Development of an Environmental Monitoring System for Greenhouse Disease Management

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Dedication

I would like to dedicate this thesis to my husband, Shaun Kelly, for being so patient through the research process and for helping to proof read. I would also like to dedicate this to my parents, Ed and Terese Dillard, my grandparents, Ron and Norma Yost, and to all of my family members and friends for supporting me throughout my education and my life. I love you all.

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Abstract

A commercial African violet (*Saintpaulia ionantha*) grower experiences yield loss due to a leaf spot disease known as *Corynespora casssiicola*. Spotted leaves make the plants unmarketable. Outbreaks of the disease are costly and difficult to prevent. Greenhouse monitoring systems currently available on the commercial market do not have sufficient spatial or temporal resolution to be able to correlate the environmental conditions of the greenhouse with disease outbreaks. A new system was designed specifically to monitor for disease favorable conditions. The system developed for this project consists of several sensor stations and a coordinator station. The coordinator station is connected to a PC and periodically collects data from all sensor stations through a wireless communications network. Data enters the PC in an easy to analyze comma-delimited format. Each sensor station is entirely self-contained and battery operated to minimize inconvenience to producers. The stations are small enough to fit into the footprint of a four inch potted plant. Each station measures temperature, relative humidity, and light levels and can last for at least two months on a single battery charge. When tested in a commercial greenhouse, sensor stations were able to detect significant spatial differences in environmental conditions. By placing these stations at regular, close intervals throughout the greenhouse producers can gain a more accurate picture of current environmental conditions in their crop than they have been able to obtain in the past. If these readings are combined with disease outbreak information, producers will be able to determine if there is a correlation between certain environmental conditions and disease outbreaks.

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1 Introduction

1.1 Overview

Greenhouse production is an expensive and high-risk method of producing a crop. While the financial benefits of being able to deliver a crop at any time of year are high, the costs of growing the crop and maintaining the facilities are also high. By definition, all greenhouses offer some degree of environmental control. The simplest structures are covered with a translucent material that protects crops from adverse environmental conditions. Greenhouses that are more sophisticated can provide precise temperature control through heating and cooling, shade cloth and supplemental lighting to ensure an exact range of light and high-end control systems to automate the production of plants from start to finish. In addition to controlling the environment, producers must also be concerned with managing insect pests and plant pathogens. In the wild or in field-grown crops, large-scale outbreaks are mitigated by predators or by host plants being spaced further apart. In a greenhouse, the densely packed, sheltered plants are more vulnerable to pathogens. Once a disease outbreak occurs, the warm, humid environment and the continual presence of the host plant make the disease nearly impossible to control. The most common cause of disease in plants is fungi. Producers must continually spray fungicides to prevent the loss of a crop due to infection. This prolonged use of fungicides, in addition to posing a safety hazard to exposed workers, can reduce sensitivity of fungi to pesticides.

Fungi that cause disease in plants have optimum environments at which they are able to infect plants and spread throughout a crop. If the optimal environment is known for a particular disease, the disease may be avoided or reduced by preventing the triggering environmental

conditions from occurring. If environmental conditions conducive for disease outbreaks cannot be avoided, fungicide usage may be necessary. The quantity of fungicides used for disease control may be reduced if they are applied only when conditions are conducive for disease development. One major challenge of this environmental approach to disease prevention is the large variation that exists spatially in the microenvironment surrounding a crop in a greenhouse. The environment for a field crop is assumed to be more or less homogenous; however the environment in a greenhouse crop can vary greatly. It is difficult to obtain information on where environmental differences occur in the crop and what the differences are. Environmental control of disease in a greenhouse crop would require high resolution spatial and temporal monitoring through a vast network of sensors. These sensors would need to be near the plant canopy where they could measure the actual environmental conditions the plants are experiencing. A large network of sensors integrated into crop production can be costly to producers and interfere with their normal operations.

The disease monitoring system developed for this project overcomes these challenges by utilizing low cost, wireless technologies to create a system that is transportable and occupies no more space than a small flowerpot (figures 1 and 2). No point-to-point wiring is required for sensor stations in the system. The individual sensor stations in the monitoring system operate for several months without requiring maintenance. All data from sensor stations transmit to a single coordinator station where the data is downloaded by the producer for analysis. Because the system is wireless, sensor stations can be moved around the greenhouse at will, and the system can be scaled to any size operation with very little set up. Producers simply have to turn on the system, setup the sensor stations throughout the greenhouse (figure 3), and they are ready to start monitoring and recording environmental conditions throughout the crop.

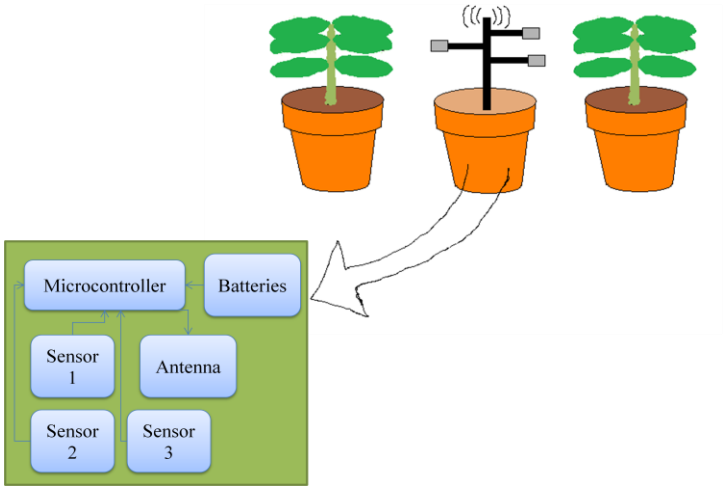


Figure 1: Conceptual drawing of a sensor station.

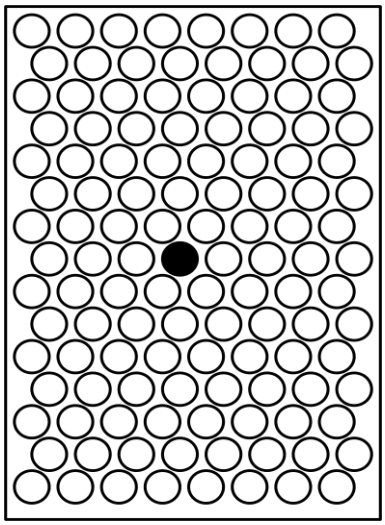


Figure 2: Overhead illustration of sensor station on a greenhouse table.

White circles represent potted plants. Black circle represents a sensor station.

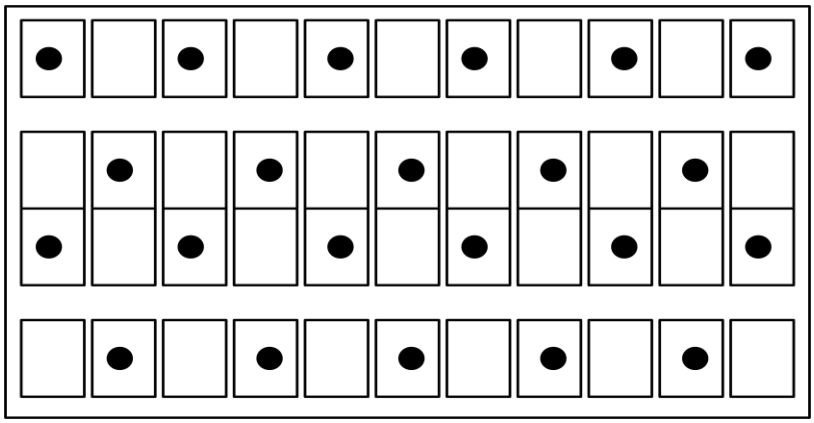


Figure 3: Overhead illustration of sensor stations dispersed throughout a greenhouse. White rectangles represent tables of potted plants in the greenhouse. Black circles indicate which tables a sensor station would be placed on.

1.2 Background

In 2007, the greenhouse and nursery industry in the United States had $16.6 billion in sales (USDA, 2007). Within that industry, potted plant production alone grossed more than $1.2 billion in sales. Greenhouse and nursery production is a growing market with an overall increase of 13% from 2003 to 2007. The profit margins for this industry are very tight. Any plants that cannot be sold due to disease, insect damage, overall appearance, or poor market timing can greatly hinder an operation's ability to survive economically.

The warm and humid environment of a greenhouse and the dense population of plants create an ideal environment for plant diseases and pests to survive year round. If a disease establishes itself in a crop, it can decimate producers' profits. For example, in the spring of 2009, Bonnie Plants sold potted tomato starter plants to a number of major retailers in the northeastern United States. After many of these tomato plants had been sold in stores, it was

discovered that the crop had a potential infection of late blight. Late blight is a very serious plant disease. All of the tomato plants had to be recalled. The recall cost Bonnie Plants an estimated $1 million in sales in addition to damaging their reputation among retailers and customers (Unknown, 2009).

Holtkamp Greenhouses, Inc. is a business operating in Nashville, TN that specializes in potted ornamental plants. While they grow a large variety of plants such as coleus, poinsettias, and ferns, the majority of their space is dedicated to the production of African violets (*Saintpaulia ionantha*). In the past few years, Optimara has encountered a disease problem on their African violets caused by the target leaf spot caused by *Corynespora cassiicola*. *Corynespora cassiicola* is a fungus that causes necrotic spots on the leaves of the plants. Since these plants are sold as ornamentals, spotted leaves make the plants unmarketable. Although severe outbreaks of disease occur periodically, there are always a few plants in the greenhouse with the leaf spot. As long as the number of spots is small, the affected leaves can be removed, and the plant can be salvaged. During a severe outbreak, symptomatic plants are rouged, and the remaining plants are sprayed with a prophylactic fungicide. These outbreaks cause a significant economic loss to the company. Since it is certain that a susceptible host, African violets, is always present, and the pathogen is constantly present since low levels of the disease can always be detected, the most likely cause for severe outbreaks of disease is a change in the environment. An environmental monitoring system is needed to monitor the crop with a high spatial and temporal resolution and determine what type of an environment is triggering the outbreak of the disease. A search was made of commercially available systems and none was found that could easily meet or be adapted to meet the needs of this project. This unrealized need was the inspiration for the greenhouse monitoring system developed for this project and detailed in this document.

1.3 Objectives

The general objective was to develop a system to control or prevent outbreaks of *Corynespora cassiicola* in *Saintpaulia ionantha* greenhouses by early detection of disease favorable conditions. This project designs, prototypes, and evaluates an environmental monitoring system to determine if there is a correlation between conditions inside the greenhouse and outbreaks of the disease. Specifically, this system should:

- Integrate multiple sensor stations and a coordinator station into a network
- Be deployable in a commercial greenhouse environment
- Have sensor stations entirely self contained and battery operated
- Collect data on environmental conditions
- Fit in the footprint of a four inch potted plant
- Be minimally invasive to minimize inconvenience to producers
- Be simple to operate

2 Review of Literature

2.1 Disease

2.1.1 Plant Pathogenic Fungi

The most prevalent cause of plant disease is pathogenic fungi. Devastating plant diseases caused by fungi have been observed since ancient times. Plant pathogenic fungi were responsible for chestnut blight and the Irish potato famine. Fungi obtain their nutrients by excreting digestive exoenzymes and absorbing the nutrients through cell walls (Trigiano et al., 2008). One way that fungi can spread through a crop is through asexually produced spores called conidia (figure 5). For a fungus to cause disease in a plant the proper environment must be present (figure 4). Fungi prefer damp high humidity environments. Moisture is needed to carry nutrients to hyphal cells, for fungi to germinate, and for penetration of leaf tissue. The optimum environment for most species of fungi is between 25°C-30°C with a pH between 4 and 7 (Trigiano et al., 2008).

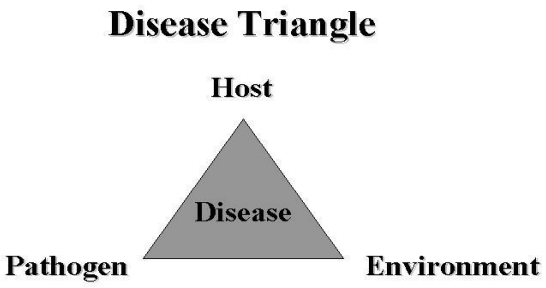


Figure 4: Disease Triangle (Trigiano et al., 2008). Plant disease is an interaction of host, pathogen and environment.



Figure 5: Conidium of *Corynespora Cassiicola*.

2.1.2 Disease in Greenhouses

The production of crops in greenhouses presents a unique challenge to disease management. Greenhouses allow producers to maintain ideal conditions for crop growth year round. Unfortunately, the conditions conducive for plant growth are often also ideal for the growth and spread of plant pathogens (Menzies and Belanger, 1996). Producers walk a fine line by trying to optimize environmental conditions for plant growth but not for proliferation of pathogens. Greenhouse production also allows growers to attain much higher yields than in field-grown crops. This increased yield means that plants grown in greenhouses are often placed much closer together than when they are grown in a field. "Because plant population densities in greenhouses are usually very high and closely confined by the greenhouse walls, some virus diseases, foliar blights, leaf spots, stem and fruit rots, root rots and other diseases can become severe very quickly (Averre et al., 2000)." Often a grower will have lost most of the crop by the time signs of the disease are evident enough to warrant action.

Along with these challenges, greenhouses also have potential advantages in disease management. "The high labor, high technology inputs of the greenhouse industry provide unique opportunities for disease control (Belanger and Menzies, 1996)." By growing crops in a greenhouse, producers have demonstrated their willingness to spend extra resources to deliver a crop out of season. Through the environmental control technology in place in many greenhouses and simple changes in management practices, growers may be able to reduce the severity of disease in their crops. "Since plant disease [is] strongly affected by temperature and humidity, the best way to combat disease is to manipulate the greenhouse environment. Unlike the weather outdoors, we can control the greenhouse environment (Eshenaur and Anderson, 2004)." Most plant pathogenic fungi need high humidity or standing water to germinate and develop properly. These conditions can be avoided in greenhouses without hurting the plants through practices like, spacing plants further apart to prevent humidity build up in the canopy and delivering water straight to the media when possible rather than by overhead watering. Also, monitoring light levels, temperature, and humidity to determine plant water needs and watering only when needed can reduce the humidity in a greenhouse and especially in the micro-climate surrounding the plants (Eshenaur and Anderson, 2004).

2.1.3 *Corynespora cassiicola*

Corynespora cassiicola is a plant pathogenic fungus that was described by Wei in 1950. The fungus spreads from plant to plant by germ tubes germinating from conidia. *Corynespora cassiicola* is commonly known as target leaf spot because of the necrotic lesions left on plants. The extensive list of plants for which *C. cassiicola* is a pathogen and the many more plants on which it can survive as an endophyte makes this fungus difficult to study or control. Not every strain of *C. cassiicola* is pathogenic on the same plants (Schlub et al., 2009). The strain that causes disease in African violets has not been well studied.

Schlub et al. (2009) reported that disease caused by *C. cassiicola* was observed above 20°C with severe disease occurring at 32°C. He also reported that high humidity and leaf wetness were needed for 16-44 hours for disease to be present (Schlub et al., 2009). Madhavi et al. (2009) confirmed the high humidity requirement when he reported maximum germination and germ tube growth occurred at 95%RH. He also reported that when *C. cassiicola* was cultured in alternate darkness and light, germination was greater than when it was cultured under continuous light or continuous dark. UV exposure reduced spore germination (Madhavi et al., 2009).

When searching for environmental causes that enhance disease outbreaks, one must identify the proper parameters and when they occur. Some diseases remain latent for long periods, and epidemics can explode once detected. The triggering environmental event may have long since passed. Fernandes et al. (2003) reported that after inoculating coleus plants with a known pathogenic strain of *C. cassiicola* that disease spots were evident on the plants in less than 24 hours. Rapid spread of the disease is implied by growers who report that one day there is only a small amount of disease and the next day most of the crop is showing symptoms of infection. Madhavi et al. (2009) also noted that while some conidia had germinated within one hour, 90% were germinated within 24 hours. It is important to note that the strains of *C. cassiicola* in these two studies and the plants they were studied on are not the same as those being observed in this research, so there is a possibility that times for germination and infection will differ.

2.2 Expert Systems

As electronics and computers become smaller and more affordable, their use in agriculture has become more prevalent. The combination of computers and sensors in the greenhouse can be

invaluable in helping growers make informed, timely decisions that will increase yields, produce higher quality plants, and decrease the instances of disease. One way of utilizing electronics in the greenhouse and nursery industry is through expert systems. An expert system is "a computer program using expert knowledge to attain high levels of performance in a narrow problem area (Donahue et al., 1991)." Expert systems were being developed for use in agriculture as early as the 1990's (Donahue et al., 1991). These systems consisted of yes/no questions that farmers would answer on a computer screen. The computer program would then determine what type of problem the farmer was facing and suggest an appropriate course of action. As computer power has increased and sensors have become smaller and cheaper, newer models have been created that rely more on electronic measurements and less on human input. Expert systems today can collect information from the greenhouse environment, analyze it, and then inform the grower about what is happening. There are many systems available on the market that interface with the control systems to adjust the environment or alert the grower as necessary. Hu et al. (2007) recently developed an expert system for managing greenhouse vegetable production. The system measured environmental parameters that affect plant production such as temperature, humidity, and light intensity inside and outside of the greenhouse. The data acquisition also had the ability to measure CO_2 concentration, wind speed and direction, and rainfall. Their system had one sensing station placed on the greenhouse rafters high above the plant canopy in each greenhouse. These stations were hard wired to a PC dedicated to greenhouse data acquisition. An alarm was in place to alert the growers if any parameter exceeded acceptable operating conditions.

2.2.1 Wireless Sensor Networks

One hurtle that has been preventing the implementation of expert systems in many smaller and midsized greenhouse operations is the high start up cost and the inconvenience of the hard

ware. A promising solution to these issues is wireless sensor networks (Pawlowski et al., 2009). Wireless sensor networks typically consist of a master device from which instructions can be relayed throughout the network and one or more slave devices that report back to the master device. The master device often interfaces with a personal computer to gain information on the wireless sensor network, download data collected by the network, or alter the program that the network is running (figure 6).

Another type of wireless sensor network that has been made popular by the ZigBee Alliance is the mesh network. Mesh networks consist of coordinators, routers, and end devices. In a mesh network the coordinator can send information to and from routers and end devices, routers can relay information to end devices and other routers, and end devices can talk to one router called their parent or to the coordinator (figure 7). There are two ways that a mesh network can be configured, a star pattern of routers and end devices (figure 7) or a more nebulous network of only routers (figure 8).

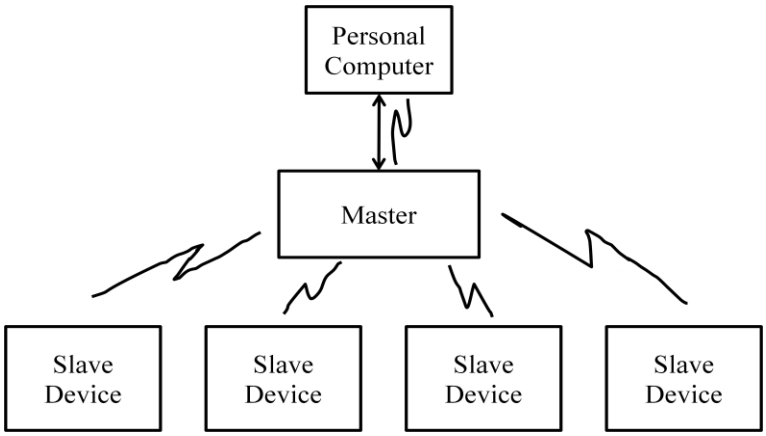


Figure 6: Illustration of a typical wireless sensor network.

End devices tend to use less power than routers. Since they only transmit and receive from one other device, end devices can be put into sleep mode when not operating. If it is certain that an end device will never be out of range of a router then a star pattern configuration can yield extra power savings. If however the nodes of the network are subject to frequent relocation, a network of all routers would be preferable. Mesh networks operating on the ZigBee protocol maintain tables that calculate the most efficient path from a router or end device to the

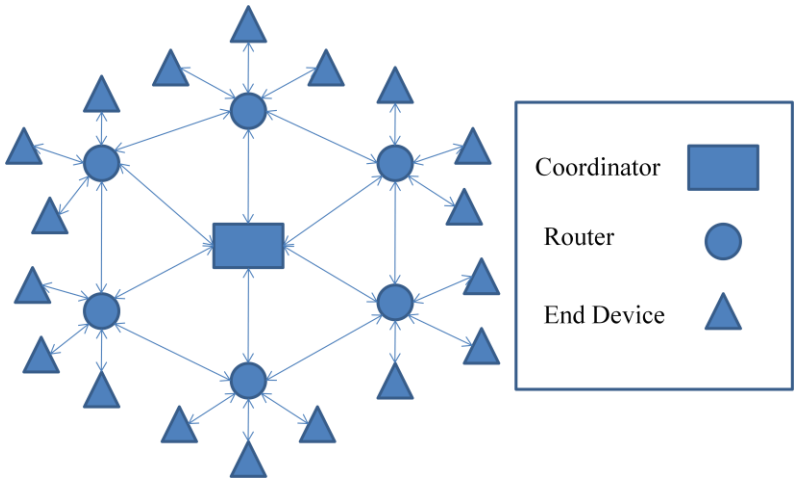


Figure 7: Illustration of a "Star-Pattern" mesh network. Arrows indicate paths of wireless communication. Networks can be much larger than the one illustrated here.

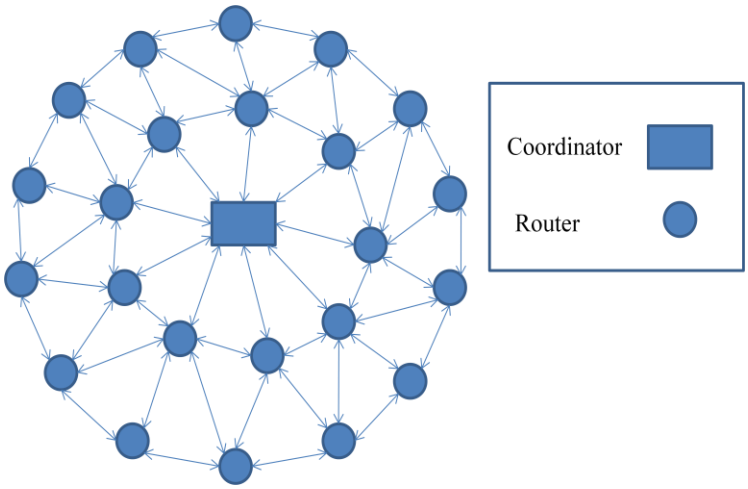


Figure 8: Illustration of a mesh network made only of routers and a coordinator. Arrows indicate paths of wireless communication. Networks can be much larger than the one illustrated here.

coordinator. The ability of a ZigBee network to relay information to the coordinator by hopping from one router to the next makes mesh networks far more energy efficient than a more traditional master/slave network. In a traditional wireless sensor network, all slave devices must be able to communicate directly with the master device. Therefore, for a given distance traditional systems require more powerful transmitters to communicate than a ZigBee system. ZigBee networks also have the ability to self heal. If a router dies, the devices connected to it will automatically find another path for sending their data to the coordinator. If a router or end device is moved, it will rejoin the network in its new location without input from the user.

Since there is no cabling involved in a wireless sensor network, growers can start a system with just a coordinator and a few end devices or routers and easily add more nodes at a later time as funding becomes available (Lea-Cox et al., 2008). The absence of power cords and data

cables also makes wireless sensor networks less intrusive to growing operations. Van Tuijl et al. (2008) implemented a 100 node mesh network in a cucumber greenhouse. They noted that mesh networks are ideal for studying containerized plants that will be moved throughout the greenhouse and the small size and relatively low cost of wireless sensors allow for the study of temperature variation and disease progression. The attempt at measuring temperature and humidity in a large greenhouse using a wireless sensor network was successful. However, several challenges that still hinder the expanded use of wireless sensors in a greenhouse were identified. One issue identified was the packaging of sensors. Most plastics cannot withstand the solar radiation and high humidity of a greenhouse, and many packaging choices can cause heat buildup that electronics cannot tolerate. Temperature and humidity sensors must be shielded from direct solar radiation to prevent erroneous readings but must still be in contact with the surrounding environment. One potential concern is that the 2.4 GHz frequency used in wireless systems is attenuated by water rich objects such as plants (Van Tuijl et al., 2008).

3 System Design

To be able to monitor the environment of greenhouses closely enough to be able to predict disease outbreaks, a monitoring system with high spatial and temporal resolution is needed. The system designed for this project is capable of that type of high resolution monitoring. The goal of this project was to develop a proof of concept prototype system that could later be refined and implemented on a commercial scale. The system should:

- Demonstrate an ability to communicate wirelessly in a fully operational greenhouse
- Design sensor stations that could operate for multiple months without recharging or replacing
- Collect environmental data that could lead to a disease prediction model
    - Measure temperature, humidity, and light
- Incorporate an enclosure to protect electronics in a greenhouse environment
- Transmit data from individual sensor stations to a coordinator
- Transmit data from a coordinator to a personal computer
- Be easy to install, maintain, and utilize

3.1 Wireless Network

There are multiple choices for wireless communication currently on the market such as Bluetooth and ZigBee. For this project, the wireless communication protocol chosen needs to:

- Operate over at least two hundred feet in a greenhouse environment
- Allow for seventy five sensor stations on one network
- Operate for at least 90 days on a single battery charge from a battery small enough to fit into a device that meets the previously stated requirement of a footprint no bigger than a four inch potted plant.

Both Bluetooth and ZigBee fulfill the first two requirements. While Bluetooth is more widely implemented in the market today and is older and consequently more well tested, a Bluetooth system requires far more power to relay information over the same distance as a ZigBee system. This is due largely to the fact that ZigBee allows for a mesh network design whereas Bluetooth does not. Since the greenhouse monitoring system is a network of sensor stations distributed throughout a greenhouse, the mesh network is ideal, and the power savings that can be realized with a ZigBee system make it the preferred communication protocol for this project.

3.1.1 Microcontroller and Radio

For the sake of keeping the sensor stations as small as possible, a combined microcontroller (MCU) and wireless communication system was chosen. The Texas Instruments(TI) CC2530 is a low power "system-on-a-chip" able to perform the basic tasks needed for this project and is a ZigBee capable receiver and transmitter. The CC2530 has 21 general input/output pins, 256 KB of programmable flash memory, four internal timers, and three power modes. There is also an on board 12-bit analog-to-digital converter (ADC) with 8 channels. The MCU operates on a supply voltage between 2 and 3.6VDC power. Battery voltage is monitored using the onboard ADC. Figure 9 illustrates how the TI CC2530 interacts with other sensor station components at a system level.

The ZigBee stack (Z-stack) program, provided by TI with the CC2530, is compliant with the latest ZigBee and ZigBee PRO stack profiles. The manufacturer's intention is for end users to develop programs within Z-stack. By adding their personal code to the designated areas within a Z-stack workspace, end users gain access to all the necessary functions of a fully operational ZigBee network. Z-stack is developed in the C/C++ programming language. The preferred compiler of Texas Instruments for the CC2530 is the IAR Embedded Workbench.

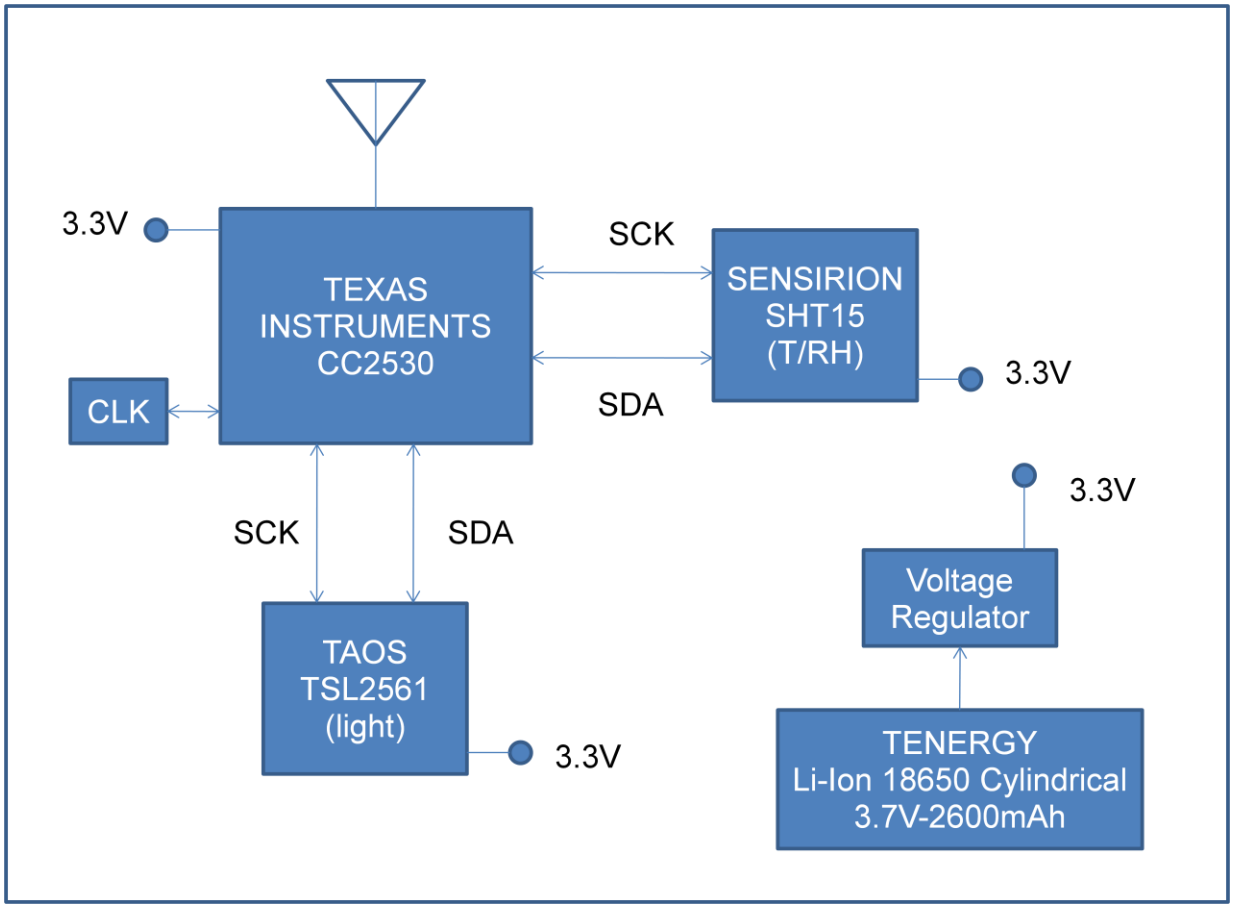


Figure 9: Conceptual map of sensor station

The network created by Z-stack automatically sets up a network that is capable of multi-hopping and is self healing. It is very simple to distinguish devices as coordinators, routers, and end devices in Z-stack, and it only requires one line added to the preprocessor to utilize power savings.

3.1.2 Network design

Initially the plan for the monitoring system was to have a network made entirely of routers. As demonstrated earlier a network consisting of only routers and a coordinator provides the most

flexibility in a system and ensures there will be no issues with reaching the coordinator in a system where devices may be continually moving. Z-stack does not allow routers to use power saving modes. Only end devices are permitted to enter sleep modes. This is due to the fact that a router must always be ready to act as a hopping point and be able to receive data from one device that needs to be passed on to another device in the system. Not only does this mean that a router's CPU cannot sleep but also that the radio on a router will be functioning most of the time. The radio draws more power in the sensor stations than any other component. For this reason, it became necessary to configure the sensor stations as end devices. The routers draw too much power to meet all of the design objectives. For example, if each station were given enough battery power to last for a few months, the size of the battery would exceed the footprint of a four-inch pot. If the routers and batteries were designed to fit into a four-inch pot, operating them would be limited to one or two days. The compromise was to only use routers when the system was implemented in a greenhouse too large to be serviced by a coordinator and end devices alone and to use as few routers as possible to be able to reach all areas of the greenhouse. When routers are needed, sensor stations can be converted to accept auxiliary power (electrical utility or solar).

3.2 Sensors

3.2.1 Temperature and humidity

To simplify the sensor station programming, circuit board design, and sensor station housing design, the SHT15 combined temperature and humidity sensor from Sensirion was selected. The combination of humidity and temperature sensing in one device saves physical space on the sensor station and also limits the number of input pins being used on the microcontroller. The SHT15 digitally interfaces with the microcontroller through the I^2C protocol. According to the manufacture, the sensors are interchangeable and do not require individual calibration

curves. The interchangeability of sensors was confirmed in this project through testing in an environmental chamber. The reported operating range for the temperature sensor (-40 to 123.8°C) and the humidity sensor (0-100%) falls well within the range of expected environmental conditions in a greenhouse. The SHT15 can operate on 2.4-5.5V input. Sensors only take readings when commanded by the microcontroller. This power saving mode reduces the overall cumulative power requirements. The reported accuracy of this device is ±0.3°C for the temperature and ±1.8%RH for relative humidity. While 1.8%RH in the range of 0-100%RH may seem like a large error, it is acceptable for this project. The monitoring system is designed to collect environmental data within a greenhouse for the purposes of tracking disease. The sensors in this monitoring system are monitoring a population of plants. As with any population of living organisms there will be great variation from specimen to specimen. While there will be similarities and general patterns that can be discovered, there will not be an exact temperature and humidity combination that will trigger disease in a plant. Instead there will be a range of environmental conditions in which the occurrence of disease is more likely. The accuracy of the SHT15 is more than capable of distinguishing the changing environmental conditions that may trigger disease. The accuracy of the humidity sensor will decrease as the relative humidity rises above 90%RH but is still acceptable for this project.

3.2.2 Light sensor

The initial goal for the project was to measure ultra-violet light, photosynthetically active radiation(PAR), and infrared light. However, no cost effective filters were found that could be adjusted to fit over a photodiode to provide the desired spectrums. Hence, ultra-violet light was not included in the final design objectives. A single device that approximates the human eye response was used instead. The TSL2561 from Texas Advanced Optoelectronic Solutions (TAOS) is a light-to-digital converter. It has a 16 bit digital output with an I^2C digital interface.

The TSL2561 is comprised of two photodiodes. The first is sensitive only to the infrared range(750nm ≤ λ ≤ 1000nm). The second is sensitive over the visible and infrared range (380nm ≤ λ ≤ 1000nm). By using a calibration curve the infrared reading can be subtracted out of the reading from the second diode providing a human eye approximation. The visible spectrum is close enough to the same range as PAR (400nm ≤ λ ≤ 700nm) to be considered synonymous in this project. Therefore, this one device provides both the desired PAR and infrared readings. The TSL2561 operates on 2.7-3.6V input within the ranges of -30 to 70°C. The light reaches the sensor through a light pipe in the sensor station housing. The light pipe attenuates the light, so, as the manufacturer notes in the data sheet, it was necessary to recalibrate the light sensors. The sensor is equipped with an onboard ADC that converts the signal from the photodiodes to a digital output. The sensor automatically rejects 50/60Hz lighting allowing discrimination between natural and supplemental (AC) illumination. There is also a programmable sleep mode that allows the microcontroller to turnoff power to the photodiodes when they are not being read. This ability of the sensor to sleep is important for keeping the power requirements of the sensor stations as low as possible.

3.3 Enclosure

The enclosure chosen for the sensor stations was an ABS plastic NEMA 4 enclosure made by Budd Industries. It was important to have a NEMA 4 or better enclosure to protect the electronics against water and dirt that will be encountered during normal greenhouse operations of a greenhouse. Enclosures were fabricated in house to accommodate mounting holes for sensors, the antenna, and external power switch. The power switch was mounted in the lid of the enclosure. All other mounting points were in the main body of the enclosure (figure 10).

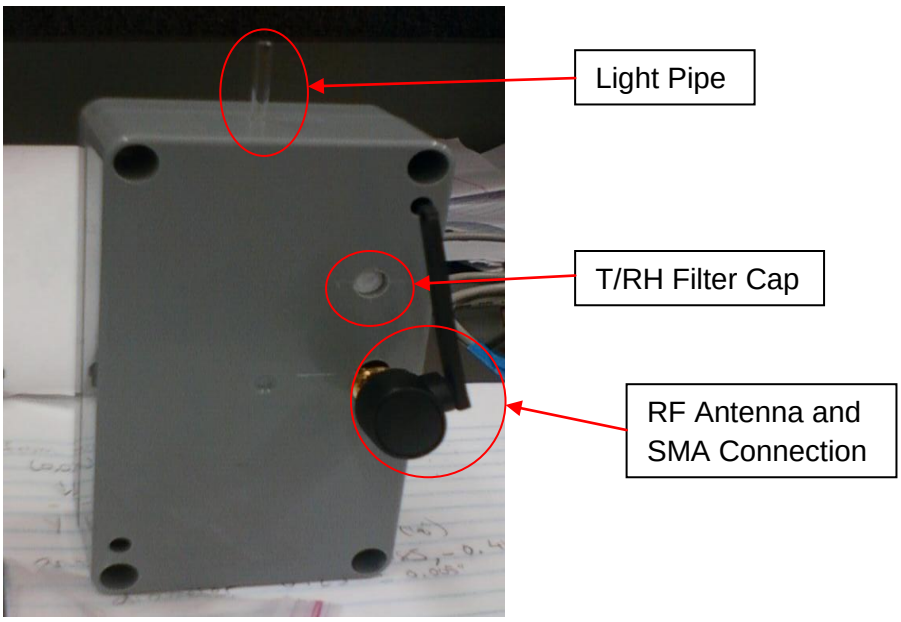


Figure 10: Sensor Station

The light pipe seen coming out of the top of the box (figure 10) is a Mentor light pipe that was designed to fit over surface mount LEDs for use in display panels. The variability in spectral attenuation through the light pipe is unknown, requiring some calibration for each sensor station. Since the TSL2561 light sensor by TAOS is the same size as a surface mount LED, this light pipe works well for this project. The filter cap shown was specifically designed for the SHT1x sensor line, and therefore was easily integrated into the sensor station design. Texas Instruments provides a Titanis 2.4 GHz swivel SMA antenna by Antenova with each of its CC2530 Evaluation Modules (CC2530EM) and is the antenna shown in the picture. The antenna is connected to the circuit board in the enclosure through a standard SMA male connector. All holes cut into the box were sealed with liquid silicon to ensure no water could enter the box through the normal operation of a sensor station.

3.3.1 Batteries

After studying the power requirements of the sensor stations, it became obvious that the AA batteries that were initially going to be used would not provide enough power to last for multiple months. A single rechargeable 3.7V Li-Ion battery from Tenergy was used in each sensor station instead. The entire case of the battery is electrical ground for the battery. The batteries were therefore wrapped in electrical tape to ensure that a power pin on the circuit board did not break through the thin coating and short the battery. The batteries are attached to the lid with Velcro, and can be taken out and disconnected from the power switch when recharging is required (figure 11).

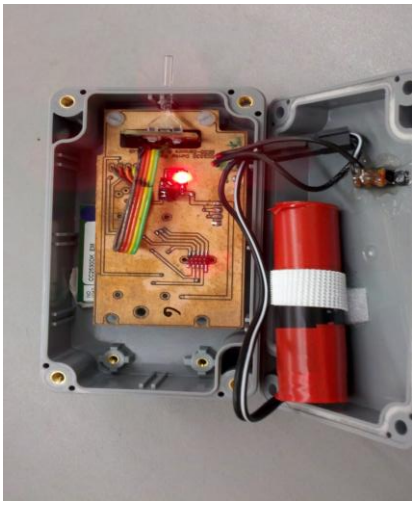


Figure 11: Inside view of Sensor Station

3.3.2 Circuit Board

Each sensor station contains one main circuit board and two carrier boards. The carrier boards hold the temperature and humidity sensor and light sensor in place to take readings from outside the enclosure. Carrier boards are connected electronically to the main circuit board through a ribbon cable (figures 12 and 13). The main circuit board contains integrated circuit that regulates the battery voltage (~3.7) down to 3.3V. A quick visual check that the board is

receiving power can be observed with an onboard LED. The main circuit board also contains a connection for downloading programs and debugging and connections for attaching a CC2530 evaluation module. The CC2530 pin density is too high for prototyping in-house. Therefore, a CC2530EM was used instead that includes a small profile daughterboard, CC2530 MCU, and antenna that is easy to interface in a prototyping environment (0.1" pin spacing). The main circuit boards were designed and fabricated to take advantage of the existing screw mounts in the enclosure (figures 11, 12, and 13).

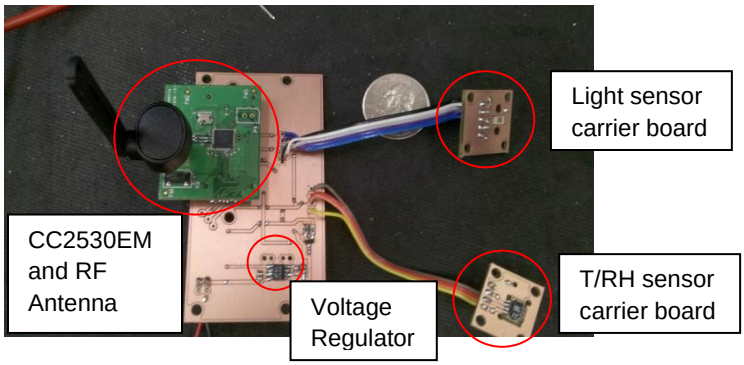


Figure 12: Top side view of circuit boards

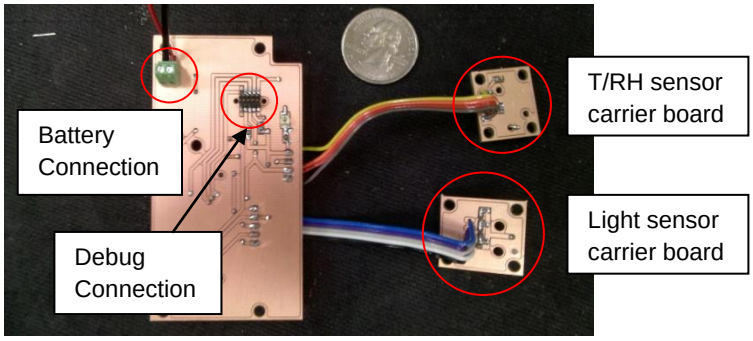


Figure 13: Bottom view of circuit boards

3.4 Software

All programming was implemented through Z-stack. A single programming workspace was used to program coordinators, routers, and end devices. The IAR Embedded workbench compiler and Z-stack allows users to choose which type of device is being programmed from a drop down menu. Within the code that was added to Z-stack to run the monitoring system, routers and end devices are both considered sensor stations and from a programming stand point are treated the same. The coordinator does not have sensors and has to interact with a personal computer. To keep the code for both types of devices in one workspace, a simple variable was defined in the workspaces main ".h" file that distinguishes between the two. The only code that was added to or changed in Z-stack was added to the main files with the same name as the workspace. The only exception to this was whole files that were added to the hardware abstraction layer to allow the temperature and humidity sensor and the light sensor to run.

3.4.1 End Device Program

On power-up, an end device will attempt to join a network. After this first join request a variable named BIND_CHECK is set to TRUE to prevent the device from inadvertently unbinding from its parent. The end devices take sensor readings once every minute. Every fifth reading the end device averages the readings and transmits them to the coordinator. Readings are transmitted in their raw integer format rather than being converted to a more readable format to prevent the accumulation of errors. Before transmitting the readings, the end device converts them to character strings that can be transmitted as ASCII code. The readings are concatenated into one long comma delimited string so that the data can later be saved as a ".csv" file. Along with the sensor readings, the end device also sends its name. Originally, the network short address of the device was used as the name, but since devices would seemingly randomly change

names, it became necessary to program in a specific name for each sensor station. The name was manually set in the ".h" file for each device before downloading to the board. This is cumbersome and not desirable for any kind of mass production, but, with careful attention to detail, it works.

In order to achieve a battery life of at least one month for end devices, power management techniques have been enabled. This means that in between scheduled sensor readings the device will go into a light sleep mode. In this light sleep mode the device can be awakened by a timer, making it ideal for this application. The deep sleep mode cannot be used to achieve further power savings because it requires an external interrupt to wake it from sleep. By using the sleep mode the end devices power consumption averages less than 1mW, which is low enough to last for a few months on one battery charge. To prevent the battery charge from going too low, each end device checks the battery voltage before sending readings to the coordinator. It then adds "OKAY" or "CHANGE" to the end of the packet of sensor readings. A simplified flow chart of the end devices program can be seen figure 14.

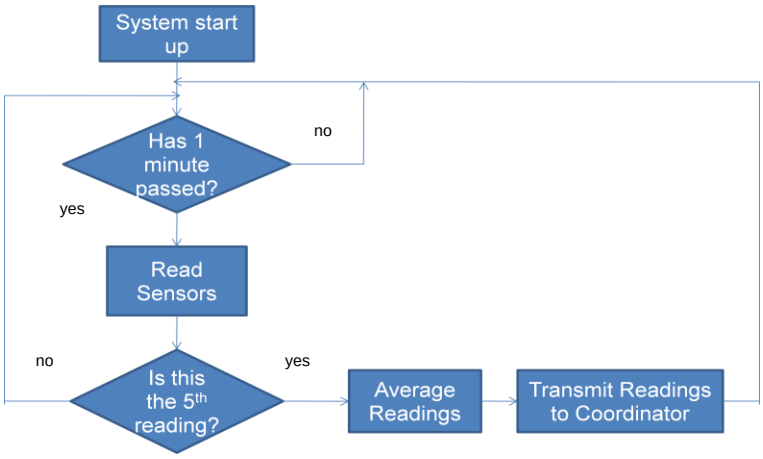


Figure 14: Flow chart of sensor station program

3.4.2 Router Program

The router program operates in exactly the same way as an end device program except that it does not sleep. Routers must be prepared to transmit and receive at all times and therefore cannot enter a sleep mode. Other than that, they are named, take readings, and transmit data in the same way as an end device.

3.4.3 Coordinator Program

The coordinator program is responsible for setting up and maintaining the network. Every time the coordinator program passes through the five-second timer loop it attempts to join with any device in the network requesting to join. The coordinator does not take any sensor readings of its own. Sensor stations wirelessly relay their data packets at predetermined intervals to the coordinator. The coordinator then sends these packets to a personal computer through a universal asynchronous receiver/transmitter (UART) connection via an RS232 cable. The data packets are sent in a comma delimited format for ease of processing. The coordinator performs no further analysis or conversion of the data. The coordinator sends the data through the UART connection in the same raw format that it receives it in from the sensor station. Rather than having the sensor stations sending a time stamp along with their data packets, the coordinator maintains one clock for the entire system and appends the current system time to data packets after they are received and before they are transmitted to the PC.

4 Evaluation of System

4.1 Sensor Testing

4.1.1 Software Testing

The software for this project was developed over a period of many months. After experimenting with the CC2530 in the ZigBee development kit and determining that it would work for the project, hardware abstraction layer (HAL) files needed to be written to operate the sensors. Both the light sensor and the temperature and humidity sensor utilize the I^2C communication protocol. The CC2530 and its associated software are not preprogrammed to handle I^2C communications. This means that it was necessary to develop the code for I^2C communication and add it to the HAL. To test that these files were implementing a proper I^2C communication, an oscilloscope was connected to the clock line and data line of the sensors. Signals were captured on the screen and examined to make sure the clock line was pulsing correctly, and that both the CC2530 and the sensors were controlling the data lines in turn, and that the data bit was changing at the proper time.

Each portion of the program was tested for functionality in the lab and corrected until every part was working, however a program can never truly be said to be free of bugs.

4.1.2 Temperature and Relative Humidity Sensor

Three initial prototype boards were placed in an environmental test chamber and cycled through temperature and humidity ranges that are typical of a greenhouse environment (0-40°C and 40-100%RH). One test cycled through a range of temperatures while holding humidity steady. Another test cycled humidity while holding temperature steady. The environmental chamber

was not able to control humidity at lower temperatures. When this happened, the resulting profile was too erratic to be useful for sensor station testing. Data points in these ranges were not considered for analysis. The prototype boards were not enclosed and did not have filter caps over the sensors. The initial prototype boards used an SHT75, the same sensor as the SHT15, but it comes on a carrier board that makes it easier for initial prototyping. The initial prototype boards were running an earlier version of the monitoring program. Sensors collected data every five seconds and did not average values. Temperature data collected in the environmental control chamber during a cycle test showed no hysteresis and confirmed that the sensors are effectively interchangeable. The average error for the temperature sensor was ±0.32°C, which is almost exactly what was reported by the manufacturer. The maximum temperature error was a difference of 8.06°C. The sensors had the most trouble at the extreme ends of hot and cold (figure 15). The average error for the relative humidity sensor was 0.75%RH, which is smaller than reported in the manufacturer data sheet. The maximum humidity error was a difference of 5.28%RH. The sensor had more trouble with lower and higher humidity (figure 16). This is consistent with what was shown in the data sheet. In addition the sensors track each other very closely as can be seen in a zoomed view of the data (figure 17).

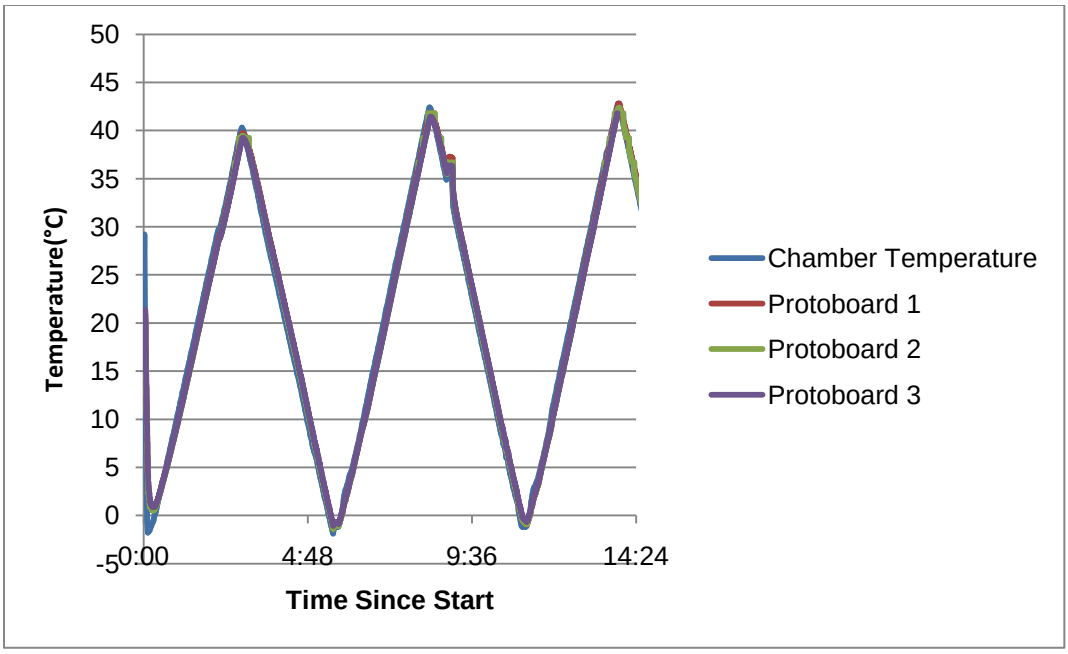


Figure 155: Temperature sensor testing in environmental chamber

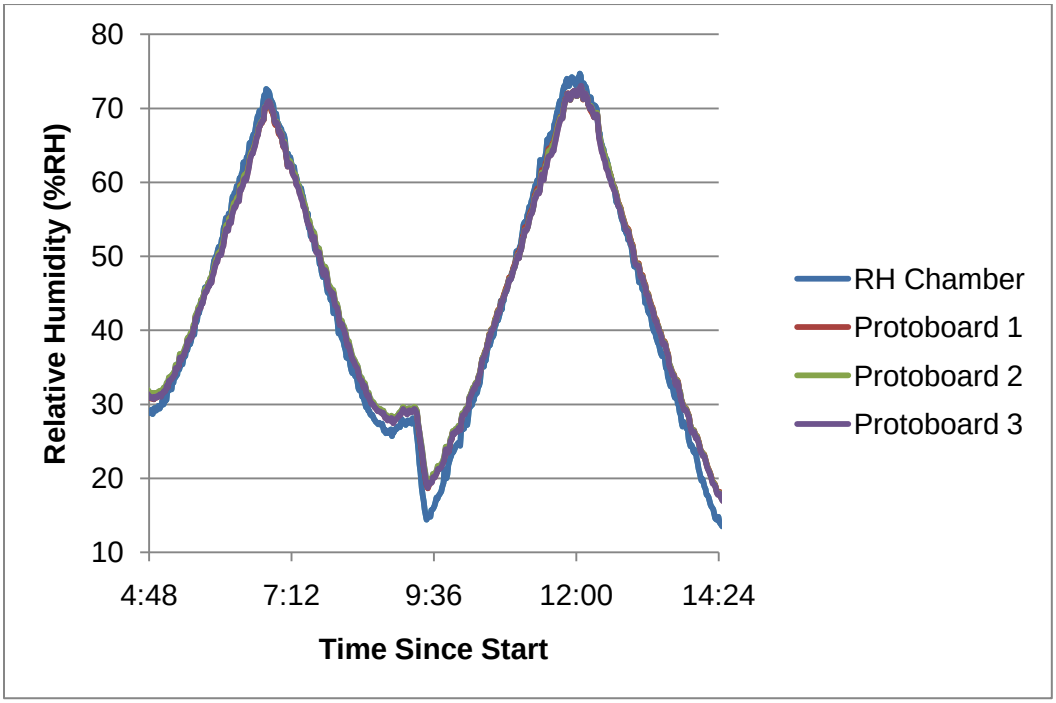


Figure 166: Relative humidity sensor testing in environmental chamber

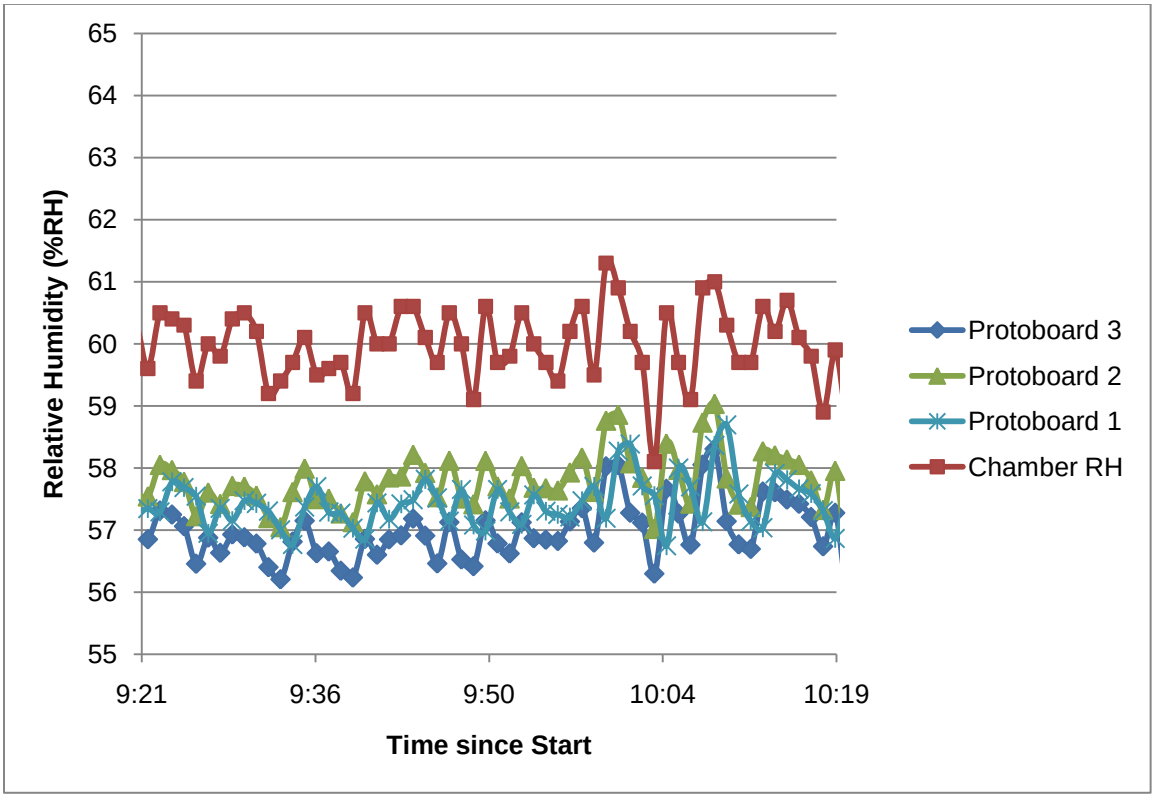


Figure 177: Comparison of relative humidity sensors

After the sensor stations were built and placed in enclosures, they were retested in the environmental chamber. The aim was to see if the filter cap on the sensor or having the circuit board enclosed caused any change in sensor performance. This was an abbreviated test. The two test profiles were for shorter lengths of time and focused on testing the sensors at three humidity levels and three temperatures. The sensor stations were running the final program that was described in the system design section of this document. As can be seen in figures 18 and 19, the sensor stations performed similar to the initial environmental chamber testing. There is likely some error accumulation due to an initial “over-flow” error.

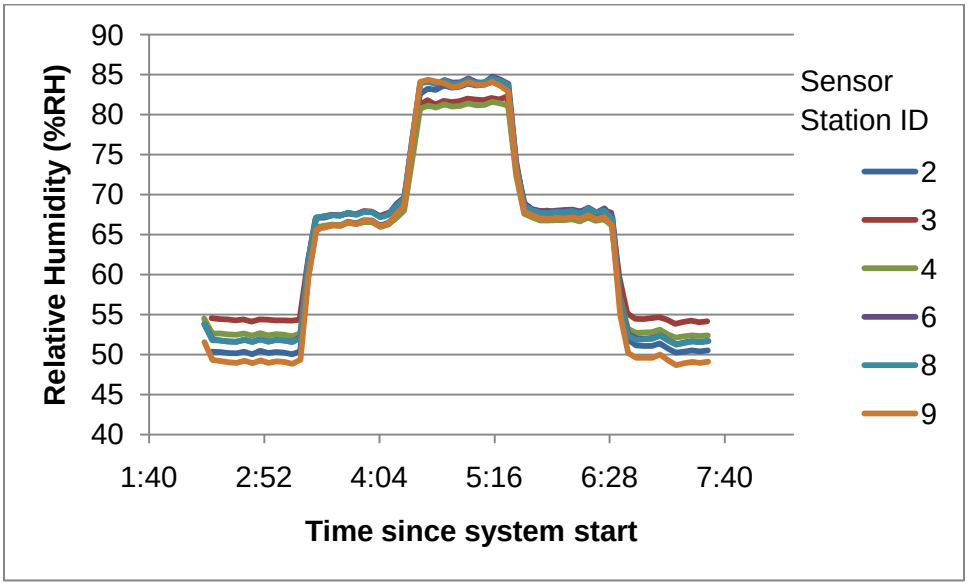


Figure 18: Sensor station testing of relative humidity in environmental chambers

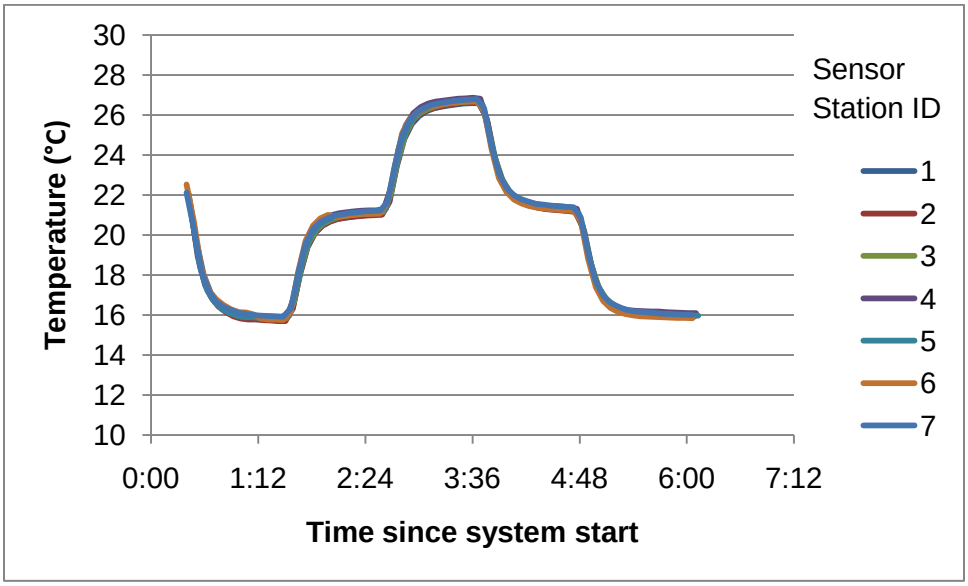


Figure19: Sensor station testing of temperature in environmental chamber

4.1.3 Light Sensor

The three initial prototype boards were tested under several different light sources and levels, and those readings were compared with readings from a light meter. It was discovered that

- The light sensors were saturated in full sunlight
- The provided calibration curve for the light sensors did not agree with the light meter.

A representative of TAOS, the manufacturer of the light sensor pointed out that a recalibration would be required after the light pipe was added, since the light pipe would attenuate the signal. No further calibration was done with the light sensors on the initial prototype boards.

After the final sensor stations were built, a modified program was created to take light readings from the stations every 30 seconds. This version of the program was to be used for the purposes of calibrating the light sensors only. Readings were taken from three sensor stations at multiple light levels and compared with a LiCor light meter. Five readings were taken from each sensor station at each light level. With the light pipe in place, light sensors were no longer saturated in full sunlight. The infrared sensor reading was subtracted from the infrared plus visible sensor reading. The difference was graphed versus the LiCor light meters reading (figure 20). The LiCor light meter reported the photosynthetic photon flux(PPF) in $\mu mol*m^{-2}s^{-1}$. PPF is a measure of the amount of photosynthetically active radiation (PAR). The resulting linear regression provides a calibration curve to convert the difference between the raw sensor readings into $\mu mol*m^{-2}s^{-1}$. The linear regression has an R^2 value of 0.94 indicating a good fit. Despite the high correlation value, the light sensor had the poorest correlation of all the sensor inputs. While the results from the test are adequate for a proof of concept system, it is probably the portion of the system with the most room for improvement.

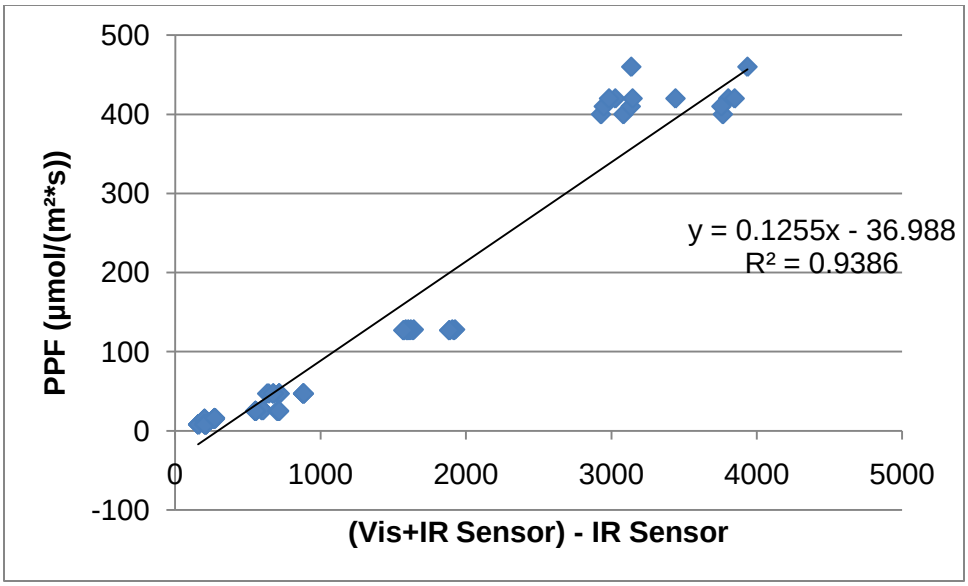


Figure 180: Light sensor calibration curve

4.2 Wireless Testing

4.2.1 Testing of wireless communication

The CC2530 microcontroller was tested for wireless communications by executing a simple Z-stack program that continually sent the device's network short address to the coordinator. Using this program and battery boards, the hopping and healing capabilities of the network were tested. Several battery boards were configured as routers and joined to the network. One of the routers was taken to increasing distances from the coordinator until it was no longer reporting its name. Another router was placed half way in between the router that had lost communication and the coordinator. As soon as this was done, the lost router immediately rejoined. This demonstrated the network's ability to hop and to heal itself if it loses communication. These tests were performed indoors, outside, and in a greenhouse with the results being the same in all cases. This ability of devices to hop from one point to another and to rejoin the network after it has gone out of range was seen at every stage of testing, with every

program throughout the project. It can be assumed that despite some of its pitfalls, Z-stack does creates robust ZigBee networks.

4.2.2 Line-of-Sight Wireless Communication Testing

Using the same battery boards and program, some simple line of sight tests were performed. In the UT trial gardens, two devices successfully communicated at the maximum available test distance of 114m . In the greenhouse, the maximum distance was only 51m due to dense foliage. This was the maximum distance were reliable readings could be achieved. Past 51m, readings became intermittent and then ceased. Further testing was done using the packet sniffer provided with the CC2530 ZigBee Development Kit. The packet sniffer was a CC2531 on a USB dongle with a printed circuit antenna. It reported the signal strength of packets it was sniffing. Using these readings, numeric values were attached to the line of sight testing. Tests were run in three different locations; two outside locations and one indoor hallway. The results were a linear correlation that showed the further away a device was the weaker the signal (figure 22). There was a lot of noise in the data due to imperfect testing conditions. However, the monitoring system will be implemented in imperfect testing conditions. Since signal strength is dependent on many unpredictable outside factors, it would be wise to not push the monitoring system to maximum distances.

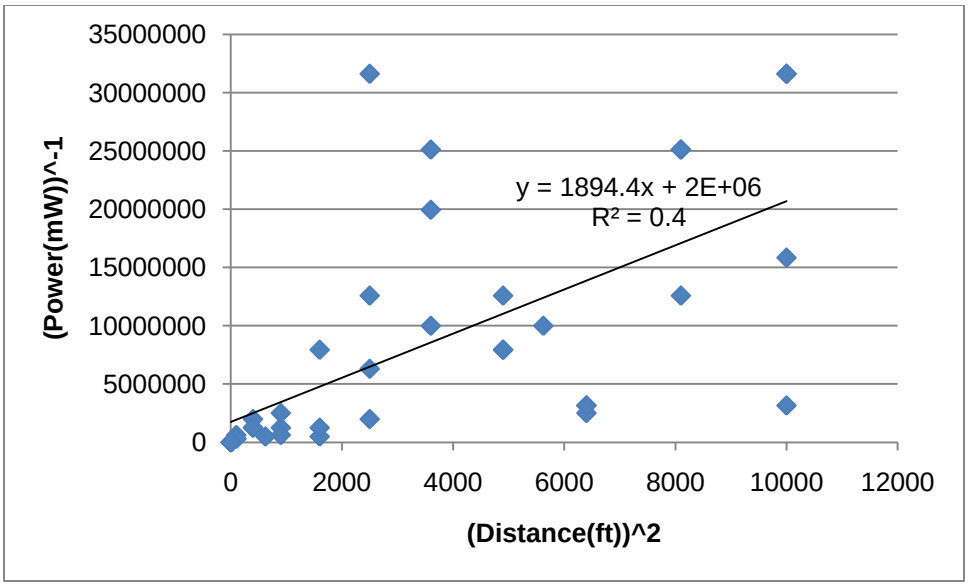


Figure 19: Line-of-sight signal strength testing based on distance between routers.

4.3 System Testing

After testing all of the individual components of the data acquisition system, the system was tested as a whole to see if all of the sub-components worked together. This was done by allowing the system to run over night in the lab. After the system was shown to be working in the lab a two day test in a greenhouse at the University of Tennessee, East Tennessee AgResearch and Education Center's Plant Sciences Unit and a one day test at a commercial greenhouse in Nashville were successfully conducted. Minor adjustments were made to the operating program after each test. The greenhouse at the plant science farm was small so no routers were required. For the commercial greenhouse, two end devices were reconfigured as routers to achieve the desired distances for sensing. With only a single router in place the system was capable of receiving data from sensor stations over 91m from the coordinator.

5 Results and Discussion

During field tests at the plant science greenhouse, eight sensor stations were setup in a network with a coordinator and left to run for two days. The sensor stations were placed on different tables with strawberry plants at varying levels of maturity. The strawberry greenhouse was a Quonset style house covered with plastic. Data from four of the sensor stations were graphed (figures 22, 23, and 24).

There were clear variations between sensor stations in temperature and humidity (figures 23 and 24). The light data was noisy to the point of not being useful (figure 25). Further investigation of the data acquisition revealed a memory overflow error on a signed integer. Potential reasons for noisy data could be from attempt to correct the overflow error, influence of the light pipe on spectral attenuation, or the light in the greenhouse is actually that variable.

All sensor station readings can be seen to stabilize and come into agreement each night with temperature and light falling and relative humidity rising.

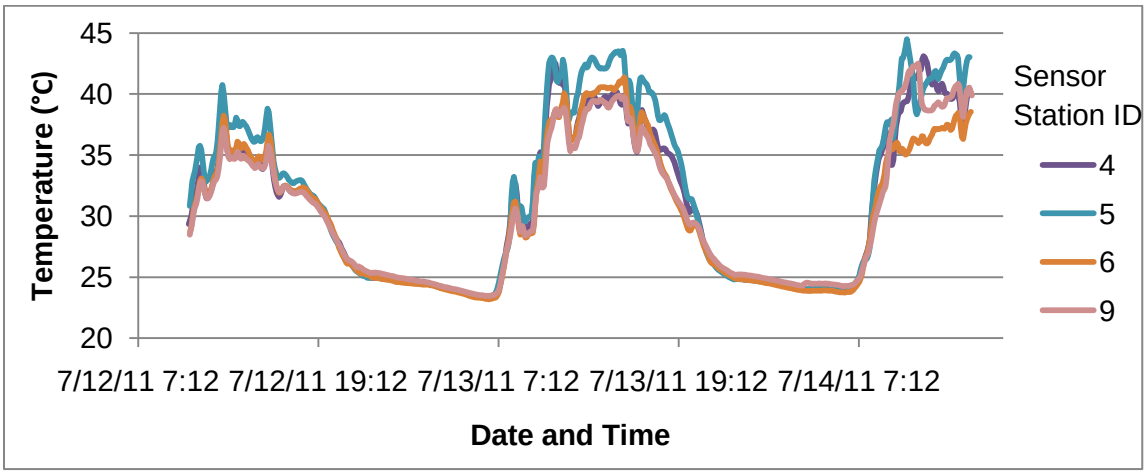


Figure 202: Illustrates the spatial and temporal temperature variability within a production

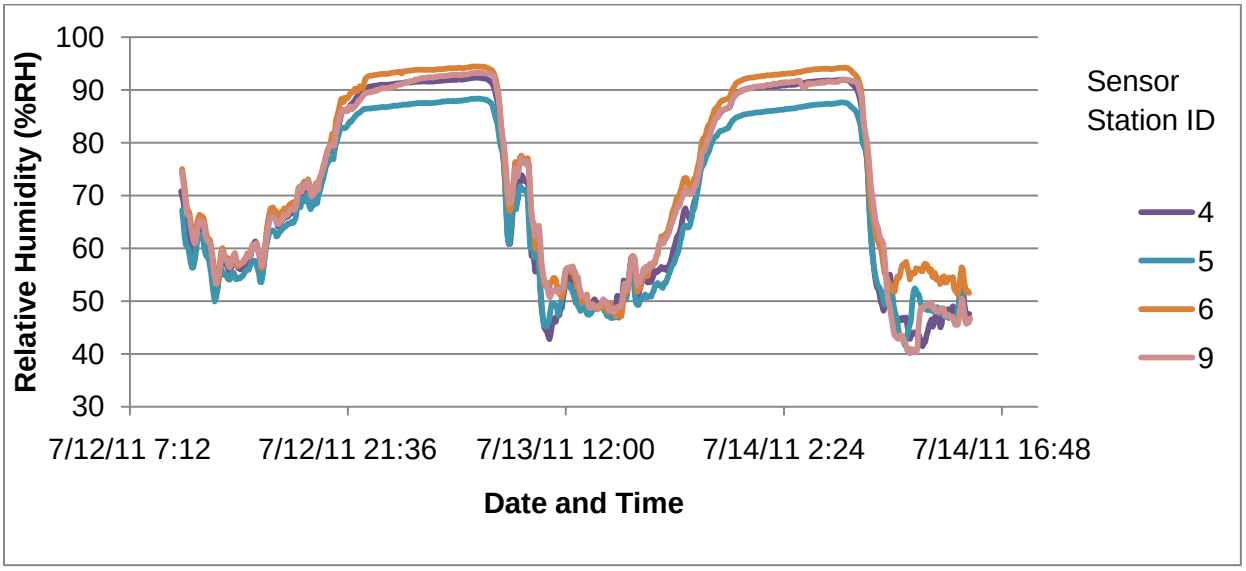


Figure 213: Relative humidity data for the same time period as noted in figure 22.

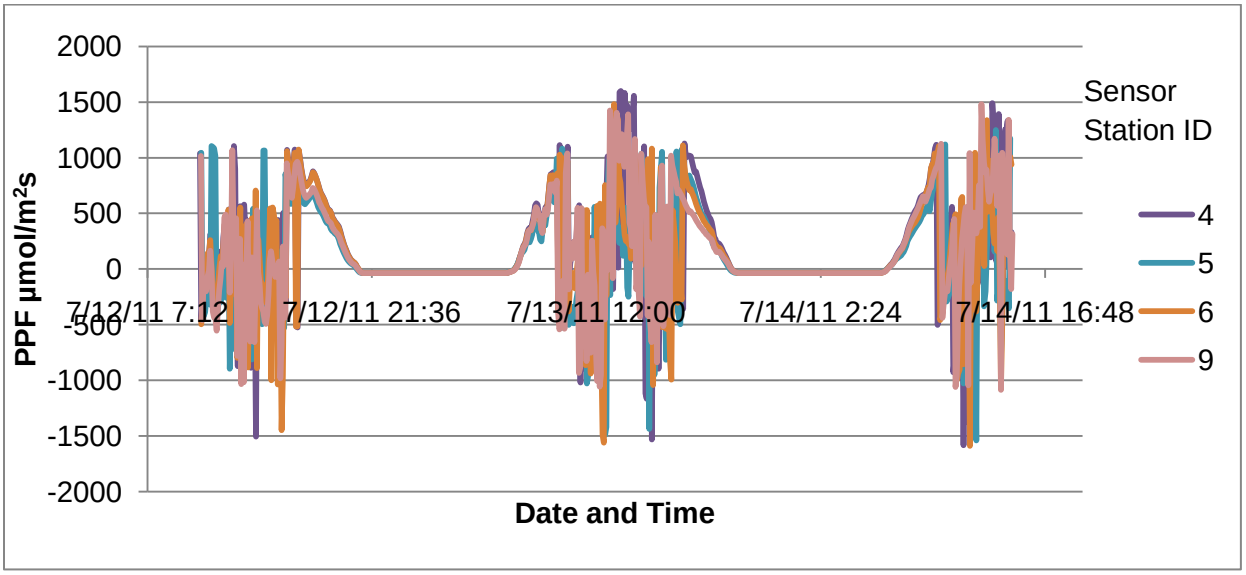


Figure 224: Natural light measurements collected in the greenhouse (note: the light readings are in error due to a programming error resulting from a memory overflow error).

Data from the commercial greenhouse is graphed in figures 25, 26, and 27. The commercial greenhouse was a glass greenhouse divided into eleven ranges with shade clothes drawn on the day of testing. The tests took place over ranges 6 and 7 which were in the middle of the greenhouse. For the first hour and a half of data capture, sensor stations were being moved around in the two ranges, and that data is therefore not shown. The final setup of the monitoring system had one sensor station configured as a router in each range and three end devices each placed past the routers and beyond the range of the coordinator. Sensor station 9 was configured as a router and placed approximately 51m from the coordinator in Range 7. Sensor stations 1, 2, and 3 were also placed in Range 7, and extended the communication range for the system to the end of the range, a distance of nearly 76m. Sensor station 8 was also configured as a router and placed in Range 6 with sensor stations 4, 5, and 6 placed in the same range. Sensor station 7 was malfunctioning and was not used. The issues with sensor station 7 have since been resolved. After the sensor stations were settled in their various locations, they observed clear environmental differences. Based on the results of sensor testing in an environmental chamber, it is safe to assume that the observed differences were true variations in the environment and not caused by differences in the sensors themselves. It is particularly interesting to note the temperature and humidity readings of sensor stations 4 and 9. These two sensor stations had the largest discrepancies for temperature and humidity readings of any of the sensor stations. They were in two separate ranges within the same house and were placed on tables with different crops. Sensor station 4 was on a table with larger, more vegetative plants and consequently registered a lower temperature and higher relative humidity (figure 28). Sensor station 9 was in a more open environment on a table with much smaller plants. It registered higher temperatures and lower relative humidity (figure 29). Light readings for the commercial greenhouse field test were more stable but still subject to the same problems

as the light data from the plant science farm field test. The programming issue that caused the initial problem has since been fixed.

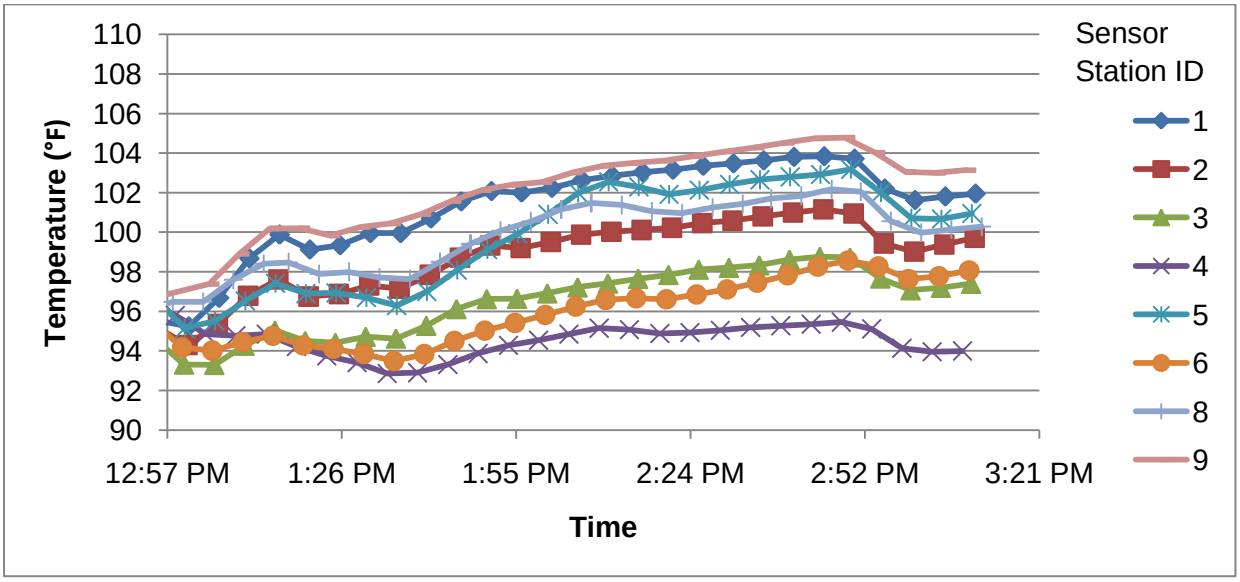


Figure 25: Example of the spatial and temporal relative humidity variability in a commercial greenhouse.

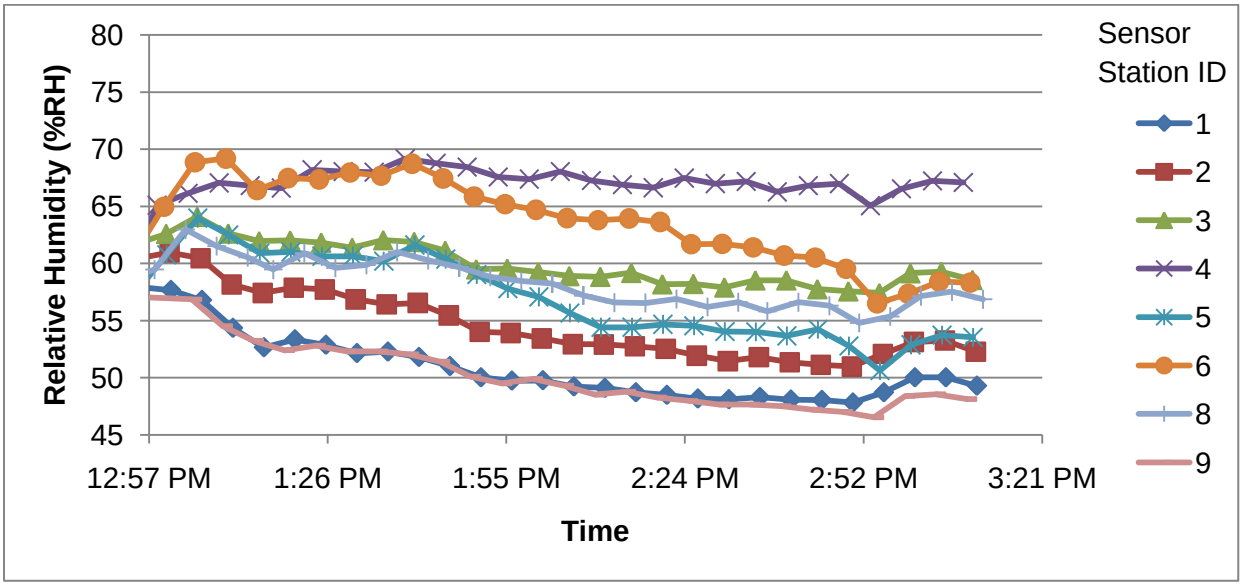


Figure 236: Sample of light data obtained in a commercial greenhouse.

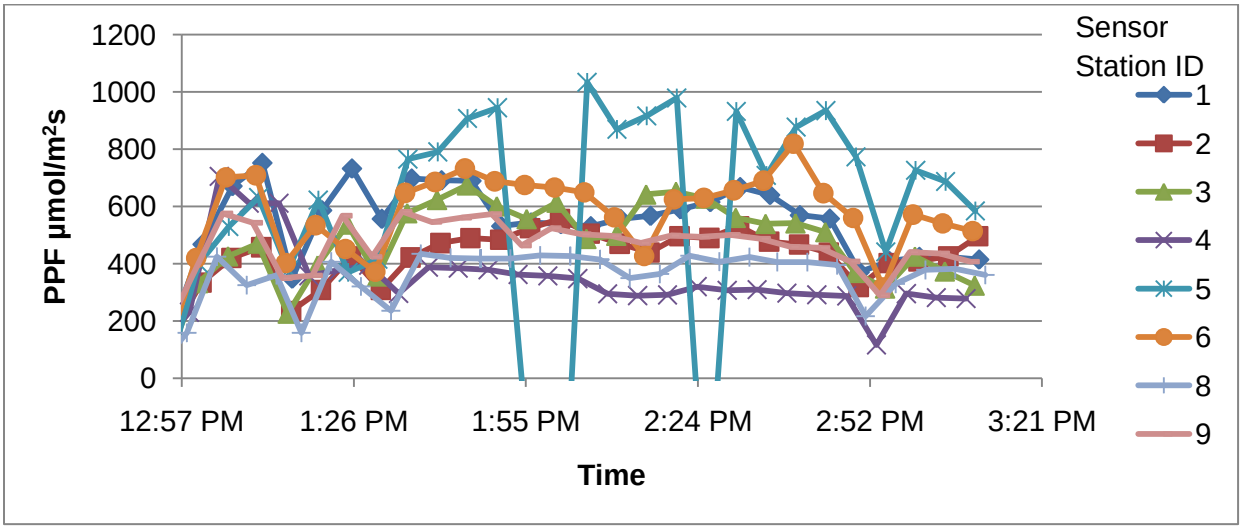


Figure 247: Commercial greenhouse light data

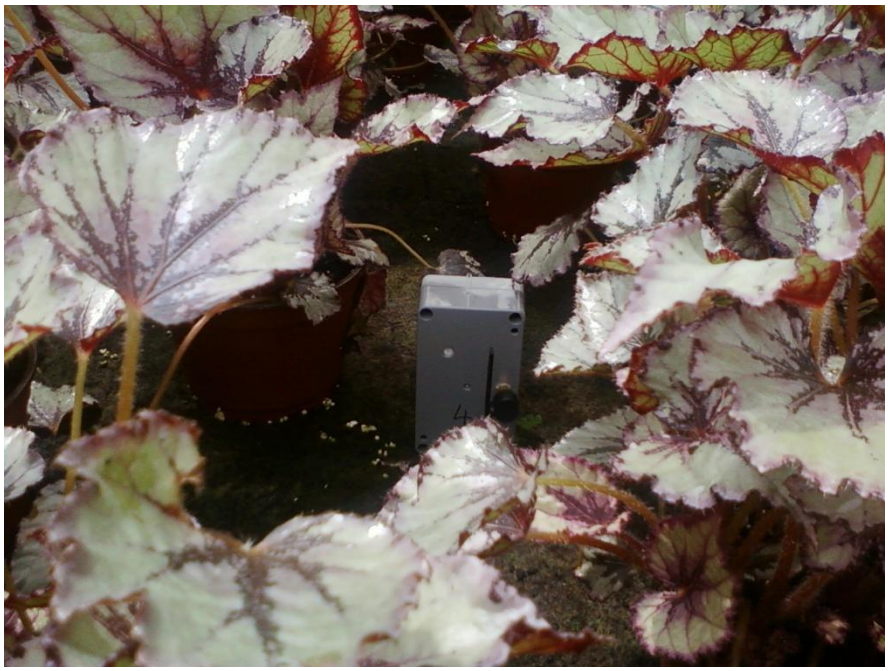


Figure 258: Photograph of sensor station #4 during a commercial greenhouse system evaluation.



Figure29: Sensor station #9 located in a commercial greenhouse

6 Conclusion and Recommendations

The monitoring system designed for this project was able to bring all the individual components of sensors, programming, and wireless communication together to work as a cohesive system. In addition, the system was able to detect significant differences in environmental conditions spatially within a greenhouse. This ability to detect spatial variations demonstrates the benefit to greenhouse management that a system of several sensors placed at the plant canopy can have over one or two centrally located sensors. It also demonstrates that, fully implemented, the system should be able to meet the project goal of collecting data at a high spatial and temporal resolution to determine if there is a correlation between specific environmental conditions and the outbreak of *Corynespora cassiicola*.

While the monitoring system performed adequately enough to meet the design goals for a prototype, proof of concept system, there are still many things that can be improved in later versions.

- The sensor stations' ability to join the network could be improved by having sensor stations check for prior joins before terminating the joining process
- The overall program could be improved to make data analysis quicker and easier (e.g. an improved graphical user interface).
- Enclosures for the routers and coordinator need to be optimized for production
- Further studies are needed on the light sensor to determine if the sensor has adequate accuracy for use in the creation of disease prediction models
- Improve the user interface to make the system more appealing to a commercial market

Overall, the monitoring system has demonstrated the feasibility of creating a low power, greenhouse monitoring system consisting of several wireless devises. Similar monitoring systems could have applications in agriculture that reach far beyond predicting disease in greenhouse crops. As the radio and MCU technology continue to improve, this will allow users to create wireless networks that are smaller and cheaper. Before these types of systems can find wide acceptance within agriculture, the developing environments will need to be made simpler and more robust. If development can be simplified so that any engineer can understand and use the wireless technology, then wireless monitoring systems will become a valuable tool in the spatial management of greenhouse and conventional cropping systems.

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Appendix

Comments and Recommendations

Although the idea of an easy ZigBee programming environment was initially appealing, Z-stack and the CC2530 proved to have many problems. There are over 37 documents associated with Z-stack and the CC2530 that range from a few pages to 260 pages in length. These documents and the Z-stack program itself are still being updated, often without any notification to the end user. This array of documents is difficult to navigate and seems to be incomplete from the perspective of new user. It is not always clear where to find needed information. Important details often can only be found by reading the code itself. TI gives users the freedom to change anything within the Z-stack, but it is not always clear when one piece of code interacts with another, causing end users to make seemingly benign changes that in effect crash the whole program. The method in which they have asked users to splice in their own code also makes it difficult to save different iterations of programs without having to reformat the entire workspace. Added to these difficulties, Texas Instruments has, unfortunately, proven themselves to be either unwilling or unable to assist end users in understanding the product and adjusting it to use in non-TI projects. Despite the many difficulties encountered, once the user has a basic grasp on how to make the whole system work, the CC2530 along with Z-stack does deliver on its promise of quick implementation of a low power ZigBee network.

There were many errors in the first few attempts at programming the I2C subroutines. Some examples of things that had to be corrected are incorrect start conditions and extra clock cycles. Once the I2C program had been well tested, there was not much trouble in following the corresponding data sheets to write the code for the different sensor and add that code to the HAL.

It was recently discovered that the five minute totals of sensors readings were being saved into a variable that was too small to store them. This caused the larger sums to wrap back around and give erroneous readings. Since it was not an issue with smaller sums it did not show up in bench top testing where the lab is dim, cool, and dry, but in the environmental chamber the error became clear(figure 15). Obviously, it never reached 500°C in the environmental chamber. In fact, during the time that the sensor stations where showing 500°C the chamber temperature sensor was reading 26.6°C. Once the sensor stations reached a certain temperature, the five minute total was too large and caused the variable to overflow. Since every sensor station was showing the same error, it was clear that this was a programming issue. This issue has now been corrected by storing the totals in a larger variable. Even though the program appears to be working, new programming errors will surely surface over time.

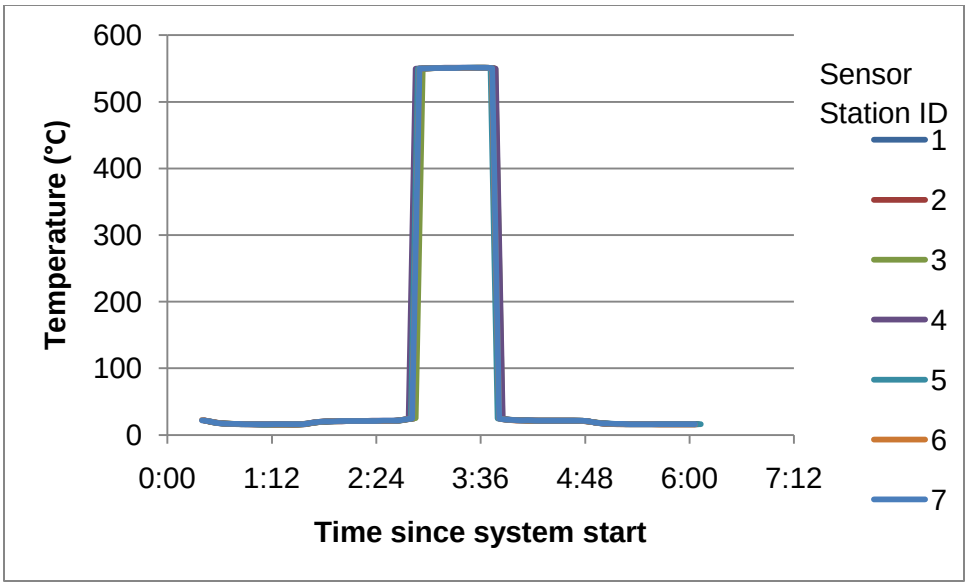


Figure 30: Graph of environmental chamber data with programming error

The data from the temperature test was taken before the error with numbers over flowing was found and corrected (figure 15). The data at the highest temperature level therefore had to be converted back to the correct readings.

Vita

Crystal Kelly was born on April 7th, 1986 in Louisville, Kentucky. She was raised in Chattanooga, Tennessee were she attended Harrison Elementary School, Brown Middle School, and The Baylor School. In August of 2004 she began attending the University of Tennessee at Knoxville. While at UTK, she was involved in many different activities including the engineering honor society, Tau Beta Pi, and serving as president of the College of Engineering Ambassadors. Crystal was also fortunate enough to spend five semesters throughout her undergraduate career as a co-op student at the NASA Kennedy Space Center in Florida. She graduated magna cum laude in May of 2009 with a Bachelor's degree in Biosystems Engineering and a Minor in Mathematics. She began pursuing a Master's of Science degree in Biosystems Engineering in August of 2009. Her first year in graduate school she received the J. Wallace and Katie Dean Fellowship award. In her second year, she was inducted into the honor society of agriculture, Gamma Sigma Delta, and served as the colleges graduate student representative on the University of Tennessee Institute of Agriculture advisory board.