. coin cell)	DS3231	ELECFANS	Alibaba	1	$2.39	$2.39	$1.87
LiPo Battery	SY803060	HJ	Alibaba	1	$5.38	$5.38	$4.32
Temp Humidity Sensor	DHT22	ELECFANS	Alibaba	1	$4.54	$4.54	$3.56
MicroSD Card	TF/MicroSD(2G)	Sandisk	Alibaba	1	$1.20	$1.20	$0.95
MicroSD Module	CH376S	Risym	Alibaba	1	$0.72	$0.72	$0.67
BLE 5.0 Module	ESP32-C3	Espressif Systems	Digikey	1	$2.03	$2.03	$2.03
PCB(incl. labor)	NA	NA	macrofab	1	$37.11	$37.11	$4.54
Yield						100.00%	93.00%
Subtotal						**$67.39**	**$31.63**
Housing	NA	NA	Alibaba	1	$0.26	$0.26	$0.26
Packing	NA	NA	Alibaba	1	$0.05	$0.04	$0.04
Shipping			Canada Post	1	$45	$4.5	$4
Return						0.00%	5.00%
Tax & Duty						5.00%	5.00%
Landed cost						**$79.59**	**$39.61**

Table 5 System Budget

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*** Cost of yield:**

We estimate the yield rate is 93%. Major parts of components are shipped from China since Alibaba has a huge price advantage. If the quality of the product is faulty, then we have to throw it away because the cost of returning the broken component to China is too high and not worth doing so. In this regard, we suppose the yield is about 93%.

*** Cost of return:**

An article in 2020 suggested that the return rate for consumer electronics is 8% [3]. Assuming that out of this eight percent, three percent of the products have no product quality issues, so we can re-sell this three percent, then only five percent of the products are not resellable, so we assume a return rate of 5%.

*** Cost of PCB:**

The PCB costs are estimated by using the online tools provided by Macrofab. There is a project that has similar complexity as this project. Based on that price, we add some extra cost since our product's PCB is a little bit more complex.

*** Cost of Housing:**

The housing cost is based on the existing products that have similar size on Alibaba. Once we have an order for more than 3000, we can let the factory open the mold to manufacture the customized housing appearance.

*** Non-Recoverable Engineering(NRE) Cost:**

Non-Recoverable Engineering(NRE) Cost = $39.61 + 1\%(39.61 * 1000) = \$435.7$

*** Cost of other components:**

All other component costs are listed on their website.

*** Manufacture cost in larger quantities**

Based on our research on the sales of air quality sensors sold online, there is a chance that we can sell 500+ per month if our sensors are popular among consumers. There are two reasons for this prediction. First, we used sensor fusion technology, so we have three PM sensors and one temperature and humidity sensor in our system, thus the cost is higher than the products of competing companies. In this regard, we may not be attractive enough for those consumers who are price sensitive. Second, because our positioning of this product is high precision, our target customers are researchers or laboratories, because ordinary customers do not need such high precision instruments. According to supply chain theory, a stable inventory should be 1.1 times the monthly sales volume, which is 550 units. Although the target of 1,000 was not reached, the availability of this can be dynamically adjusted according to changes in market demand. The table below shows the cost in quantity 500 and 1000.

Component	**Cost in 500**	**Cost in 1000**
All components (excl. PCB)	$33.67	$29.56
PCB (incl. labor)	$5.26	$4.54
Yield	93.00%	93.00%
Housing	$0.26	$0.26
Packing	$0.04	$0.04
Return	5.00%	5.00%
Tax & Duty	5.00%	5.00%
Landed cost	$44.53	$40.51

Table 5 System Budget in 500 and 1000

According to the statistics, the cost of manufacturing 1000 products will be $4 lower than the cost of 500 products. While this is attractive, the risk of outputting products above the safety stock needs to be subsequently evaluated.