ECE 445

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Mobile Hive Checker Project Proposal

Team #1

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1. Introduction

1.1 Problem

Beekeepers must routinely monitor hive conditions to maintain healthy colonies and prevent colony loss. Critical environmental parameters such as temperature, humidity, and carbon dioxide (CO_2) concentration directly impact brood development, honey production, and overall colony health. However, traditional monitoring requires physically opening the hive, which stresses the bees, disrupts their internal thermal regulation, and can negatively affect productivity and behavior when performed frequently.

Conversely, insufficient monitoring increases the risk of swarming, starvation, disease, or freezing, any of which can result in the loss of an entire colony. Each lost hive can cost a beekeeper approximately $100–$200 in replacement costs alone, not including lost honey production or pollination value. On a broader scale, honeybee decline is associated with habitat loss, pesticide exposure, climate change, and improper apiary management (Mull et al., 2022). Because pollination supports global agriculture and ecosystem stability, hive loss represents both an economic and environmental concern.

While commercial hive monitoring systems exist, many require permanent installation and cost approximately $100 per hive, making them impractical for hobbyist and small-scale beekeepers. Additionally, many products are manufactured overseas, limiting accessibility and domestic technical support. These factors motivate the need for a low-cost, portable, and minimally invasive hive health assessment device.

1.2 Solution

The proposed solution is a portable Mobile Hive Checker device that allows beekeepers to assess colony health without opening the hive. Two slim sensors attached via cables are inserted through the hive entrance, while the main electronics enclosure remains external. This minimizes disruption to the bees while allowing real-time measurement of internal hive conditions.

The device measures temperature, relative humidity, and carbon dioxide concentration.

An ESP32 microcontroller processes sensor data and displays readings on an integrated screen. The system compares measured values against predefined healthy operating ranges and provides a clear "PASSED" or "FAILED" result. This allows beekeepers to quickly determine whether intervention is necessary while avoiding unnecessary hive disturbance.

The system is battery-powered and portable, allowing it to be used across multiple hives without permanent installation.

1.3 Visual Aid

Figure 1. *Visual Aid Representation of Design*

Note. Images used: *What are the dimensions of a medium bee box* (HonestBee, n.d.); *4046* (DigiKey, n.d.-a); *DC-58P Heavy-Duty Electronics Enclosure* (Polycase, n.d.-a); *DHT21 AM2301 Capacitive Digital Temperature Humidity Sensor* (HiLetgo, n.d.); *3349839-left-hand-outstretched.jpg* (Kara98, 2014, CC BY-SA 4.0); *LP-31P Plastic Electronics Box* (Polycase, n.d.-b); *Arduino Pro Micro* (Pk0001, 2019, CC BY-SA 4.0); *PTS645SL43-2 LFS* (DigiKey, n.d.-b); *SEN0159* (DigiKey, n.d.-c).

1.4 High-Level Requirements

The following is a list of 3 quantitative characteristics this project should exhibit to solve the problem.

1. <u>Measurement Accuracy</u> : The device will measure hive temperature with an accuracy of ±0.54 °F (±0.3 °C), relative humidity with an accuracy of ±2 % RH, and CO_2 concentration with an accuracy of ±(50 ppm + 5 % of reading).

2. <u>User Interaction</u> : The device will respond to a push button input. Pressing the ON/OFF button shall power the display and show a Start Screen, followed by a Testing Screen during data acquisition. Pressing the Reset button shall return the device to the Start Screen. A manual boot button shall allow firmware recovery if necessary.

3. <u>User Output</u> : The device will display measured temperature, humidity, and CO_2 values. The device will display "PASSED" if all measurements are within acceptable ranges (70–97 °F, 50–60 % RH, $CO_2 < 80,000$ ppm). If any measurement falls outside these ranges, the device shall display "FAILED."
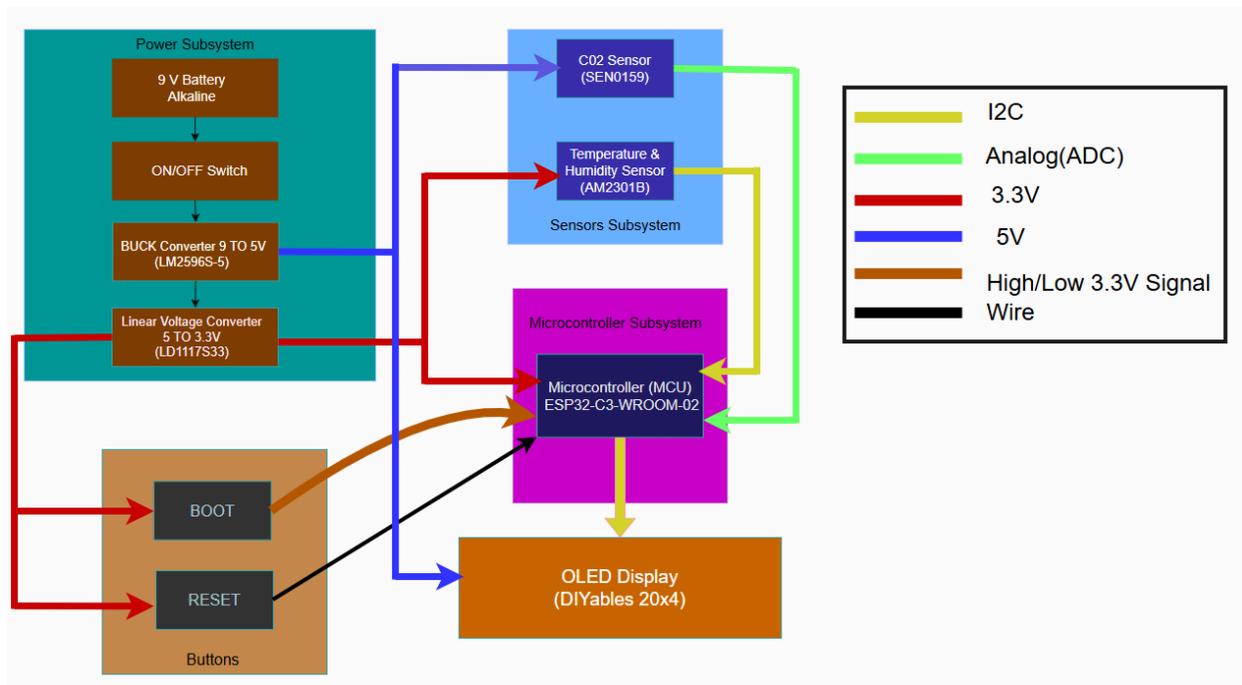
2. Design

2.1 Block Diagram

Figure 2. *Block Diagram of Design*

2.2 Subsystem Overview

2.2.1 Sensor Subsystem

This subsystem measures internal hive temperature, humidity, and CO_2 concentration.

Maintaining temperature between 70–97 °F is critical for brood survival. The selected temperature sensor provides ±0.54 °F accuracy, sufficient to detect meaningful deviations.

Humidity must remain between 50–60 % RH for proper nectar dehydration and brood health. The selected humidity sensor provides ±2 % RH accuracy.

CO_2 concentrations above 8 % (80,000 ppm) may indicate overcrowding or poor ventilation. The selected CO_2 sensor measures 400–100,000 ppm with ±(50 ppm + 5 % of reading) accuracy.

The temperature/humidity sensor and CO_2 sensor are mounted on extended cables, allowing insertion into the hive while keeping the main enclosure external. Sensor outputs interface with the ESP32 microcontroller for processing.

2.2.2 Power Subsystem

The system is powered by a 9V battery. The battery voltage is stepped down to 5V using a DC-DC buck converter to improve efficiency. The 5V rail powers the CO_2 sensor and the Display. A 3.3V low-dropout (LDO) regulator steps the 5V rail down to 3.3V to power the ESP32 microcontroller and Temperature and Humidity Sensor. The voltage rails are labeled and distributed according to subsystem requirements.

2.2.3 Microcontroller and Logic Subsystem

The ESP32-C3-WROOM-02 microcontroller collects data from all sensors and processes the results. Temperature and humidity data are transmitted via I²C. The CO_2 sensor provides an analog voltage output (0–5V), which is scaled using a voltage divider to ensure the ESP32 ADC input does not exceed 3.3V.

The ESP32 processes measurements and compares them against defined thresholds. Results are displayed via I²C to the LCD.

The ESP32 operates at 3.3V and has a typical active current significantly lower than 345 mA (that value represents peak transmission current under Wi-Fi usage). Since we do not require the wireless features, the average system current will be substantially lower.

2.3 Subsystem Requirements

2.3.1 Sensor Subsystem

Requirements	Verification
● The Temperature and Humidity Sensor shall operate within ±5 % of its rated +3.3V supply voltage.	● Measure Temperature and Humidity Sensor +3.3V supply voltage using a multimeter.
● The CO_2 Sensor shall operate within ±5 % of its rated +5V supply voltage.	● Measure CO_2 Sensor +5V supply voltage using a multimeter.

Requirements	Verification
- The Temperature and Humidity Sensor shall provide temperature accuracy of ±0.54 °F and humidity accuracy of ±2 % RH. - The CO_2 sensor shall provide CO_2 accuracy of ±(50 ppm + 5 % reading)	Compare sensor readings to known environmental references or calibrated instruments.

2.3.2 Power Subsystem

Requirements	Verification
- The battery shall supply 9V DC. - Buck Converter shall regulate 9V to 5V ±5 % under full load. - The Linear Voltage Regulator shall regulate 5V to 3.3V ±3 %.	Measure output voltages under load conditions using a multimeter
The power subsystem shall supply at least 1A peak current without voltage droop exceeding 5 %.	Apply maximum expected load and verify voltage stability.

2.3.3 Microcontroller and Logic Subsystem

Requirements	Verification
- The microcontroller successfully receives data from the peripheral sensors when data is available. Data will be received from: - Temperature and Humidity Sensor CO_2 Sensor	- Observe output data on serial monitor to confirm successful communication - Ensure data is received after push button is pressed
The microcontroller successfully boots the system with the USB-C mode	- Observe the booting sequence on serial monitor - Could push button manually to boot it as fail-safe option

● The microcontroller successfully delivers information to the display ● The display successfully shows the correct data from the microcontroller conveniently to the user	● Ensure correct output is displayed by comparing output data from the serial monitor to the display

2.4 Tolerance Analysis

Measurement Uncertainty

A major risk to the Mobile Hive Checker is measurement uncertainty near the pass/fail thresholds. Because hive health is determined by comparing measured temperature, humidity, and CO_2 values to acceptable ranges, sensor tolerances may cause values near these limits to be misclassified.

The acceptable temperature range is 70–97 °F, and the temperature sensor has an accuracy of ±0.54 °F. At the lower limit of 70 °F, measurements may range from 69.5 °F to 70.5 °F, meaning a healthy hive could be incorrectly marked as FAILED. However, the total temperature range is 27 °F, so the sensor uncertainty represents only about 2 % of the range, which is acceptable for detecting meaningful temperature changes.

- **Temperature:**
    - Range = 27 °F (70–97 °F)
    - Uncertainty = ±0.54 °F (~2 % of total range)
    - Impact: Minimal risk of incorrect classification.

The acceptable humidity range is 50–60 % RH, with a sensor accuracy of ±2 % RH. At 50 % RH, readings may range from 48 % to 52 %, meaning that readings near the boundary could occasionally fall outside the acceptable range. This uncertainty represents about 20 % of the total 10% acceptable range, which is relatively large. However, humidity in a hive changes gradually, and values near the limits already indicate emerging suboptimal conditions. Therefore, occasional boundary misclassification is acceptable for this application.

- **Humidity:**
    - Range = 10 % RH (50–60 %)
    - Uncertainty = ±2 % RH (20 % of acceptable band width)
    - Impact: Higher relative uncertainty. However, gradual environmental change reduces the likelihood of repeated misclassification.

The CO_2 threshold is set at 80,000 ppm, and the sensor accuracy is ±(50 ppm + 5 % of the reading). At this threshold, measurements may range from approximately 75,950 ppm to 84,050 ppm. Although this introduces uncertainty near the limit, CO_2 levels approaching this value already indicate dangerous hive conditions, making the tolerance acceptable for a diagnostic tool.

- **CO_2 at 80,000 ppm threshold:**
    - Range = >80,000pm
    - Uncertainty = ±(50 + 0.05 × 80,000) = ±(50 + 4000) = ±4050 ppm
    - Impact = Thus actual reading could range from ~75,950 ppm to 84,050 ppm. Because 80,000 ppm represents extreme hive conditions, this tolerance is acceptable for diagnostic purposes.

While sensor inaccuracies may affect measurements near decision boundaries, the selected sensors provide sufficient accuracy for the intended purpose to prompt the beekeeper to action when the hive starts to reach those unhealthy boundaries.

Power Feasibility Analysis

Another important consideration in our design is the ability of the battery to supply sufficient current to all components during operation. Because the device is intended to be portable and used across multiple hives, accurate estimation of current draw is necessary to ensure reliable operation and acceptable runtime.

A standard 9V alkaline battery can typically supply approximately 300–600 mA for short durations, though sustained operation near the upper limit may cause voltage sag and reduced battery life. Therefore, the worst case current draw must be carefully evaluated.

$$28 \text{ mA} + 0.00098 \text{ mA} + 500 \text{ mA} + 40 \text{ mA} = 568.001 \text{ mA}$$

This results in an approximate total current draw of 568 mA, which is close to the upper limit of a typical 9V battery's current capability. Because the estimated draw approaches the maximum supply capability, the LCD backlight brightness will be reduced to lower display current.

Although the calculated draw is within the 600 mA upper range, sustained operation at this level may reduce battery life significantly and may cause voltage droop under load. This represents a potential design risk and will be validated through load testing. If voltage instability occurs, an alternative higher-current battery solution (such as a rechargeable Li-ion pack) may be considered.

Component	Operating Voltage	Current Draw
MCU	3.0 - 3.6 V	345 mA (peak with WiFi) 28 mA (Active CPU (no radio))
Temperature and Humidity Sensor	3.3V-5.2V (recommended supply is 5V)	0.00098 mA (measuring) 250 μA (dormant)
CO_2 Sensor	0 - 5V (recommended supply is 5V)	500 mA (absolute max)
LCD Display	2.8-5.5V	40 mA (lowered by decreasing backlight via a potentiometer already on display)

3. Ethics and Safety

Humans need honeybees. The pollination helps increase the type and amount of plants and crops. This product will help society as it will allow hobby beekeepers continual success for keeping bees alive all year round. Increasing the presence of bees will increase pollination, which will thus increase the prosperity of plants and crops. As the honeybee population continues to decrease This is especially important in current times as the number of honeybees are decreasing at a rapid rate due to "habitat loss, improper apiary management, pesticide usage, [and] climate change" (Mull et al., 2022). While we can't control many of these environmental factors, our design aims to improve apiary care through a monitored hive (IEEE CoE 3).

This project was evaluated for ethical and safety concerns during development and potential misuse. The design aligns with the IEEE and ACM Codes of Ethics by prioritizing public welfare, honesty, competence, and harm prevention (IEEE CoE 1).

Ethically, the device aims to reduce stress on bee colonies by minimizing hive intrusion, benefiting the environment through improved pollination and honey production. The system does not collect personal data and presents minimal risk of misuse. Ethical risks are further reduced through accurate performance claims, clear documentation, and disclosure of system limitations (IEEE CoE 5).

Safety is a major focus of the project. All electronic components are properly insulated and enclosed to prevent electrical hazards, and materials are chosen for safe outdoor and agricultural use. Additionally, our design includes appropriate covers to further protect all components

against harsher weather conditions. While the components are not claimed to be water proof or resistant, there should be ample protection against damages from the hive's internal environment.

Key safety practices include avoiding battery short circuits, keeping liquids away from electronics, preventing battery overload, using correctly sized wiring, monitoring heat from voltage regulators, ensuring correct battery polarity, and regularly inspecting for exposed wires. All components are housed in a protective enclosure to reduce shock risk. Additionally, all elements of the PCB in this design have been further inspected by a member in the University of Illinois's ECE445 Staff.

All team members completed required laboratory safety training, including electrical safety. Overall, the project follows the IEEE Code of Ethics by prioritizing safety, accurately representing performance, working within the team's expertise, and supporting respectful collaboration (IEEE CoE 6).

4. References

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