Dryer Temperature Probe & Towel Bacteria Detector

ECE 445 Final Report

Team 34 - Joshua Rodriguez, Michael Pauls, and Yeongyoon Park

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TA: Charles Ross

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Abstract

Bath towels provide an ideal environment for harmful bacteria and mold to grow given that they are often damp and stored in a dark bathroom. Team 25 of spring 2019 originally addressed the problem of bath towel bacteria by creating a cleaning cabinet using UV LEDs. This report outlines our monitoring solution designed to detect and alert the user when bacteria and mold are present on a bath towel. Our solution is noticeably less expensive than its predecessors, and it is the first of its kind to focus exclusively on monitoring rather than blindly eliminating bacteria.

1. Second Project Motivation

1.1 Problem Statement

Bath towels are typically used every day, often after a shower, but people rarely think about how often they should clean their bath towels. Studies have shown that few people wash their bath towels more frequently than once a week. Because bath towels are often damp, stored in a dark bathroom, and left to air dry, they provide the perfect environment for unwanted bacteria to grow. This can lead to a buildup of unwanted substances like mold, mildew, or bacteria on the towel which can result in an unpleasant odor that makes the towel unsuitable for drying use [1]. Knowing when a bath towel is beginning to exhibit signs of unwanted bacteria could provide insights into when a bath towel should be cleaned.

1.2 Solution

We propose building a monitoring device that lets users know when to wash their bath towels. Our unit would accomplish this by monitoring the amount of emitted CO_2 from bacteria and mold. As mold develops it emits CO_2 as a byproduct. In mold-free environments, there are typically around 400 parts per million (ppm) of CO_2. With mold, CO_2 concentrations can spike to over 1,000 ppm [2]. If the towel is deemed moldy, the user will be alerted via a speaker emitting noise. There will also be a smartphone app allowing users to assess the various levels of bacteria present on their towels.

This project was originally done in Spring 2019 by team #25. However, their project focused on cleaning the towel with a relatively expensive UV LED solution. Rather than detecting the amount of bacteria, a UV LED cabinet was triggered on a timer and blasted the towel with disinfecting light regardless of if the towel actually needed cleaning or not. Their cleaning UV cabinet cost around $200.

Our solution proposes simply identifying when a towel should be cleaned and alerting the user of this. Because towels can be cleaned using traditional washer and dryer units, we sought to eliminate the inclusion of expensive UV LEDs and a cleaning cabinet altogether. Rather, we can capitalize on the existing infrastructure (in-unit washers and dryers) as our cleaning mechanism and provide a monitoring solution for towel-bourne bacteria. Additionally, this will be beneficial if users are away from home when a bath towel would not be regularly used since unnecessary cleaning would not occur.

Other attempts at preventing towel bacteria growth have rarely been made yet there are a few consumer products that exist. Special towel detergents are available to be used in a washer unit. These work primarily to reduce odor from bath towels but don't objectively specify when a towel should be washed [3]. Salons also have heated cabinets designed to keep towels bacteria-free, but these units require a significant amount of energy since they are continuously operating. Our solution is the first to accurately identify when a bath towel should be washed.

1.3 High-Level Requirements

- Our device will detect CO2 concentration in the surrounding air in ppm with an accuracy of +/- 10%
- It will audibly alert the user if a towel is good or bad based on if CO2 concentration is at or above 1000 ppm near the towel.
- The unit can operate in a high humidity environment that is at least 70% relative humidity without resulting in faulty operation.

1.4 Visual Design

Below is a drawing of the front and side views of the monitoring unit respectively. It will be attached directly to a user's pre-existing towel rack and will reside under a hanging towel. It will be attached by a plastic connecting component that wraps around a towel rack.

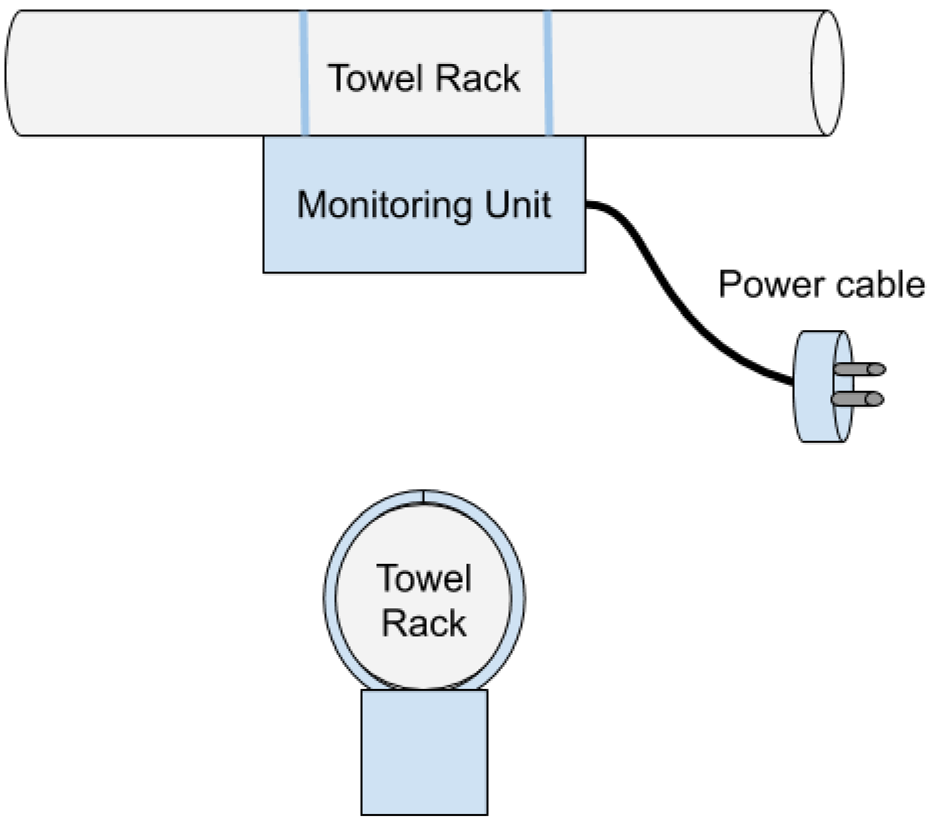

Fig. 1. Diagram of device’s position during operation.

1.5 Block Diagram

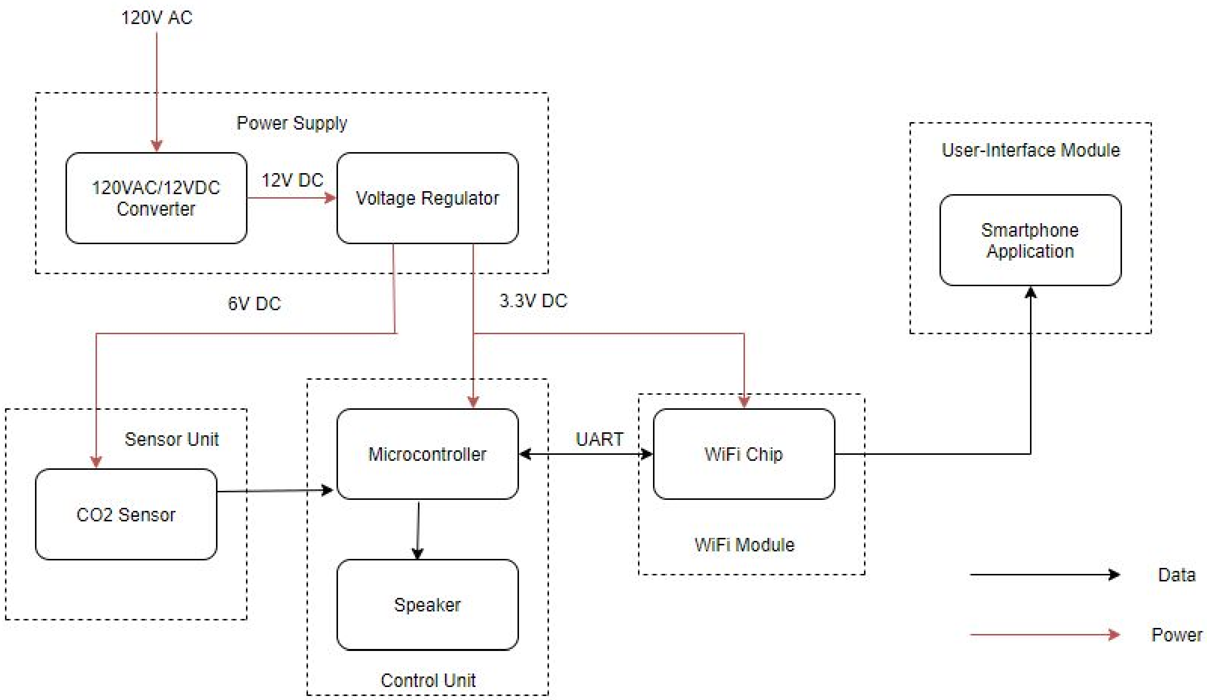

Fig. 2. Device block diagram. Black lines indicate data transfer and red lines indicate power transfer.

2. Second Project Implementation Details and Analysis

2.1 Cost Analysis

Our development costs assume a developer salary close to $95,000 which is the ECE Illinois average for computer engineers right after graduation. This roughly translates to $50/hour. Our prototype will take roughly 10 weeks to complete with three people working for 10 hours each week. We've included a 2.5 multiplier to account for any unexpected incident failures. The total labor cost to develop this prototype comes out to:

$$\$50/hr \, * \, 2.5 * 10 \, hr/week \, * \, 3 \, people \, * \, 10 \, weeks \, = \$37,500$$

The component costs for the prototype are depicted below:

Component	Cost (Prototype)	Cost (bulk manufacturing)
VEL18US120-US-JA (AC adapter)	$12.75	$10.71
L7806CD2T-TR (6V voltage regulator)	$0.77	$0.30
LP2985IM5X-3.3/NOPB (3.3V voltage regulator)	$0.79	$0.28
C315C104M5U5TA7303 (0.1µF capacitor) x5	$1.20	$0.25
MFS201N-9-Z (switch) x2	$2.30	$1.18
ATMEGA328P-PU (microcontroller)	$2.08	$1.73
MG811 (CO2 sensor)	$49.75	$39.75
SP-1504 (speaker)	$1.92	$1.07
PCB (PCBWay)*	$23.00	$1.50
AMW007 (WiFi Chip)	$6.10	$5.78
Casing	$2.00	$0.50
Total	**$102.66**	**$63.05**

*PCB prototype cost including shipping cost 18$, minimum order quantity of 5

2.2 Hardware and Software Modules

The below sections describe our modules and submodules as depicted in our block diagram (see section 1.5).

Power Supply

The power supply will power the entire circuit and its components. It will convert a building's AC voltage to DC voltage levels suitable for the operation of different hardware components. It also has a switch that allows the user to turn the device on or off.

120V/12V AC/DC Converter

The AC/DC converter steps down the 120V AC wall voltage to a suitable 12V DC level for the input for the voltage regulator. This consists of an off-the-shelf AC adapter that is rated at 12V/1.5A.

Voltage Regulator

The voltage regulator takes in the 12V input from the AC/DC converter and outputs a constant 6V and 3.3V output. The 6V output voltage powers the CO2 sensor. The 3.3V output voltage powers the microcontroller and the wifi chip. A capacitor is needed on the input and the output respectively for stability.

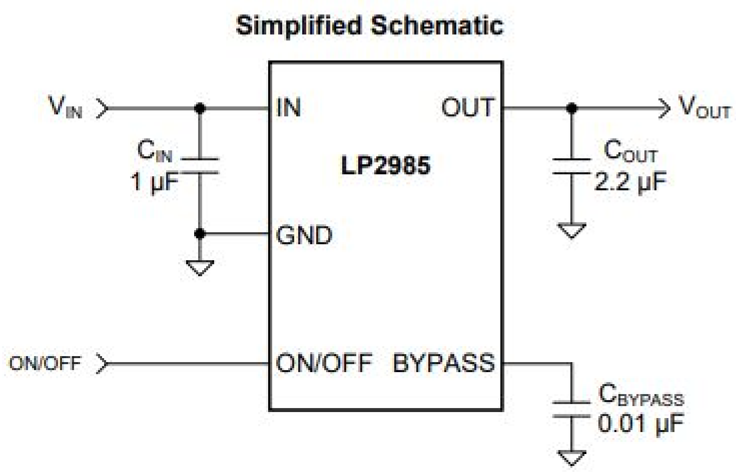

Fig. 3. Voltage regulator and input and output capacitor configuration [4].

Requirement	Verification
6V voltage regulator outputs a 6V +/- 0.1V output with at least 200 mA.	1. Connect a DC power supply into the input of the voltage regulator. 2. Connect a digital load to the output of the voltage regulator. 3. Connect an oscilloscope probe to the output of the voltage regulator. 4. Turn the DC power supply on to 12V. Set the digital load to 200 mA. 5. Verify that the voltage stays within an acceptable range and that the output current meets the expected value.
3.3V voltage regulator outputs a 3.3V +/- 0.3V output with at least 250 mA.	1. Connect a DC power supply into the input of the voltage regulator. 2. Connect a digital load to the output of

	the voltage regulator. 3. Connect an oscilloscope probe to the output of the voltage regulator. 4. Turn the DC power supply on to 12V. Set the digital load to 250 mA. 5. Verify that the voltage stays within an acceptable range and that the output current meets the expected value.

Control Module

Microcontroller

The microcontroller consists of an ATmega328P-PU that converts the analog signal from the CO2 sensor to digital via an ADC. It then takes the digital data, computes the CO2 concentration, and send the data to the wifi chip via UART.

Requirement	**Verification**
Gain of ADC shows correct value and does not have bias.	1. Connect a 3.3V DC input from the DC power supply to the Vcc pin of the microcontroller. 2. Connect another DC power supply to the pins PB3 and PB4 3. Set gain as x5 and compare the voltage displayed on the ADC and the voltage meter by manually multiplying the output of the voltmeter by 5. 4. Recalibrate the gain to reduce the bias
Microcontroller calculates CO2 concentration given input CO2 sensor voltage to within +/- 10% error of expected value.	1. Connect a 3.3V DC input from the DC power supply to the Vcc pin of the microcontroller. 2. Connect another DC power supply to the pins PB3 and PB4

	3. Set a known input voltage by the DC power supply 4. The microcontroller should compute the correct associated CO_2 sensor value that is expected within 10% error. 5. Repeat this process for different input voltages within the expected range of the CO_2 sensor.

Speaker

The speaker is connected to the microcontroller and provides an audible indication of the CO_2 concentration that the device detects. If the threshold is exceeded, the speaker produces an audible warning sound that indicates that the towel is noticeably dirty and that the user should clean or change it.

Requirement	**Verification**
The speaker produces a sound when the CO_2 concentration threshold of 1000 ppm is detected by the microcontroller.	1. Connect the speaker to one of the analog output ports of the microcontroller that is connected to a 3.3V DC power supply. 2. Send a dummy signal value that exceeds the set CO_2 threshold to the microcontroller. 3. Note that the speaker should produce a sound that is audible from 1 meter away for one second indicating that the value is too high.

Sensor Unit

CO2 Sensor

The CO_2 sensor detects the concentration of CO_2 in the surrounding air and outputs a voltage that is inversely proportional to it. The MG811 CO_2 sensor uses an electrochemical reaction to output a voltage that decreases as CO_2 concentration increases.

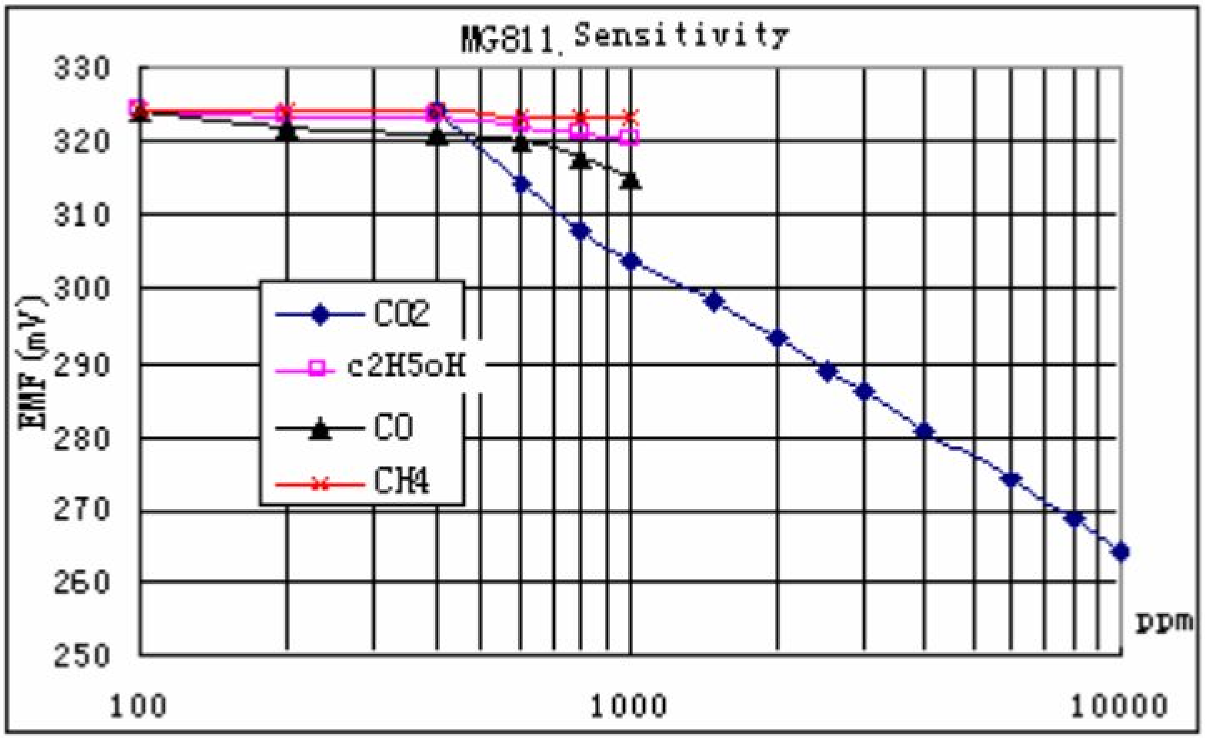

Fig. 4. Output voltage response of MG811 to various gas concentrations. [5]

Requirements	**Verification**
The CO2 sensor should generate a voltage within a tolerance of +/- 10% of the expected output voltage at a given CO2 concentration.	1. Connect a DC power supply of 6V to the input pin of the CO2 sensor 2. Place an oscilloscope probe on the output pin of the CO2 sensor. 3. Measure and note the surrounding CO2 concentration by using another air quality detector. 4. Measure and note the output voltage of the CO2 sensor. 5. Compare the measured output voltage to the MG811 datasheet to determine the CO2 concentration. 6. The resulting CO2 concentration should be within +/- 10% of the air quality detector measured CO2 concentration.

WiFi Module

WiFi Chip

The wifi chip communicates with the microcontroller via UART and connects to the user's home wifi. It is then able to send CO2 concentration values to connected devices via this manner.

Requirement	**Verification**
The WiFi module should successfully connect to the user's home WiFi.	1. Connect a 3.3V DC power supply to the Vcc input of the WiFi chip. 2. Attempt to connect the WiFi module to the home network using the microcontroller. 3. Pinging a known device on the network should result in a response, indicating a successful connection.
The WiFi module should successfully send data through the user's home WiFi.	1. Connect a 3.3V DC power supply to the Vcc input of the WiFi chip. 2. Send dummy data from microcontroller to WiFi module via UART. 3. WiFi-connected smartphone device should be able to receive sent data via the smartphone application.

User-Interface Module

Smartphone Application

The smartphone application allows the user to connect to the device via wifi and read the current CO2 concentration that it is detecting. A warning is displayed if the concentration is above the threshold value. The application can also affect the control unit by resetting the microcontroller in case of faulty operation or disabling the use of the speaker.

Requirement	Verification
Application generates a color code indicating the level of CO_2 concentration that is detected.	1. At the debugging phase of the application, write test cases assigning dummy CO_2 concentrations ranging from 0 to 1500. 2. A value between 0 and 400 should result in a white color code, indicating that the data is incorrect or the device is operating incorrectly (household concentration shouldn't normally be below 400ppm). 3. A value between 400 and 800 should result in a green color code, indicating normal household CO_2 levels. 4. A value between 800 and 1000 should result in a yellow color code, indicating slightly elevated CO_2 levels. 5. A value greater than 1000 should result in a red color code, indicating CO_2 levels that may indicate the presence of bacteria or mold on the towel, requiring it to be replaced or washed.

Physical Case

Our external casing will have to be robust and able to withstand the humid conditions of a bathroom. Our casing will have two main components, the main body which houses all of our electronics and the external clips which keep the unit attached to a towel rack. This case can be 3D printed for the purposes of our prototype and partially coated with a hydrophobic spray. However, for mass production, injection molding plastic would be more ideal. The external arms will allow the case to easily attach to a towel rack. These will be printed using a flexible plastic which may be pried open by the consumer's hands and placed around a towel rack.

Tolerance Analysis

The most critical part of this device is the microcontroller taking the CO_2 sensor output voltage and interpreting an accurate enough CO_2 concentration from the data it is given. ADC resolution is not of concern since the relative voltage drop of roughly 25mV is relatively large for a concentration increase from 400 to 1000 ppm and the increase in concentration should be noticeable. The main concern is in the effect of other factors in the output voltage of the CO_2 sensor. Since it is dependent on an electrochemical reaction, other gases also slightly affect the result including carbon monoxide (CO) and ethanol (C_2H_5OH). In high enough concentrations which are quite unlikely for household use, this could result in a drop of up to 6mV.

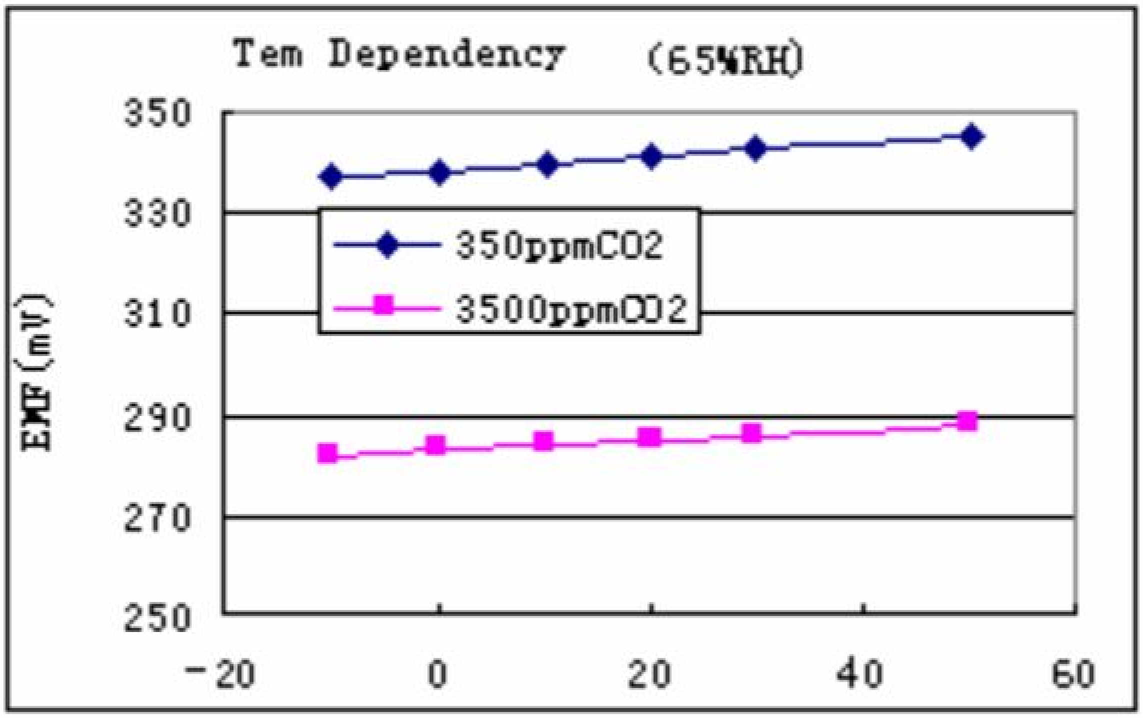

Fig. 5. Output voltage response of MG811 to ambient temperature. [5]

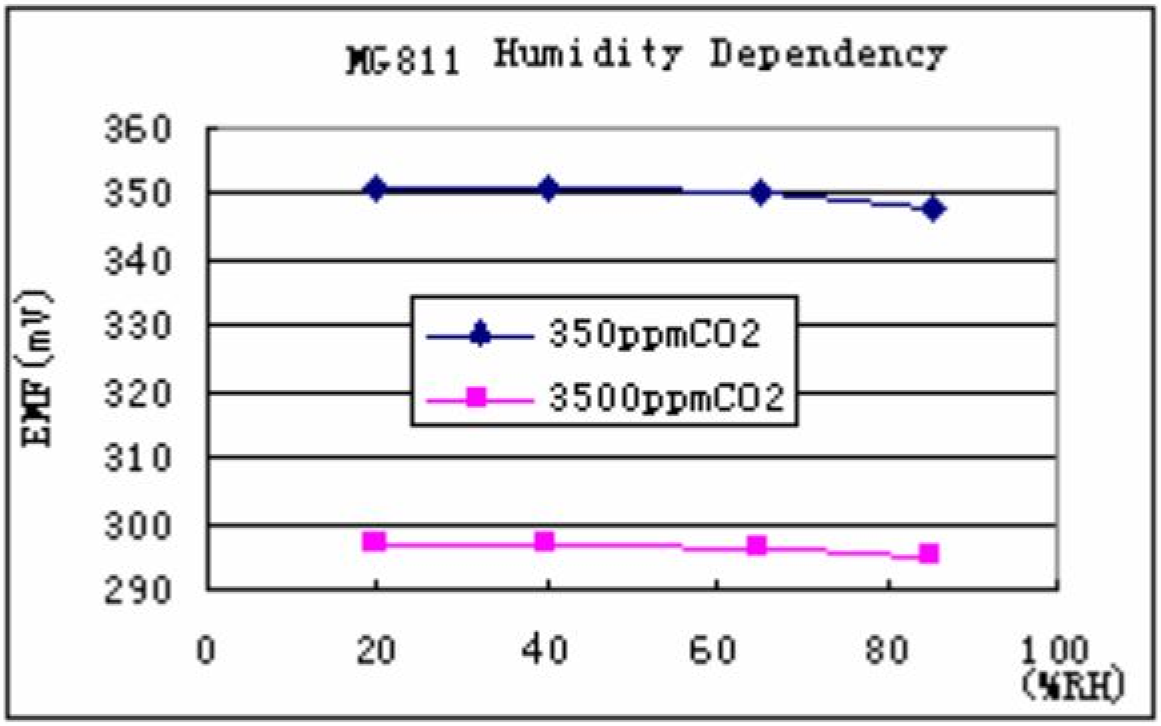

Fig. 6. Output voltage response of MG811 to ambient relative humidity. [5]

Besides gas concentration, humidity and temperature can also affect the resulting output voltage. A slightly higher temperature than room temperature results in about a 4mV increase while a relatively large relative humidity of 85% results in about a 3mV decrease. These conditions are expected in a shower-like bathroom environment where the unit could be used. Overall, this results in a maximum expected change of a 5mV decrease. Around 1000 ppm where the output voltage should be 305 mV, it is instead 300 mV, resulting in a 1.6% error, well below the stated threshold of 10%. The CO2 sensor then contributes, at worst, 10% of the maximum allowable error, an allowable threshold.

3. Second Project Conclusions

3.1 Implementation Summary

From section 2, we have established the plan for manufacturing the towel bacteria detector. We have analyzed the requirements for each necessary part of the device, and selected the most price efficient parts that meet the requirements. Since we were not able to access the physical components, our team instead analyzed theoretical humidity, CO2, and voltage levels that a consumer's environment may have, and we ensured that our components would properly function in these environments. We did this by extensively researching and delving into data sheets to find tolerance limits. Much of this work is presented in various subsections of section 2. We then utilized our findings to create exhaustive requirement and verification tables. By doing this, we have extensively planned out the development and testing process which would make development faster and more efficient if one were to physically obtain these components.

Our work on this theoretical implementation was accomplished by assigning team members different roles. Josh worked on developing and designing the power supply and sensor part of the device. He researched the most suitable components and kept track of their costs. Mike worked on researching environmental factors like humidity and CO2 concentrations. He also took on the role of researching and outlining the problem at a high level, the differences between our solution and the previous solution, and how the device would be used by consumers. Yeongyoon worked on researching the microcontroller, wifi unit, and user interface. He implemented the R&V tables for these modules. Finally, the entire team worked together to create the figures, models, and tables which are in this report.

3.2 Unknowns, Uncertainties, Testing Needed

While we have data on how humidity affects CO2 concentration, the effects of humidity on the electrical components of the device are unknown. Our plan for protecting our device from humid conditions was to create a secure, waterproof casing and to coat the most vulnerable components in a hydrophobic spray. However, there are still various tests needed to prove and verify a few things about the device. The first part of the device that is affected by the humidity is performance of the CO2 sensor. We will need to test various levels of humidity in order to get accurate data of how the sensor will work and get biased. This condition will cause non-linearity in sensor data, so such bias needs to be carefully accounted for to get maximum performance. Also, we need to test the security of parts of the device under humid conditions. The working environment of our device will be very humid when the user takes a shower for a long time or with hot water temperature without the ventilation on. In these cases, our device needs to be verified how much it could function under harsh humid conditions.

Another unknown is the location where the device needs to be placed. We have proposed to place the device under the tower holder, but we do not know if this position is optimal for the device’s performance. Finding an optimal placement for this device will require placing the device in various places under the same conditions and analyzing the data alongside a second CO2 detector to find the optimal position.

The ideal CO2 concentration for alerting the user is also an uncertainty. While we have researched and found theoretical levels of dangerous CO2 concentrations, we will have to test different environmental conditions ourselves to verify the accuracy of our research. In order to obtain the best performance of our device, we will need to employ a biology lab to test the bacteria level of various bath towels and correlate the CO2 level of the towel.

3.3 Ethics and Safety

Our product will certainly have associated safety and ethical concerns since it is operating in a humid environment with electrical components, detecting harmful CO2, and preventing the spread of disease-causing bacteria. Operating in a humid and wet environment poses significant challenges to electrical components. Failure to properly secure and enclose a device in such an environment can result not only in electrical failure but also can pose a safety risk to those using the device. The IEEE Code of Ethics states as its first principle “to hold paramount the safety, health, and welfare of the public” [4]. In order to abide by this principle, we will enclose our device in a waterproof casing, spraying our most vulnerable components like our PCB with a hydrophobic coating, and providing caution labels on our packaging to prevent improper use like submerging the device in water.

Another key concern is how well our solution can detect CO2 produced by bacteria and mold. CO2 electrical sensors do have tolerance for error. As a result, we will provide a clear and honest description of these limitations on the product’s packaging. This is in line with the third IEEE principle “to be honest and realistic in stating claims” [6]. We view this as necessary since we don’t want our sensor to be interpreted and used solely as a life-saving CO2 detector when it is not.

We also want a safe amount of voltage to be delivered to our device. This is of the utmost importance when operating in a wet and humid environment. Here, our voltage regulator will be key to mitigating any risk to users of this product. We will require a safe voltage step down from our power supply, and we have to extensively test this vital component.

Bacteria and mold can often grow on damp bath towels, and these substances can pose significant health risks to humans. Because of this, it is vital that our sensors work properly in detecting bacteria. Having disease-causing bacteria go undetected can be harmful to users especially if they have a high level of confidence in our device working. The risk of our device giving false positives can be lessened with extensive unit testing. It can also be mitigated by including a cautionary label on our product packaging.

3.4 Project Improvements

The first function that could have the best improvement is the connection of the device with the internet. If we had more time to work on this project, it would have been possible to implement an independent cloud server for managing the devices. We could connect the device to a server and manage sensor data from the server, as most IoT services work. By incorporating this server connection across many devices, we could effectively gather sensor data and make improvements to the ideal threshold of CO2 level to alert users to change the towel. Also, in this way, any user can read the sensor’s output wherever he or she is located.

A second improvement we could have made involves improving the analysis of CO2 sensor data. There are many conditions that could change the accuracy of CO2 sensor data. It could change by humidity level or non-linearity of the CO2 sensor measurement. If we had more time to test the CO2 sensor, we could have obtained a more accurate CO2 level for when the device should alert the user to change the towel.

We could have tried to find another way to measure the health of a towel. To improve the performance of the device, we could have incorporated different sensors that detect different byproducts of bacteria, including microbial volatile organic compounds. With different types of sensors, we could effectively increase the accuracy of our device. Additionally, our device would be less dependent on CO2 detection.

Lastly, we are not clear whether it will be ideal to utilize an AC power supply. Although AC power supply has its benefits, we will still need to do more user testing on consumer behavior and preferences. We could specifically test to determine if the size of our device is small enough for users' preferences, and we could identify the feasibility of plugging in our device into a wall socket.

4. Progress Made on First Project

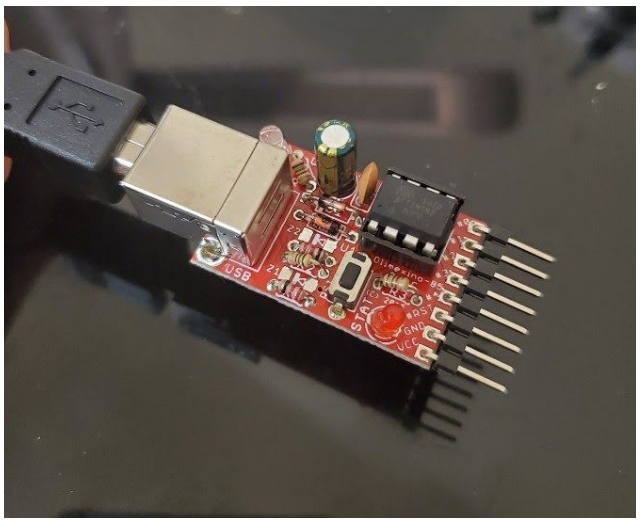

Fig. 7. ATtiny 85 microcontroller development board

After our design review, we soldered our development board for use with our microcontroller. The functionality of the device was verified by inputting a program that toggles on an LED every 5 seconds. After the development board was verified, we tested the bluetooth connection with the nRF52833 bluetooth development kit. Yeongyoon had a nordic toolbox smartphone app that could be used to test and debug the bluetooth connection with a microcontroller. We implemented a simple bluetooth serial connection program for Attiny 85 microcontroller, and went ahead to test the attiny bluetooth serial library. We were able to search and connect with our microcontroller, but we were not able to send temperature data from the attiny to our smartphone app.

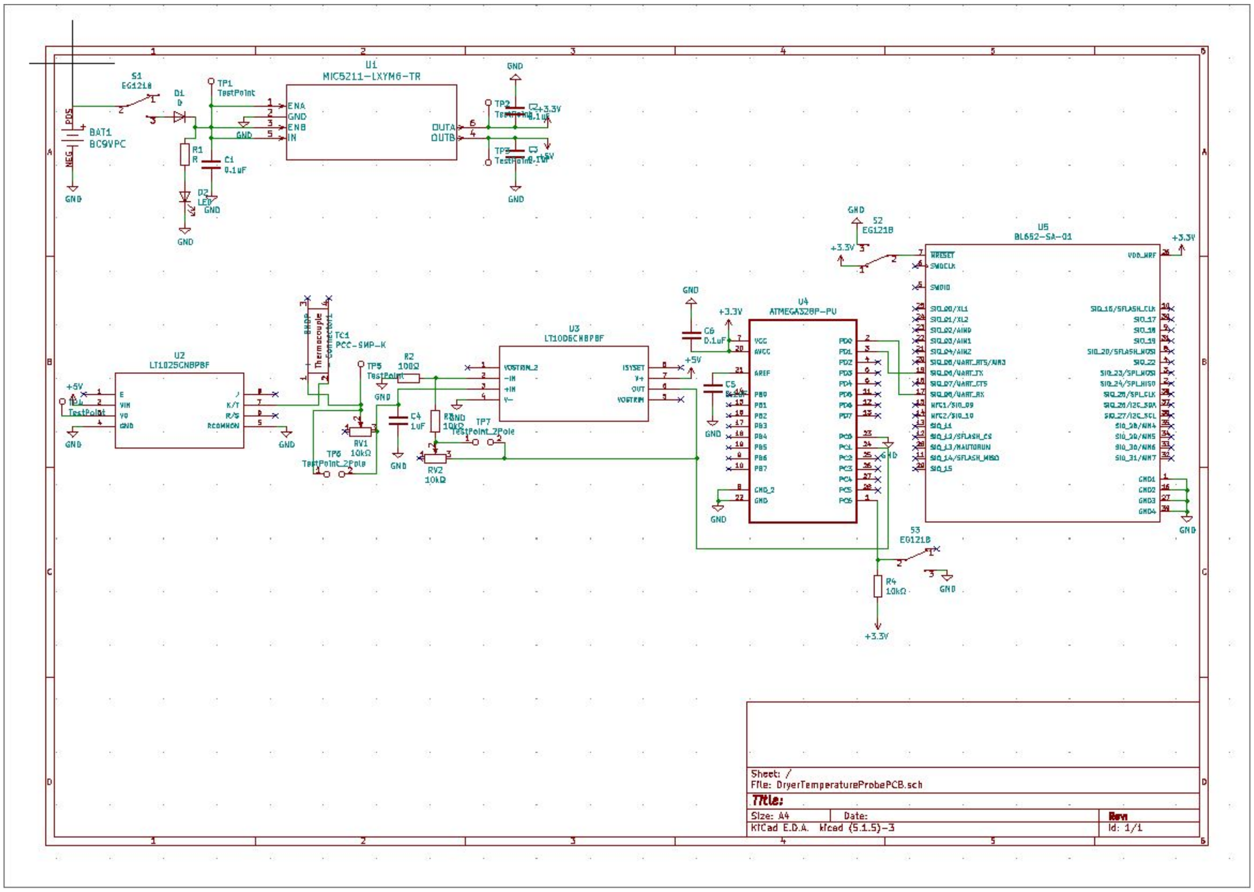

Fig. 8. Dryer temperature probe circuit diagram

Several hardware revisions were also added to the physical design and layout of our circuit board. Active low reset switches were placed on the appropriate pins of the microcontroller and bluetooth module. A red indicator LED was placed between the battery switch and the voltage regulator to indicate to the user that the device is powered on. An LT1006 operational amplifier was placed between the low-pass filter and the microcontroller to boost the thermocouple voltage signal and result in a greater degree of accuracy in temperature reading due to the limited precision of the microcontroller's ADC.

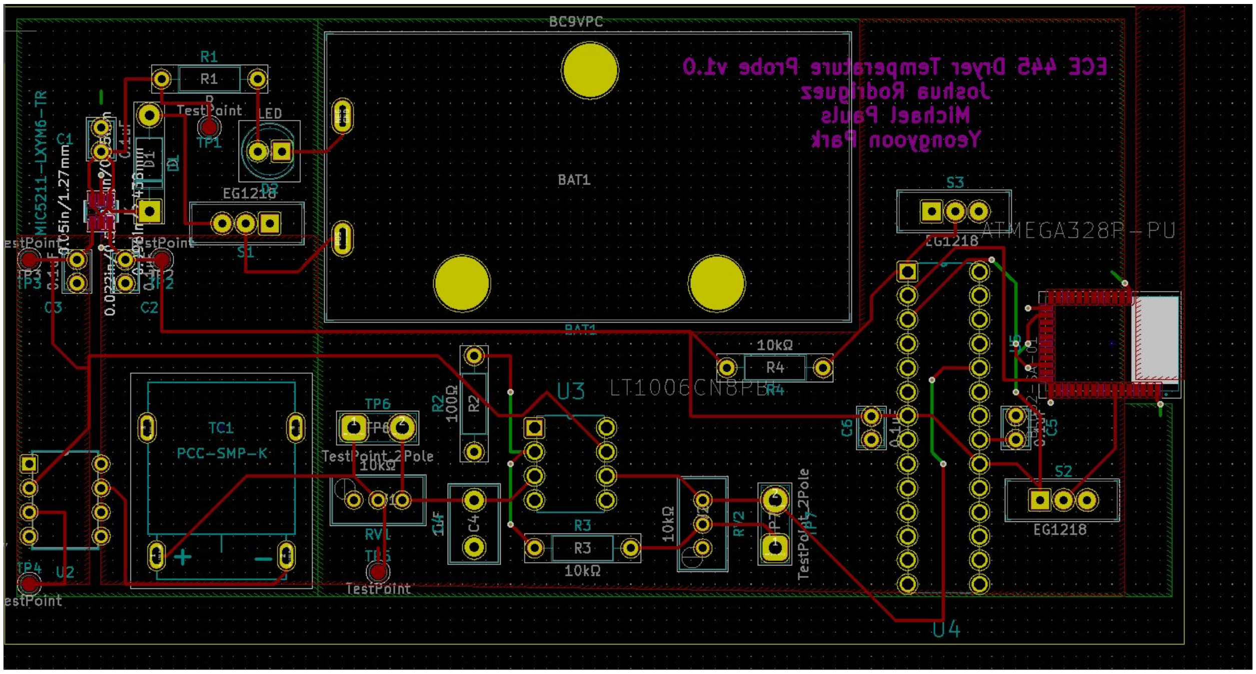

Fig. 9. Dryer temperature probe PCB layout

In addition to the circuit diagram a functional PCB layout was also constructed for the first iteration of the physical design of the dryer temperature probe, as seen in fig. 9.

5. References

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