Hamza Shabir | 4052549

A REPORT ON THE DESIGN AND SECURITY STAGES OF BUILDING AN IOT PROTOTYPE THAT MONITORS CO2 CONCETRATION IN THE AIR.

IOT DESIGN AND SECURITY - REPORT

Word Count | 3200 ~

Table of Contents

Abstract

This report explores the background of the problem which is the increase in CO2 concentrations and a way to mitigate that by building an IOT device prototype which allows to keep track of CO2 levels and also the application domain associated to this problem and the prototype. Furthermore, the report goes through the development stages of the prototype which include architecture, design and implementation.

It then presents thoughts on the current level of security and threats of the prototype, before summarizing the main findings from the prototyping and evaluation.

Introduction

Air pollution has been increasing all over the world. The average CO_2 levels in the air have almost doubled in the last 60 – 70 years due to the industrial revolution. Higher concentration of CO_2 in the environment is reported to have negative effect on an individual's physical and mental health and also have a negative impact on one's productivity and along with many other environmental effects.

One way we could try to mitigate the side effects of increasing CO_2 levels is by monitoring these levels and analysing the data gathered so we can take necessary steps to improve the air quality around us.

To address this, we will be using an internet of things (IOT) enabled device which will be specific for our use case. The device will have sensors that will periodically retrieve the required values, these values will then be processed to be human readable and displayed on a display screen for live readings of CO_2 concertation along with humidity and temperature and also for notifying the user if CO_2 concentrations are higher than expected. These values will also be collected and stored on cloud for any future analysis.

Background

According to (Mulhern, O. 2020) CO2 levels before the industrial revolution were at around about 280 parts per million (PPM) and in modern day because of industrialization and burning of fossil fuels those levels have risen to about 420 parts per million and the levels continue to increase. And in Metropolitan environments, these levels are more like 500 parts per million.

As a matter of fact, the above-mentioned values are for outdoors and we spend most of our time indoors and with the recent pandemic even more of our time Is being spent in indoor environments due to increase in people working/studying from home, and indoor environments are often poorly ventilated where the CO2 levels can reach upwards of 1,000 parts per million. And what's important here is that researchers have carried out controlled experiments to test the higher-order decision-making abilities of office employees at varying levels of CO2, and they found out that at 1,000 parts per million mark, there is a 15% decrease in cognitive functionality (Allen et al., 2016). That's a big deal because we spend a lot of our time in these sorts of closed environments.

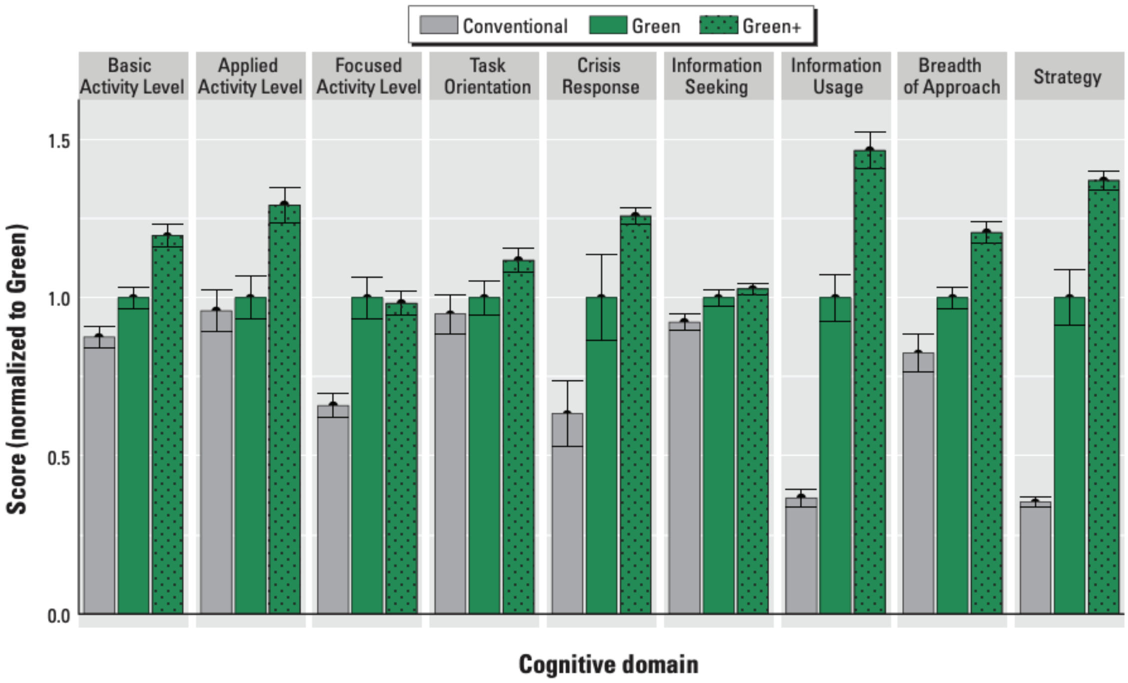

Figure 1: Various cognitive domains tested across 3 different CO2 environment modals (Allen et al., 2016).

The figure above shows how the average cognitive scores were higher under green building conditions (where CO2 concentrations were lower compared with conventional building) and on green+ (where CO2 concentrations were even lower compared with conventional building) even higher than the green building conditions.

Another example, researchers carried out controlled experiments at schools to examine the effects of school indoor air quality (IAQ) on academic outcomes in US states like Texas, Idaho, and Washington, and they found out that in over 50% of those classrooms, students and teachers alike were being exposed to CO2 levels well above the 1,000 parts per million mark. In the same studies, they found out that when CO2 levels reached 1,400 parts per million, the cognitive functionality of an individual dropped by a staggering 50%. And at around 2,000 parts per million mark, all sorts of other side effects start to appear, some people report headaches, laziness, poor concentration, loss of attention, increased heart rate, and slight nausea.

CO_2 levels in bedrooms and vehicles frequently reach levels of around 4,000 parts per million, and these are also the places that we spend a lot of our time in. Regardless, these levels aren't uncommon and these values are expected to go even higher so the best thing we can do is to investigate these exposures further and also in other indoor environments, where decrements in cognitive function and decision making could have significant impacts on health, productivity, learning, and safety.

An IOT device can be very useful for this use case. Before discussing further about the IOT prototype we should first define what is internet of things (IOT)? “The Internet of Things (IoT) describes the network of physical objects “things” that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet. These devices range from ordinary household objects to sophisticated industrial tools” (Oracle.com, 2020). The thing in IOT (internet of things) can be referred to as a vehicle with sensors, sensors on traffic lights in a public transport management system, a farm animal with a biochip inserted for identification purposes or in our case a CO_2 monitor. IOT is a very broad and complex field and for simplicity it can be characterised into different application domains. And the application domains that are related to our prototype are:

Wearables – a device that can be worn as an accessory or embedded in clothing or a user’s body. In our case this could be a wearable accessory of some sort which has a display for keeping track of CO_2 levels.

Smart living environment for aging well – using smart technologies which allow a safe, healthy and independent living. In our case this could be a wearable attached to the user which keeps track of the levels wherever they go or another device which is fitted in a specific room or space which keeps track of the CO_2 levels so those can be monitored by the housing society or their carer and then appropriate actions could be taken to improve the air quality.

The CO_2 monitor prototype proposed could be used in both of these application domains as major principles of wearables like collecting individuals’ subjective data can be helpful in smart living environments for aging well. This can be done by using a set of sensors to log the values to notify its users with the onboard display and to send the values to cloud where this data can be visualised.

Prototype Development

In this section of the report, we will go through the development process of the above proposed prototype discussing first the architecture and then the development of the prototype detailing the sensors used and how the data is transmitted and visualised and finally discussing the implementation of the prototype.

Architecture

An architecture establishes reference standards for the design, implementation and the integration of IOT products and services in layers which helps with evaluation and monitoring of the IOT system and also helps in scalability. Due to the simplicity in design of the prototype, the architecture referenced was WSO2 architecture. This is a 5 layered architecture with 2 extra cutting layers which are associated with the other 5 layers as displayed in the figure below.

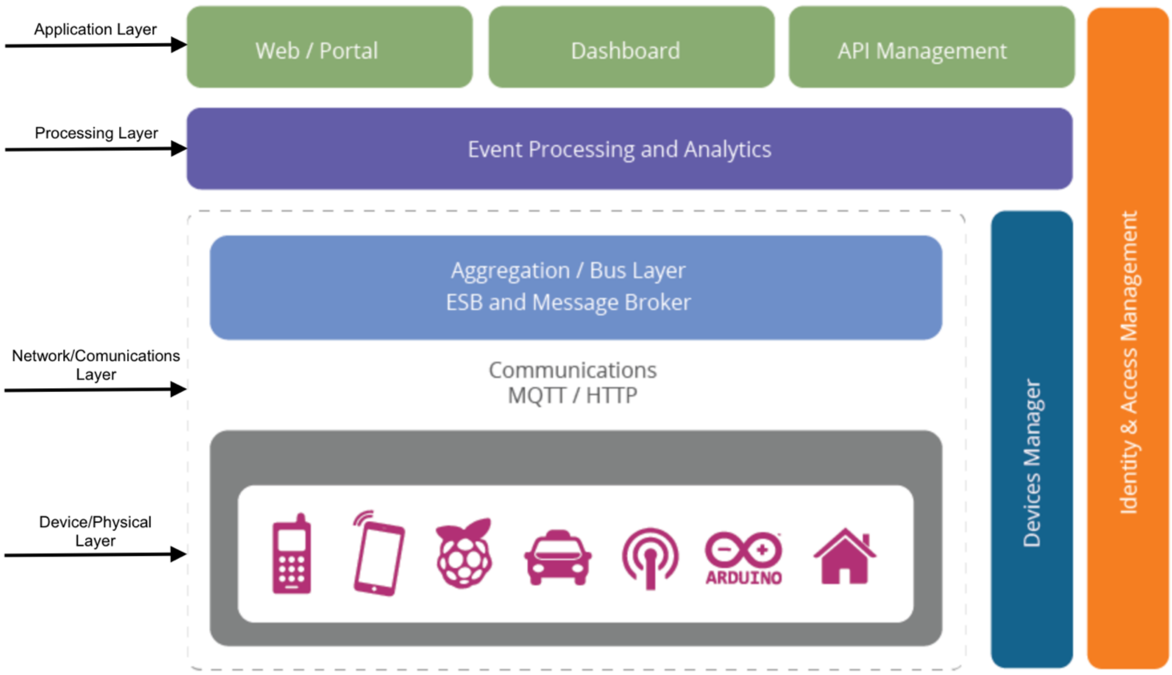

Figure 2: WSO2 Reference Architecture for IOT (Wso2.com, 2016).

We will discuss all these layers in relation to the CO2 monitor prototype.

Device/Physical Layer: This is the layer at the bottom of the architecture normally one of first layers of any IOT system. This involves “things” which are devices with a set of sensors that communicate with the internet directly or indirectly. These devices are capable of collecting the data from sensors and then formatting and processing that data before it’s sent over the network. In our case we have a set of sensors that collect the required values which are processed locally to be viewed by the user on a screen.

Network/Communications Layer: This layer comes right after the devices layer. This layer supports the connectivity of the device and provides an overview of how data is moved from the device to the cloud. In this layer a normal device has a Wi-Fi adapter which allows it to connect directly to a WIFI network where the processed data is sent to the cloud. But in our case, this is different. The prototyping device we are using does not have a direct Wi-Fi connection so instead the device is connected to a computer via serial where the data is logged and then a Node JS application retrieves that data and the date is sent to cloud via HTTP protocol and the get request. This approach does have drawbacks which will be explored in the security stage of the report.

Processing Layer: This layer is responsible for storage and any further processing of data received. Date is aggregated into the storage system as soon it arrives. We are using 2 different types of cloud storage systems (ThingSpeak and Blynk) to store the data and both have a slightly different process of aggregating this data.

Application Layer: This is the layer where data is visualised. The cloud storage systems used both provide ability to present the data in tables and analyse with complex queries like checking the variations in the data values.

Device Management: This handles the maintenance and control of the device. In our case the computer connected to the device is responsible for the management of the device like enabling/disabling device specific settings, resetting the device if there's any issues or adding new features and also handling the data to be passed to network layer.

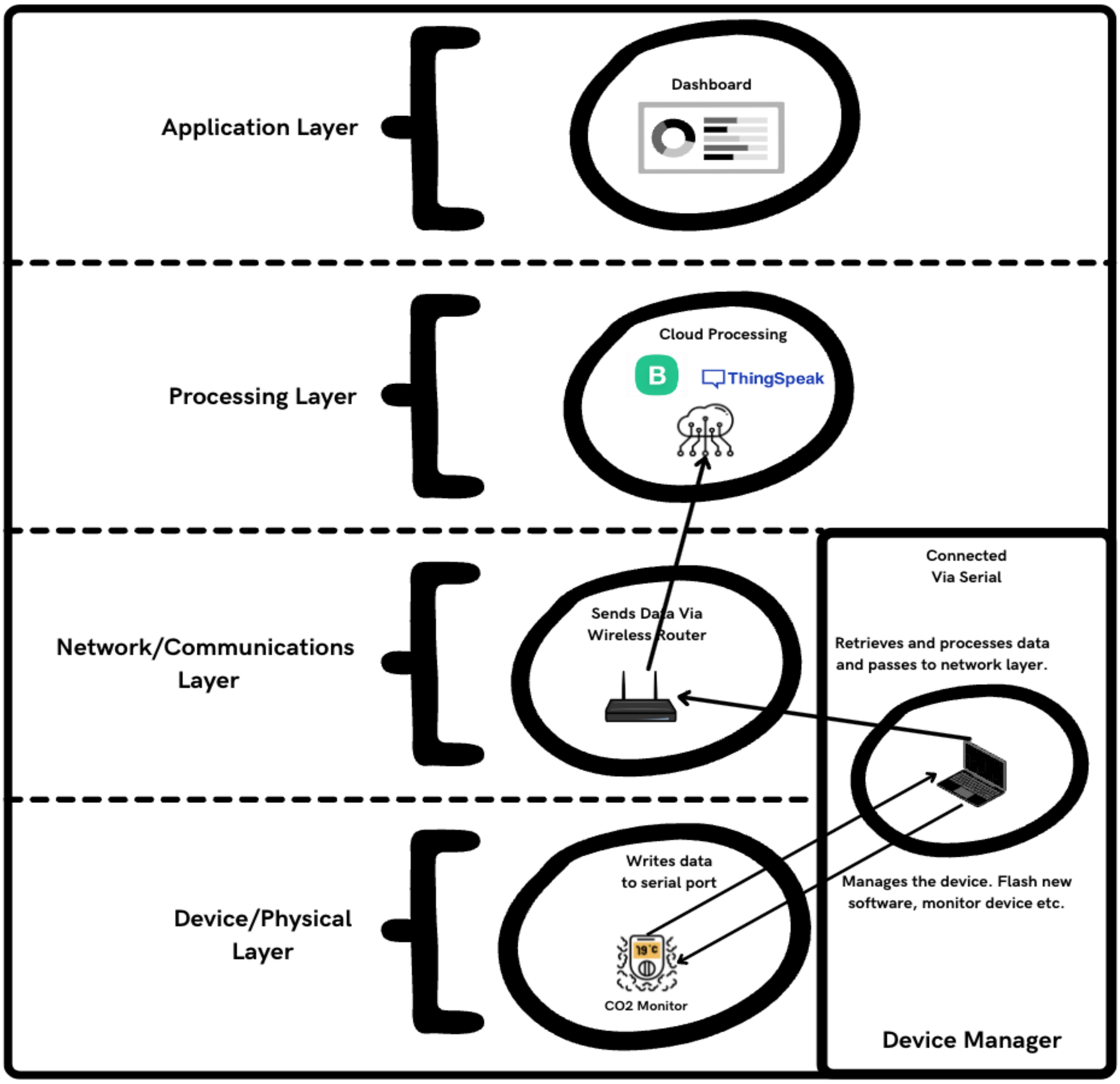

Figure 3: The proposed Architecture.

The following layers were not used:

Aggregation/Bus Layer – Because currently there is only one device so we can route communications directly to the cloud. This layer "aggregates and combines communications from different devices and routes the communications to a specific device" (Wso2.com, 2016) which is not required for our use case.

Identity and Access Management – Access management layer is not required at the moment because there is no sensitive data being retrieved. But this could be considered in the future if the device starts collecting user specific data like location.

Design

The CO2 monitor prototype was build using the following components:

Arduino Mega 2560 – The brains of the prototype and is an electronic hardware development/prototyping board. This is used to power the sensors and get appropriate values with the use of software and any other processing required like in our case calculating AQI.

DHT22 Sensor – This is a Humidity and Temperature sensor.

1K Ω Resistor – This is required on the data line of the DHT22 sensor for reliable readings.

MQ135 Sensor – This is a Gas sensor which offers a low-cost solution for detecting the concertation of gases in the Air (especially CO2) in PPM (parts per million).

OLED Display – This is required to display current readings from the above-mentioned sensors.

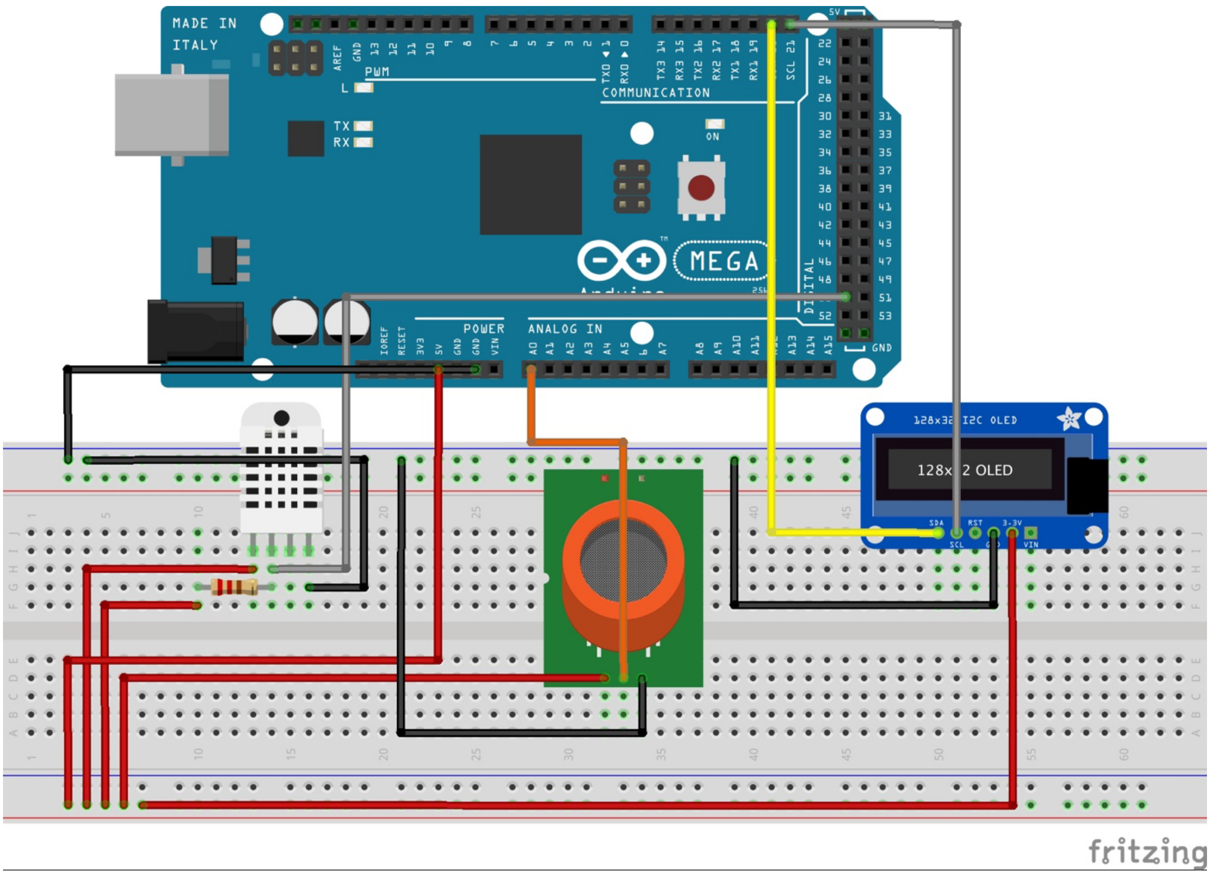

Figure 4: CO2 Monitor prototype design.

Fritzing was used to create the breadboard design of the prototype listed above. This design shows the layout of sensors and their connection with the micro-controller.

After the micro-controller gets the required data with the help of sketches (micro-controller code/program programmed using C++) and third-party libraries (Shabir, 2022) which format the analogue values retrieved from sensors into standard and human readable data. Temperature in degree centigrade, humidity in percentage and CO2 concentration in PPM (parts per million). As mentioned above in the architecture section of the report, this micro controller does not have a Wi-Fi module so to overcome this issue we first serialize the formatted data into a JSON (JavaScript Object Notation) object and write it into the serial stream.


```
{
  "temperature": "22",
  "humidity": "77",
  "co2Value": "1050"
}
```


Figure 5: JSON object after it is deserialized.

A Node JS application then retrieves this from the serial stream and de-serializes the data into a Java Script object which is then again formatted appropriately for the 2 different cloud platforms that are being used and sent using REST API HTTP get request (Shabir, 2022). This happens every minute.

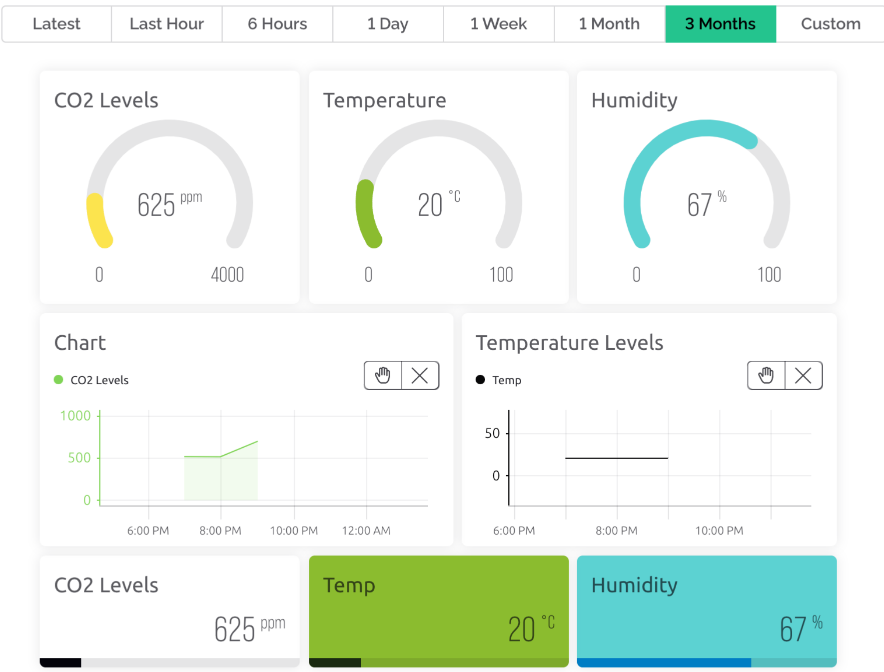

Figure 6: Blynk cloud Dashboard.

The data sent to Blynk is displayed nicely in a dashboard where we have gauges (display is colour based so if values are higher the colour changes so the user is aware) that display the live values being sent from the prototype and charts that display the variation in values over time.

Figure 7: Thing Speak dashboard.

The data is also sent to Thing Speak cloud where we have another dashboard with similar gauges and charts. Here we can do much more complex calculations between these values which could be helpful for users.

Figure 8: Display notifying that the sensor is heating up.

The formatted data is also displayed on an OLED screen. When the device is first powered on, we wait for around 2 minutes so the heating element inside of the MQ135 sensor can heat up properly so we get reliable data.

Figure 9: Display showing live CO2 levels.

After that the display cycle through a few screens to display relevant information.

First displaying the live CO2 levels in PPM. The reading and the graph changes if there is a change in value.

Figure 10: Display showing all sensor values.

Then the Average of CO2 reading and the current temperature and humidity readings are displayed.

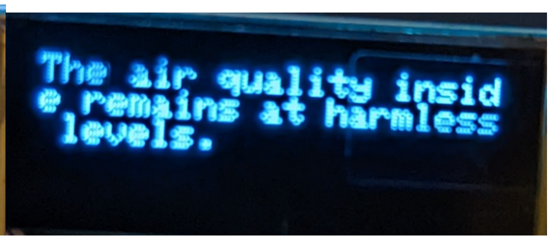

Figure 11 & 12: Display showing CO2 AQI infromation.

Lastly, we compute the current AQI (air quality index) related to CO2 which consists of a AQI index from (1-6) and rating associated with that index and also the meaning for that rating so the user is well aware of these readings.

RATING	INDEX	CO2 PPM	MEANING
Excellent	1	0 - 400	The air inside is as fresh as the air outside.
Fine	2	400 - 1000	The air quality inside remains at harmless levels.
Moderate	3	1000 - 1500	The air quality inside has reached conspicuous levels.
Poor	4	1500 - 2000	The air quality inside has reached precarious levels.
Very Poor	5	2000 - 5000	The air quality inside has reached unacceptable levels.
Severe	6	from 5000	The air quality inside has exceeded maximum workplace concentration values.

Figure 12: AQI specific to CO2 Concentration's (Heinecke, 2020).

This is the Breeze Systems CO2 specific AQI calculation system which was used in the above-mentioned Figure's 9 & 10. This provides the users with a descriptive scale which can show how polluted the air is as the individual readings of PPM can be quite over whelming for users.

Implementation

The prototype built, works as expected. It collects CO2 concertation values wherever the user goes and then notifies the user if the values are getting higher than expected by calculating a specific AQI for CO2 and all the values are stored so users can keep track of these values by the use of 2 cloud dashboards where both live and historic values are plotted and stored. This all allows the users to take any necessary step to improve their surrounding air quality. If there in a living environment they can try to improve indoor ventilation or if driving a vehicle then they can try opening a window.

Due to time constraints, there were some additions which could have further helped users.

GPS Integration – a GPS sensor could be added to the prototype which would allow the values to be associated with GPS coordinates. This would help in sorting the values by specific areas like user's home or work place. And could also help in lowering the number if readings taken as we could add additional interval if user hasn't move.

Visualising effect of temperature and humidity on CO2 values – this is mostly software related as we already have all the required readings. The temperature and humidity values were added because of that but due to complexity this feature cannot be implemented in the first prototype.

Security Evaluation

As IOT consists of a vast network of inter connected physical objects (objects with limited computing power and capacity) that exchange data (Balbix, 2020) via the internet it makes the security aspect of the model quite challenging.

IOT models require security in almost every layer of their architecture no matter the complexity or size of the model. This section of the report will go through the security evaluation (using the STRIDE model) of CO2 monitor prototype per layer basis, highlighting the most significant risks.

	Threat	Property Violated	Threat Definition
S	Spoofing identify	Authentication	Pretending to be something or someone other than yourself
T	Tampering with data	Integrity	Modifying something on disk, network, memory, or elsewhere
R	Repudiation	Non-repudiation	Claiming that you didn't do something or were not responsible; can be honest or false
I	Information disclosure	Confidentiality	Providing information to someone not authorized to access it
D	Denial of service	Availability	Exhausting resources needed to provide service
E	Elevation of privilege	Authorization	Allowing someone to do something they are not authorized to do

Figure 13: STRIDE acronym for threat types (SEI Blog, 2018).

Device Layer – Tampering

As the main application of this prototype is that user can rely on consistent and reliable data, in this layer the biggest security threat would be Tampering with the device or sensors like damaging the components or interfering with the sensors in way that would make them unreliable. As the current prototype has all the connections on the breadboard without any enclosure a possible mitigation for this would be to create an integrated circuit board where the connections are not easy to interfere with and also add an enclosure.

Device Manager – Spoofing, Repudiation, Denial of Service and Information disclosure

As mentioned above, this prototype does not have a Wi-Fi module which would have allowed us to make the API calls through the micro controller to pass the sensor data to cloud. And the way around that has some issues, as we are connected to a computer and if the computer is plagued by any security vulnerabilities that would mean an un-reliable connection and grant device managerial access, which means access to upgrade or wipe firmware and add/remove features. A way to mitigate this would be to use a secure Wi-Fi module.

Network Layer – Tampering, Spoofing and Denial of Service

The data is processed and then published to Thing Speak and Blynk cloud services over the Wi-Fi of the computer device. This opens up a lot of space for any potential security threat vulnerabilities like interception of data while it's being sent to the cloud service, impersonation of device to inject false data or overloading the RESTAPI HTTP calls so the frequency of the data flow is disturbed or no data is sent through due to the service being inaccessible. This is mostly an issue when there is data flow over trust boundaries so a possible mitigation would be to make these calls over an encrypted channel or using the MQTT communication protocol which is more secure than HTTP.

Processing Layer – Spoofing and Tampering

Spoofing and Tampering threats can occur within this layer which are discussed before and this could also follow the same mitigations discussed earlier.

Application Layer – Spoofing, Information Disclosure and Denial of Service

This is a Dashboard where users can keep track of their current or previous CO2 data although these isn't any private data being stored with those values but we might to add some user specific data in future so we should have mitigation in place for potential threats like Spoofing, Information Disclosure and Denial of service all of which have been discussed before and follow similar mitigation strategies. One other case of spoofing can also occur, as there is a developer who manages the dashboards, if the developers account is hacked (Spoofing) this would allow them access to that data so to mitigate this issue w could introduce Roles for developers with read or write access based on the role and also introduce some sort of MFA (multi factor authentication).

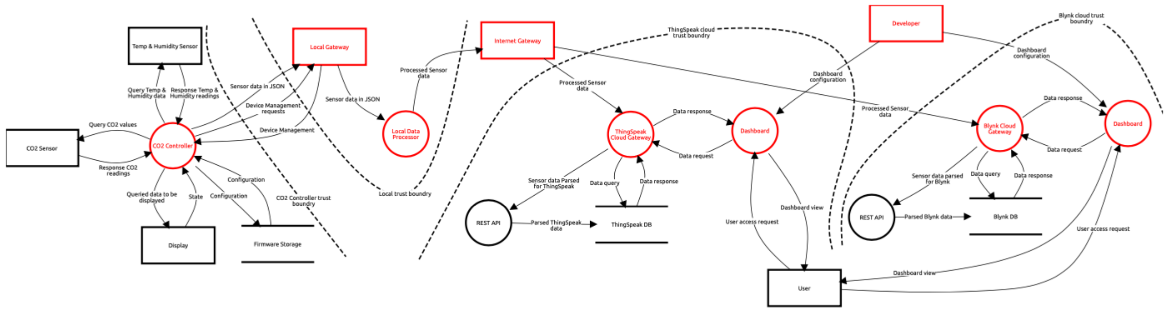

Figure 14: Threat model diagram for the IOT Prototype.

The figure above shows the Threat Model diagram for CO2 monitor prototype. The diagram layouts the data flow of the prototype and also trust boundaries between different parts of the prototype. It also highlights the parts at security risk.

Conclusion

To conclude, going through the process of researching about the problem and the application domain and then designing the prototype based on that and then finally evaluating the security of the prototype has been a rewarding experience has taught me a lot about the IOT field.

The prototype built achieves the goal of keeping the users aware of CO2 contraptions around them but there are some limitations to the design because expectations were lowered during the development stage due to some unforeseen circumstances and not fully understanding the complexity of IOT systems. There are also some possible future improvements to the prototype that the report mentions in the implementation stage.

References

1. Mulhern, O. (2020). *A Graphical History of Atmospheric Carbon Dioxide Levels Over Time*. [online] Earth.org. Available at: Earth.Org [Accessed 11 Nov. 2022].

2. Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J. and Spengler, J.D. (2016). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environmental Health Perspectives*, [online] 124(6), pp.805–812. doi:10.1289/ehp.1510037 [Accessed 12 Nov. 2022].

3. Oracle.com. (2020). *What is the Internet of Things (IoT)?* [online] Available at: Oracle [Accessed 12 Nov. 2022].

4. Wso2.com. (2016). *A Reference Architecture for The Internet of Things.* [online] Available at: Wso2 [Accessed 12 Nov. 2022].

5. Hamza Shabir (2022). *hamzazmah/iot-project: Internet of things (IOT) prototype for measuring co2, temperature and humidity.* [online] GitHub. Available at: GitHub [Accessed 22 Nov. 2022].

6. Heinecke, R. (2020). *Calculating an actionable indoor air quality index - Breeze Technologies*. [online] Breeze Technologies. Available at: Breeze Technologies [Accessed 12 Nov. 2022].

7. Balbix. (2020). *IoT Security Challenges and Problems | Balbix*. [online] Available at: Balbix [Accessed 17 Nov. 2022].