2021-2022 Capstone in Electrical Engineering: NAU Teaching Greenhouse

TESTING REPORT

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CONTENTS

Project Overview 2

System Architecture 3

Project Requirements 3

Key Requirements 5

Types of Test 5

Major Tests 7

Analysis of Results 9

Lessons Learned 9

Appendix A: Sensor Electrical Schematics 10

Project Overview

The project's client is Dr. Tina Ayers, Professor of Biology at Northern Arizona University. Dr. Ayers teaches a wide range of botany courses and is an active researcher. She is in charge of the Teaching Greenhouse, located on north campus. This greenhouse is used for growing plant specimens to be dissected in various botany courses, and is home to the NAU Botany Club which has partially funded the project. The greenhouse is divided into two sections: the north house is kept warm and dry for growing cacti and succulents, while the south house is kept cool and moist for the benefit of orchids, carnivorous plants, and other cool-weather specimens.

The project's most important goal is to allow Dr. Ayers and other greenhouse personnel to remotely monitor the environmental conditions in the greenhouse, including air temperature, humidity, and soil moisture content. The client also requires smartphone notifications when temperature in either zone of the greenhouse exceeds the safe range for the plants grown in that section. A secondary objective was to install automatically controlled air mixing fans in the south house. Because of the evaporative cooling system and the relatively still air in the south house, significant temperature gradients often form between the top and bottom of the south house. These gradients are believed to exceed 10 degrees Fahrenheit, and they make it difficult to provide ideal growing conditions throughout the south house. The air mixing fans are intended to create turbulence in the greenhouse, thereby mixing the air to reduce or eliminate this undesired temperature gradient.

The project's design is separated into several major parts. Central to the system is a computer console based on a Raspberry Pi 4B+. The console, installed in the equipment room at the north end of the greenhouse, allows the client to view sensor data, rename sensors, specify the conditions that should generate an alarm notification, and change settings that govern the mixing fan controller. The Pi is connected to the NAU network via Ethernet cable, as well as to a private network established specifically for the greenhouse. This private network is necessary since it was desired that sensor data be reported wirelessly for user convenience, and the NAU Guest wireless network does not have adequate coverage in the greenhouse. Two types of sensor module are provided: air sensors and soil sensors. Each type is based on the D1 Mini microcontroller and is equipped with a lithium battery, a solar cell, and a barrel plug for providing DC power to sensors that do not receive adequate sunlight for solar operation.

The mixing fans are controlled by MAQ20 equipment donated by the Dataforth Corporation of Tucson, AZ. Dataforth's MAQ20 line is a range of modular data acquisition and control equipment designed for use in industrial environments. This project uses two DIOH (Digital Input/Output High Voltage) modules to provide individual control of eight 120VAC circuits for mixing fans or other relatively low-power applications. Four of these channels are currently brought out to standard outlets in a wet-location receptacle box. The other four channels are currently reserved for future expansion.

System Architecture

The system architecture is shown below in Figure 1. Data and power flows throughout the system are shown in blue and red, respectively. Data flows shown with dashed lines take place over wireless connection, while those shown as solid lines take place over copper. The four formal tests documented in this report are marked in orange, and will be discussed further in the Key Tests section of this report. Note that although only a single air sensor and a single soil sensor are shown in the diagram, the project includes 10 air temperature/humidity sensors and four soil moisture sensors.

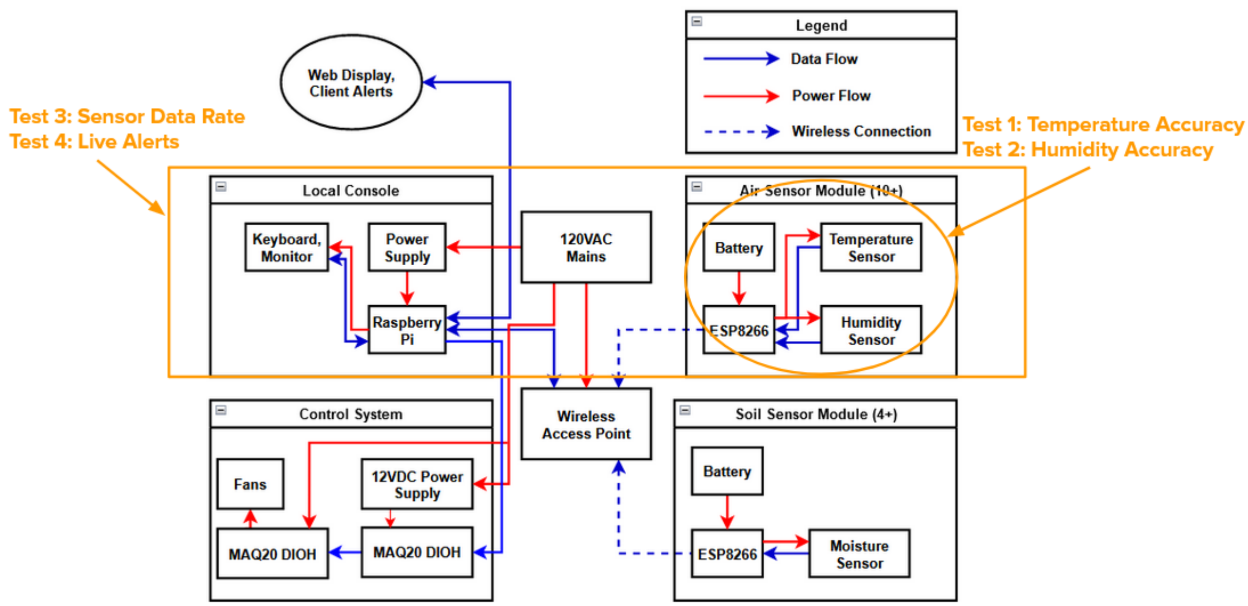

Figure 1. System architecture with key tests marked.

Project Requirements

The project requirements were formalized and agreed to by the team and client in late October of 2021. Some requirements have been eliminated, as shown in Table 1. Otherwise, no changes have been made to the project requirements.

Table 1. Testing Workbook Requirement page.

TEACHING GREENHOUSE - MASTER TESTING LIST - UPDATED 1 APRIL 2022				
Type of Test	Status	Req #	Requirement	Remarks
Inspect		1.1.1	The north house shall be equipped with at least two temperature and humidity sensor modules.	The sensors exist and have been functionally tested, but have not yet been delivered to the customer.
Inspect		1.1.2	The south house shall be equipped with at least eight temperature and humidity sensor modules.	
UTM		1.1.3	Temperature sensors shall be accurate to +/- 2°F or better.	
UTM		1.1.4	Humidity sensors shall be accurate to +/- 5% or better.	
UTS		1.1.5	All sensors shall operate properly in temperatures from 40 to 120 °F.	Tests were passed but the tests did not cover the entire specified ranges.
UTS		1.1.6	All sensors shall operate properly from 0 to 100% humidity.	
Inspect		1.2.1	The greenhouse shall have at least 3 mobile sensors that are available to monitor the moisture content of the soil in any container.	
UTM		1.2.2	Soil moisture content readings shall be accurate to +/- 5% or better.	
UTS		1.2.3	Soil moisture sensors shall comply with the operating conditions specified for temperature and humidity sensors.	
UTS	*	2.1.1	Temperature and humidity data shall be retrieved from sensors and stored at intervals of 15 minutes or less.	
UTS		2.1.2	Environmental logs shall include, at a minimum, the temperature and humidity reported by each sensor and the time and date of the reading.	
Inspect		2.1.3	The system shall have adequate storage to retain logged data for at least two years.	
Integrate	*	3.1.1	A web interface shall numerically show temperatures and humidities from the latest reading.	
UTS		3.1.2	The web interface shall be accessible from off campus without use of the VPN.	
Inspect		3.2.1	The web interface shall be able to show graphs of recent temperature and humidity data, either individually per sensor, or using an average for each section of the greenhouse.	
~~UTS~~		~~3.2.2~~	~~The time range of the graphs shall be user-selectable (allow the user to view data from the last 24 hours, 7 days, month, etc).~~	Client prefers all such graphs shown simultaneously.
UTS		3.2.3	The system shall provide a method for users to retrieve a CSV file containing all logged data, without requiring user knowledge of linux tools such as scp or sftp.	
UTS & Integrate	*	4.1.1	A smartphone alert will notify Tina Ayers or other greenhouse personnel when user-defined safe temperature or humidity ranges are exceeded.	
UTS		4.1.2	A method shall be provided for users to add/remove alert recipients.	
UTS		4.1.3	A method shall be provided to adjust temperature setpoints and any control conditions.	
(not testable)		4.1.4	The alert will be in a concise, numerical listing of data.	Ambiguous
UTS		4.1.5	The system will notify all alert recipients within 5 minutes of an unsafe condition being detected.	
UTS		4.2.1	All alert recipients will be notified within five minutes of a sensor failure being detected.	
Inspect		4.2.2	At least two extra sensor modules will be left behind to allow for user replacement of failed modules.	
Inspect		4.2.3	Documentation will be provided so that new modules can be constructed if necessary.	Documentation to be produced in the coming weeks
Inspect		5.1.1	At least two mixing fans shall be installed in the south house.	Fans on hand but not installed
Inspect		5.1.2	Mixing fans shall be rated for wet locations.	
Inspect		5.1.3	Mixing house fans shall not be battery-powered.	
UTS		5.1.4	The system shall be able to turn the fans on and off. At minimum, the following control modes will be provided:	
UTS		5.1.4.1	Always on	
UTS		5.1.4.2	Always off	
UTS		5.1.4.3	On during user-specified hours	
UTS & Integrate		5.1.4.4	On when excessive temperature differentials are detected within the greenhouse.	
~~Integrate~~		~~5.2.1.1~~	~~The system shall control the south house glycol heater to maintain a user-selected temperature in the south house.~~	Client no longer needs this functionality.
~~Inspect~~		~~5.2.1.2~~	~~The temperature selection method shall be calibrated in degrees Fahrenheit.~~	
~~Integrate~~		~~5.2.2.1~~	~~The system shall control the wet wall and south house exhaust fan to maintain a user-selected temperature in the south house.~~	
~~Inspect~~		~~5.2.2.2~~	~~The temperature selection method shall be calibrated in degrees Fahrenheit.~~	
Inspect		6.1.1	Equipment left in the greenhouse at the conclusion of the project shall not use solderless breadboards or other temporary circuit construction techniques.	
Inspect		6.2.1	All equipment shall adhere to relevant safety standards.	We are not qualified to test this.
Inspect		6.2.2	Equipment operating above 12V shall comply with the National Electrical Code.	

Key Requirements

Although all project requirements exist for a reason, some requirements are more pressing than others. These key requirements are: taking sensor readings no less often than every 15 minutes, providing remote display of sensor data, and sending smartphone notifications when unsafe temperatures are detected.

The latter two requirements are the primary motivation for the project. If notifications of unsafe temperatures were not provided, hundreds or thousands of dollars worth of plants would likely die in the event of freezing or excessively hot temperatures developing in the greenhouse. Without the continuous data display, the client could not trust that the system was functioning properly at any given point in time, and therefore the client would likely feel the need to physically travel to the greenhouse on particularly cold nights to check on conditions. Finally, the third critical requirement allows the first two to be effective. Greenhouse glass can break or a heater can fail at any time. Allowing more than 15 minutes to elapse between measurements presents an unacceptable risk of dangerous conditions going undetected for long enough to cause serious injury or death to the plants the system is meant to protect. Were this a commercial project, failing any one of the three critical requirements would likely cause the client to reject the entire project and refuse to pay.

Types of Test

When testing a product against a set of requirements, several types of test can be used. The test type is not arbitrary; rather, an appropriate test method is selected based on the nature of the requirement to be tested. For example, a requirement involving sequential logic would most likely be tested using the step-by-step method. In contrast, a requirement that a device operate properly over a range of inputs would be tested using the matrix method. Other options include an integration test, which checks that multiple subsystems interact properly, and an inspection test, which is used for simple requirements that can be tested without actually operating the system. On this project, all four types of test were performed, as discussed below.

The simplest test type, Inspection, was performed to verify the project's compliance with requirement 5.1.3 "Mixing fans shall not be battery powered." An inspection test was appropriate here, since the requirement can be fully tested simply by looking at the fans and observing that there is no place to insert a battery, and that the fans are equipped with standard Edison plugs for connecting to a 120 VAC supply.

The first two formal tests performed for this project were of the Matrix type. These tests verified compliance with requirements 1.1.3 "Temperature sensors shall be accurate to +/- 2℉ or better" and 1.1.4 "Humidity sensors shall be accurate to +/- 5% or better". Tests 1 and 2 were designed, performed, and reported by RJ and JL, respectively. The matrix test type was appropriate for these tests because the requirements specify that the sensors should be accurate to the specified tolerance *over their entire operating range*. In order to test compliance, the sensors had to be exposed to a range of temperature and humidity conditions. A step by step test was inappropriate because there was no reason to believe that the reported data would be affected by anything other than the ambient temperature and humidity.

The third formal test was conducted using the step by step method. This test verified the project's compliance with requirement 2.1.1: "Temperature and humidity data shall be retrieved from sensors and stored at intervals of 15 minutes or less." As discussed previously, compliance with this requirement is critical to the success of the project. This test was not designed to verify the system's response to any particular set of conditions; rather, it was designed to test the system's stability over a somewhat extended period of time. Customer acceptance testing may include an equivalent test performed over a longer period, such as the 72 hour burn-in period commonly specified in the construction field. The step by step method was appropriate because a guaranteed stable starting condition was required.

The last formal test was an integration test. This test verified compliance with requirement 4.1.1 "A smartphone alert will notify Tina Ayers or other greenhouse personnel when user-defined safe temperature or humidity ranges are exceeded." Because the test was intended to verify that multiple subsystems (sensors, Node server, database, and Discord bot) interact as intended, the test is automatically considered an integration test. Again, the requirement to notify greenhouse personnel of unsafe temperatures is critical to the success of the project and the team cannot afford to have this functionality fail during the customer acceptance test.

Major Tests

Test 1: Temperature Accuracy

This test was performed using the matrix method. The device under test was brought into a climate–controlled room with the room thermostat pre-set to 70 degrees Fahrenheit. The temperature readout from the device under test was compared to the indication from the commercial thermometer-hygrometer used for Test 2 (shown in Figure 2A). The thermostat setting was then increased by two degrees Fahrenheit, the room temperature was allowed to stabilize, and the temperature indications were compared again. The process was repeated up to a thermostat setting of 90 degrees Fahrenheit. At each step, the DUT and commercial thermometer indications were reported to match within the 2-degree requirement.

Test 2: Humidity Accuracy

This matrix test was performed by operating a team-produced air sensor in a small enclosed bathroom. At the beginning of the test, the room was dry. A humidifier was started, which slowly increased the humidity in the enclosed space. A commercial thermometer-hygrometer (Figure 2A) was used for comparison. Throughout the test, the commercial sensor was observed. When the commercial sensor indicated a designated test point (20 % relative humidity to 60 %RH in 5% steps), the next serial output from the team-developed air sensor (Figure 2B) was compared to the commercial reading. All test points were reported as meeting the 5 %RH accuracy requirement.

Figure 2A. Commercial thermometer-hygrometer for test comparison.

```
16:27:01.177 -> Attempting to connect to DHT22...
16:27:01.177 -> --------------------
16:27:01.177 -> 23.40%
16:27:01.177 -> --------------------
```

Figure 2B. Serial output from the device under test.

<u>Test 3: Data Rate</u>

This test confirms the system's stability over a period of several hours.

Per the test instructions, five air sensors were set up. For convenience, each of the five test sensors was set to be in the "north house" although the test physically took place in the engineering building. The ControlDesk application was used to confirm that data was being received from each of the test sensors, as shown below in Figure 3. Note that the "data age" readout for each of the "RATE TEST" sensors shows a recent report, easily complying with the 15-minute maximum reporting period requirement.

Throughout the testing process, the ControlDesk application was observed periodically. This was not a required part of the test. However, if a sensor had stopped working during the test, observing the readout would have likely alerted the tester to the failure and obviated the need to continue the test for the full three hours. Such a condition would have been indicated by the "Data age" readout for one or more sensors showing greater than 15 minutes.

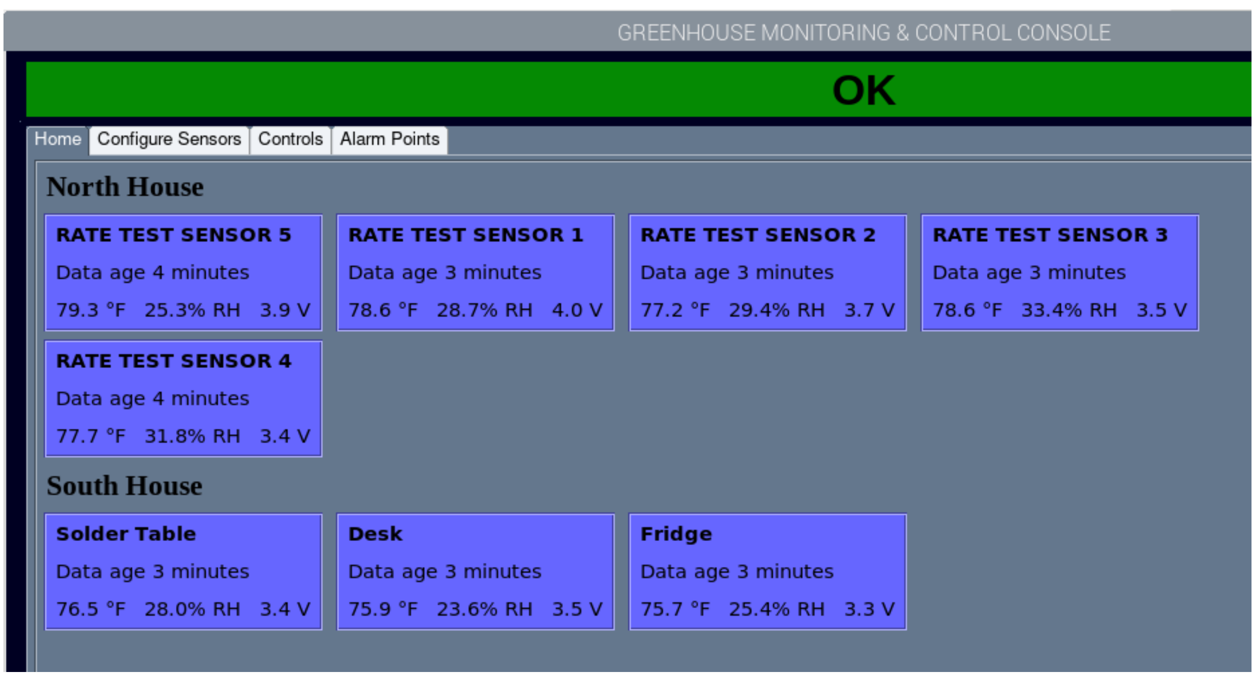

Figure 3. ControlDesk window during the data rate test.

Analysis of Results

All of the formal tests were performed successfully. This was as expected, since every feature was tested informally many times before being subjected to a formal test.

Lessons Learned

No issues were encountered during the formal testing. As shown in the Requirements table earlier in this report, some of the other tests are currently failed. In each case, the relevant feature has not yet been developed. The project's performance could most easily be improved by adding those features. The Requirements table also shows some requirements in gray with strikethroughs; these requirements were cancelled because the client no longer desired the relevant functionality or preferred an alternate user interface style. No other changes were made to the requirements.

In general, the requirements were acceptable as written. However, requirement 4.1.4 "The [smartphone] alert [for unsafe temperatures] will be in a concise, numerical listing of data" was not testable. Determining whether an alert is concise is subjective, and therefore no valid test can be performed. In a commercial setting, this requirement would need to be clarified or formally removed. However, for this project, we are simply ignoring the requirement for testing purposes and are willing to make minor changes if the client requests them.

No test-fix-test cycles occurred during the formal testing, because no feature was subjected to a formal test before the feature's developer was satisfied with the feature's performance. However, many test-fix-test cycles occurred during the undocumented informal testing that occurs during development of all projects involving software.

No regression testing was performed or found necessary; our project is simple enough and the consequences of failure are minor enough that regression testing was found to be unnecessary.

Nothing in particular was learned about testing. However, we did find that some time was wasted by completely designing a test procedure before the feature to be tested was fully developed. Changes in the feature implementation required the testing steps to be modified, leading to lost efficiency.

<u>Appendix A: Sensor Electrical Schematics</u>

Presented below are the electrical schematics for the air and soil sensors. From these schematics, PCB layouts were developed and boards were milled in-house.

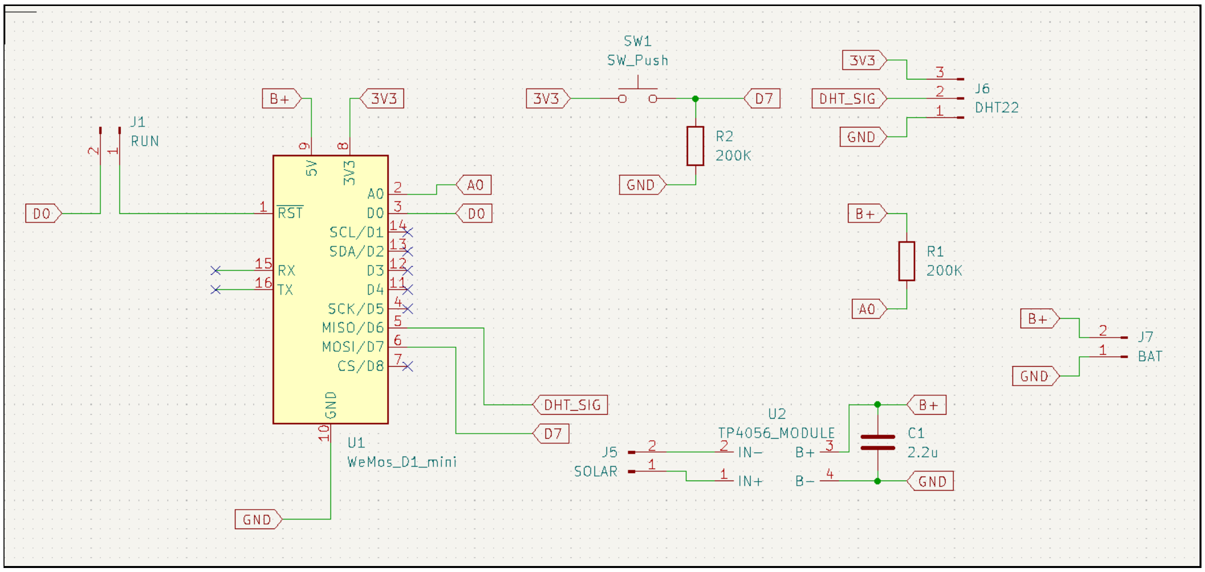

Figure 4. Air sensor schematic.

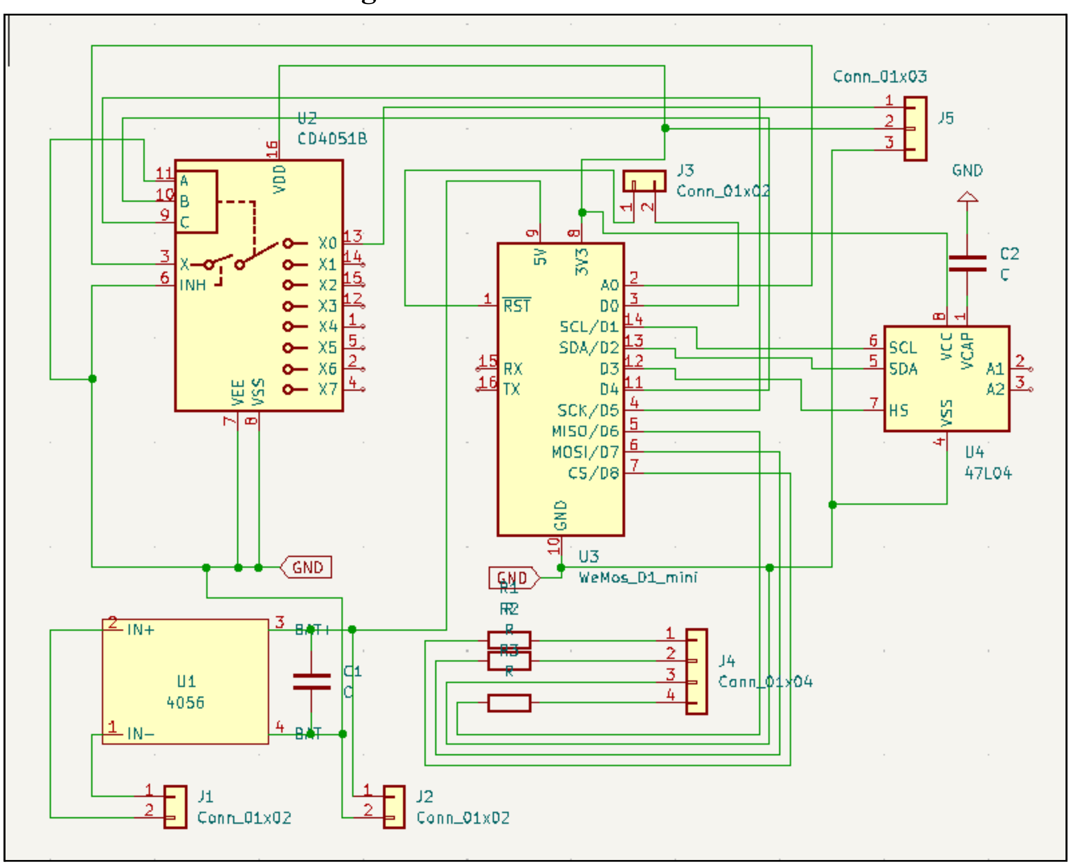

Figure 5. Soil sensor schematic.

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To: Robert Severinghaus, Mahsa Keshavarz
From: EE486 Team 6 - Emilia Connelly, Alexia Risley, Jiaxin Liu, Ruopeng Jia
Date: April 1, 2022
Subject: Greenhouse Project Testing Report

The attached report serves to document the formal testing performed on the NAU Teaching Greenhouse environmental monitoring and controls project. This project aims to provide greenhouse personnel with remote monitoring ability, smartphone notification of unsafe environmental conditions in the greenhouse, as well as automatically controlled air mixing to reduce undesired temperature gradients. The project has taken place over a period of seven months, since September of 2021. As of this writing, the products have been tested in the lab environment and substantially meet the requirements set out by the team and client. The system is scheduled to be delivered to the client in the afternoon of Wednesday, April 6 by mutual agreement. The total time spent performing various tests on the project is estimated to be approximately 20 engineer-hours. This time includes approximately 30 informal tests performed in the process of creating the system. Of that time, approximately six hours was spent on the four formal tests documented in this report. The product has passed all formal unit and integration tests performed.

Attached: Testing Report