Automated Wireless Greenhouse Management System

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ABSTRACT

Increases in greenhouse sizes have forced the growers to increase measurement points for tracking changes in the environment, thus enabling energy saving and more accurate adjustments. However, increases in measurement points mean increases in installation and maintenance cost. Not to mention, once the measurement points have been built and installed, they can be tedious to relocate in the future. Therefore, the purpose of this Masters thesis is to present a novel project called "Automated Wireless Greenhouse Climate Management System" which is capable of intelligently monitoring and controlling the greenhouse climate conditions in a preprogrammed manner.

The proposed system consists of three stations: Sensor Station, Coordinator Station, and Central Station. To allow for better monitoring of the climate condition in the greenhouse, the sensor station is equipped with several sensor elements such as CO_2, Temperature, humidity, light, soil moisture and soil temperature. The communication between the sensor station and the coordinator station is achieved via ZigBee wireless modules and the communication between coordinator station and the central station is achieved via long range RF modems.

An important aspect of designing a wireless network is the reliability of data transmission. Therefore, it is important to ensure that the developed system will not lose packets during transmission. An experiment was carried out in one of the greenhouses at Plant and Food Research Ltd, New Zealand in order to determine the functionality and reliability of the designed wireless sensor network using ZigBee wireless technology. The Experiment result indicates that ZigBee modules can be used as one solution to lower the installation cost, increase flexibility and reliability and create a greenhouse management system that is only based on wireless nodes.

The overall system architecture shows advantages in cost, size, power, flexibility and distributed intelligent. It is believed that the outcomes of the project will provide the opportunity for further research and development of a low cost automated wireless greenhouse management system for commercial use.

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1. Introduction

1.1 Greenhouse History

Crop cultivation has been around for a longtime. It plays a crucial role in the continuous development of human civilization. Tradition crop cultivation requires a tremendous amount of hard work and attention and there are several disadvantages in implementing traditional cultivation techniques:

- Weather dependent factors: plants' growth and development are primarily governed by the weather conditions.
- Pests and diseases: plants growing under traditional cultivation technique are significantly affected by pests and diseases.

It was discovered that there are indications that already many thousands years ago civilizations in countries such as China, Egypt and India employed means of protection against cold, wind and excessive solar radiation [1]. These methods of protection were employed only to provide a short-term protection for plants against harsh climate conditions. However, no further development occurred until the late 15th century and early 16th century, when European explorers brought back exotic plants acquired in the course of their travels. Many were tropical plants that could not endure the cold European climates. The result was the creation of greenhouses and these early greenhouses were originally referred to as "*giardini botanic*" also known as "botanical gardens" [2].

1.2 Project Statements and Objectives

A greenhouse allows the growers to produce plants in places where the climate would otherwise be unfeasible for the growing of plants. The production of crop plants is independent of the geographic location and the time of the year. The greenhouse also provides shelter for the plants, protects them from harsh weather conditions, insects and diseases. It allows the plants to grow under optimum conditions, which maximizes the growth potential of the plants. The quality and productivity of crop plants is highly dependent on the management quality and a good management scheme is defined by the quality of the information gathered from the greenhouse environment.

The greenhouse system is a complex system. Any significant changes in one climate parameter could have an adverse effect on another climate parameter as well as the development process of the plants. Therefore, continuous monitoring and control of these climate factors will allow for maximum crop yield. Temperature, humidity, light intensity and CO_2 are the four most common climate variables that most growers generally pay attention to. However, looking at these four climate variables will not give the growers the full picture of the operation of the greenhouse system. Previous research [3] has used sensors such as leaf temperature and leaf wetness sensor in conjunction with ambient temperature sensor and humidity sensors to investigate the greenhouse's status. These methods were found to be impractical as the wetness of plant leaves varies from one leaf to another and by the location of the plant in the greenhouse. Not to mention, several different types of plants are usually grown in the same greenhouse and different plants have different leaf textures as well as surface geometry. These factors would greatly affect the distribution of water on the leaf surfaces resulting in inaccurate observations.

In general, the greenhouse system can be divided into two main components that interact in a more or less strong way: internal atmosphere and soil conditions. The behavior of the greenhouse system is highly dependent on these interactions. Most growers and researchers are more interested in the internal atmosphere of the greenhouse and often overlook the importance of soil conditions. According to Kirkham [4] the absorption and transportation of water and nutrients are dependent on the condition of the soil. Therefore, it is essential to maintain the temperature and the moisture level in the soil at an optimum level in order to keep the plant healthy.

Greenhouses have a very extensive surface where the climate conditions can vary at different points. It is very common to install only one sensor in a fixed point of the greenhouse as representative of the main dynamics of the system. One of reasons behind this is that typical greenhouse installations require a large amount of wires and cables to distribute sensors and actuators. Therefore the system becomes complex and expensive and the addition of new sensors or actuators at different points in the greenhouse is thus quite limited. Not to mention, modern greenhouses are typically big, therefore measurement point increases are unavoidable. As a result, a dramatic increase in installation cost is almost certain. Wireless Sensor Network (WSN) is becoming the solution to many existing problems in modern day industries. WSN can operate in a wide range of environments and provide advantages in cost, size, power, flexibility and distributed intelligence. Thanks to rapid growth in the wireless communication industry, many wireless technologies are now available on the market for both personal and industrial uses. Among these emerging wireless technologies ZigBee was reported as one of the most exploited wireless technologies in modern day industries [5]. ZigBee wireless technology is capable of providing large scale low power networks and devices that could run for years on inexpensive batteries. Not to mention its low cost and low network complexity characteristics making it ideal for many agriculture applications such as greenhouse climate monitoring.

Early control systems were as simple as closing and opening windows or turning on/off valves to control heating and irrigation. These systems often consisted of several electrical devices such as thermostats and timers and are often referred to as "*Time-driven*" controllers. However, time-driven control methods cannot deliver the level of automation and efficiency required in today's dynamic greenhouse environment [6]. As the operation cost increases, the level of complexity of greenhouse management also increases. This will ultimately affect the demand for monitoring and control capability. Thanks to the computer revolution in the eighties, an opportunity was created to meet the need for improved control [7]. Consequently there have been dramatic improvements in control technology as well control methodology. In the modern day, computerized controllers are becoming increasingly commonplace, particularly for distributed real-time sensing and control. Therefore the objective of this novel project is to design and develop a ZigBee-based wireless greenhouse management system that is capable of intelligently monitoring and controlling the greenhouse climate environment in a preprogrammed manner. The main advantages of the proposed design in comparison with previous works are:

- It has the ability to monitor six different greenhouse climate parameters (temperature, relative humidity, light intensity, CO_2, soil moisture and soil temperature).

- The system does not need cables to run and has lower power consumption.
- It comprises embedded wireless sensor nodes that can be used to collect real-time environmental data.
- It allows communication between the central station and actuators that are located in different parts of the greenhouse.
- Moreover, the system is easy to relocate once installed and maintenance is relatively cheap and easy. The only additional cost occurs when the batteries run out.

1.3 Outline of the thesis

The structure of the report is arranged as follows:

- Chapter 2 provides essential background information on the greenhouse climate factors and their influences on the development process of the plant. This section also briefly discusses some of the related researches on the application of wireless sensor network (WSN) in greenhouse climate monitoring. A general overview on some of the existing commercial systems that can be used to monitor the greenhouse climate is also discussed in this section.
- Chapter 3 is devoted to a review of a range of commercially available sensor technologies that could be used for this particular research and addresses their merits and demerits. This chapter also explains the experimental methods used to determine the accuracy and reliability of the selected sensors. Experimental results are also discussed in this chapter.
- Chapter 4 briefly introduces some of the existing wireless technologies. The experimental method used to test the reliability and feasibility of ZigBee is also explained in detail in this chapter.
- Chapter 5 explains and describes the hardware and software design of the proposed system. Problems and challenges encountered, and design choices are also explained in this chapter.

- Chapter 6 explains the software design and implementation of the proposed controller. This chapter also explains the proposed experiment method used to determine the reliability and capability of the proposed controller.
- Chapter 7 presents the experimental setup and procedures for testing the feasibility and reliability of the proposed system.
- Chapter 8 summarizes the contributions made and the results achieved. Future work is also briefly discussed in this chapter.

2. Literature Review and Market Survey

2.1 Literature Review

2.1.1 Environmental Factors and Plant Growth

2.1.1.1 Introduction

As a plant grows, it undergoes many developmental changes, including formation of tissues and organs such as leaves, stem, flowers and roots. The main source of nutrients used to aid this development process is often found in its surroundings. In other words, the development of a plant is solely dependent on the conditions of the environment in which plants are grown. The environment consists of many different factors including light, ambient temperature, soil temperature, humidity, soil moisture, and CO_2. These climate factors play an important role in the quality and productivity of plant growth. Either directly or indirectly, most plant problems are caused by environmental stress. In some cases, poor environmental conditions can either damage a plant directly or indirectly. In other cases, environmental stress could weaken the plant and strip off its immunity and protection against diseases and harsh weather conditions. A good understanding of these climate factors allows the grower to be more aware of any potential problems that may affect the development of the plants and appropriate actions can be drawn to prevent these problems from happening

2.1.1.2 Temperature Effects

Temperature influences most plant development process including photosynthesis, transpiration, absorption, respiration and flowering [8]. In general, growth is promoted when the temperature rise and inhibited when temperature falls. The growth rate of a plant will not continue to increase with the increasing of temperature. Each species of plant has a different temperature range in which they can grow. Below this range, processes necessary for life stop, ice forms within the tissue, tying up water necessary for life processes. Above this range, enzymes become inactive and again processes essential for life stop [9]. Therefore the temperature should be maintained at optimum level whenever possible.

2.1.1.3 Humidity Effects

Humidity is important to plants because it partly controls the moisture loss from the plant [1]. The leaves of plants have tiny pores, CO_2 enters the plants through these pores, and oxygen and water leave through them. Transpiration rates decrease proportionally to the amount of humidity in the air. This is because water diffuses from areas of higher concentration to areas of lower concentration [10]. Due to this phenomenon, plants growing in a dry room will most likely lose its moisture overtime. The damage can be even more severe when the difference in humidity is large. Plants stressed in this way frequently shed flower buds or flowers die soon after opening [11]. High humidity can also affect the development of plant. Under very humid environments, fungal diseases most likely to spread, on top of that air becomes saturated with water vapor which ultimately restricts transpiration. At time of reduced respiration, the water uptake is low, and therefore transport of nutrients from roots to shoots is also restricted. Plants are exposed to high humid environment for a long period of time and may suffer deficiencies.

2.1.1.4 Light Effects

All things need energy to grow, human and animals get energy from food. Plants, on the other hand, get energy from sun light through a process called photosynthesis [12]. This is how light affects the growth of a plant. Without light, a plant would not be able to produce the energy it needs to grow. Aside from it's effect through photosynthesis, light influences the growth of individual organs or of the entire plant in less direct ways. The most striking effect can be seen between a plant grown in normal light and the same kind of plant grown in total darkness. The plant grown in the dark will have a tall and spindling stem, small leaves, and both leaves and stem, lacking chlorophyll, are pale yellow [12]. Plants grown in shade instead of darkness show a different response. Moderate shading tends to reduce transpiration more than it does photosynthesis [10]. Hence, shaded plants may be taller and have larger leaves because the water supply within the growing tissues is better. With heavier shading, photosynthesis is reduced to an even greater degree and, weak plants result [10].

2.1.1.5 Carbon Dioxide (CO_2) Effects

Carbon dioxide (CO_2), according to its chemical structure is a natural gas, which is very dangerous to humans in high concentrations, but a lifeline for trees and plants. It comprises 40-50% of the dry matter of a living organism [13]. The air consists of nitrogen, oxygen and carbon dioxide. Air, on average, contain slightly more than 0.03 (300ppm) percent of CO_2 [9]. As the result of climatic changes, the concentration of CO_2 in today's environment is slightly higher (varies between 350~400ppm).

Plants acquire energy from light through a process called photosynthesis [12]. This process involves the absorption of energy from sunlight and uses it in conjunction with CO_2 and water to produce sugar and other organic compounds, such as lipids and proteins. The sugars are then used to provide energy for the plant. The carbohydrates are transferred to various parts of the plant and transformed into other compounds need for the growth and maintenance of the plant. This conversion process is in the following equation [9].

$$CO_2 + \mathit{Water} + \mathit{Energy\ from\ sunlight} \rightarrow \mathit{Carbohydrate} + \mathit{Oxygen}$$

As high CO_2 enhances photosynthesis, it generally improves both production and quality. However the effect of CO_2 may not always be an increase in quality and yield. Yield can be increased at the expense of quality. The response can shorten the period between planting and production, with plants become bigger and more bulky, faster seedling germination and growth, or faster maturation of the flowers [14]. These effects may not always be desirable, especially if quality is the main goal. Therefore CO_2 should always be maintained at an optimum level whenever possible

2.1.1.6 Soil Moisture

Water is taken by the root system and lost through transpiring leaves. Evaporation from the leaves is the driving force for transfer of water across the plant and only a small proportion of the uptake water is used for growth. It was calculated that the water lost per day by transpiration from some plants is equal to twice the weight of the plant [15]. The rate of water lost depends on the condition of soil, air flow, relative humidity in air and the temperature of the environment. Loss of water from the soil by means of drainage is quite common during the dry season. When absorption of water by the roots fails to keep up with the rate of transpiration, loss of turgor occurs, and the stomata close [9]. This immediately reduces the rate of transpiration as well as photosynthesis. If the loss of turgor extends to the rest of the leaf and stem, the plant will eventually wilt. In more extreme cases burns may begin on the margin of leaves and spread inward affecting whole leaves

While necessary to point out the importance of having soils well moistened, it is also important for the growers to be aware of the effects of overly moist soil on the development of plants. If the soil is flooded with water, the oxygen content of the plant's root substrate is reduced by the higher average water content in the pores, resulting in damage to the roots [9]. A plant with damaged roots cannot extract water and essential nutrients from soil properly and will eventually wilt and die in a short of period of time. Therefore, water is needed to be supplied to the plants often enough so that there is a sufficient amount for plants at all time, but not so often that the air is limited in the soil.

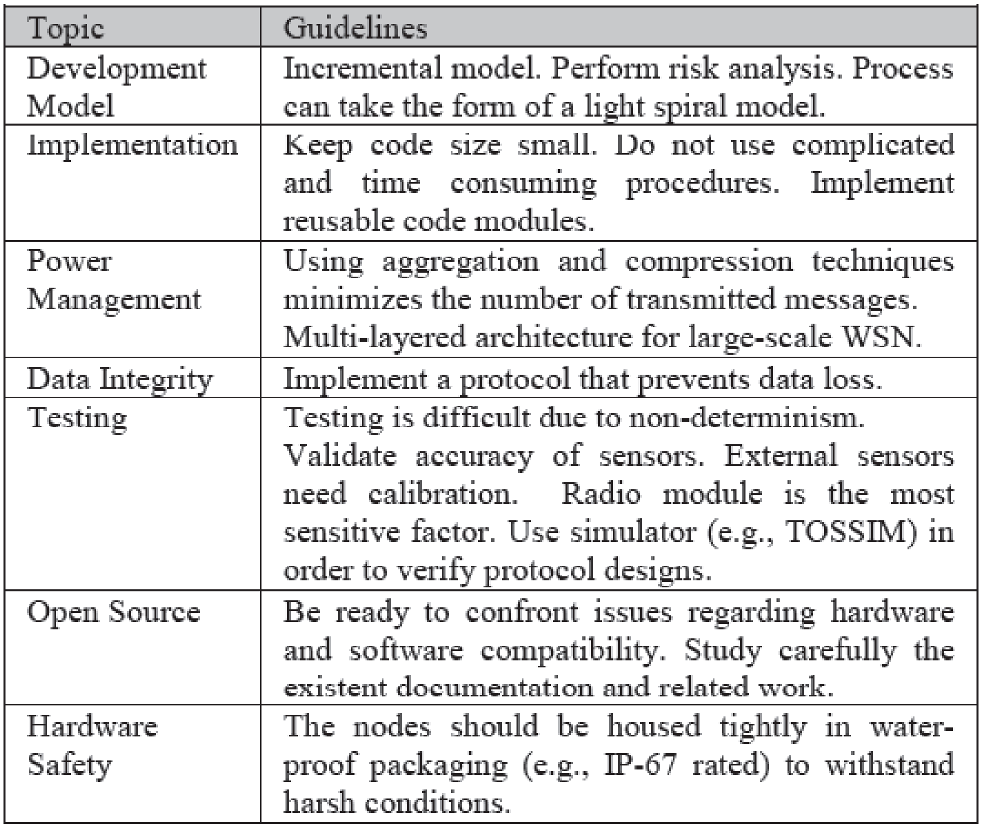
2.1.1.7 Conclusions

The environment which plants are grown in is the driving force behind the development of plants. The environments consist of many different factors that affect the developmental process of plants in a more or less strong way. Not only that various environment factors are interrelated and they cannot be considered singly without regard to the effect on the others, as well as the total effect on the plant. Some of these relationships are obscure, others are clear but all are easily overlooked. Therefore a good understanding of the effects of these climate factors and their relationships will allow for prevention and early detection of any potential problems.

2.1.2 Wireless Sensor Network (WSN) In Environmental monitoring

With the continuous development of modern day industries and the continuous progress of human society, the needs of people for a better living environment has greatly increased. Many sophisticated environmental monitoring systems were developed over the last decades. However these systems have mostly been wire connected and this limits the use and implementation of these systems because of their high expense in installation and maintenance. Thanks to the rapidly growth in wireless communication industry, a large number of projects regarding wireless environmental monitoring are running or successfully completed all over the world [16]. One such effort was an application of wireless sensor network (WSN) in an extremely dangerous and hostile environment of the Tungurahua volcano [17], where scientists have successfully deployed a WSN to monitor the volcanic eruptions using a series of low-frequency acoustic sensors. Another study was carried out by Meijuan *et al.* [18]. They proposed a wireless mesh network for atmospheric environmental monitoring. Their developed system network was proven to have a strong self healing capability and network robustness (any data collection node can be added to or replaced from the system network at any moment in time without having any effects or influences on the system network itself).

Although some aspects in wireless sensor networks may be generic, it is important to carefully consider the specific requirements of the application, especially when it is as demanding as environmental monitoring. Giannopoulos *et al.* [19] proposed a number of guidelines and techniques for implementing a WSN for environmental monitoring. They also discussed how certain parameters have been selected for maximizing network reliability and lifespan and how certain issues have been confronted such as network synchronization and data consistency. Table 2-1 summarizes their design guidelines for building a WSN for environmental monitoring.



Topic	Guidelines
Development Model	Incremental model. Perform risk analysis. Process can take the form of a light spiral model.
Implementation	Keep code size small. Do not use complicated and time consuming procedures. Implement reusable code modules.
Power Management	Using aggregation and compression techniques minimizes the number of transmitted messages. Multi-layered architecture for large-scale WSN.
Data Integrity	Implement a protocol that prevents data loss.
Testing	Testing is difficult due to non-determinism. Validate accuracy of sensors. External sensors need calibration. Radio module is the most sensitive factor. Use simulator (e.g., TOSSIM) in order to verify protocol designs.
Open Source	Be ready to confront issues regarding hardware and software compatibility. Study carefully the existent documentation and related work.
Hardware Safety	The nodes should be housed tightly in water-proof packaging (e.g., IP-67 rated) to withstand harsh conditions.

Table 2-1: Design guidelines for building a WSN for environmental monitoring [19]

2.1.3 Wireless Sensor Network (WSN) in Greenhouse management

In recent years, environmental monitoring using wireless sensors technology has become more important. Especially in the agriculture industry, because wireless sensor technology is very suitable for distributed data collecting and monitoring in tough environments [20]. A recent survey [21] of the advances in WSN applications has reviewed a wide range of applications for WSN and identified the agriculture industry as a potential area of deployment, together with a review of the factors influencing the design of sensor networks for this application. Intel Corp was found as one of the main players in the early implementation of wireless sensor networks in the agriculture industry[22]. They conducted a trial installation of 18 temperature sensor nodes for a period of several weeks in an Oregon vineyard. The aim of this experiment was to monitor the temperatures during the winter nights and to determine the time to pick the grapes.

Research and implementation of WSN in greenhouses climate management was carried out all over the world over the last few years. One of such applications was the use of a web-based WSN platform for greenhouse climate monitoring and control. Qiang *et al*. [23] developed a web-based monitoring and control WSN platform for greenhouse climate monitoring. The system consists of 3 nodes; sink node, wireless sensor node and wireless control node. The wireless sensor node's main job is to collect greenhouse climate information. The task of the sink node is to analyze and process the information received from each sensor. The responsibility of the control node is to control the climate inside the greenhouse based on the collected greenhouse data. A similar study was carried out by the Rinnovando group [24]. Their research was carried out in a tomato greenhouse in the South of Italy. The Rinnovando group developed a web-based WSN for greenhouse monitoring that allows the users to keep track of any changes in the greenhouse climate over the internet. The system is also utilized Short Message Service (SMS) to allow the system itself to directly alert the user on any abnormal changes in the greenhouse environment through an exchange of a simple short text message. Another study on greenhouse climate management system based on WSN was carried out at Sunchon National University in South Korea [25]. The system consists of sink nodes, a database server computer and actuator nodes. The sink nodes are responsible for collecting environmental data and sending the collected data to a local database server. The actuator nodes act according to the information extracted from the collected environmental data. This research also focused on examining the correlation between variation of condition of leaf and the incidence of harmful insects.

Teemu *et al*. [26] suggested a different approach for implementing WSN in a greenhouse environment by making use of a commercial wireless sensing platform provided by Sensinode Inc. The hardware design of the system consists of Sensinode's Micro.2420 U100 operates as a basic measuring node, with four commercial sensors (humidity, temperature, light and CO_2). The idea behind this development is to test the reliability and feasibility of a prototype wireless environment monitoring system in a commercial greenhouse. The experimental result shows that the network can detect local differences in the greenhouse climate caused by various disturbances in the environment.

In line with the rapid development in the telecommunication industry, many research projects have fully utilized Global System for Mobile Communication (GSM) and Short Message Service (SMS) to relay collected data from the greenhouse environment to computers or directly alert the operator through their mobile phone. Spring 2007, Hui *et al* [20] discussed SMS as an effective and economical solution of communication protocol in their developed WSN for greenhouse climate monitoring . Their work is later followed by Othman *et al.* [3] late July 2009. They proposed a preliminary infrastructure development of a greenhouse WSN that allows for continuous data monitoring of carbon dioxide and oxygen level in environments in remote areas. The system adopts the Wireless Radio Frequency (WRF) method which allows the user to receive report messages from the greenhouse via GSM.

2.1.4 ZigBee Wireless technology applications

Thanks to the continuous development in wireless communication industry, many wireless technologies have emerged and are now available on the market for both personal and industrial uses. ZigBee is one of these emerging wireless technologies. ZigBee wireless technology is capable of providing large scale low power wireless networks and devices that could run for years on inexpensive batteries. Not to mention, it’s low cost and low network complexity characteristics make ZigBee wireless technology ideal for almost any types of applications.

2.1.4.1 Industrial Control

There has been increasing interest in the ZigBee standard, in particular industrial controls. One such application was carried out by Jing Bian [27]. He proposed a system that can implement real-time monitoring and intelligent warning for the underground coal mine environment using ZigBee wireless technology to overcome the limitations of previous systems which are mainly reliant on wires and cables for data transmission.

Cao *et al*. [28] presented an application of ZigBee in wireless natural gas meter recording and transmission. Their system consists of gas meters, wireless sensor nodes, data collector, management centre and wireless communication networks. The data is transmitted from the sensor nodes to the data collector using ZigBee communication network. The system uses an Ethernet connection to transmit data from the data collector to the management centre.

Other research on ZigBee application for industrial controls was carried out by Sarkimaki *et al*.[29]. The purpose of their research was to determine the applicability of the ZigBee technology in electric motor rotor measurements. Requirements for data transmission and electrical structure were also discussed. A prototype wireless ZigBee-based torque sensor was built and tested. According to the experimental results, data transmission using ZigBee wireless technology has proven to be very reliable and it was concluded that ZigBee is indeed suitable for this kind of application.

2.1.4.2 Home Automation

An intelligent home automatic system will not only enable the residents to integrate home equipment via Web or telephone, but also achieve remote monitoring of home security systems, including anti-theft, anti-gas leak, fire and other functions. Anan *et al.* [30] discussed some key issues in the usage of Wi-Fi technology in home automation and how ZigBee wireless technology can be used to solve the problem and ensure the reliability of data transmission.

Yong *et al* [31] developed a smart digital door lock system for home automation using ZigBee wireless technology. In the proposed system, ZigBee is embedded in a digital door-lock unit, which acts as a central controller of the overall automation system. The door lock unit used in this system consists of an RFID reader for user authentication; touch LCD, motor module for opening and closing of doors and windows, sensor modules for detecting the condition inside the house, communication module, and main control module. The developed system enables the user to conveniently control and monitor home environment before entering or leaving the house. Furthermore, it also allows home owner to remotely monitor the condition inside the house through the internet or any other public networks [31]

2.1.4.3 Medical Care

Nowadays wireless health monitoring systems have been widely developed and implemented all around the world. They allow the users to effectively monitor their health status or their patients' health status. More and more wireless health monitoring systems and devices are still being developed by researchers all over the globe. One such study was carried out by Xi *et al.* [32] from Beijing Jiaotong University. Their developed system consists of a set of physiological sensors, ZigBee modules and a central controller. Physiological data collected by the sensors is transmitted to the central controller via ZigBee wireless network where the data is stored, analyzed and visually presented to the users.

Another study on ZigBee WSN application on medical and health care was also carried out by Karandeep Malhi [33]. The research took place in the School of Engineering at Massey University in New Zealand. She developed a wireless wearable non-invasive physiological monitoring device which allows for the detection of the body temperature and heart rate of a person. This type of device is extremely useful for elderly family members or those with medical conditions to call for help in times of distress.

2.1.4.4 Environmental monitoring

ZigBee wireless technology has became an important issue in environmental monitoring in recent years [34]. The relatively low cost, low power consumption and low network complexity factors allow for easy installation and implementation of a dense population of ZigBee wireless sensing nodes in almost any kind of environment. Zhiyong et al. [35] took advantage of ZigBee's features and proposed ZigBee based WSNs for environmental temperature monitoring to predict climate change in the environment. Another effort in applying ZigBee wireless technology in environmental monitoring was carried out by Zulhani *et al*. [36]. Realizing the critical condition of the polluted water resources in Malaysia, the Zulhani group proposed a ZigBee based environmental monitoring system that aims at monitoring the quality of natural water resources in Malaysia by using various ZigBee sensor nodes with a network capability that can be deployed for a continuous monitoring purpose.

2.2 Market Survey

2.2.1 Introduction

There are several systems available on the market that are capable of monitoring the climate conditions in the greenhouse. This section reviews 3 existing monitoring systems that can be used to monitor greenhouse climate.

2.2.2 Winland EnviroAlert

“Windland EnviroAlert” has the capability of monitoring up to four wired sensors and four wireless sensor sensors. Each sensing unit has its own designated relay output meaning that the user can have transmitters activate, dialers call or activate alarms when the programmed thresholds are exceeded. This system has a wireless range of 300 metres between the sensor units and base units, making it ideal for almost any type of monitoring applications.

The following are its main features [37]:

- Data logging - capture and download sensor readings, alarm and event history (has USB port for easy data retrieval)
- Simultaneous operation of eight sensors
- Easy to read large LCD display
- Auxiliary output relay for local audible alarm
- Auxiliary alarm silence feature with 10 minute timer
- Temperature & humidity Hi / Lo set points
- Output relays can be configured to be initially energized or de-energized
- Tamper proof password lock setting
- Snap fit mounting base with main housing for easy access
- Plug in terminal strip connectors for easier wire termination
- Current sensor readings are displayed on home screen
- Sensor configuration retained in memory if power is lost

Figure 2-1: Winland EnviroAlert

Following are the weaknesses that existed in the system:

- Sensing units are sold separately
- Is not specifically designed for greenhouse climate monitoring but general purpose environment monitoring only
- High power consumption
- Doesn’t support wireless mesh networking
- Has no climate control capability

2.2.3 Watchdog Wireless Crop Monitor

“WatchDog Wireless Crop Monitor” can be used in almost any kind of environmental monitoring applications that require constant temperature and humidity monitoring. It uses remote sensing units to measure and wirelessly transmit the temperature and humidity readings. The base unit can support up to a maximum of 16 sensing units and is capable of simultaneously operating and controlling all 16 sensing units anywhere within 300 metres range. However, if more than 16 sensing units are to be deployed within 300 metres of the base unit, additional monitoring unit is required. The base unit comes with a distress alarm and warning light that will activate when the programmed thresholds are exceeded.

Figure 2-2: WatchDog Wireless Crop Monitor

The following are its main features [38]:

- Simultaneous operation of up to 16 sensing units
- Easy to read large LCD display
- Auxiliary output relay for a local audible alarm
- Temperature & humidity Hi / Lo set points
- Output relays can be configured to be initially energized or de-energized
- System is expandable, can have multiple Watchdog Sensors operating on the same system

Following are the weaknesses that existed in the system:

- Sensing units are sold separately
- Doesn’t support wireless mesh networking
- Is not specifically designed for greenhouse climate monitoring but for general-purpose environment monitoring only
- System configuration can be tedious
- Has no climate control capability

2.2.4 Sensaphone alarm Dialer

"Sensaphone Alarm Dialer" is a fully-programmable environmental monitoring system that offers extensive on-site and remote environmental monitoring. It comes with a distress alarm dialer feature that is capable of dialing up to four phone numbers when an alarm condition is breached. In addition, the users can also call the system to get a real-time update on the current condition of the environment. The system is equipped with 4 alert zones and each zone can support up to a maximum of 1 sensing unit at a time. It can support up to a maximum of 4 sensing units and is capable of simultaneously operating all 4 sensing units

Figure 2-3: Sensaphone Alarm Dialer

Its main features are listed as follows [39]:

- Four zones configurable as temperature or dry contact
- Each zone can be individually enabled or disabled
- Fully automatic input configuration
- Calibration for each zone
- Power monitor
- User-recordable voice messages
- Dial out to four telephone numbers
- Alarm dial out via voice and numeric pager
- Microphone for onsite listen-in
- Relay output (manual or automatic control)
- Four status LEDs
- Surge protection on all zones, telephone line, and power supply

- Wall or desktop installation

Some of its weaknesses are listed as follows:

- Sensing units are sold separately
- Is not specifically designed for greenhouse climate monitoring but general purposed environment monitoring only
- Doesn’t support wireless mesh networking
- Has no climate control capability
- System is not expandable

2.2.5 Conclusions

Looking at the issues and complexity of the existing systems we have designed and developed a novel greenhouse management system to overcome some of the weaknesses of the existing systems. The key advantage of our developed system over the existing ones is that our system is specifically designed for greenhouse climate monitoring. The developed system will be easy to use, reliable, portable, cost effective, scalable and more importantly has an ability to analyze and mange greenhouse climate in a preprogrammed manner.

3. Sensor Research and Evaluations

3.1 Introduction

Sensor technologies have made an enormous impact in modern day industries. There are thousands of sensors available on the markets that are ready to be attached to a wireless sensing platform. Therefore, this particular section of the thesis will be looking at some of the sensor technologies that are available on the market that could be used for this particular research. We will also discuss their operating principles as well as addressing their advantages and disadvantages.

3.2 Temperature Sensing Technology

Temperature sensing technology is one of the most widely used sensing technologies in the modern world. It allows for the detection of temperature in various applications and provides protection from excessive temperature excursions. Currently there are four different families of temperature sensors available on the market. Dependent on the applications; each family of temperature sensors has its own advantages and disadvantages. Therefore this section will give an overview of these temperature sensors.

3.2.1 Thermocouples

A thermocouple [40] is a sensor for measuring temperature. It consists of two dissimilar metals, joined together at one end. When the junction of the two metals is heated or cooled, a voltage is produced that can be correlated back to the temperature. Thermocouples are suitable for measuring over a large temperature range. They are less suitable for applications where smaller temperature differences need to be measured with high accuracy. For such applications thermistors and resistance temperature detectors are more suitable. Applications include temperature measurement for kilns, gas turbine exhaust, diesel engines, and other industrial processes.

Figure 3-1: Thermocouples

Advantages:

- Wide temperature range (-233°C - 2316°C)
- Relatively cheap
- Highly accurate
- Minimal long-term drift
- Fast response time.

Disadvantages:

- The relationship between the temperature and the thermocouple signal is not linear
- Low output signal (mV)
- Vulnerable to corrosion
- Calibration of thermocouples can be tedious and difficult.

3.2.2 Resistance Temperature Detectors (RTD)

RTDs [40] are widely used in many industrial applications such as: air conditioning, food processing, textile production, plastics processing, micro-electronics, and exhaust gas temperature measurement. RTDs are sensors used to measure temperature by correlating the resistance of the RTD element with temperature. Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core. The element is usually quite fragile, so it is often placed inside a sheathed probe to protect it.

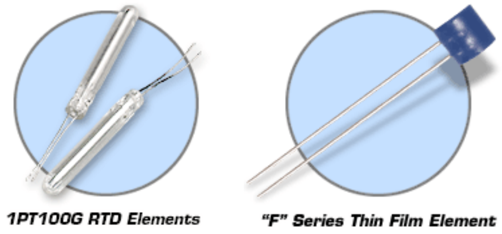


Figure 3-2: Resistance Temperature Detectors

Advantages:

- Linear over wide temperature operating range
- Relatively accurate
- Good stability and repeatability at high temperature (65-700°C)

Disadvantages:

- Low sensitivity
- Higher cost when compared to thermocouples
- Vulnerable to shock and vibration

3.2.3 Thermistors

A thermistor [40] is a temperature-sensing element that is composed of sintered semiconductor material which exhibits a large change in resistance proportional to a small change in temperature. Thermistors usually have negative temperature coefficients which mean that the resistance of the thermistor decreases when the temperature increases. Thermistors are not as accurate or stable as RTDs but they are easier to wire, cost less and almost all automation panels accept them directly.

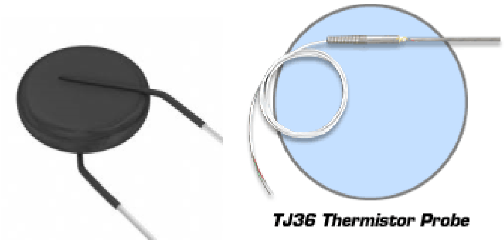


Figure 3-3: Thermistors

Advantages:

- Highly sensitive
- Low cost
- Accurate over small temperature range
- Good stability

Disadvantages:

- Non-linear resistance-temperature characteristics
- Self heating
- Limited temperature operating range

3.2.4 Integrated Circuit (IC) Temperature sensors

Integrated circuit (IC) temperature sensors [41] are semiconductor devices that are fabricated in a similar way to other semiconductor devices such as microcontrollers. In low cost applications most of the sensors stated above are either expensive or require additional circuits or components to be used. However, IC temperature sensors are completed silicon-based sensing circuits, with either analog or digital outputs. IC temperature sensors are often used in applications where the accuracy demand is low. IC semiconductor temperature sensors can be divided into the two categories: analog temperature sensors and digital temperature sensors. Analog sensors are further divided into two categories: voltage output temperature sensors and current output temperature sensors

Figure 3-4: Integrated Circuit (IC) temperature sensors

Advantages:

- Low cost
- Excellent linearity
- Relatively accurate
- Have relatively small physical size

Disadvantages:

- Limited temperature range
- Self heating
- Fragile

3.3 Humidity Sensing Technology

A humidity sensor measures and regularly reports the humidity level in the air. They can be used in homes for people with illnesses affected by excess humidity, as part of home heating, ventilating, and air conditioning systems. Humidity sensors can also be used in cars, office and industrial systems, and in meteorology stations to report and predict the weather. When it comes to humidity sensing technology, there are three types of humidity sensors: capacitive, resistive and thermal conductivity humidity sensor. This section discusses their operating principles as well as addressing their advantages and disadvantages.

3.3.1 Capacitive Humidity Sensors (CHS)

Capacitive Humidity Sensors (CHS) [42] are widely used in industrial, commercial, and weather telemetry applications. CHS consists of a substrate on which a thin film of polymer or metal oxide is deposited between two conductive electrodes. The sensing surface is coated with a porous metal electrode to protect it from contamination and exposure to condensation. The substrate is typically glass, ceramic, or silicon. The changes in the dielectric constant of a CHS are nearly directly proportional to the relative humidity of the surrounding environment.

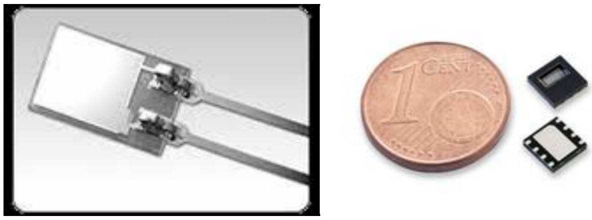


Figure 3-5: Capacitive humidity sensors

Advantages:

- Ability to function in high temperatures environments (up to 200°C)
- Near linear voltage output
- Wide RH range
- High condensation tolerance
- Reasonable resistance to chemical vapours and contaminants
- Minimal long-term drift
- High accuracy
- Small in size and low cost

Disadvantages:

- Limited sensing distance
- Sensor integration can be tedious and difficult.

3.3.2 Resistive Humidity Sensors (RHS)

Resistive Humidity Sensors (RHS) [42] measure the changes in electrical impedance of a hygroscopic medium such as: conductive polymer, salt, or treated substrate. These sensors are suitable for use in control and display products for industrial, commercial, and residential applications. RHS consists of noble metal electrodes either deposited on a substrate by photo resist techniques or wire-wound electrodes on a plastic or glass cylinder [42].

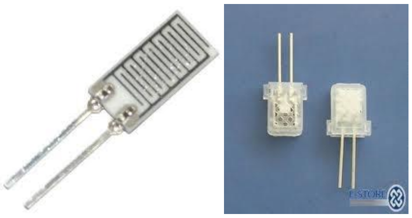


Figure 3-6: Resistive humidity sensor

Advantages:

- Fast response time
- Near linear voltage output
- High accuracy
- Small size
- Low cost
- Wide RH range

Disadvantages:

- Lower operating temperature in compare to CHSs
- Sensitive to chemical vapors
- Low tolerance against contaminants
- Low condensation tolerance.

3.3.3 Thermal Conductivity Humidity Sensors (TCHS)

Thermal Conductivity Humidity Sensors (TCHS) [42] measure the absolute humidity by quantifying the difference between the thermal conductivity of dry air and that of air containing water vapor. These sensors are suitable for applications such as; kilns for drying wood; machinery for drying textiles, paper, and chemical solids; pharmaceutical production; cooking; and food dehydration. TCHS consists of two matched negative temperature coefficient (NTC) thermistor elements in a bridge circuit; one is hermetically encapsulated in dry nitrogen and the other is exposed to the environment [42].

Figure 3-7: Thermal conductivity humidity sensor

Advantages:

- Very durable
- Ability to operate in high temperatures environments (up to 600°C)
- Excellent immunity to many chemical and physical contaminants
- High accuracy
- High condensation tolerance

Disadvantages:

- Responds to any gas that has thermal properties different from those of dry nitrogen
- Expensive

3.4 Light Sensing Technology

Light from the sun is responsible for nearly all life on the earth. Sunlight fuels the process of photosynthesis where plants convert carbon dioxide and water into carbohydrates [43]. Plants use light in the range of 400 to 700 nanometers. This range is most commonly referred to as PAR (photo-synthetically active radiation). Monitoring PAR is important to ensure their plants are receiving adequate light for photosynthesis. Typical applications include forest canopies, greenhouses monitoring etc. This section will present some of the popular light sensors on the market that can be used for environmental monitoring applications. Their advantages and disadvantages are also discussed in this section.

3.4.1 Photometric Sensors

Photometric sensors are designed to measure visible radiation that has spectral response similar to that of human eye. Some of the applications for photometric sensors include interior and industrial lighting, outdoor illuminate, illuminance engineering and passive solar energy.

Figure 3-8: Photometric Sensors

Advantages:

- Highly sensitive
- Good stability
- Fast response time (10us)
- Low temperature dependency
- Excellent linearity

- Small in size

Disadvantages:

- Expensive
- These sensors are mostly used to measure indoor lighting conditions. For environmental applications, PAR and Solar Radiation sensor are preferred.

3.4.2 Light Dependent Resistor (LDR)

Similar to photometric sensors, LDRs measure visible light as seen by the human eye. LRD is basically a resistor that has internal resistance increases or decreases dependent on the level of light intensity impinging on the surface of the sensor.

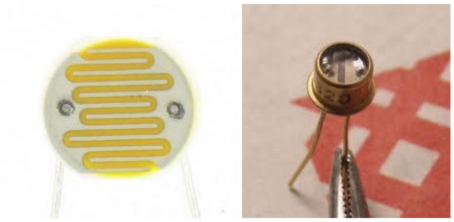


Figure 3-9: Light dependent resistors

Advantages:

- Very cheap
- Fast response
- Linear output
- Small in size

Disadvantages:

- Like Photometric Sensors, LDRs are mostly used to measure indoor lighting conditions.

3.4.3 Pyranometers

A Pyranometer [44], also known as a Solarimeter is an instrument used to measure the combined intensity of incoming direct solar radiation and diffuse sky radiation. It compares the heating produced by the radiation on blackened metal strips with that produced by an electric current. These sensors are commonly used for agriculture, meteorological and solar energy applications. The sensor is composed of a silicon photovoltaic detector mounted in a miniature head [45].

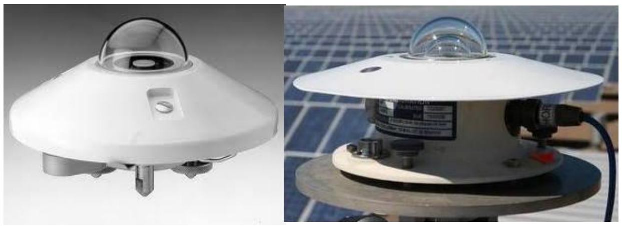


Figure 3-10: Pyranometers

Advantages:

- Highly accurate
- Excellent linearity
- Good stability
- And fast response time.

Disadvantages:

- Bulky
- Expensive

3.4.4 Quantum Sensors

Quantum sensors measure the photosynthetic photon flux density (PPFD) of photosynthetically active radiation (PAR) [45]. They are one of the most popular types of light sensor in the agriculture and environmental industries.

Figure 3-11: Quantum Sensors

Advantages:

- Very sensitive
- Fast response
- Highly accurate
- Excellent linearity
- Good stability
- Small in size.

Disadvantages:

- Expensive

3.5 Soil Moisture Sensing Technology

Moisture is undesirable whether it appears in agriculture, houses, textiles, packaging materials, electronic appliances or dry food process [3]. Moisture detection is important in a number of different situations. For example measurement of soil moisture is useful for minimizing the amount of irrigation water applied for growing plants and for optimizing plant growth. Because of the importance of knowing the moisture content of materials, various techniques have been developed to measure it. This section outlines a number soil moisture detection technologies are available on the market as well as addresses their advantages and disadvantages.

3.5.1 Frequency Domain Reflectometry (FDR) Soil Moisture Sensor

Frequency Domain Reflectometry [46] is *s*ometimes referred to as a capacitance sensor. Soil sensor probes use the FDR method of soil moisture measurement employ an oscillator to generate an electromagnetic signal that is propagated through the unit and into the soil. Part of this signal will be reflected back to the unit by the soil. This reflected wave is measured by the FDR probe, telling the user what the water content of the soil is.

Figure 3-12: Frequency Domain Reflectometry (FDR) Soil Moisture Sensors

Advantages:

- Highly accurate
- Fast response time
- Inexpensive

Disadvantages:

- Need to be calibrated for the type of soil they will be buried in.

3.5.2 Time Domain Reflectometry (TDR) Soil Moisture Sensor

Time Domain Reflectometry (TDR) sensors work by propagating a pulse down a line into the soil, which is terminated at the end by a probe with wave guides [9]. TDR systems measure water content of the soil by measuring how long it takes the pulse to come back.

Figure 3-13: Time Domain Reflectometry (TDR) Soil Moisture Sensors

Advantages:

- Highly accurate
- Fast response

Disadvantages:

- Calibration can be tedious and difficult
- Expensive
- Easy to corrode

3.5.3 Gypsum Blocks

Gypsum blocks use two electrodes placed into a small block of gypsum to measure soil water tension [46]. The amount of water in the soil is determined by the electrical resistance between the two electrodes within the gypsum block. More water present in the soil will reduce the resistance, while less water will increase it.

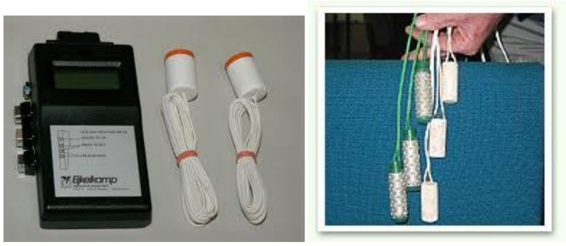


Figure 3-14: Gypsum Blocks

Advantages:

- Inexpensive
- Easy to install

Disadvantages:

- Have to be replaced periodically
- Sensitive to the saline content of water.

3.5.4 Neutron Probes

Using neutron probes is another way to measure soil moisture content. A probe is inserted in the ground which emits low-level radiation in the form of neutrons. These neutrons collide with the hydrogen atoms contained in water, which is detected by the probe [46]. The more water content in the soil, the more neutrons are scattered back at the device.

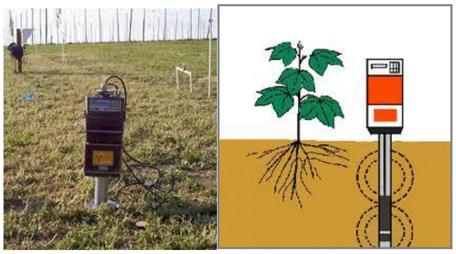


Figure 3-15: Neutron Probes

Advantages:

- Very accurate
- Fast response

Disadvantages:

- Expensive
- Users have to be registered with the government due to radioactive elements used to emit the neutrons.

3.6 Carbon Dioxide (CO_2) Sensing Technology

Carbon dioxide CO_2 is one of the most common by-products of living organisms [47]. The gas itself is safe in low concentration, however in high concentration it could be life threatening. Measuring CO_2 is important in monitoring indoor air quality in many industrial processes. Two types of CO_2 detectors are available to measure CO_2 level in the environment: Electrochemical CO_2 Sensors and Non-dispersive Infrared (NDIR) CO_2 Sensors. This section discusses their operating principles as well as addressing their advantages and disadvantages.

3.6.1 Solid State Electrochemical (SSE) CO_2 Sensors

Solid state electrochemical (SSE) CO2 sensor [48] adopts a galvanic structure with a sodium-ion conducting electrolyte of beta alumina, operating at 450^{o}C. Carbonate based sensing material is deposited on one side as a sensing electrode and counter electrode is attached on the other side as a reference electrode [48]. When the sensor is exposed to the environment, the sensor will generate voltage outputs in respect to the level of CO_2 in the environment. Their applications include greenhouse, farming, land fill gas monitoring, indoor air quality motoring and hazardous area warning signals.

Figure 3-16: Electrochemical CO_2 Sensors

Advantages:

- Cheap
- Relatively accurate
- Real-time sensing
- High tolerance against contaminants
- Small in size.

Disadvantages:

- Require a significant amount of power because they operate at high temperature
- Need at least 24 hours of preconditioning before it could be used

3.6.2 Non-dispersive Infrared (NDIR) CO_2 Sensors

Non-dispersive Infrared (NDIR) [49]sensors are spectroscopic sensors that are capable of detecting CO_2 level in a gaseous environment based on its absorption characteristic. The key components are an infrared source, a light tube (or a chamber), an interference (wavelength) filter, and an infrared detector. The gas is pumped or diffuses into the light tube and the electronics measures the absorption of the characteristic wavelength of light [49]. NDIR CO_2 sensor applications include indoor air quality monitoring, greenhouse farming, gas leak detection, automotive and flue gas emissions.

Figure 3-17: Non-dispersive Infrared CO_2 Sensors

Advantages:

- Fast real-time sensing
- Low power consumption
- High contamination tolerance
- Small in size.

Disadvantages:

- Carbon monoxide often coexists with CO_2 and absorbs a similar wave-length range as CO_2 which results in inaccurate measurement of CO_2 concentration
- Expensive

3.7 Sensor Selection

Sensor technologies were reviewed and evaluated. A table was drawn to summarize the characteristics of each sensor. The result of comparisons can then be used for selecting the right type of sensor technology for the project.

Criteria	Thermocouple	RTD	Thermistor	IC's
Temperature Range	(-233°C - 2316°C)	(-205°C - 649°C)	(-38°C - 260°C)	(-40°C - 260°)
Long-term Stability	Good	Excellent	Poor to Fair	Good
Accuracy	Medium	High	Medium	Medium
Repeatability	Fair	Excellent	Fair to Good	Excellent
Sensitivity	Low	Medium	Very High	High
Response	Medium to Fast	Medium	Medium to Fast	Fast
Linearity	Fair	Good	Poor	Excellent
Self Heating	No	Very Low to Low	High	Medium
Size	Small to Large	Small to Medium	Small to medium	Small
Cost	expensive	Expensive	Cheap	Relatively cheap
Humidity Sensing Technologies				
Criteria	RHS	TCHS	CHS	
Humidity Range	5%-95%	0-100%	5%-95 %	
Long-term Stability	Good	Excellent	Good	
Accuracy	High	High	High	
Repeatability	Fair to Good	Excellent	Excellent	
Sensitivity	Medium	High	High	
Response	Medium	Medium to Fast	Fast	
Linearity	Good	Excellent	Excellent	
Size	Small	Small to Medium	Small	
Cost	Cheap	Expensive	Relatively cheap	
Carbon Dioxide Sensing Technologies				
Criteria	SSE	NDIR		
Long-term Stability	Good	Excellent		
Accuracy	Medium	Medium to High		
Repeatability	Good	Good		
Sensitivity	High	Medium		
Response	Fast	Medium		
Linearity	Good	Good		
Size	Small	Medium to Large		
Cost	Relatively Cheap	Expensive		
Light Sensing Technologies				

Criteria	Photometric	LDR	Pyranometers	Quantum Sensors
Long-term Stability	Good	Good	Good	Excellent
Accuracy	High	Medium	High	High
Repeatability	Good	Good	Good	Excellent
Sensitivity	High	Medium	High	Very High
Response	Fast	Fast	Fast	Fast
Linearity	Excellent	Good	Good	Excellent
Size	Small	Small	Small to Medium	Small
Cost	Expensive	Cheap	Expensive	Expensive
Soil Moisture Sensing Technologies				
Criteria	FDR	TDR	Gypsum Blocks	Neutron Probes
Long-term Stability	Good	Fair	Fair	Excellent
Accuracy	High	High	Medium	High
Repeatability	Excellent	Excellent	Fair	Excellent
Sensitivity	High	High	Low	High
Response	Fast	Fast	Slow	Fast
Linearity	Excellent	Excellent	Fair	Good
Size	Small	Medium	Medium	Large
Cost	Relatively Cheap	Expensive	Cheap	Very Expensive

Table 3-1: Sensor technologies comparison

3.7.1 Temperature and humidity sensors selection

Greenhouse temperature is often maintained between T_{max}(24°C Day/18°C Night) and T_{min} (20°C Day/16°C Night) [50]. This information allows us to narrow down our options for selecting a right temperature sensing technology for the project. Reviewing temperature sensors and their key features, thermocouple and RTD are more suitable for industrial applications that require the sensor to be exposed to a high temperature environment or applications where smaller temperature differences need to be measured with high accuracy. For this particular project thermistors and IC temperature sensors are preferred. Comparing thermistor and IC temperature characteristics and key features, it is possible to conclude that IC temperature sensing technology is more suitable than thersmistors.

Three humidity sensing technologies are currently available on the market. Each has their strengths and weaknesses. Comparing these humidity sensing technologies, it was found that thermal conductivity humidity sensor has the best overall performance. However in terms of price, it is very expensive in comparison to resistive and capacitive sensors. Therefore resistive and capacitive humidity sensors are more preferred. In terms of linearity and repeatability, capacity humidity sensors are proven to be far more superior than resistive type, therefore capacitive humidity sensor technology was chosen for this project

Sensirion Inc. offers one of the best options available for temperature and humidity sensing. SHT75 [51] is Sensirion's family of temperature and humidity sensor. This sensor allows for the measure of temperature and humidity to the highest accuracy [51]. Not to mention the low cost factor, excellent linearity and small size, allow it to be applied in almost any application. This sensor incorporates a band gap temperature sensor and a capacitive polymer sensing element for relative humidity sensing. Both sensors are seamlessly coupled by a 14bit analog to digital converter and a signal conditioning circuit, which results in superior signal quality, insensitivity to external disturbances and fast response time [51]. The only disadvantage in using this sensor is the interfacing problem due to the necessity of having to manually program each sensor individually prior to using them. For non-programming background users, interfacing these sensors could be tedious and frustrating.

3.7.2 CO_2 Sensor Selection

There are two types of CO_2 sensors on the market: Electrochemical and Non-dispersive Infrared (NDIR) CO_2 sensors. Both sensor technologies have their strengths and weaknesses. When compared to the Electrochemical CO_2 sensor, the NDIR CO_2 sensor has more technical advantages in terms of long-term stability and low power consumption. But in terms of installation cost, accuracy and linearity electrochemical CO_2 sensors are superior to NDIR sensors. In conclusion, the electrochemical sensor is a better choice for low cost applications. In comparison to many existing electrochemical CO_2 sensors on the market, TGS4161 sensors from Figaro Inc were found to be the cheapest, more accurate and have the lowest power consumption. Their high tolerance against humidity and temperature, make them ideal for any kind agriculture applications.

3.7.3 Soil Moisture Sensor and Soil Temperature Sensor Selection

Four types of soil moisture sensing technologies currently available on the market are FDR, TDR, Gypsum Blocks and Neutron probes. Neutron probes were found to be very expensive and bulky. The user requires a licence and needs permission from the government to operate the device due to its nature of operation [46]. Gypsum blocks have the worst overall features when compared to other soil moisture sensing technologies, which left us with FDR and TDR. Comparing FDR and TDR overall features and characteristics, it is possible to conclude that both technologies are ideal candidates for this application. However, it all comes down to the cost and long term stability. FDR sensors were found to be better in terms of price and long-term stability, therefore they were chosen for this project.

VG400 Soil moisture sensor and THERM200 soil temperature sensors were both purchased from Vegetronix Inc. In comparison to other sensors of the same type on the market, these sensors are far cheaper and superior in terms of power consumption, linearity, durability and were made solely to measure the temperature and moisture of the soil. Therefore these sensors were found to be ideal for this particular work.

3.7.4 Light Sensor Selection

Light sensing technology is considered to be one of the most widely used sensing technologies in modern day industry. There are a wide range of light sensors on the market that are available for many applications. Therefore a careful selection of light sensors is essential.

Plants absorb sunlight and use it to fuel the photosynthesis process. Sunlight in range of 400 to 700 nanometers are normally used by plants and are often referred to as Photo-synthetically Active Radiation or PAR [15]. Monitoring PAR is important to ensure the plants are receive adequate light for photosynthesis process. Four types of sensors were designed to serve this particular purpose: photometric sensors, light dependent sensors, pyranometers and quantum sensors. Pyranometers and quantum sensors are best suited for measuring sunlight. However, these sensors are very expensive and therefore we need to turn to a much cheaper option. In this case LDR sensors were found to be the cheapest option available when compared to photometric sensors. NOPR12 sensors were chosen for this research because their spectral response is approximately from 380 to 740 nm, which is within the PAR range. However, for precision agriculture applications, it is preferable to use quantum sensors or pyranometers.

3.7.5 Conclusions

It can be concluded that certain tradeoffs are being made in selection of the devices before implementing the hardware on PCB. These tradeoffs are mainly size, features, resources, cost, and availability. The next chapter focuses on explaining the experimental methods and procedures carried out to determine the sensitivity and accuracy of the selected sensors.

3.8 Sensor Experimental Setup and Results

3.8.1 Introduction

Six sensors investigated for this project are: SHT75 humidity and temperature sensor, TGS4161 electrochemical carbon dioxide sensor, NORP12 light dependent resistor, VG400 soil moisture sensor and THERM200 soil temperature sensor. This section gives some insights on the construction of each sensor, their key features and explains the experimental methods and procedures carried out to test their sensitivity and accuracy. Experimental results are also discussed in this section

3.8.2 SHT75's Characteristics and Construction

The SHT75 [51] humidity and temperature sensor is Sensirion's family digital humidity and temperature sensor. The sensing element consists of a band gap temperature sensor and a capacitive humidity sensing element. A side from the inbuilt sensing technologies, SHT75 also contains an amplifier, analog to digital converter, and One-time Programmable Memory (OTP). Each SHT75 sensor was individually calibrated in a precision humidity chamber and the calculated calibration coefficients are programmed onto the chip's OTP. These coefficients are used to internally calibrate the sensor's signal.

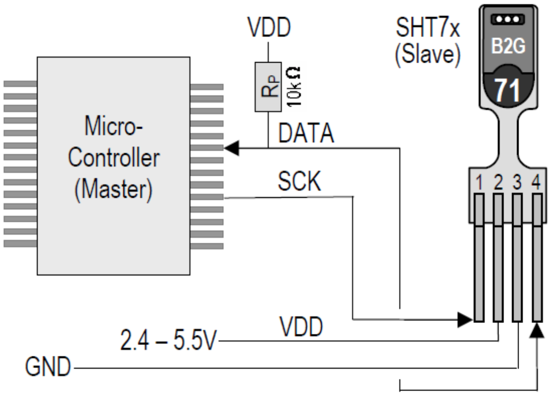


Figure 3-18: SHT75 connection layout [51]

A typical application circuit is shown on Figure 3-18. The sensor comes with 4 pins: VDD, GND, Serial Clock (SCK) and DATA pin. The serial clock pin on the sensor is used for input signal only. The serial data pin on the other hand is bidirectional. A voltage source between 3.3 - 5.5V is required to power the sensor.

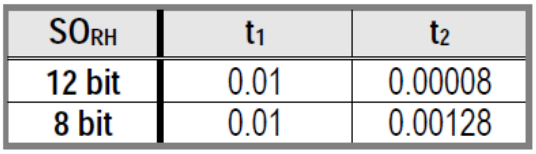
Both serial data and serial clock pins are connected to separate pins on the microcontroller. The SCK line is used to synchronize the communication between the microcontroller and the sensor. The DATA line is used to transfer data in and out of the sensor. In order to avoid signal contention, the microcontroller must drive the DATA signal low. Therefore, a pull up resistor of 10k ohm is needed to be connected between the serial data line and the microcontroller to pull the signal high [51].The relative humidity can be expressed using the following equation:

$$RH = (T - 25) * (t_1 + t_2 * SO) + Hl \qquad \textbf{(3-1)}$$

Where:

- RH is relative humidity (%)
- t_1 and t_2 are temperature compensation coefficients
- SO is measurement resolution
- H_l linear humidity (%)

The temperature compensation coefficient can be acquired from Table 3-2.



SO_{RH}	t_1	t_2
12 bit	0.01	0.00008
8 bit	0.01	0.00128

Table 3-2: Temperature compensation coefficients [51]

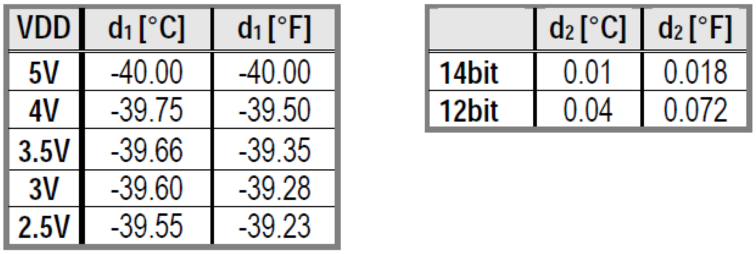
The ambient temperature can be expressed using the following equation:

$$T = d_1 + d_2 * Sot \tag{3-2}$$

Where:

- T is ambient temperature (°C)
- d_1 and d_2 are temperature conversion coefficients
- SOt is measurement resolution

The temperature conversion coefficient can be acquired from Table 3-3



VDD	d_1 [°C]	d_1 [°F]
5V	-40.00	-40.00
4V	-39.75	-39.50
3.5V	-39.66	-39.35
3V	-39.60	-39.28
2.5V	-39.55	-39.23

	d_2 [°C]	d_2 [°F]
14bit	0.01	0.018
12bit	0.04	0.072

Table 3-3: Temperature conversion coefficients [51]

3.8.3 VG400'S Characteristics and Construction

The VG400 sensor [52] is VEGETRONIX^{TM}'s Family of soil moisture sensor. This sensor allows for low power consumption and low cost operation. The probe consists of 3 wires: Ground, VDD and Vout. It requires an input voltage range between 3.3V to 20V to operate and output a voltage range between 0 to 3V in relation to the moisture content in the soil.

These voltage characteristics make it very easy and convenient for microcontroller interfacing applications. VG400 is insensitive to water salinity and it doesn't corrode over time as conductivity based probes do, making it an ideal device for any applications that require minimal attention and maintenance.

Figure 3-19: VG400 soil moisture sensor

VG400's key features [53] are:

- Extreme low cost
- Not conductivity based.
- Pre-calibrated
- Insensitive to salinity.
- Probe does not corrode over time.
- Rugged design for long term use and small size.
- Consumes less than 600uA for very low power operation.
- Precise measurement.
- Measures volumetric water content (VWC) or gravimetric water content (GWC).
- Output Voltage is proportional to moisture level.
- Wide supply voltage range.
- Can be buried and is water proof.
- Probe is long and slender for wider use, including smaller potted plants.

The sensor measures the dielectric constant of the soil using transmission line technique and its output voltage is linearly proportional to the moisture content in the soil. The relationship between sensor output voltage and the moisture content in the soil can be expressed using the following equation:

$$SM(\%) = (V_{out} * 21.186) - 10.381 \qquad \textbf{(3-3)}$$

Where:

- Sm is the moisture content of soil in percentage
- Vout is the output voltage of the sensor

3.8.4 THERM200'S Characteristics and Construction

Similar to VG400, this sensor also has a 3 wire interface; ground, VDD and output. It has a temperature span from -40°C to 85°C and high accuracy of ±0.5°C. THERM200 [52] key features are similar to VG400 in terms of low cost and low power consumption. This sensor probe outputs a voltage range between 0 to 3V in relation to the temperature in the soil. Similar to the VG400, THERM200 is insensitive to water salinity and it doesn't corrode over time as conductivity based probes do making it an ideal device for any applications that require minimal attention and maintenance.

Figure 3-20: THERM200 soil temperature sensor

THERM200's key features [52] are:

- Low cost ($29.95 per unit)
- No need to calibrate.
- Rugged design for long term use.
- Small size.
- Consumes less than 3mA for very low power operation.
- Precise measurement.
- Output Voltage is linear to temperature.
- No complex Steinhart-Hart equations are needed to convert voltage to temperature.

- Wide supply voltage range.
- Can be buried and is water proof.
- Probe is long and slender for wider use, including smaller potted plants.

When compared to THERM200, thermistors are less accurate, and it requires the use of complex Steinhart-Hart equation which contains complex calculations such as logarithmic and third order terms, which are difficult for microcontrollers to compute [52]. THERM200 output voltage is however linearly proportional to the temperature; therefore no complex equations are required to calculate the temperature from output voltage. The relationship between sensor output voltage and soil temperature can be expressed using the following equation:

$$S_{temp}\left(°C\right) = \left(C_{out}\left(mV\right) * 41.67\right) - 40 \qquad \textbf{\textit{(3-4)}}$$

Where:

- Stem is Soil temperature in degree Celsius
- Vout is the output voltage generated by the sensor

3.8.5 NORP12' Characteristics and Construction

The NORP12 [54] light dependent sensor was purchased from Element14. the NORP12 consists of two Cadmium Sulphide photoconductive cells with spectral responses similar to that of the human eye. Cadmium Sulphide is a high resistance semiconductor and if light falling on the device is of a high enough frequency, photons absorbed by the semiconductor will supply electrons with enough energy to jump into the conduction band, the resulting free electrons conduct electricity, thereby lowering output resistance [55].The cell resistance increases and decreases with change in light intensity. Figure 3-22 shows the electrical characteristics of the sensor. NORP12 resistance can reach 9K ohm in dark conditions and about 10 ohm in full brightness. Figure 3-21 shows the typical responses of NORP12 with changes in light intensity.

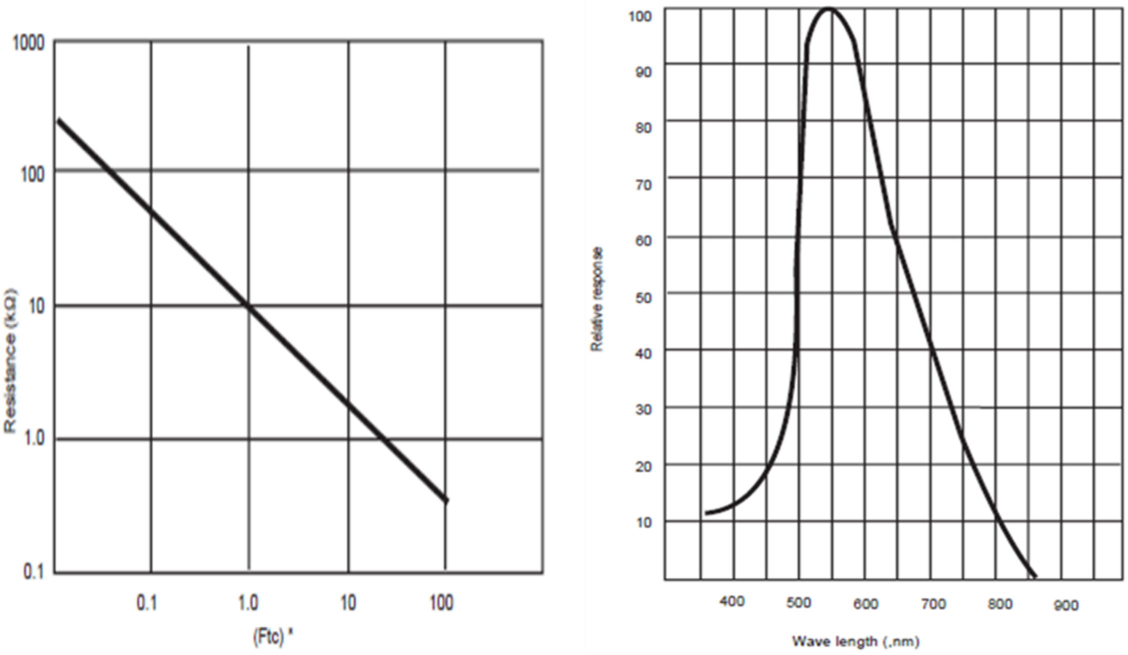
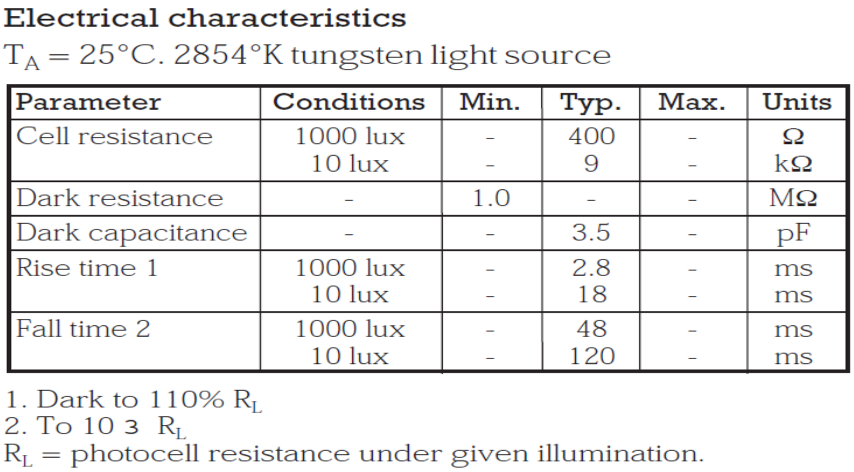


Figure 3-21: Graph of resistance as function of illumination (left) and spectral respond (right) [54]



Electrical characteristics

$T_A = 25°C$. 2854°K tungsten light source

Parameter	Conditions	Min.	Typ.	Max.	Units
Cell resistance	1000 lux 10 lux	- -	400 9	- -	Ω kΩ
Dark resistance	-	1.0	-	-	MΩ
Dark capacitance	-	-	3.5	-	pF
Rise time 1	1000 lux 10 lux	- -	2.8 18	- -	ms ms
Fall time 2	1000 lux 10 lux	- -	48 120	- -	ms ms

1. Dark to 110% R_L
2. To 10 3 R_L

R_L = photocell resistance under given illumination.

Figure 3-22: NOPR12 electrical characteristics [54]

Figure 3-23: NORP12 light dependent resistor

The relationship between the change in sensor resistance (R_L) and light intensity (Lux) can also be expressed using the following equation [56]:

$$RL\left(Kohm\right) = 500 \div Lux \qquad \textbf{(3-5)}$$

Where:

- RL is the sensor's internal resistance (ohm)
- Lux is the SI unit of illuminance and luminous emittance measuring luminous power per area

3.8.6 TGS4161'S Characteristics and Construction

The TGS4161 is Figaro's new solid electrolyte CO_2 sensor that offers minimal power consumption, high tolerance against contamination and long term stability. The construction of the sensor is shown on Figure 3-24. The sensor sensing element consists of a solid electrolyte formed between two electrodes (Sensing Electrode and Counter Electrode) together with a heater substrate. When the sensor is exposed to CO_2 gas the following electrochemical reaction occurs [57]:

- Cathodic reaction: $2Li+ + CO_2 + 1/2O2 + 2e- = Li2CO_3$
- Anodic reaction: $2Na+ + 1/2O_2 + 2e- = Na2O$
- Overall chemical reaction: $Li2CO_3 + 2Na+ = Na2O + 2Li+ + CO_2$

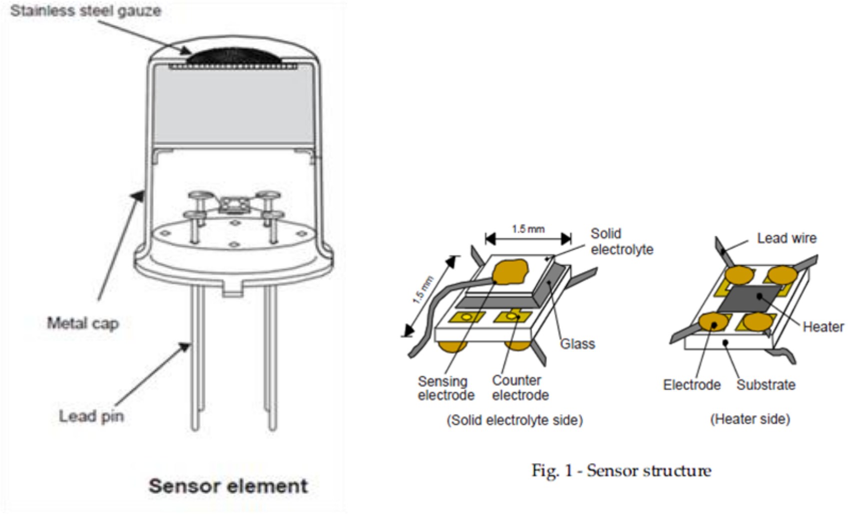


Figure 3-24: TGS4161 construction

The CO_2 concentration can be measured by monitoring the changes in electromotive force generated by the sensor. CO_2 can be calculated by using Ernest's equation [57]:

$$EMF(mV) = \left(\left(E_c - (R * T)\right) \div 2F\right) * ln\left(P\left(CO_2\right)\right) \qquad \textbf{(3-6)}$$

Where:

- P(CO2) is concentration of CO2 (ppm)
- Ec is half cell reduction potential (mV)
- R is gas constant (8.314 L/(mol).K)
- T is temperature (Kelvin)
- F is Faraday constant (9.649*10^4 C/mol)

To calculate the electro-motive-force of the sensor, the half-cell-reduction potential is required (Ec). However, Ec value varies from one sensor to another [57], therefore the only way to obtain an equation that represents the relationship between output EMF and CO_2 concentration is through an experiment. This experiment will be discussed in more detail in the sensor calibration section. A typical application circuit of TGS4161 is shown in Figure 3-25. The sensor requires a heater voltage of 5V in order to maintain the sensing element at the optimum temperature. While the solid electrolyte is heated via the heater layer, it exhibits an electromotive force (EMF) and thus a voltage across its remaining two terminals (3 and 2)

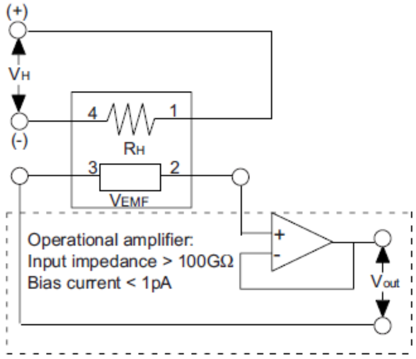


Figure 3-25: TGS4161 application circuit [57]

This sensor was also tested for different gas types as well as humidity dependency. The results of the experiment are shown in Figure 3-26.

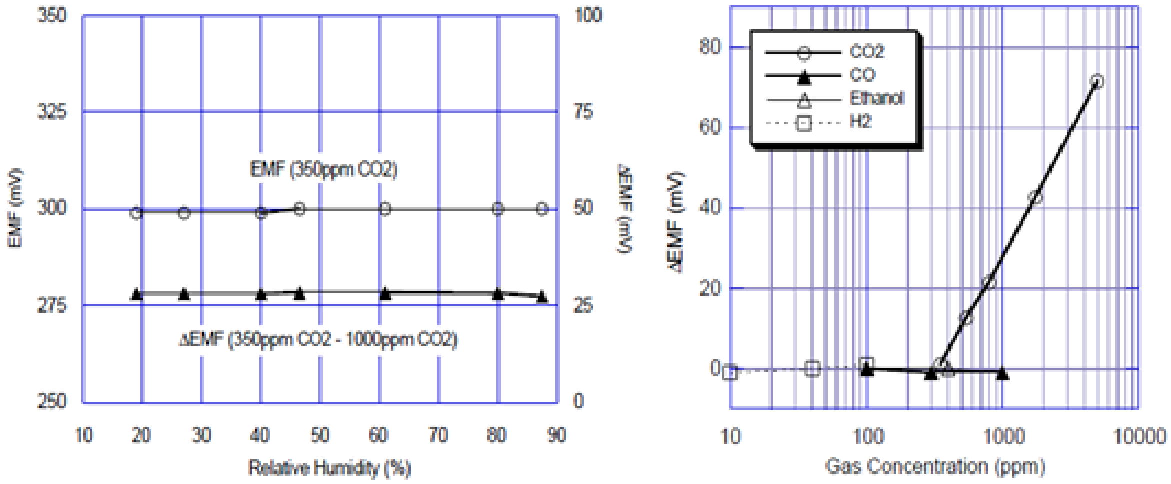


Figure 3-26: Humidity dependency test (left) and sensor sensitivity to various gases (right)

The ΔEMF versus gas concentration figure shows a very strong linear relationship between CO_2 concentration and the output voltage. In comparison to other gases such as CO, Ethanol and H_2, the sensitivity of TGS4161 is very low as evidenced by a relatively flat slope and very low in the response output voltage. TGS4161 was also tested for humidity dependency and the result shows a very low humidity dependency which indicates that TGS4161 sensor is very robust and is ideal for agriculture applications.

3.8.6.1 CO_2 Sensor Calibration

TGS4161 sensors are not calibrated, therefore it is necessary to calibrate the sensors before they can be used. The calibration process involves two steps; Sensor Stabilization and Span Calibration.

- *Sensor Stabilization* – before the sensor can be used it is required to undergo a preconditioning period of approximately 24 hours. An experiment was carried out, and it was discovered that it requires approximately 2 days (48 hours) for the sensors to fully stabilize.
- *Span Calibration* – Span calibration helps to determine the characteristics of the sensor when it's being exposed to a range of CO_2 concentrations. Calibration equipment includes: calibration chamber, rotameters, compress air, CO_2 gas cylinder, and pressure regulators.

All four sensor units were enclosed in a 1.2 litre testing chamber. Compressed air is mixed with CO_2 and blown into the bag for 3 minutes to allow the air inside to be fully replaced with the new air. The overview of the calibration process is shown in Figure 3-27 and Figure 3-28.

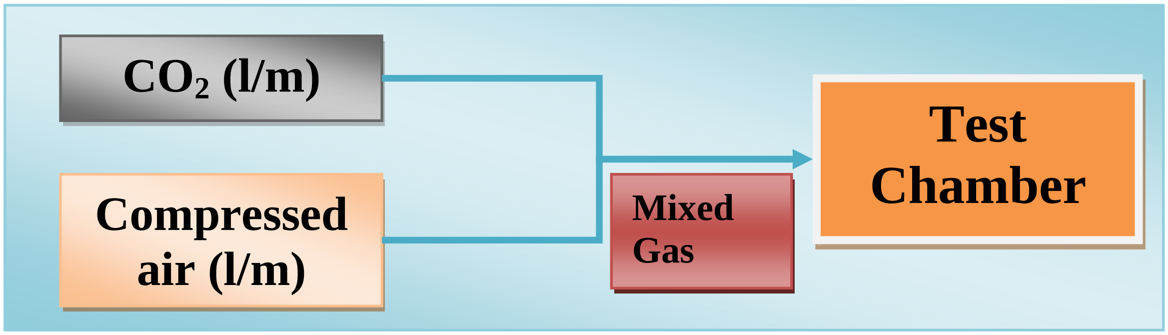


Figure 3-27: Sensor calibration overview

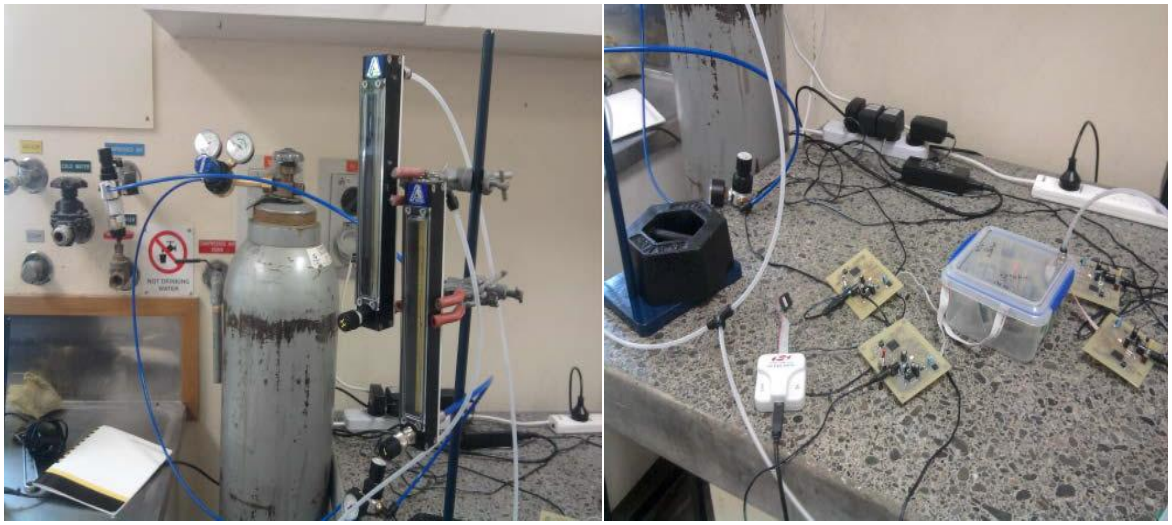


Figure 3-28: Sensor calibration setup

CO_2 concentration ranges between 350 – 2500 ppm were chosen for the experiment. The percentage concentration of CO_2 in the testing chamber can be calculated using equation the ***(3-7).***

$$C_{2} = CO_{2}\left(l.m\right) \div \left(CO_{2}\left(l.m\right) + Air\left(l.m\right)\right) \tag{3-7}$$

Where:

- CO_2 (l.m) = CO_2 flow rate (litre per minute)
- Air (l.m) = compress air flow rate (litre per minute)

To calculate the percentage of CO_2, a known flow rate of either CO_2 or compressed air is required. Therefore a flow rate of 10 litre/min was set for the compress air supply. The equation **(3-8)** was derived to express CO_2 concentration in terms of ppm.

$$PPM = 1\,part\ from\ 1000000\ parts$$

$$1\% = 1\,part\ from\ 100\ parts$$

$$1\% = \left(1/100\right) * 1000000 = 10000 \text{ ppm}$$

$$CO_2(ppm) = \left(CO_2(\%) \div 100\right) * 10000 \qquad \textbf{(3-8)}$$

The experiment was carried out to test the outputs of the CO_2 sensors by having the sensor exposed to a range of CO_2 concentration. Ten output samples of each sensor were taken at each concentration and the average of these samples was calculated. Table 3-4 shows the calculated average output voltage (mV) generated by each sensor at each concentration level.

BWGasProbe (ppm)	TGS4161-A(mV)	TGS4161-B(mV)	TGS4161-C(mV)	TGS4161-D(mV)
575	633.0	495.3	501.7	652.3
800	617.0	487.0	495.0	636.0
1075	603.0	469.3	488.7	625.0
1360	590.0	460.7	484.0	612.3
1660	581.3	456	478.7	605
1850	578.7	449	475	599.7
2240	566	437.3	466	590.3
2770	553.3	429.3	459.3	580

Table 3-4: Calibration result

A graph was plotted to show the relationship between the CO_2 concentrations and the changes in the output voltage of each sensor. As shown on Figure 3-29, TGS4161 sensors exhibit a good linear relationship between ΔEMF and CO_2 gas concentration on a logarithmic scale. The sensitivity curves of CO_2 show a sharp increase in ΔEMF as CO_2 concentration increases.

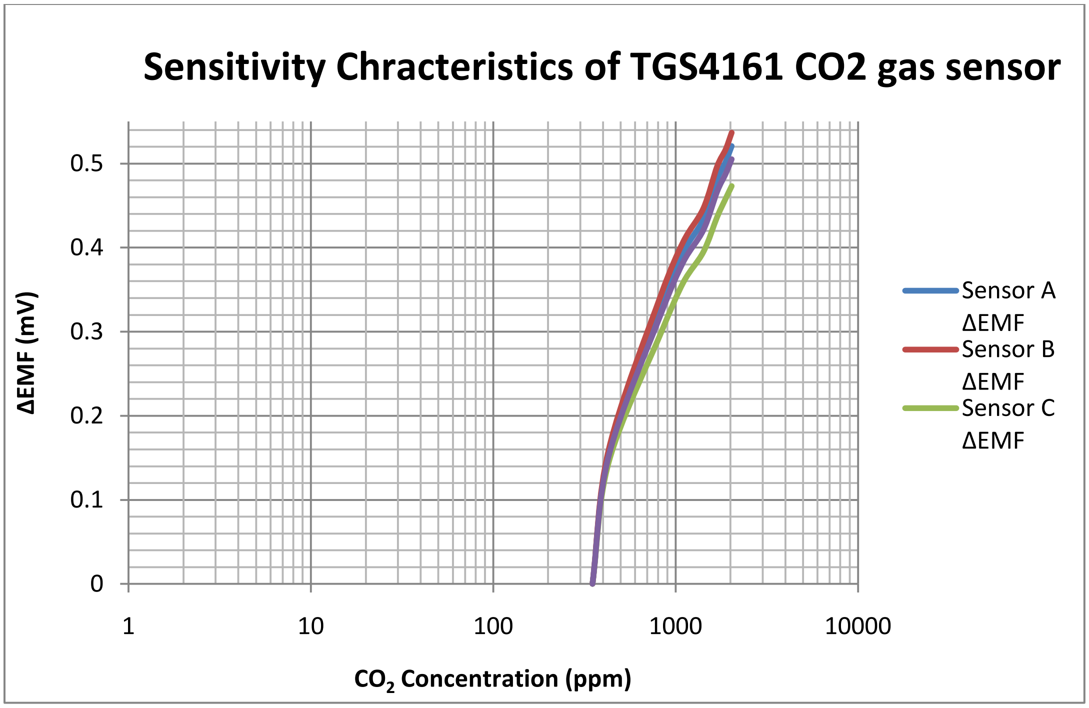


Figure 3-29: Experimental result of TGS4161 sensors

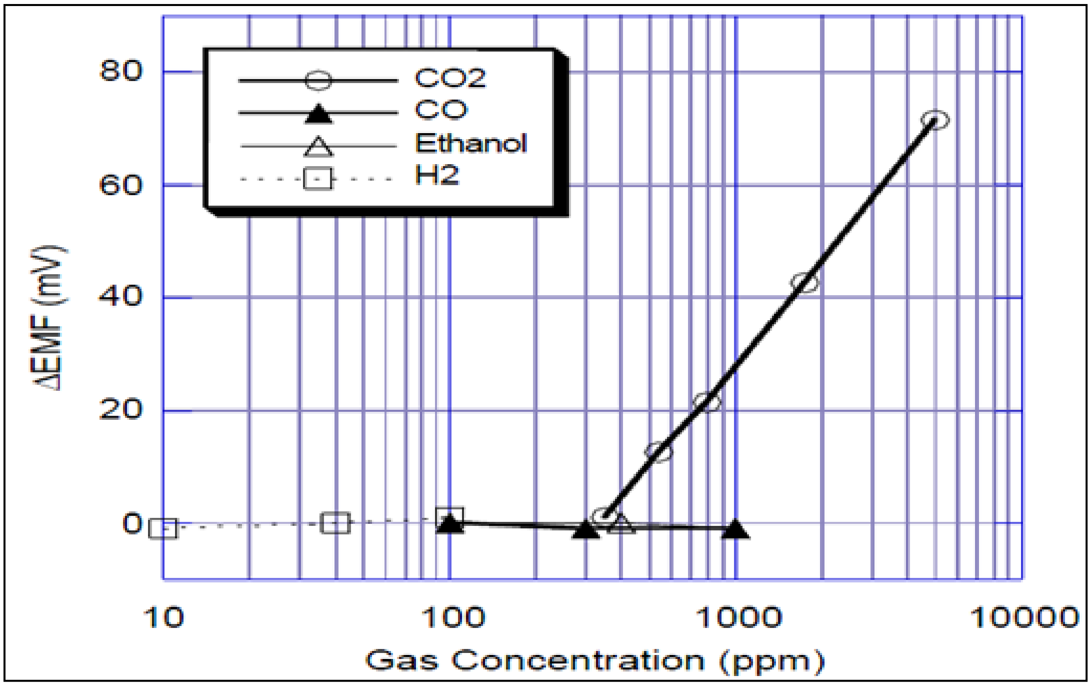


Figure 3-30: Manufacturer's plot

Figure 3-30 shows the manufacturer datasheet's plot of the typical voltage change with CO_2 concentration. Accounting for the way in which manufacturer's data presented, the slope of experimental results is similar to that expected. Equations expressing the relationship between the output voltage and CO_2's density were also obtained from the experimental result.

CO_2 Sensor A: $$\mathrm{CO}_2 = e^{((3.2362 - Vout) \div 0.18)} \tag{3-9}$$

CO_2 Sensor B: $$\mathrm{CO}_2 = e^{((3.5266 - Vout) \div 0.237)} \tag{3-10}$$

CO_2 Sensor C: $$CO_2 = e^{((3.0373 - Vout) \div 0.147)} \tag{3-11}$$

CO_2 Sensor D: $$CO_2 = e^{((3.1228 - Vout) \div 0.133)} \tag{3-12}$$

3.9 Experiment Setup

A number of experiments were carried out to test the accuracy and sensitivity of each sensor. These experiments took place in various locations such as process lab, glasshouse and a backyard. A number of calibrated commercial sensing devices were also used as reference standards for each sensor.

THERM200 and VG400 sensors were tested in a backyard. The area for testing is 1 metre by 1 metre patch of soil. Twelve random locations within the testing area were used for testing the sensors. Calibrated commercial devices such as Fluke temperature meter and MO750 soil moisture meter were also used in this experiment to determine the accuracy of the sensors. During the experiment all sensors were placed next to each other in order to minimize any unwanted potential variances

SHT75 and NORP12 sensors were tested in a glasshouse. Similar to the previous testing method, all sensors were also placed next to each other to minimize unwanted potential variances. These sensors were left running for 2 hours and the sampling interval is of 5 minutes interval. Pre-calibrated devices such as JT-06LX Lux meter and BWGasProbe were also used in the experiment to determine the accuracy of the sensors.

TGS4161's experiment took place in a process engineering laboratory at Massey University. The equipment used in the experiment consisted of: two rotameters, compress air supply, a CO_2 gas cylinder, two pressure regulators, a snap lock bag, a pre-calibrated commercial CO_2 meter (BWGasProbe) and four TGS4161 sensors. The experiment procedures are as follows:

- TGS4161 sensors and BWGasProbe are both enclosed in an air tight snap lock bag
- Compressed air is mixed with CO_2 and blown into the bag for 3 minutes to allow the air inside to be fully replaced with the new air.
- The output concentration of CO_2 can be adjusted to a desired concentration by simply changing the flow rate of either compressed air or the flow rate of input CO_2

3.10 Experimental Results and Discussions

Sensor's experimental data is plotted side by side with a calibrated commercial device. This method was used to allow for a better observation of the sensor's characteristics and its accuracy. Figure 3-31 to Figure 3-36 show the plotted experimental results.

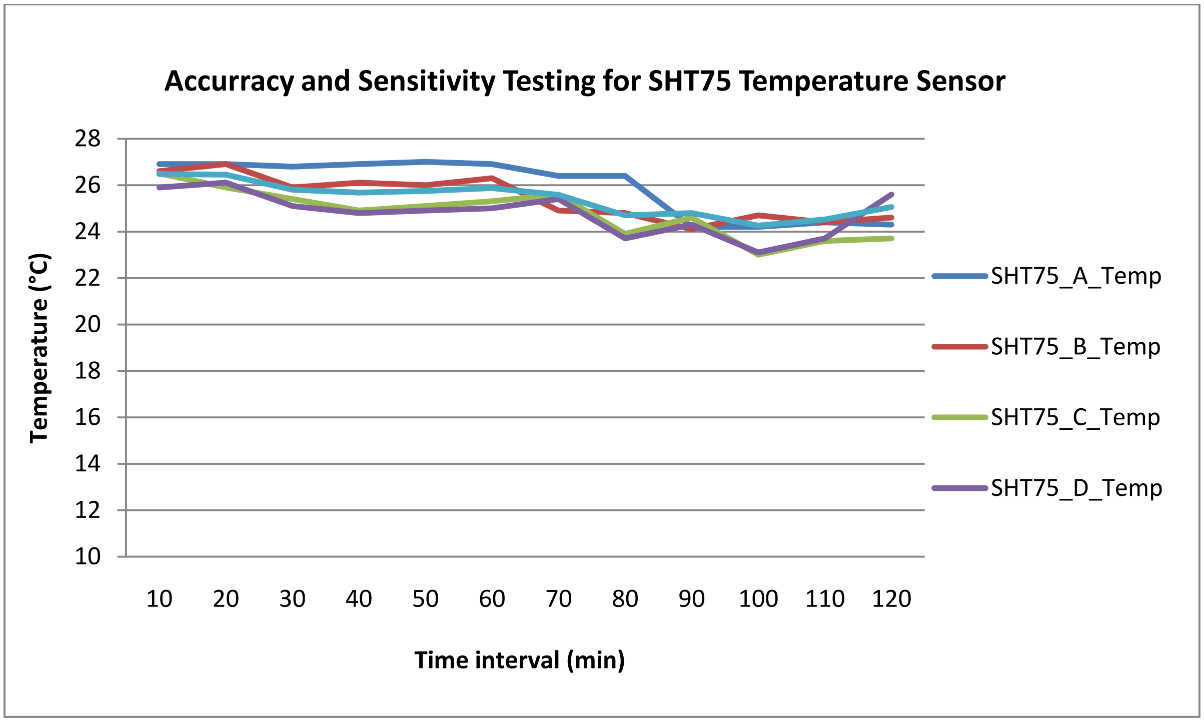


Figure 3-31: Comparison of the experimental results of the SHT75 temperature sensors results and the BWGasProbe temperature sensor

Table 3-5 shows the comparison of the absolute difference in temperature between SHT75 temperature sensors and BWGasProbe temperature detector. The average difference and standard deviation were also calculated for each sensor. According to the experimental result sensor B has the lowest standard deviation (0.214) and sensor A has the highest standard deviation (0487). The standard deviation measures the spread of the data about the mean value [58], which means a low standard deviation indicates that the data points tend to be very close to the mean, whereas a high standard deviation indicates that the data are spread out over a large range of values. Based on this theory, it is possible to conclude that sensor B is more accurate compared to the others.

time (min)	BWGasProbe _Temp (°C)	SHT75_A and BWGasProbe Absolute Diff (°C)	SHT75_B and BWGasProbe Diff Absolute (°C)	SHT75_C and BWGasProbe Absolute Diff (°C)	SHT75_D and BWGasProbe Absolute Diff (°C)
10	26.5	0.4	0.1	0.0	0.6
20	26.5	0.5	0.5	0.5	0.3
30	25.8	1.0	0.1	0.4	0.7
40	25.7	1.2	0.4	0.8	0.9
50	25.8	1.3	0.3	0.6	0.9
60	25.9	1.0	0.4	0.6	0.9
70	25.6	0.8	0.7	0.0	0.2
80	24.7	1.7	0.1	0.8	1.0
90	24.8	0.6	0.7	0.2	0.5
100	24.3	0.1	0.4	1.3	1.2
110	24.5	0.1	0.1	0.9	0.8
120	25.1	0.7	0.4	1.4	0.6
Maximum Diff(°C)		±1.7	±0.7	±1.4	±1.2
Average Diff(°C)		±0.8	±0.4	±0.6	±0.7
Standard Deviation		0.487	0.214	0.428	0.281

Table 3-5: Sensor evaluation and comparison with calibrated instrument (BWGasProbe Temperature Detector)

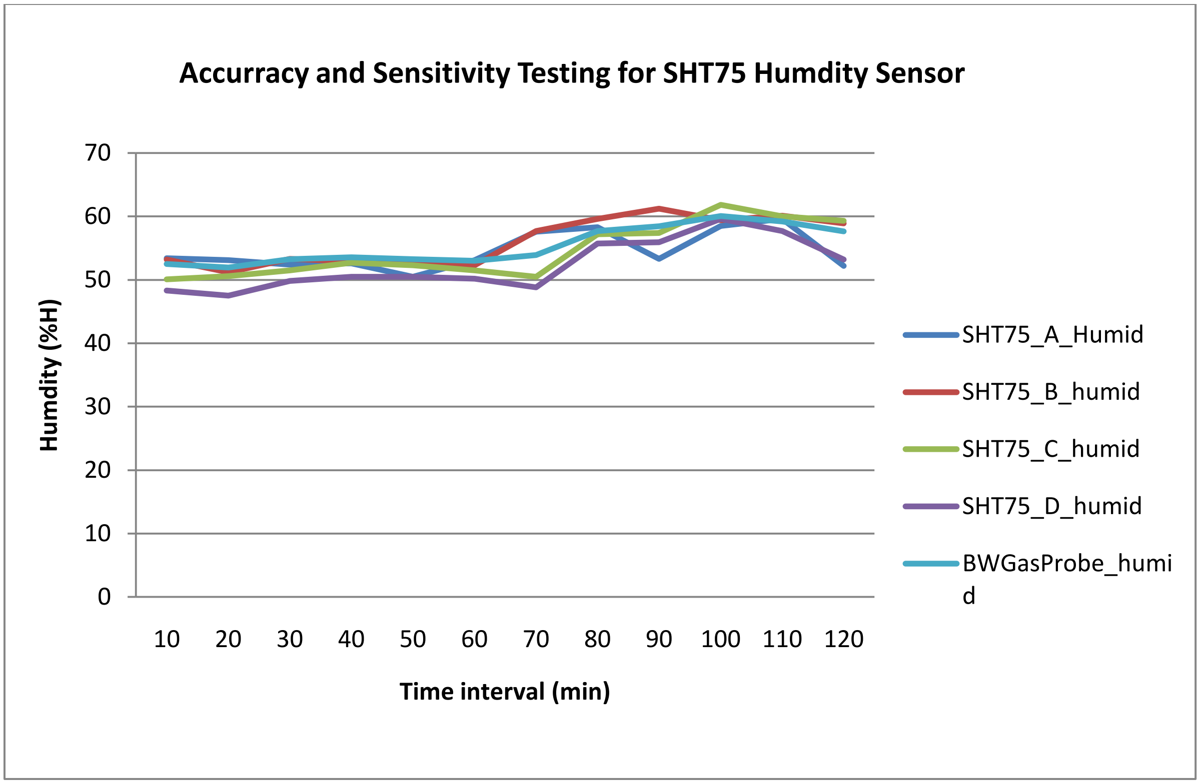


Figure 3-32: Comparison of the experimental results for the SHT75 humidity sensors and the BWGasProbe humidity sensor

Table 3-6 shows the comparison of the absolute difference in humidity between SHT75 humidity sensors and the BWGasProbe humidity detector. The experimental result shows that sensor D has the lowest standard deviation (0.369) and sensor B on the other hand has the highest standard deviation (0.599). Figure 3-31 and Figure 3-312 show the comparison of the experimental results of the SHT75 sensors and BWGasprobe. The experimental plots seem to support the theory behind the relationship between temperature and relative humidity (lowering of relative humidity increases the air temperature and vice versa) [59]. During the experiment, it was discovered that SHT75 sensors have a faster response time than BWGasProbe (according to the experiment, it takes approximately 2 minutes for the BWGasProbe to properly settle with any changes in the surroundings, whereas SHT75's response time is almost instantaneous).

time (min)	BWGasProbe _humid (%RH)	SHT75_A and BWGasProbe Absolute Diff (%RH)	SHT75_B and BWGasProbe Absolute Diff (%RH)	SHT75_C and BWGasProbe Absolute Diff (%RH)	SHT75_D and BWGasProbe Absolute Diff (%RH)
10	52.5	0.9	0.7	1.4	1.2
20	51.9	1.2	0.7	1.3	1.4
30	53.3	0.9	0	1.8	1.5
40	53.6	0.9	0.6	0.8	1.1
50	53.3	1.8	0.5	1	1.8
60	53	0.1	0.7	1.5	1.8
70	53.9	1.7	1.8	1.4	1.1
80	57.7	0.6	1.9	0.5	1.7
90	58.5	1.2	1.8	1.1	1.6
100	60.1	1.6	0.7	1.7	0.5
110	59.2	0.4	0.9	0.8	1.5
120	57.7	1.4	1.3	1.7	1.4
Maximum Difference (°C)		±1.8	±1.9	±1.8	±1.8
Average Difference (°C)		±1.058	±0.967	±1.250	±1.383
Standard Deviation (°C)		0.526	0.599	0.412	0.369

Table 3-6: Sensor evaluation and comparison with calibrated instrument (BWGasProbe humidity detector)

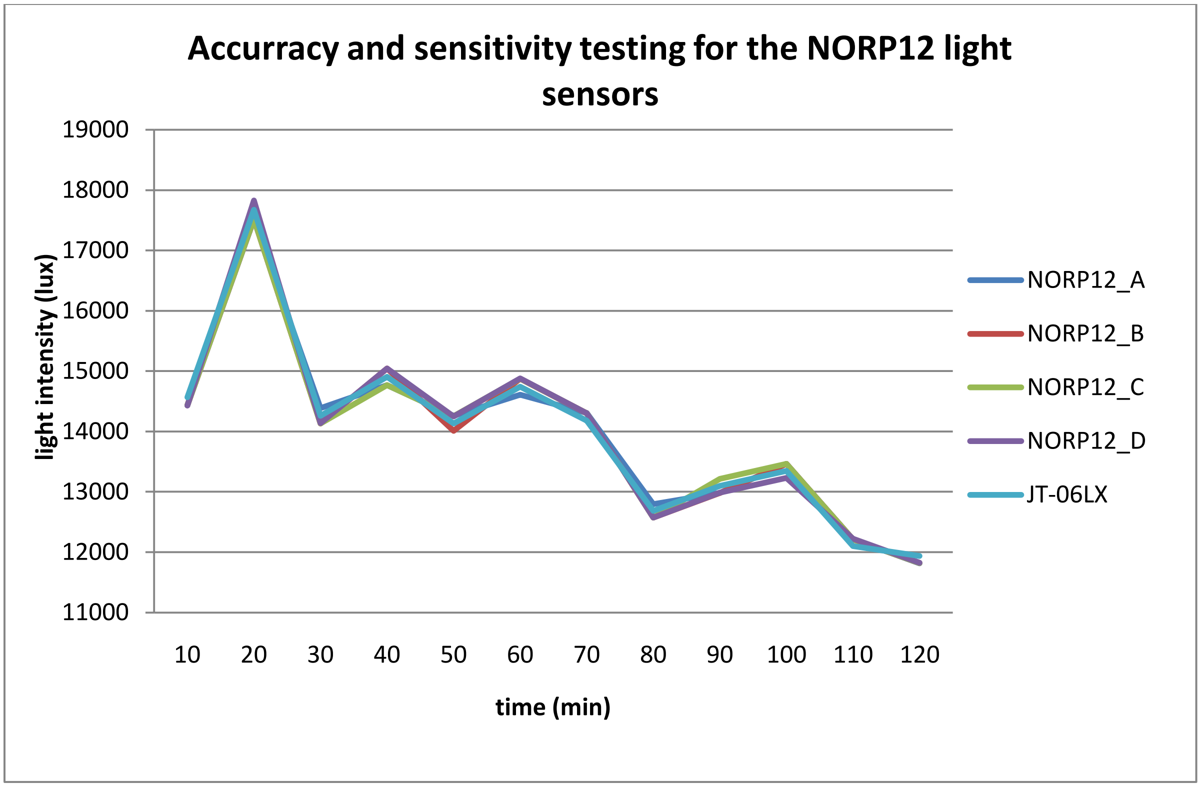


Figure 3-33: Comparison of the experimental results of the NORP12 light sensors and the JT-06LX Lux meter

Table 3-7 shows the comparison of the calculated absolute difference in light intensity between NORP12 sensors and a JT-06LX Lux meter. The experimental result shows that sensor A has the lowest standard deviation value (11.87) when compared to other NORP12 sensors. Figure 3-33 shows the comparison of the experimental results for the NORP12 light sensors and the JT-06LX Lux meter. The experimental result shows a decreasing trend in light intensity over the 2 hours testing period. As expected, both NORP12 sensors and JT-06LX Lux Meter seem to follow this same trend respectively. In terms of the sensor's reaction time to changes in the environment NOPR12 sensors have a very short response time.

time (min)	JT-06LX Lux meter (lux)	NORP12_A and JT-06LX Absolute Diff (lux)	NORP12_B and JT-06LX Absolute Diff (lux)	NORP12_C and JT-06LX Absolute Diff (lux)	NORP12_D and JT-06LX Absolute Diff (lux)
10	14568	132	133	133	139
20	17673	156	150	154	158
30	14258	126	124	124	123
40	14904	133	139	136	141
50	14133	124	122	120	118
60	14741	133	135	135	141
70	14180	125	123	122	122
80	12684	113	112	111	111
90	13099	119	117	115	115
100	13346	119	117	117	115
110	12102	112	110	110	119
120	11936	119	118	117	112
Maximum Difference (°C)		±156	±150	±154	±158
Average Difference (°C)		±125.9	±125	±124.5	±126.2
Standard Deviation (°C)		11.87	11.95	12.82	14.90

Table 3-7: Sensor evaluation and comparison with calibrated instrument (JT-06LX Lux meter)

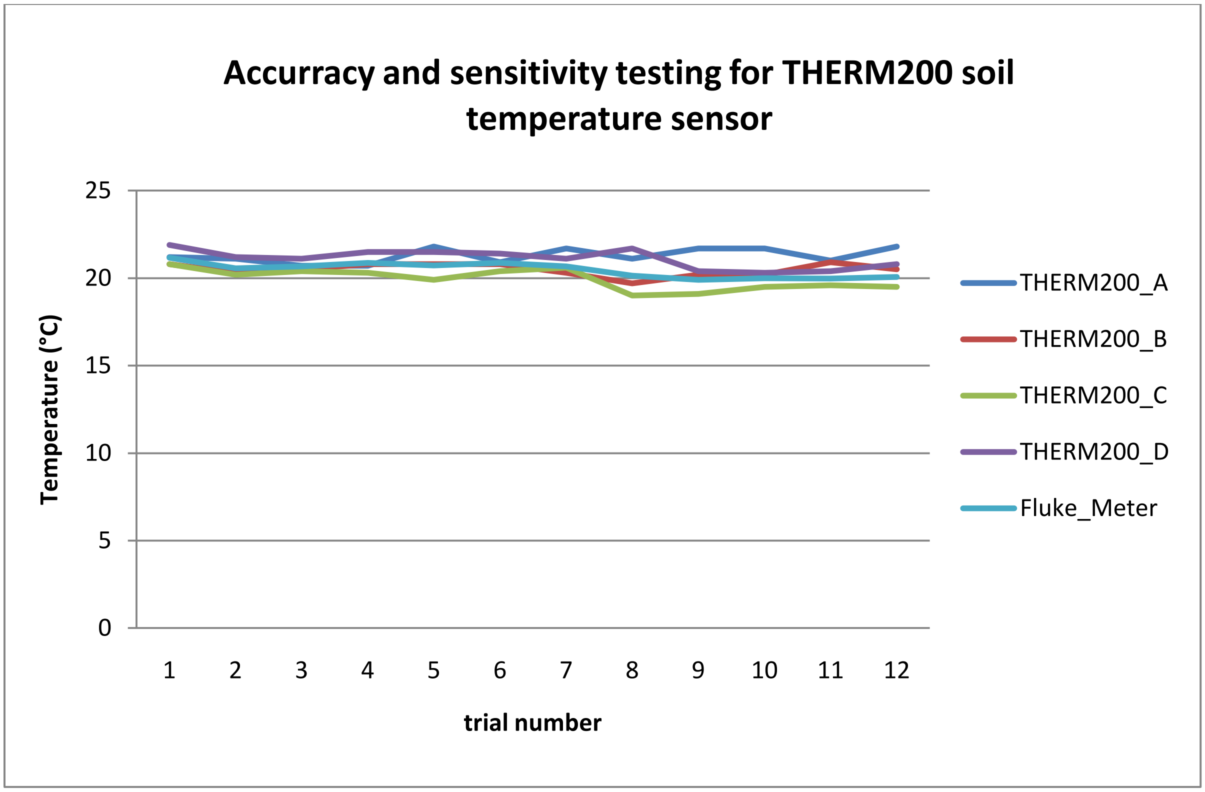


Figure 3-34: Comparison of the experimental results of THERM200 soil temperature sensors and Fluke Temperature Meter

Figure 3-34 shows the comparison of the experimental results of THERM200 soil temperature sensors and the Fluke temperature meter. Table 3-8 shows the comparison of the absolute difference in soil temperature between THERMP200 soil temperature sensors and the Fluke Temperature Meter. The calculated standard deviations show that sensor B has the lowest standard deviation (0.241) and sensor A on the other hand has the highest value of standard deviation (0.681). THERM200 sensor’s reaction time to changes in the surroundings is slightly slower than Fluke temperature meter. It was estimated that the time required for THERM200 to fully stabilize is approximately 30 seconds, which is approximately 10 seconds slower than the Fluke temperature meter. Unlike many temperature sensing technologies available on the market, THERM200 sensors were designed solely to monitor the temperature in the soil, therefore they are more preferred in the agriculture industry.

trial	Fluke Meter (°C)	THERM200_A and Fluke Meter Absolute Diff (°C)	THERM200_B and Fluke Meter Absolute Diff (°C)	THERM200_C and Fluke Meter Absolute Diff (°C)	THERM200_D and Fluke Meter Absolute Diff (°C)
1	21.2	0.0	0.4	0.4	0.7
2	20.6	0.5	0.3	0.4	0.6
3	20.7	0.0	0.2	0.3	0.4
4	20.9	0.2	0.1	0.6	0.6
5	20.7	1.1	0.1	0.8	0.8
6	20.9	0.0	0.1	0.5	0.5
7	20.7	1.0	0.4	0.1	0.4
8	20.1	1.0	0.4	1.1	1.6
9	19.9	1.8	0.3	0.8	0.5
10	20.0	1.7	0.2	0.5	0.3
11	20.0	1.0	0.9	0.4	0.4
12	20.1	1.7	0.4	0.6	0.7
Maximum Difference (°C)		±1.8	±0.9	±1.1	±1.6
Average Difference (°C)		±0.8	±0.3	±0.5	±0.6
Standard Deviation (°C)		0.681	0.241	0.286	0.326

Table 3-8: Sensor evaluation and comparison with calibrated instrument (Fluke Temperature Meter)

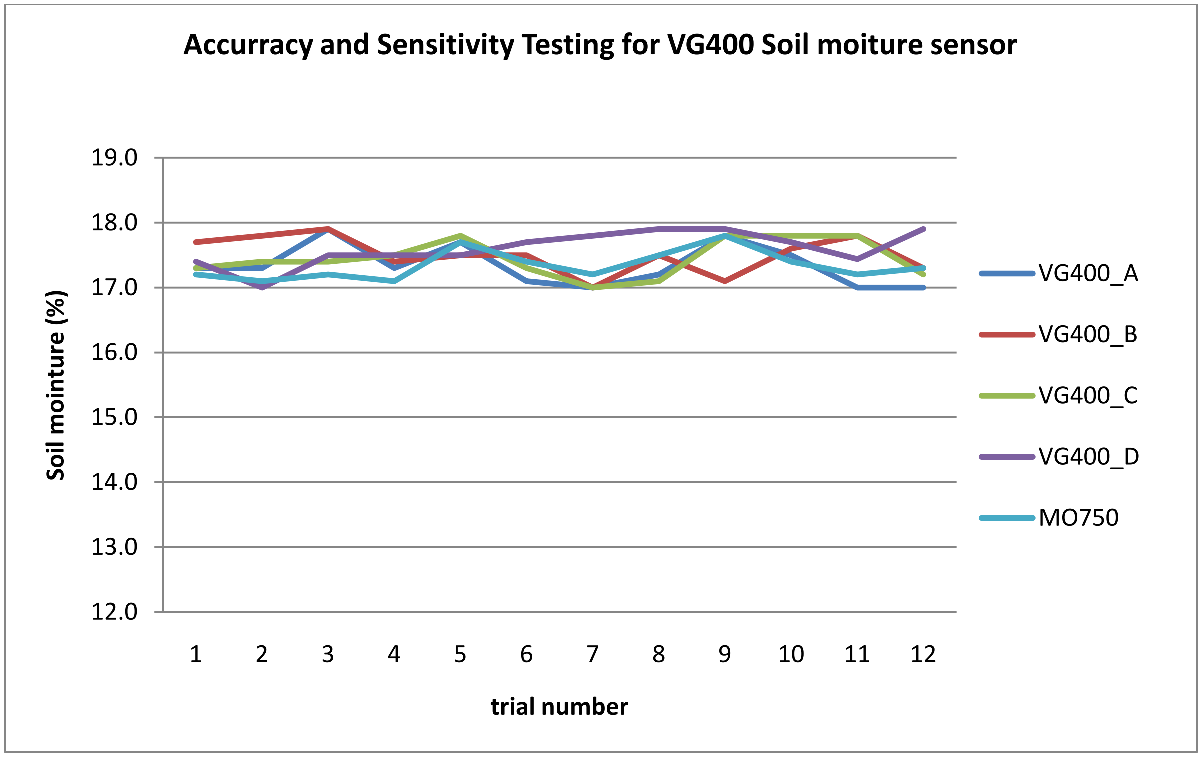


Figure 3-35: Comparison of the experimental results of the VG400 soil moisture sensors and MO750 soil moisture Meter

Figure 3-35 shows the comparison of the experimental results of the VG400 soil moisture sensors and MO750 soil moisture meter. Table 3-9 shows the comparison of the absolute difference in soil moisture between VG400 soil moisture sensors and MO750 soil moisture probe. The calculated standard deviations show that sensor D has the lowest standard deviation (0.166) when compared to other VG400 sensors. Sensor B appeared to have the highest standard deviation (0.275), making it the least accurate out of all 4 soil moisture sensors used in this system. When compared to other soil moisture sensing technologies VG400 offers a rapid response time. It was estimated that the sensor can be inserted into the soil and take a reading in just a matter of a second. VG400 sensor is designed solely for monitoring the moisture level in the soil therefore it will never corrode and is insensitive to salinity.

trial	MO750	VG400_A and MO750 Absolute Diff (%H)	VG400_B and MO750 Absolute Diff (%H)	VG400_Cand MO750 Absolute Diff (%H)	VG400_D and MO750 Absolute Diff (%H)
1	17.2	0.1	0.5	0.1	0.2
2	17.1	0.2	0.7	0.3	0.1
3	17.2	0.7	0.7	0.2	0.3
4	17.1	0.2	0.3	0.4	0.4
5	17.7	0.0	0.2	0.1	0.2
6	17.4	0.3	0.1	0.1	0.3
7	17.2	0.2	0.2	0.2	0.6
8	17.5	0.3	0	0.4	0.4
9	17.8	0.0	0.7	0	0.1
10	17.4	0.1	0.2	0.4	0.3
11	17.2	0.2	0.6	0.6	0.24
12	17.3	0.3	0	0.1	0.6
Maximum Difference (°C)		±0.7	±0.7	±0.6	±0.6
Average Difference (°C)		±0.2	±0.35	±0.24	±0.31
Standard Deviation (°C)		0.185	0.275	0.178	0.166

Table 3-9: Sensor evaluation and comparison with calibrated instrument (MO750 Soil moisture probe)

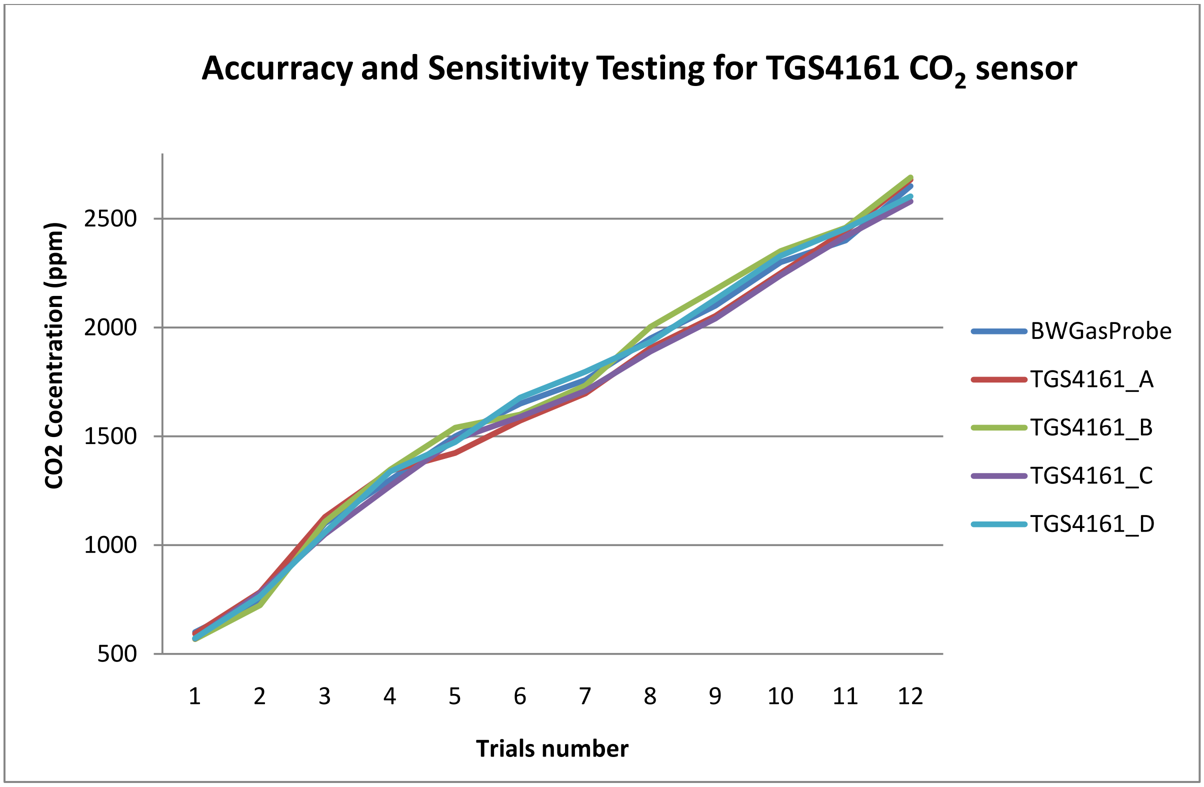


Figure 3-36: Comparison of the experimental results of the TGS4161electrochemical CO_2 sensors and BWGasProbe CO_2 sensor

Figure 3-36 shows the comparison of the experimental results of the TGS4161 electrochemical CO_2 sensors and BWGasProbe CO_2 detector. Table 3-10 shows the comparison of the absolute difference in CO_2 concentration between TGS4161 electrochemical CO_2 sensors and BWGasProbe CO_2 detector. The experimental result shows that sensor D has the lowest standard deviation (11.73) and sensor B has the highest standard deviation (19.79). TGS4161's response time to the changes in CO_2 concentration in the environment is estimated to be approximately 30 seconds. TGS4161 is a solid electrolyte type sensor, therefore it has similar characteristics to a battery. It was later discovered that the output EMF value of the sensor seems to drift slightly over time (estimated an average of 5 ppm every 4 weeks). According to the datasheet, in order to obtain a stable and accurate measurement of CO_2 a special microprocessor called FIC03272 should be used with TGS4161 sensor. The microprocessor takes in the output voltage from the TGS4161 sensor and outputs a signal which corresponds to a concentration of CO2 in the environment. CO_2

concentrations are calculated in the microprocessor based on ΔEMF, which is the change in the value of EMF from the value in a normal clean environment [57].

trial	BWGasProbe (ppm)	TGS4161_A and BWGasProbe Absolute Diff (ppm)	TGS4161_B and BWGasProbe Absolute Diff (ppm)	TGS4161_C and BWGasProbe Absolute Diff (ppm)	TGS4161_D and BWGasProbe Absolute Diff (ppm)
1	600	7	32	29	28
2	750	35	26	30	15
3	1100	30	8	50	40
4	1300	42	48	27	38
5	1500	76	40	14	26
6	1650	77	50	60	28
7	1760	62	26	50	38
8	1950	43	53	60	15
9	2100	46	75	59	30
10	2300	50	52	60	30
11	2400	45	60	20	55
12	2650	30	40	70	46
Maximum Difference		±77	±75	±70	±55
Average Difference		±45.25	±42.5	±44.1	±32.4
Standard Deviation		19.79	17.86	18.89	11.73

Table 3-10: Sensor evaluation and comparison with calibrated instrument

(BWGasProbe CO_2 Detector)

4. Wireless Technologies

4.1 Existing Wireless Technologies

Reducing cable network complexity and operational cost is the main objective of many industrial applications. Many wireless technologies were developed over the last few decades to tackle this specific problem. Thanks to the rapidly increasing trend in the wireless communication industry, many modern day applications are capable of providing a greater level of flexibility and mobility at low cost and low power consumption. Currently there are 14 existing wireless technologies available for personal industrial uses:

- Bluetooth Wireless Technology
- Radio Frequency Identification (RFID)
- Ultra-Wideband (UWB)
- Near Field Communication (NFC)
- Certified Wireless USB
- Near Field Magnetic Communication
- Wi-Fi (IEEE 802.11)
- HiperLan
- WiMax (Worldwide Interoperability for Microwave Access and IEEE 802.16)
- HIPERMAN
- WiBro (Wireless Broadband)
- 802.20
- Infrared (IrDA)
- ZigBee (IEEE 802.15.4)

A survey was conducted in order to determine the popularity of each wireless technology and it was discovered that the most exploited wireless technologies in modern day industries are: Wi-Fi, Bluetooth and ZigBee [5]. Each wireless technology has its own advantages and disadvantages, therefore a careful selection of suitable a wireless technology for the intended application is essential.

4.1.1 Bluetooth

Bluetooth wireless technology is a short range wireless communication intended to replace the cables connecting portable or fixed devices while maintaining a high level of security. Bluetooth operates at 2.4 GHz ISM band and employs the frequency hopping spread spectrum (FHSS) modulation technique [60]. Bluetooth has been considered as one possible alternative for WSN implementation[61]. A fundamental strength of Bluetooth wireless network is the ability to simultaneously handle data and voice transmissions, which provides users with a variety of innovative solutions such as hands-free headsets for voice calls, printing and fax capabilities, and synchronization for PCs and mobile phones at low power and low cost.

The main features of Bluetooth are [62]:

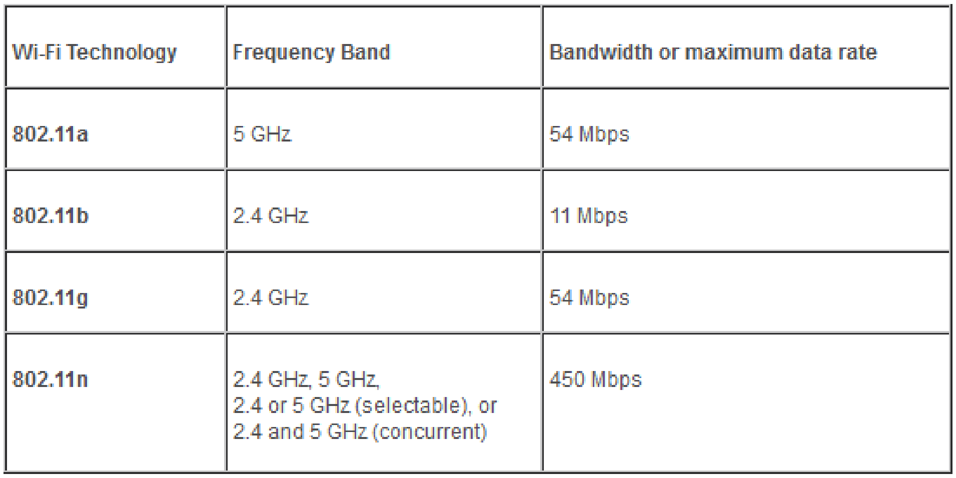
- Bluetooth technology operates in the unlicensed industrial, scientific and medical (ISM) band at 2.4 to 2.485 GHz, using a spread spectrum, frequency hopping, full-duplex signal at a nominal rate of 1600 hops/sec.
- Bluetooth technology's adaptive frequency hopping (AFH) capability was designed to reduce interference between wireless technologies sharing the 2.4 GHz spectrum.
- Data Rate
  - 1 Mbps for Bluetooth low energy technology.
  - 1 Mbps for Version 1.2; Up to 3 Mbps supported for Version 2.0 EDR.
  - Up to 24 Mbps supported for Version 3.0 HS.
- Range may vary depending on class of radio used in an implementation:
  - Class 3 radios – have a range of up to 1 metre or 3 feet
  - Class 2 radios – most commonly found in mobile devices – have a range of 10 metres or 33 feet.
  - Class 1 radios – used primarily in industrial use cases – have a range of 100 metres or 300 feet.

4.1.2 Wi-Fi

Wi-Fi is commonly called wireless Local Area Networks (WLAN), it is one of the networks in which high frequency radio waves (usually at 2.4 GHz or 5 GHz) bands are required for transmission of data from one place to another. Wi-Fi operates on several hundred metres between two places of data transmission and they support 2 modes of operation [5]:

- Ad-Hoc mode – allows stations to spontaneously form a wireless LAN, in which all stations communicate with each other in a peer-to-peer manner
- Infrastructure – the network has an access point (AP), through which each client station communicates. A typical Wi-Fi AP may have range of 45 m indoors and 90 m outdoors

Wi-Fi was intended to be used for mobile computing devices, such as laptops, in LANs, but is now often used for increasingly more applications, including Internet, gaming, and basic connectivity of consumer electronics such as televisions and DVD players. There are four generations of Wi-Fi product available [63]. Each generation is defined by a set of features that relate to performance, frequency and bandwidth.



Wi-Fi Technology	Frequency Band	Bandwidth or maximum data rate
802.11a	5 GHz	54 Mbps
802.11b	2.4 GHz	11 Mbps
802.11g	2.4 GHz	54 Mbps
802.11n	2.4 GHz, 5 GHz, 2.4 or 5 GHz (selectable), or 2.4 and 5 GHz (concurrent)	450 Mbps

Table 4-1: Wi-Fi Generations [63]

The main features of Wi-Fi are [63]:

- Wi-Fi products operate in the 2.4GHz or 5GHz bands
- Interoperability – means any Wi-Fi product from different manufactures can work together
- Backward compatibles – means new Wi-Fi products are able to work with older Wi-Fi products that operate in the same frequency band
- Robustness

4.1.3 ZigBee

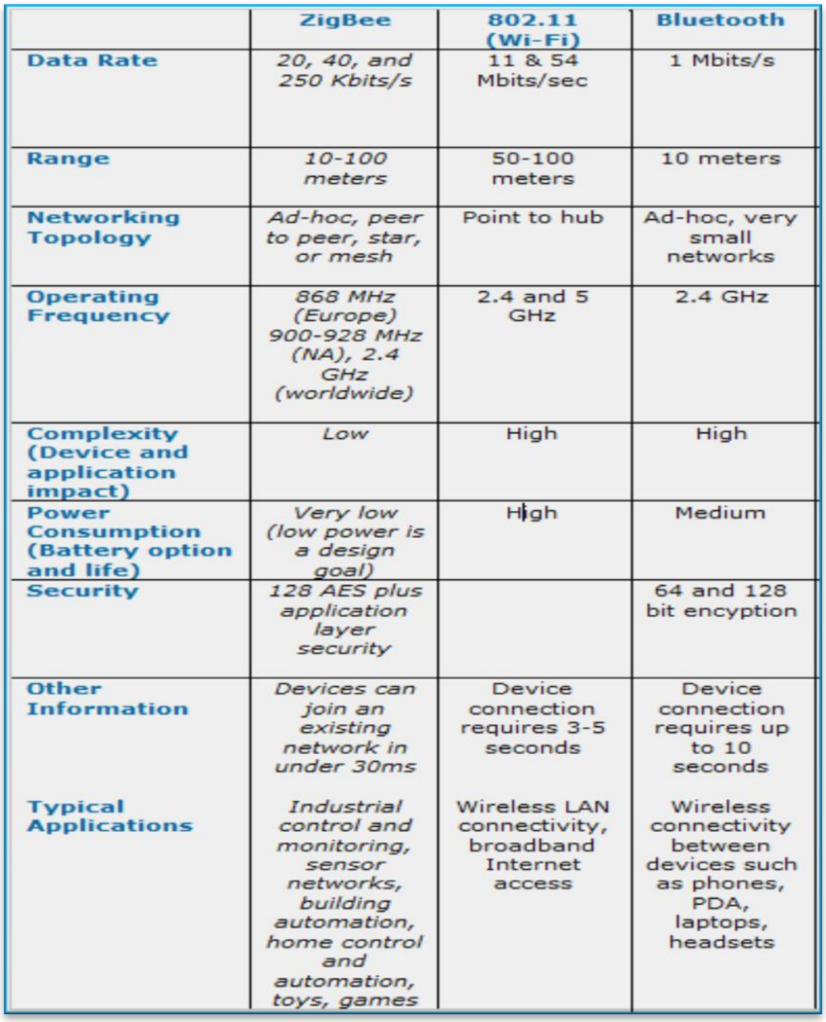
ZigBee is a new upcoming technology for short range wireless communications. ZigBee standard is being promoted and developed by ZigBee alliance which contains more than 200 members including company like TI, Freesacle, Philips and Samsung[64]. ZigBee data link layer is designed to operate on top of the IEEE 802.15.4 standard. The IEEE 802.15.4 standard is a simple packet data protocol for light weight wireless networks and specifies the Physical (PHY) and Medium Access Control (MAC) layers for multiple Radio Frequency (RF) bands, including 868 MHz, 915 MHz and 2.4 GHz [64].

ZigBee aims for cost sensitive, home and building automation [61]. Unlike many other wireless technologies such as Wi-Fi and Bluetooth, ZigBee devices provide reliable data transmission up to 100 metres or more while consuming a very small amount of power. They also support several different topologies, which make them ideal for any type of applications that is required to be both portable and low power consumption. The main features of ZigBee are [65]:

- Service discovery
- Master / Slave topology
- Automatic network configuration
- Dynamic slave device addressing
- Full handshaking for packet transfers (reliable data transfer)
- CSMA/CA channel access mechanism
- Data rate of 20kbps at 868 MHz, 40kbps at 915 MHz and 250kbps at 2.4 MHz
- Power management features

4.1.4 Comparison of ZigBee, Wi-Fi and Bluetooth

While there are many wireless technologies available on the market, ZigBee, Bluetooth and Wi-Fi are the only technologies that have the technical maturity to deliver the performance and low cost required in today wireless applications [66]. Each wireless technology has its strengths and weaknesses and having a good understanding of these characteristics will allow the end users to determine the most suitable wireless technology for their applications. Table 4-2 shows the comparison of these three wireless technologies, on the basis of their frequency range, technology, performance, range, power consumption etc.



	ZigBee	802.11 (Wi-Fi)	Bluetooth
Data Rate	*20, 40, and 250 Kbits/s*	11 & 54 Mbits/sec	1 Mbits/s
Range	*10-100 meters*	50-100 meters	10 meters
Networking Topology	*Ad-hoc, peer to peer, star, or mesh*	Point to hub	Ad-hoc, very small networks
Operating Frequency	*868 MHz (Europe) 900-928 MHz (NA), 2.4 GHz (worldwide)*	2.4 and 5 GHz	2.4 GHz
Complexity (Device and application impact)	*Low*	High	High
Power Consumption (Battery option and life)	*Very low (low power is a design goal)*	High	Medium
Security	*128 AES plus application layer security*		64 and 128 bit encyption
Other Information	*Devices can join an existing network in under 30ms*	Device connection requires 3-5 seconds	Device connection requires up to 10 seconds
Typical Applications	*Industrial control and monitoring, sensor networks, building automation, home control and automation, toys, games*	Wireless LAN connectivity, broadband Internet access	Wireless connectivity between devices such as phones, PDA, laptops, headsets

Table 4-2: Comparison of ZigBee, Wi-Fi and Bluetooth [67]

ZigBee is used mainly for remote monitoring and control applications, which typically have very low bandwidth requirements (20-250 kbps). Bluetooth is primary a cable replacement for point-to-point of consumer devices and the Wi-Fi technology is a network technology developed for data-intensive communication such as audio/video streaming and graphic web browsing. Based on the information provided by Table 4-2, ZigBee technology is capable of providing large scale low power networks and devices that could run for years on inexpensive batteries. Wi-Fi and Bluetooth on the other hand, have much higher power requirements, therefore the battery running time will be a lot shorter.

The protocol complexity between each device was compared and the result shows that Bluetooth is the most complicated protocol with 188 primitives and events in total. ZigBee on the other hand is the simplest one with only 44 primitives defined in 801.15.4[68]. This result indicates that ZigBee is the most suitable for sensor networking applications. Figure 4-1 shows the comparison of the complexity of each protocol

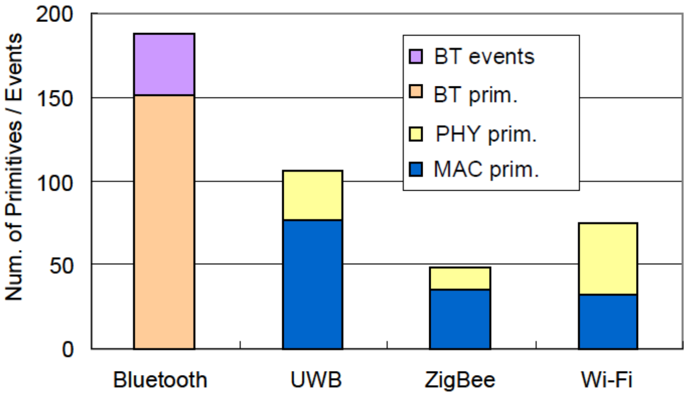


Figure 4-1: Comparison of the complexity for each protocol [68]

4.1.5 Conclusions

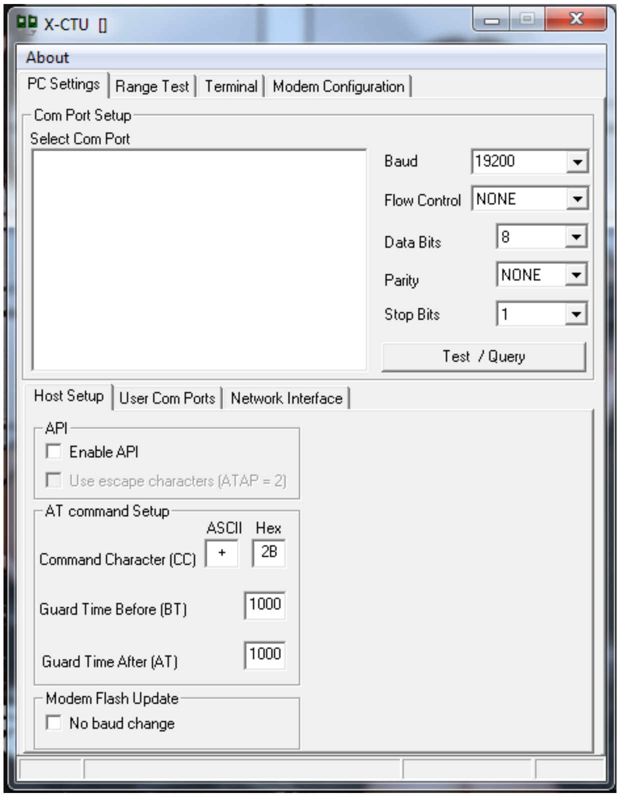
In conclusion, this section does not draw any conclusions regarding which wireless technology is more superior, since the suitability of wireless technology is solely dependent on the application. For example, ZigBee wireless technology cannot be applied to high data implementations applications such as audio/video streaming and graphic web browsing because of their high bandwidth requirements. Bluetooth and Wi-Fi on the other hand are not suitable for battery powered applications because of their high power consumption characteristics. For this particular project ZigBee wireless technology was chosen for a number of reasons:

- ZigBee has very low power consumption
- Low network complexity
- Is designed for remote monitoring and control applications
- ZigBee Networks can scale to hundreds and thousands of devices

4.2 ZigBee Wireless Communication

4.2.1 ZigBee Configuration

ZigBee wireless module is required to be configured before it can be used. To configure ZigBee module, a software program called XCTU is required. This software can be installed for free on Digi website. Figure 4-2 shows the layout of the XCTU program.



Baud 19200
Flow Control NONE
Data Bits 8
Parity NONE
Stop Bits 1

☐ Enable API
☐ Use escape characters (ATAP = 2)

	ASCII	Hex
Command Character (CC)	+	2B

Guard Time Before (BT) 1000
Guard Time After (AT) 1000

☐ No baud change

Figure 4-2: XCTU Configuration tab

The software program consists of 4 main tabs: PC Settings, Range Test, Terminal and Modem configuration

- PC setting tab – Allows the user to select between plugged in ZigBee devices for configurations
- Range test – Allows the user to test the range of wireless communication between two ZigBee modules.
- Terminal – Allows access to the computer's COM port with a terminal emulation program. This tab also allows the ability to access the radio's firmware using AT commands [69]
- Modem Configuration – Allows the user to program and configure ZigBee devices

To setup a ZigBee wireless communication network, the following requirements are needed:

- The communication network must have at least one coordinator
- All devices must have the same PAN ID and baud rate
- DL - Destination Address Low :
    - Set coordinator device to FFFF (broadcast mode)
    - Set end device to 0

If everything is setup correctly, wireless communication can be established between coordinator and end devices. This type of communication is referred to as point to point or point to multi-point communication.

4.2.2 ZigBee Feasibility

4.2.2.1 Experimental Setup

An experiment was carried out to test the reliability and feasibility of ZigBee wireless communication. This experiment was carried out to reassure the statement made by the company on the performance of ZigBee (100 m outdoors/line of sight range, 60 m indoor/urban range [65]). The School of Engineering and Advanced Technology (SEAT) was used as the test environment. The reason behind this selection is because the SEAT building is equipped with many equipment and radio devices which will put the performance of ZigBee wireless technology to the test. The components required for the experiment are as follows:

- Two ZigBee wireless modules, one is configured as Coordinator and the other as End-Device
- One USB A to B cable
- ZigBee explorer USB breakout board
- ZigBee explorer Serial breakout board
- Loop-back adaptor (acts as a repeater by looping data back for retransmission)
- A personal computer
- And a 9V alkaline battery

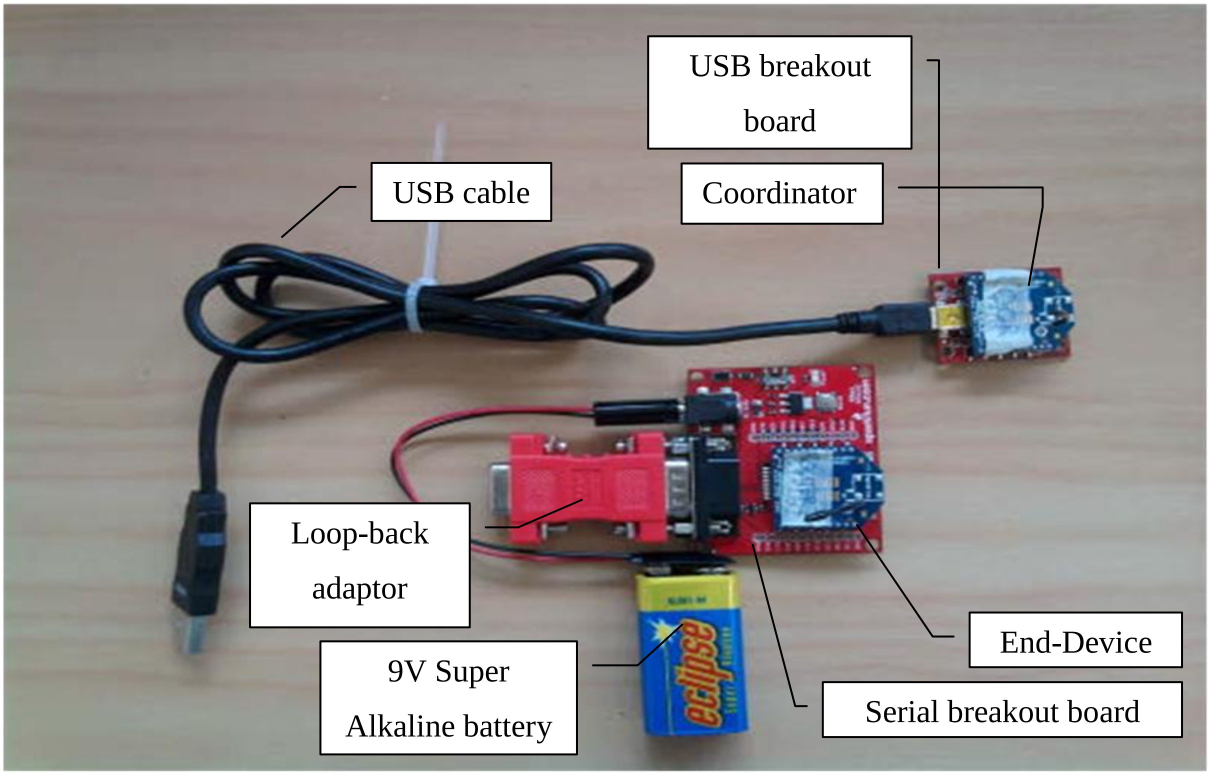


Figure 4-3: Components for ZigBee testing

The step by step setup of the experiment is as follows:

- Mount ZigBee Coordinator module onto the USB breakout board and connect it to the PC via USB cable
- Mount ZigBee End-device module onto the serial breakout board and attach the loop-back adaptor to the serial port of the breakout board.
- 9V alkaline battery will be used to power up the serial breakout board as well as the ZigBee device.

The testing procedure is fairly straightforward. Basically, the experiment is consistes of a series of tests to determine of the strength of the ZigBee radio signal with respect to the change in displacement between the coordinator and the end-device (typically an increase of 5m at the end of every test). With every test, twenty sample data packets are transmitted by the coordinator to the end-device. The reliability of the transmission is determined based on the number of received respond data packets with respect to the number of transmitted data packets. The results from the experiment will be explained in detail in the next section

4.2.2.2 Experimental Results

The experimental result is shown in Figure 4-4. As stated by Digi, the range of ZigBee wireless module is an approximately 60m indoor/urban area [65]. This statement was found to be correct according the result obtained from the experiment. As shown in Figure 4-4, the transmitted data packets were received in full at 60m and below. However, the signal strength drops significantly when the displacement increased above this limit. As the result, the number of packets received is reduced by a half at 65 m and totally at 75 m.

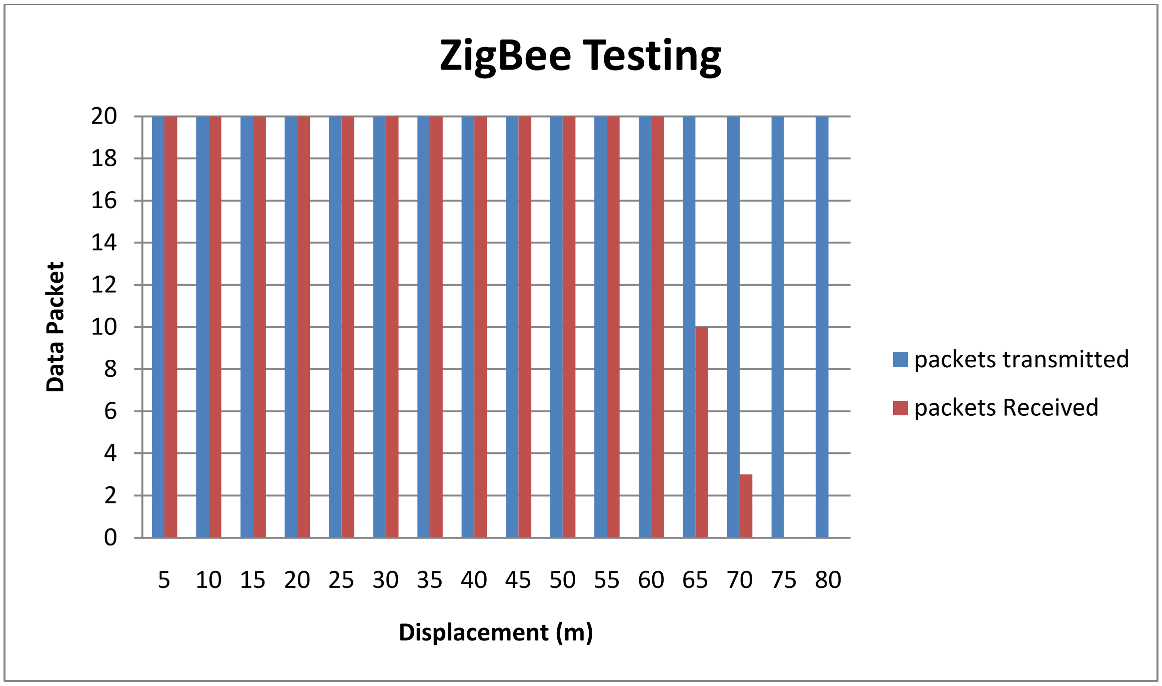


Figure 4-4: Testing the strength of ZigBee radio signal with respect to the changes in the displacement between coordinator and end device

4.2.2.3 Discussion

ZigBee wireless transmission is considered to be very stable and reliable when it operates within the recommended range. ZigBee was found to be very robust to external interferences (no sign of fluctuations in signal strength were found). A small delay between transmissions was detected when the range increases above 50m however this delay is negligible, therefore it can be neglected. In general, to ensure reliable data transmission it is recommended to limit the range to below 45m.

5. System Integration

5.1 Design Specifications

Before the system can be developed and implemented, it is important to specify the design specifications and requirements necessary for the development of the system. This section explains these design specifications and requirements in detail.

5.1.1 Central Station Requirements

The central station needs to be able to:

- Send a data collection request to coordinator station
- Send control instructions to coordinator station
- Data processing
- Data storage
- Visually display real-time data

5.1.2 Coordinator Station Requirements

The coordinator station needs to be able to:

- Receive requests and instructions from the central station
- Analyze the instruction packet
  - If it's a data collection request, forward the instruction to sensor station
  - If it's a climate control request, send an signal to activate the relay circuit
- Collect a data packet from the sensor station and send it to the central station.

5.1.3 Sensor Station Requirements

The sensor station needs to be able to:

- Receive a data collection request from the coordinator station
- Collect data from the environment

- Perform analog to digital conversion on the collected data
- Send data packets to the coordinator station

5.1.4 Development Platform

The development platform used for this project can be any type of high level languages such as VB, Java, Python and .NET. However it is up to the user’s ability to comfortably program and implement an application using any one of these high level languages. My programming knowledge is best in C#, therefore choosing a development platform wasn’t a very difficult task. Microsoft Visual C # 2010 Express editions is freeware from MSDN, therefore there was no need to purchase the software.

5.1.5 Design Constraints

The following are the design constraints that needed to be considered:

- The system must be compact and portable
- The system must have low power consumption
- The system must be reliable, robust and have a friendly user interface.

5.2 System Overview

Previous systems often consisted of two stations: a sensor station and a control station, which allowed major advances and efficiency in greenhouse climate monitoring. However there are two weaknesses that existed in these systems:

- Let’s assume that the communication between the sensing unit and the control unit is achieved via ZigBee wireless modules. The wireless range of a ZigBee module is 60 metres indoor/urban and 100 metres outdoors/line-of-sight, which means that the distance between the sensing unit and the control unit will be limited. Future relocation of the system can be frustrating, as changes in the location of one station will also require relocation of the other.

- The wireless range can be improved by replacing ZigBee modules with long range RF modems. However, there are two key issues that need to be considered when implementing this method. Firstly, the cost of long range RF modems is overly expensive. In this system, each measurement point requires one RF modem for communication. Therefore, increases in the measurement point means increases in the installation cost. Secondly, modern greenhouses are typically big, therefore measurement point increases are unavoidable. As the result, a dramatic increase in installation is almost certain.

To overcome these weaknesses, the proposed system consists of three stations: Sensor Station, Coordinator station, and Central station. The diagram of the management system is shown on Figure 5-1.

- The greenhouse station is basically a data acquisition unit. It's responsible for collecting climate variables such as temperature, humidity, soil temperature, soil moisture, light and $CO_{2,}$ and transmits the collected data to coordinator station via XBee wireless modules.
- The coordinator station acts as a router. It controls the flow of data and instructions between the sensor station and the central station in a pre-programmed manner. It also manages the local activities such as sprinkler, humidifier, exhaust fan etc.
- The central station is the main controller of the system. Its jobs are to:
    - Issue instructions to the coordinator station.
    - Process incoming data and provide an easy and convenient way that allows the users to easily access the data.
    - Store and Display real-time data.
    - Manage the greenhouse climate.

The advantages of the proposed designed in comparison to previous works are:

- ✓ The system is scalable – more measurement points can be added to the system at only a fraction of the cost
- ✓ Is flexible and reliable
- ✓ Easy to relocate once installed
- ✓ Small and compact
- ✓ Maintenance is relatively cheap and easy

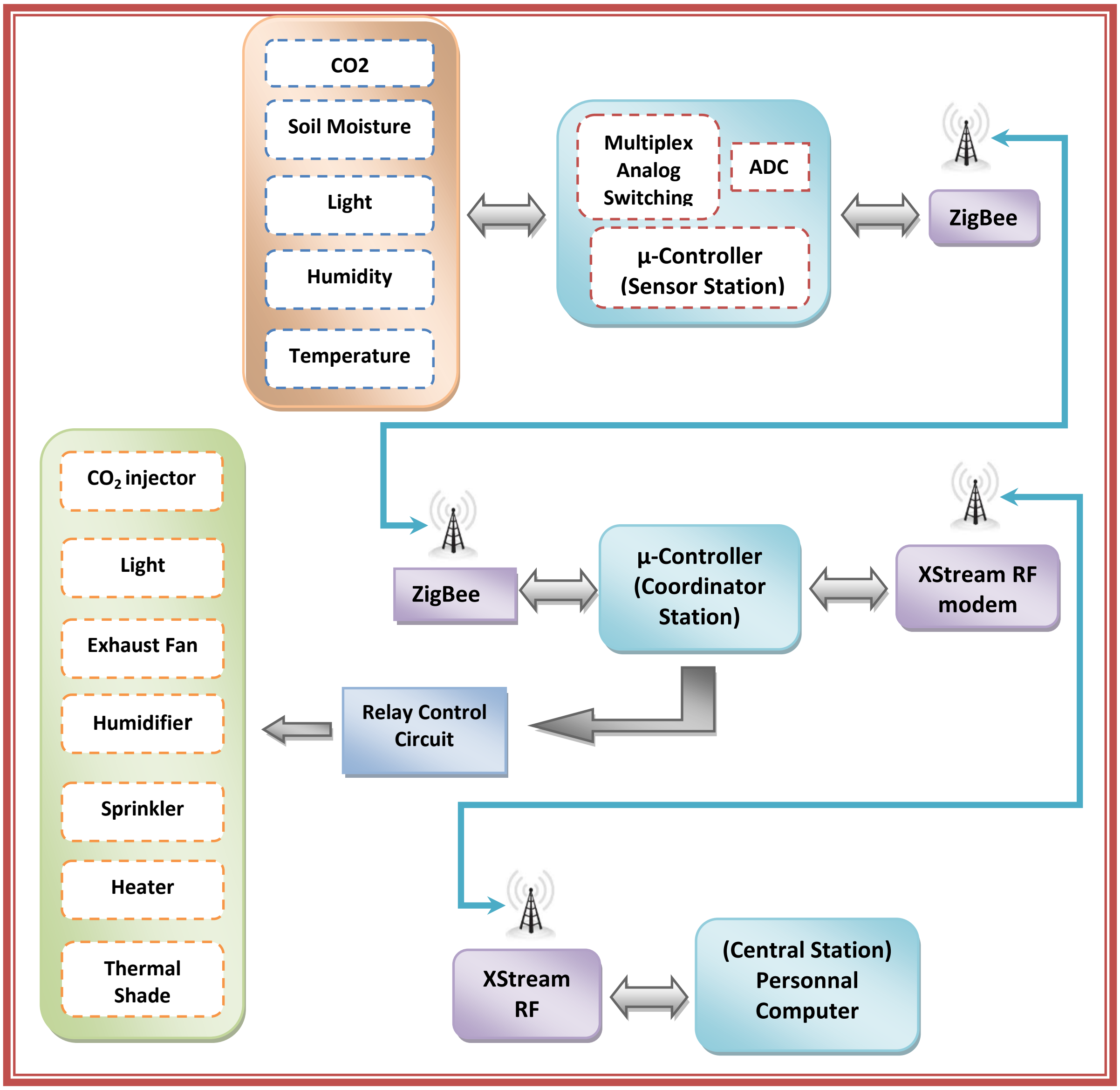


Figure 5-1: System overview

5.3 Overall Hardware Design

For hardware design the building blocks are:

- Processing unit
- Transceiver unit
- Sensor unit
- Battery level detection unit
- Relay control unit

5.3.1 Processing Unit

Both the sensor station and coordinator station require a Central Processing Unit (CPU) in order to perform various tasks such as data acquisition, data processing and data transmission. Therefore a microcontroller was integrated into each station. It is an integrated chip that has a Central Processing Unit (CPU), Random Access Memory (RAM), Read Only Memory (ROM), on chip timers, digital to analog converter and many other components that are also presented on a computer. There are a large number of commercially available microcontrollers on the market today. Depending on the type of application, each micro-controller has its advantages and disadvantages. The C805F020 microcontroller was selected for this application. This particular microcontroller was chosen for several reasons, including its ease of programming, reliability, power and robustness.

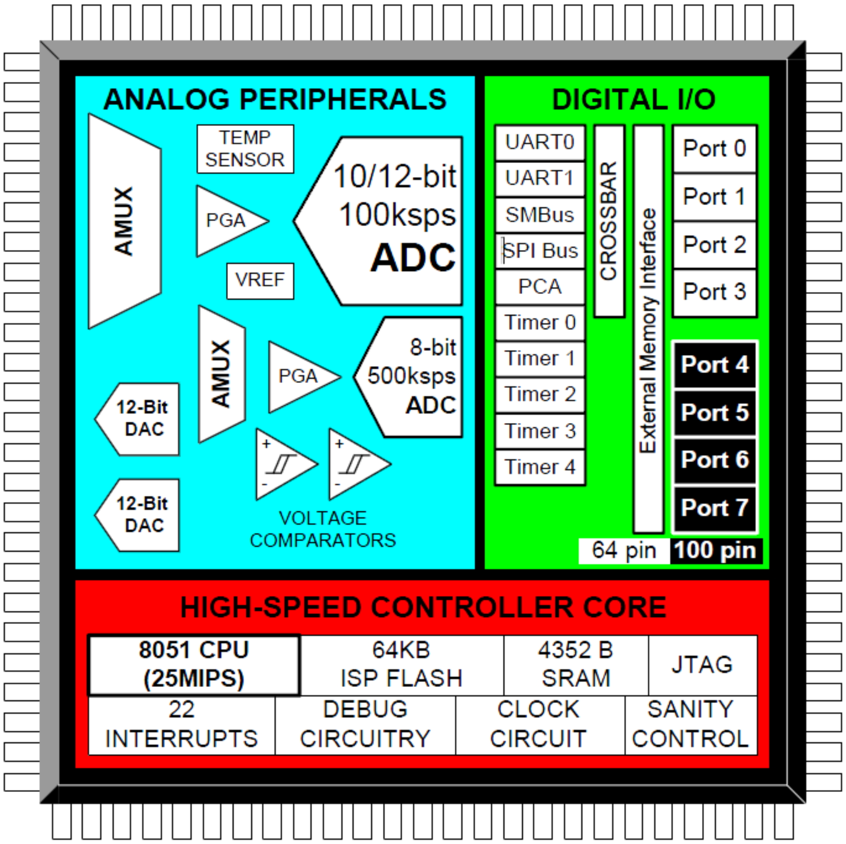


Figure 5-2: C8051F020 system overview [70]

Some of the benefits in using the C8051F020 are:

- Providing more computational power
- Has low power consumption
- Equipped with a full set of analog and digital processors.
- Has embedded debugging and in-system flash programming through a standard JTAG interface
- Has the ability to process data at a high speed.

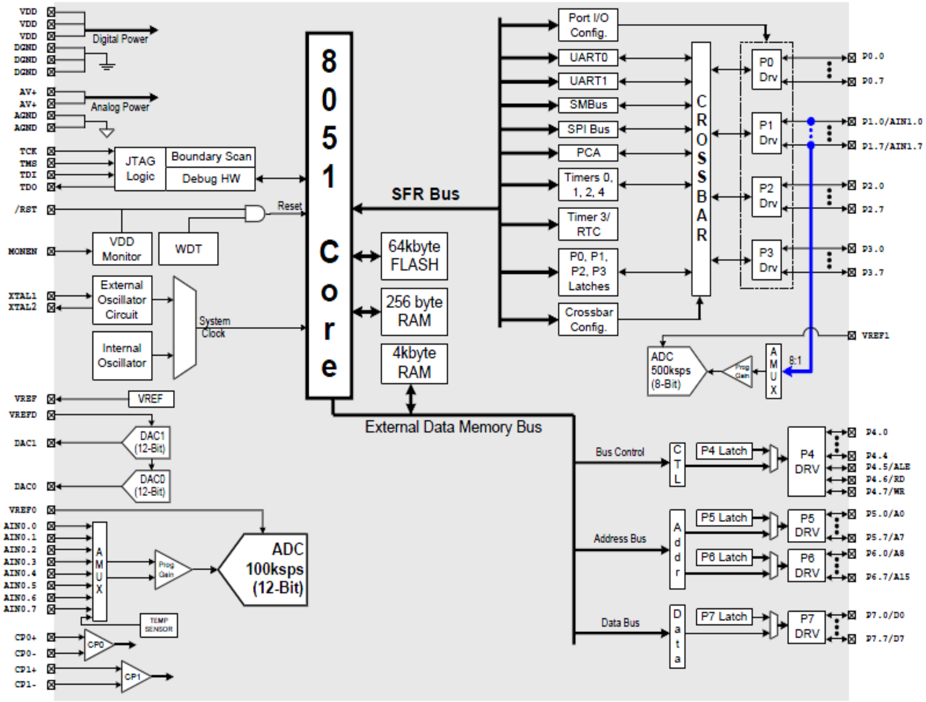


Figure 5-3: Block Diagram of C8051F020 [70]

It main features [70] are listed as follows:

- High-Speed pipelined 8051-compatible CIP-51 microcontroller core (up to 25 IPS)
- In-system, full-speed, non-intrusive debug interface (on-chip)
- True 12-bit (C8051F020/1) or 10-bit (C8051F022/3) 100 ksps 8-channel ADC with PGA and analog multiplexer
- True 8-bit ADC 500 ksps 8-channel ADC with PGA and analog multiplexer
- Two 12-bit DACs with programmable update scheduling
- 64k bytes of in-system programmable FLASH memory
- 4352 (4096 + 256) bytes of on-chip RAM
- External Data Memory Interface with 64k byte address space
- SPI, SMBus/I2C, and (2) UART serial interfaces implemented in hardware
- Five general purpose 16-bit Timers
- Programmable Counter/Timer Array with five capture/compare modules
- On-chip Watchdog Timer, VDD Monitor, and Temperature Sensor

5.3.2 Transceiver Unit

Several XBee 2mW series 2.5 were used for the communication between the sensor stations and the coordinator station. The XBee wireless module was designed to operate within the ZigBee wireless protocol. It provides a low cost, fast response and reliable solution for any type of wireless application.

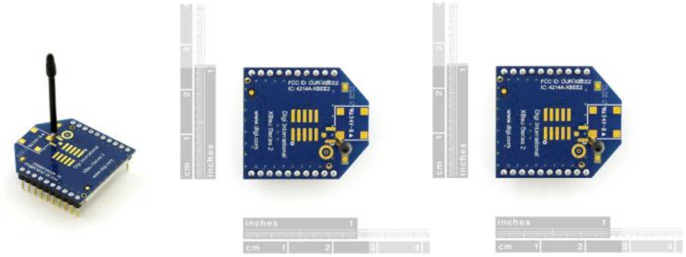


Figure 5-4: XBee 2mW series 2.5

Its main features [71] are listed as follows:

- **Long Range Data Integrity**
  - Indoor/Urban: up to 30 m
  - Outdoor line-of-sight: up to 100 m
  - Transmit Power: 1 mW (0 dBm)
  - Receiver Sensitivity: -92
  - Data Rate: 250,000 bps
- **Advanced Networking & Security**
  - Retries and Acknowledgements
  - DSSS (Direct Sequence Spread Spectrum)
  - Each direct sequence channels has over 65,000 unique network addresses available
  - Source/Destination Addressing
  - Unicast & Broadcast Communications
  - Point-to-point, point-to-multipoint and peer-to-peer topologies
  - Supported Coordinator/End Device operations

- **Low Power**
    - TX Current: 45 mA (@3.3 V)
    - RX Current: 50 mA (@3.3 V)
    - Power-down Current: < 10
- **ADC and I/O line support**
    - Analog-to-digital conversion, Digital I/OI/O
    - Line Passing

For the communication between the coordinator station and central station long range wireless modems were used. The purpose of using long range wireless communication is to allow the operator to monitor and manage the greenhouse environment without having the need for the central station to be placed close to the greenhouse. The long range wireless transceiver used in this project is a stand-alone 2.4 GHz XStream-PKG RF modem purchased from Digi Company

Figure 5-5: 2.4 GHz XStream-PKG RF modem

It main features [72] are listed as follows

- **Long Range at a Low Cost**
    - Indoor/Urban: 180 m
    - Outdoor line-of-sight: up to 16 km with high gain antenna
    - Receiver sensitivity: -110 dBm (@ 900 MHz), –105 dBm (@ 2.4 GHz)
- **Advanced Networking & Security**
    - True Peer-to-Peer (no “master” required)
    - Point-to-Point
    - Point-to-Multipoint

  - Retries and Acknowledgements
  - FHSS (Frequency Hopping Spread Spectrum)
  - hopping channels, each with over 65,000 unique network addresses available

5.3.3 Sensor Unit

The sensor may be classified in two categories according to the data transferred by them to processing unit:

- Analog Sensor – give an output as analog signal
- Digital Sensor – give an output as digital signal

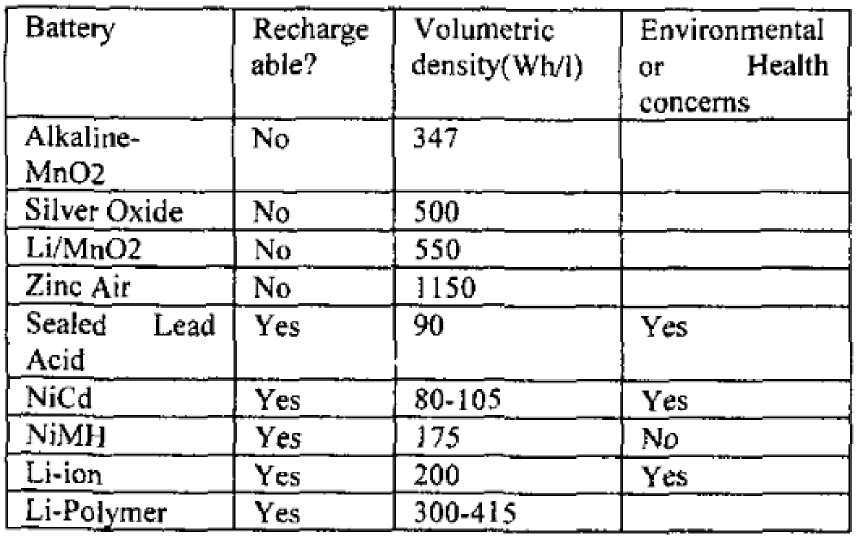
The sensor unit is made up of 1 digital sensor and 4 analog sensors:

- SHT75 [51] relative humidity and temperature digital sensor.
- TGS4161 [57] solid electrolyte CO_2 sensor
- VG400 [53] low frequency soil moisture sensor
- THERM200 [52] soil temperature sensor
- NORP12 [54] light dependent resistor

5.3.4 Battery Unit

The limitation of the wireless sensor unit can be discussed in term of the power, which is to be considered as crucial in the deployment of the sensor station. The sensor station needs to have low power consumption, and be portable and flexible. To meet these requirements a portable source of power is required to power the sensor station. Generally speaking a battery is the main source of power supply for the sensor station. In addition, it also reduces the complexity of the system.

There are two categories of battery on the market: Re-Chargeable and Non-Rechargeable. They are also classified according to the electrochemical material used for electrolysis such as NiCd, NiZnm AgZn, NiMh, and Lithium-Ion. A comparison of batteries has been done on the basis of primary/secondary and volumetric density is shown on [73].



Battery	Rechargeable?	Volumetric density(Wh/l)	Environmental or Health concerns
Alkaline-MnO2	No	347	
Silver Oxide	No	500	
Li/MnO2	No	550	
Zinc Air	No	1150	
Sealed Lead Acid	Yes	90	Yes
NiCd	Yes	80-105	Yes
NiMH	Yes	175	No
Li-ion	Yes	200	Yes
Li-Polymer	Yes	300-415	

Table 5-1: Battery technology comparison [74]

The Volumetric Energy Density (VED) of a battery is a measure of how much energy a battery contains in comparison to its volume [74]. It depends on the type of applications; if it is not an energy harvest type of application then non-rechargeable batteries are sufficient because they have a higher VED. This system is considered as a harvest type; therefore rechargeable batteries are best suited for this system. Among the non-rechargeable batteries Li-ion and Li-Polymer are both suitable for the system. However, based on the battery comparison table Li-Polymer has a higher value of VED, which will allow for a longer working life. However one disadvantage in using Li-Polymer batteries is the cost of purchase. The chemicals used to make Li-Polymer battery are expensive and therefore these batteries tend to have a higher retail price than other types of rechargeable batteries.

5.3.5 Battery Level Detection Unit

Having the system running off battery power, it is essential to inform the user on the status of the battery, therefore a battery detection unit is required. To detect the changes in the battery output voltage, a differential amplifier circuit was integrated into the detection unit. The circuit of the battery detection unit is shown on Figure 5-6. The battery level detection circuit works by providing an output voltage between 0 to 2.43V in proportion to the current voltage level of the battery. The first circuit works as a voltage follower that will effectively isolate the output voltage going into the next stage of the amplifier circuit from the signal source to avoiding a loading effect. The output of the voltage follower is fed into the inverting input of a differential amplifier circuit. This voltage input is used as a reference voltage. The difference between two input voltages is referred as ‘differential-mode’ voltage, while the sum of the two input voltages is called ‘common-mode voltage’ [75]. The amplifier delivers zero outputs in response to common-mode voltage and non-zero outputs in response to differential mode voltage.

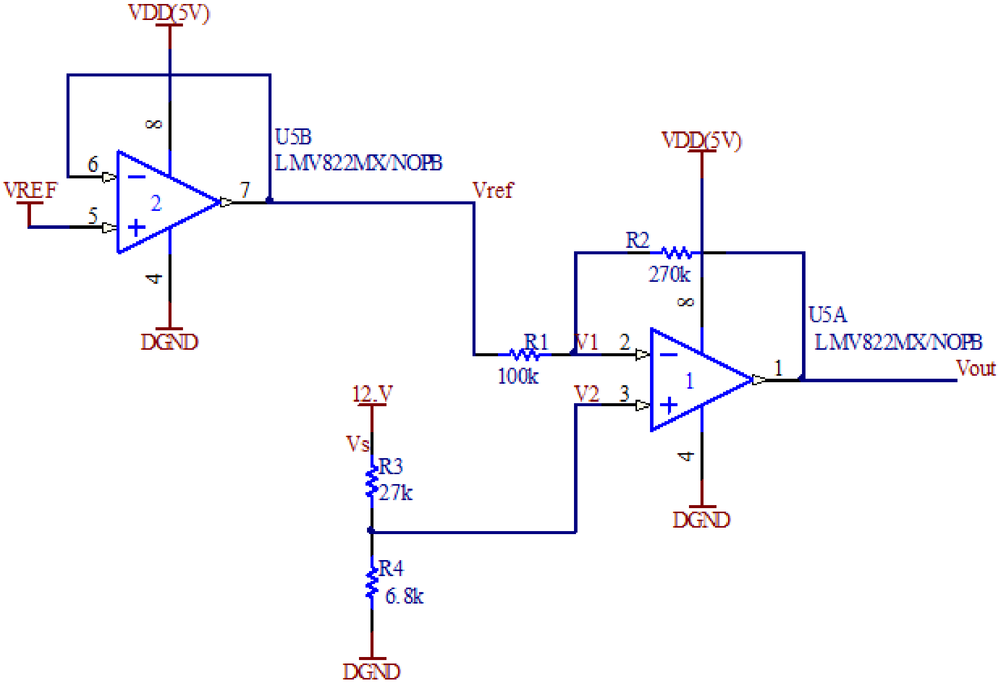


Figure 5-6: Schematic design of the battery detection unit

The above circuit can be explained using the following equations [76]:

$$v1 = vref - R1 * \left(\frac{(vref - vout)}{(R1 + R2)} \right) \quad \textbf{(5-1)}$$

$$v2 = vs * \left(\frac{R4}{(R3 + R4)} \right) \quad \textbf{(5-2)}$$

The power supply (*vs)* of the platform is a 12V Lithium Polymer battery. Since the reference voltage of the differential amplifier is set to 2.43V, therefore the output voltage of the battery needs to be stepped down to 2.43V level. A voltage divider with two resistors R3 and R4 was used to bring the 12V down to 2.43V. With *vs,* R3 and R4 are known values, the value of *vout* can be calculated by simply substitute these values into equation (5-2).

$$v2 = 12V * \left(\frac{6.8K}{(27K + 6.8K)} \right)$$

$$v2 = 2.414V$$

When *vout* is 0V, *v1* = *v2* and *vs* is approximately 8.85V, therefore *v2* = *v1* = 1.78V. Rearrange equation (5-1) for R2 and make R1 = 100k ohm.

$$R2 = \left(\frac{((vout - vref) * R1)}{(vref - v2)} \right) - R1 \qquad \textbf{\textit{(5-3)}}$$

$$R2 = \left(\frac{((0 - 2.43V) * 100K)}{(2.43V - 1.78V)} \right) - 100k$$

$$R2 = 273846 ohm$$

It was however not possible to obtain a surface mount resistor that employs a value of 273846 ohm, therefore resistor value of 270k ohm was used instead. A simulation of the Battery Level Detection was created using Altium Designer software package and the results are shown on Figure 5-7. As expected, the analog voltage input (first plot) is zero when *vs* = 1.78V (second plot).

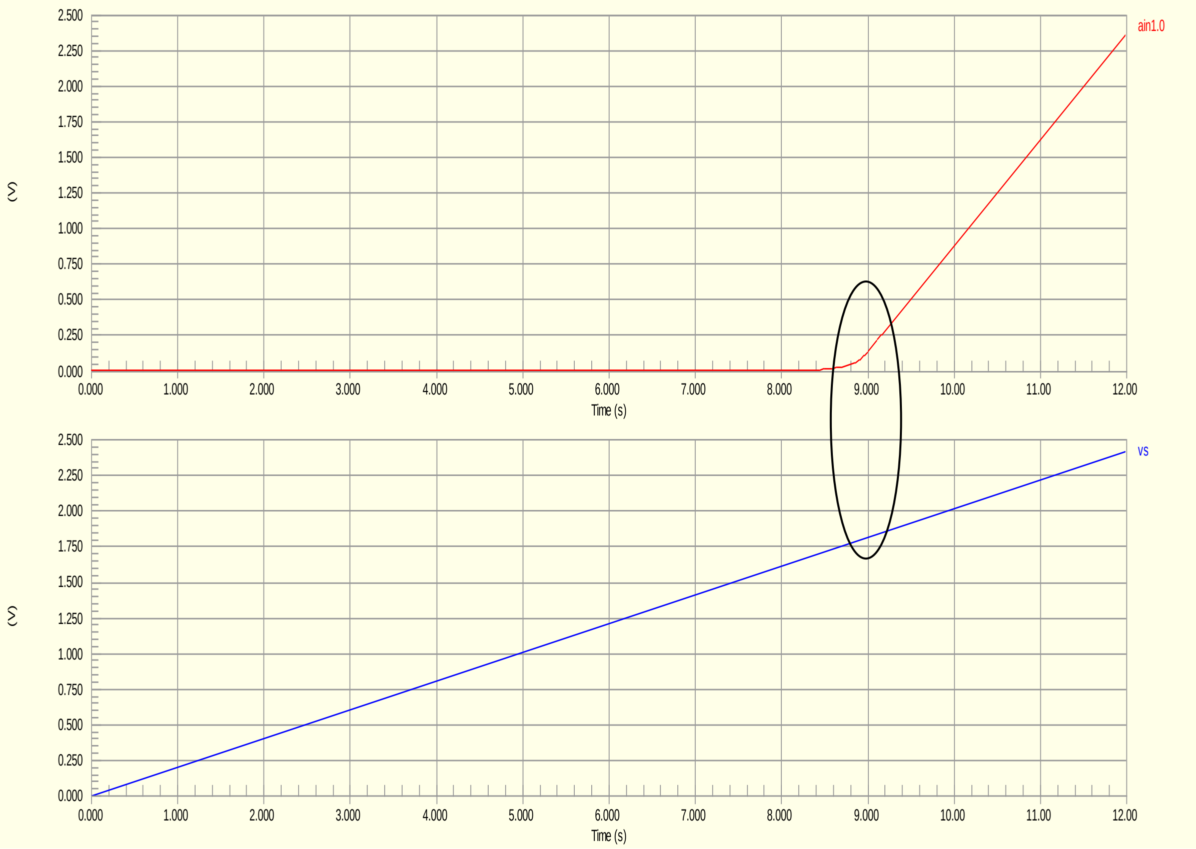


Figure 5-7: Battery detector simulation ($V_{analog\ input}$ (first plot) vs $V_{battery}$ (second plot))

5.3.6 Relay Control Unit

The relay control unit gives the system an ability to control local activities such as exhaust fan, heater, sprinkler, fogger etc. For this project a I/O 24 Relay Output Board [77] was used. The board consists of 8 relays with both Normally Open (N/O) and Normally Closed (N/C) contact rate of 250V AC or DC at 5 A. The relay coils are powered by an external supply 12VDC and can handle up to 700mA.

It main features [77] are listed as follow:

- 12V DPDT 250VAC / 30DC @ 5A Relays
- Indication LED’s for relay output status

- Screw Terminal Blocks for Relay outputs and 12V Power Input
- Easy connection by 10-way box header to suit standard IDC connector for connection to the I/O port.

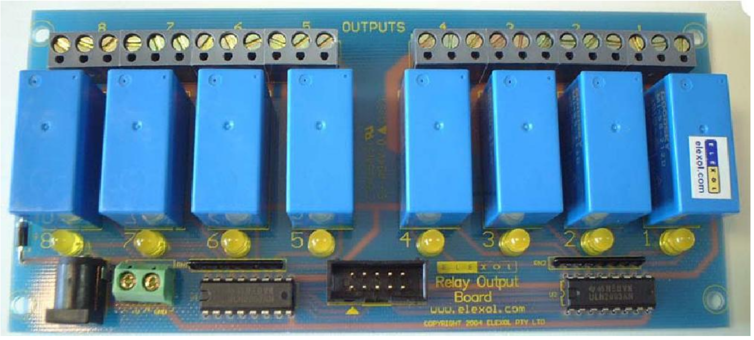


Figure 5-8: I/O 24 Relay Output Board

The relays can be activated by simply applying voltage to the input pins of the 10 pins box header. The minimum voltage required on the input pins to activate the relay is 1.6V but most cases will have TTL logic signal on the input pin to activate the relay.

5.4 Prototype Hardware Design

5.4.1 Introduction

Once again here is the project overview of the proposed system in Figure 5-9. This proposed system consists of three stations: a sensor station, coordinator station and central station. Each Station has its own responsibilities and authority. The communication between each station is established via two different wireless devices; Xbee and XStream RF modem. This section of the report explains in detail the hardware design of the system.

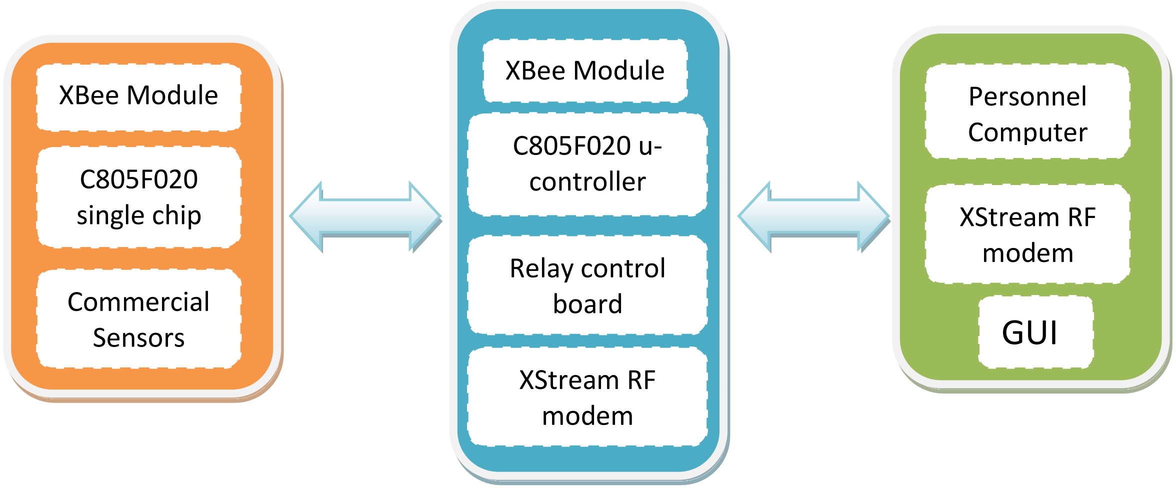


Figure 5-9: System block diagram

5.4.2 Hardware Design of the Sensor Station

The sensor station consists or two units: a Sensing Unit and a Processing Unit. These two units are connected by a ribbon cable. The design of both units was done in the Altimum Designer software package.

5.4.2.1 Sensing unit

The sensing unit consists of:

- SHT75 humidity and temperature sensor
- NORP12 light dependent resistor
- TGS4161 Electrochemical CO_2 sensor
- THERM200 soil temperature sensor
- VG400 soil moisture sensor.
- XBee wireless module
- Power supply

All sensors are powered by a 3.3V power source except for the CO_2 sensor. This sensor requires a heater voltage of 5V in order to maintain the sensing element at the optimum temperature. Therefore a voltage supply of 5V was initially provided to the sensor unit by the processing unit. To provide 3.3V to other sensors a 3.3V LM1117 regulator [78] was used. According to the information provided by the manufacturer, the output voltage of TGS4161 CO_2 sensor increases with CO_2 concentration. An experiment was carried out to test the sensor's characteristics and the result shows that at a concentration of 390 ppm, the sensor outputs a voltage of 350 mV. According to the information provided by the datasheet, the difference between the voltage output at 350 ppm concentration and 3500ppm is approximately 60 mV [57]. These output values are too small in size to be implemented into an analog to digital converter of the microcontroller. Therefore a TLC271 low power operational amplifier [79] was integrated into the sensor unit to provide a gain of 6.6 to the output voltage of the CO_2 sensor, which brings it up to a voltage output of 2.34V at 390ppm concentration.

A ZigBee/XBee wireless module [71] was included in the sensing unit to provide wireless communication between the sensor station and coordinator station. XBee wireless modules have many characteristics that are designed for wireless communication. There are some considerations that must be taken into account to accommodate the needs of the XBee. First, the pitch of the headings on the XBee is 2.0 mm and will not fit into general purpose sockets required for prototyping designs. Therefore an adapter board for XBee module is required. Second, XBee is designed to operate at 3.3V and the power supplied to the sensing unit is of 5V. Voltage regulation can be easily account for by a LM1117 regulator [78]. Figure 5-10 show the schematic designed of the sensing unit and Figure 5-11 shows the PCB design of the sensing unit.

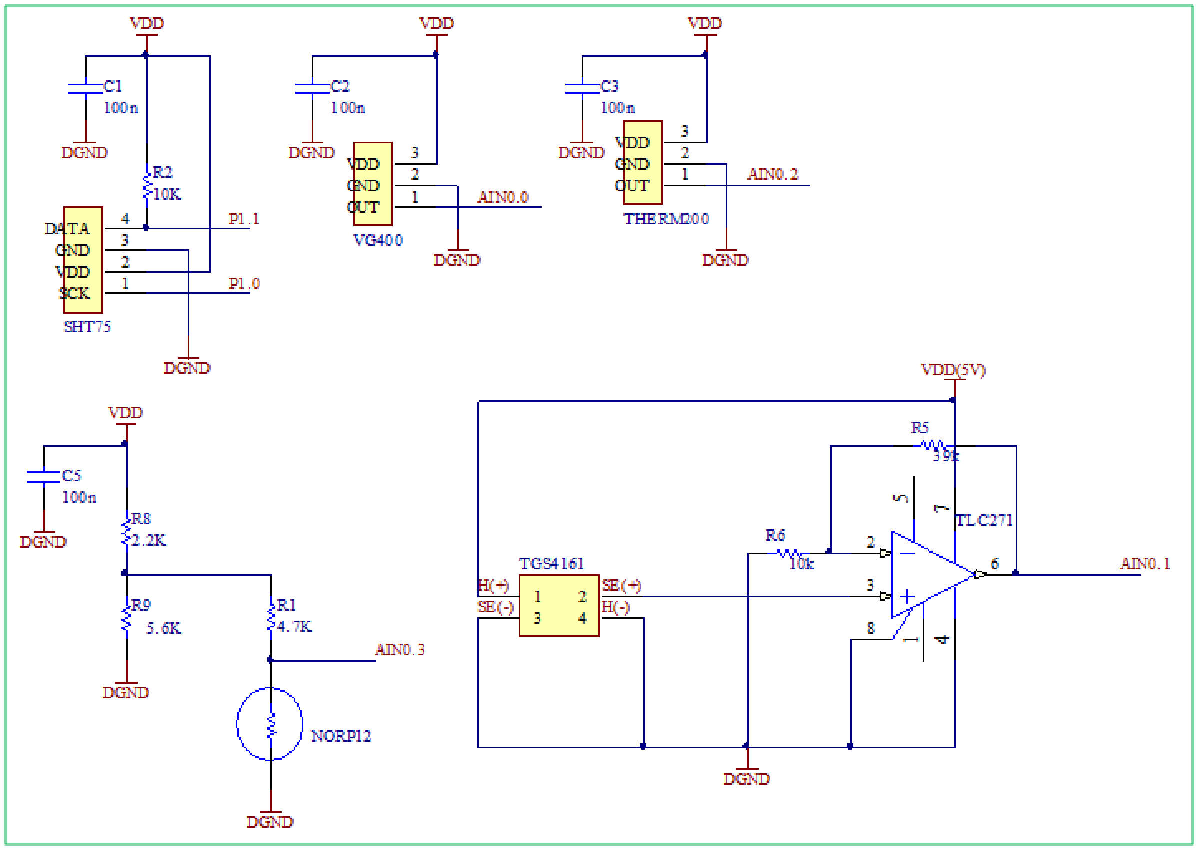


Figure 5-10: Sensing Unit schematic design

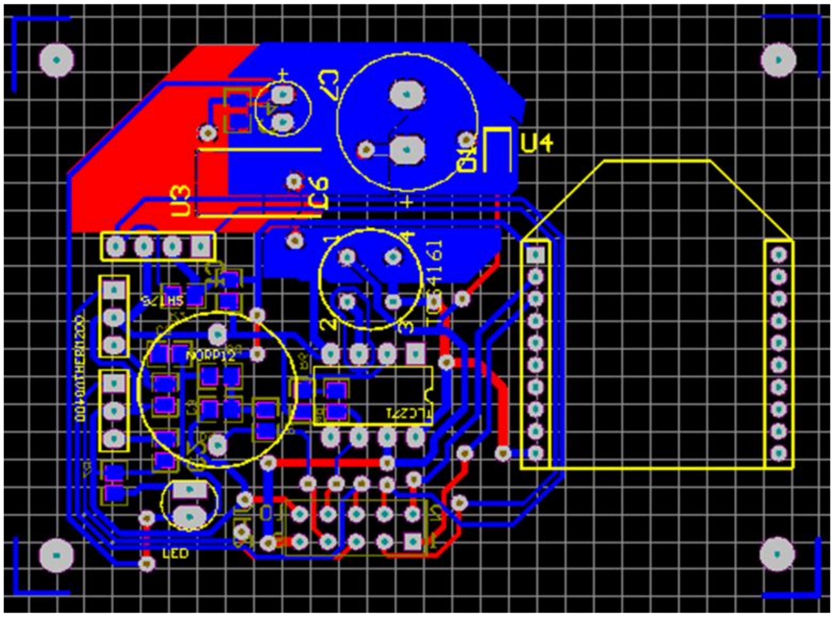


Figure 5-11: Sensing Unit PCB design

Interfacing the XBee wireless module with the C8051F020 microcontroller is very simple and effortless because both communicate with a serial UART interface. To interface the XBee wireless module with C8051F020 microcontroller, there are only four pins that needed to be connected: VDD, GND, Din, Dout. Din pin can be connected to the RX pin of the microcontroller and Dout pin can be connected the TX pin. A schematic diagram showing the pin connections is shown on Figure 5-12

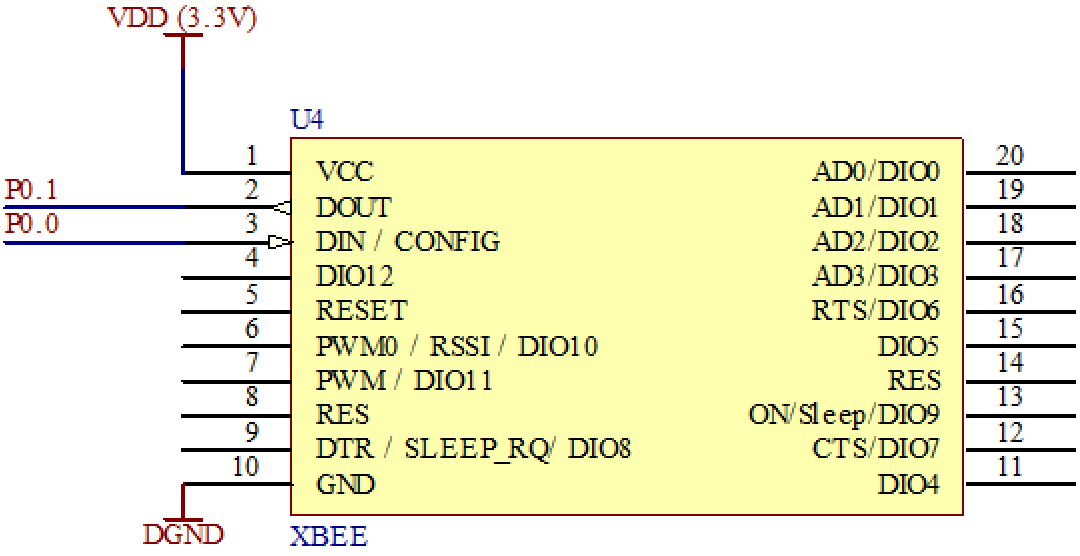


Figure 5-12: XBee electrical connection layout

5.4.2.2 Processing Unit

The processing unit consists of:

- C8051F020 single chip computer which can process data at high speed
- Battery Level detection circuit
- Power supply

A battery level detection circuit is also incorporated into the processing unit to allow for the detection of changes in battery voltage. The output of the detection circuit is routed to pin #4 of the analog port on the microcontroller.

The C8051F020 chip requires a maximum supply of 3.3V to operate. Unfortunately, most common power adaptors that are available on the market range between 5 to 12VDC. Therefore a voltage regulator circuit is required to provide necessary power for the microchip. The voltage regulator used to regulate the circuit is a REG1117-3.3V regulator provided by the Element14 distributor. The REG1117 is a high temperature resistance low dropout voltage regulator that is capable of handling up to 20V input and an output of a maximum of 800 mA. A typical connection circuit of REG1117 is shown in Figure 5-13.

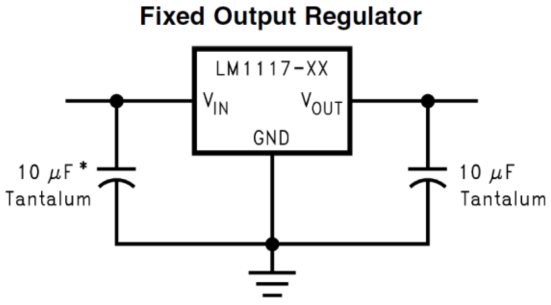


Figure 5-13: REG1117 circuit layout

The processing unit is required to provide a constant voltage of 5V to power up the sensing unit. In its current condition the processing unit is incapable of providing a 5V to power the Sensor Unit, however a voltage regulation circuit can be accounted for by a LM2594M-5V fast switching power converter that is capable of handling up to 60V input and output maximum of 500 mA. One of the most convenient features that the LM2594 has to offer is the ability to turn ON or OFF the flow of the output voltage using logic 1 or 0. This feature was found to be extremely useful for energy saving applications such as this project. A typical connection circuit of LM2594 is shown in Figure 5-14. For an application that doesn’t require the ON/OFF feature, the ON/OFF pin of the regulator can be connected to ground. Any applications that require the ON/OFF feature need to tie the ON/OFF pin to the logic pin and it can be active by either sending logic 1 or 0 to the ON/OFF pin of the regulator. The PCB design of the processing unit is shown in Figure 5-15.

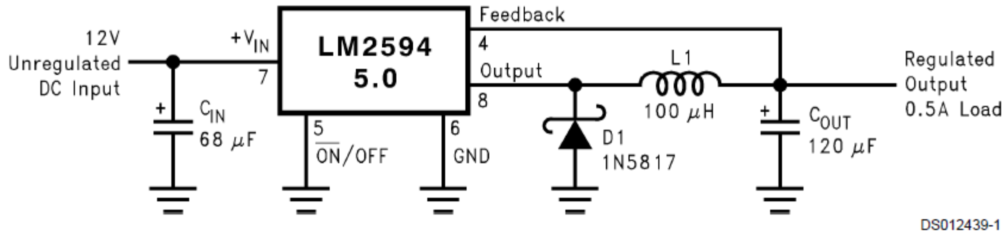


Figure 5-14: LM2594M-5V circuit layout

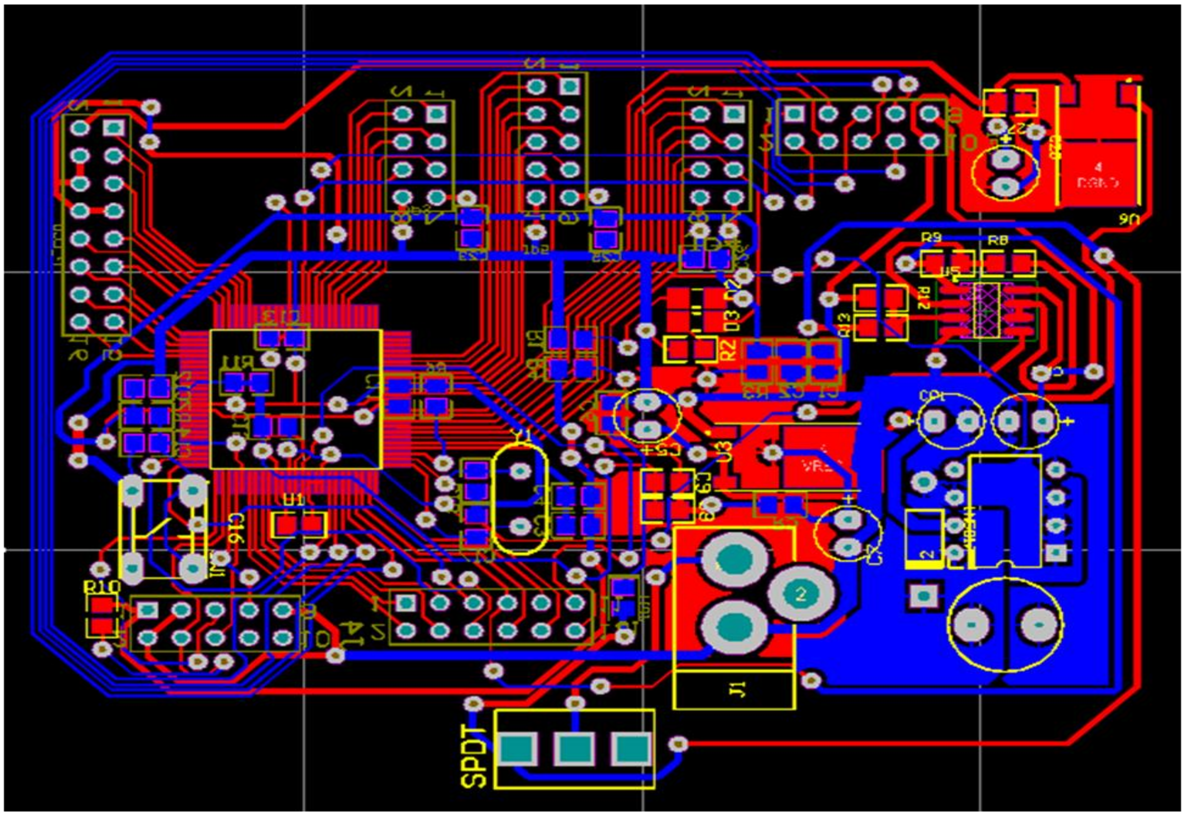


Figure 5-15: PCB design of the processing unit

An important aspect of the design was miniaturization. Therefore most circuitry components used for the sensor station are either surface-mounted or are very small in size. The final design of the sensor station including the circuitry of the sensing unit and processing unit connected via ribbon cable is shown on Figure 5-16.

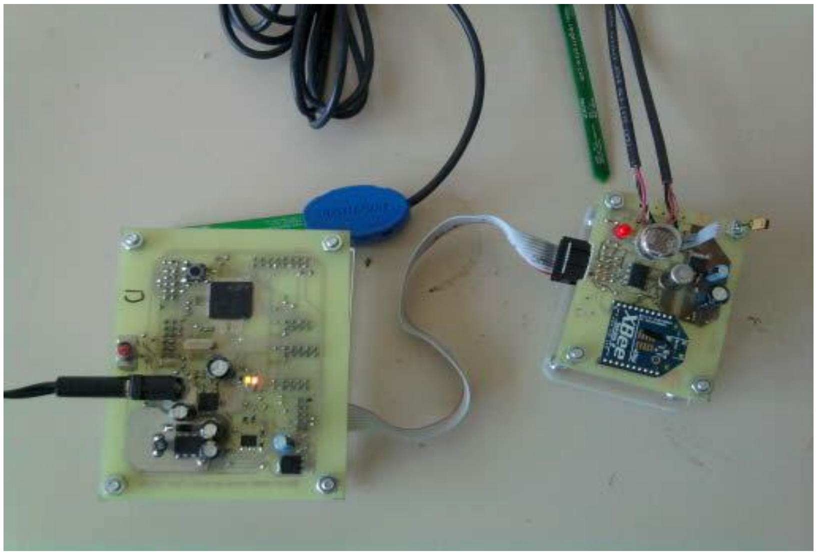


Figure 5-16: Final design of the Sensor Station

5.4.3 Hardware Design of the Coordinator Station

The coordinator station consists of:

- C8051F020 single chip computer which can process data at high speed
- Power supply
- XBee Wireless module
- 2.4 GHz XStream-PKG wireless modem
- Relay control circuit

The construction of the coordinator station is somewhat similar to the processing unit of the sensor station. This station also employs a C8051F020 single chip computer to allow for high speed data processing. As mentioned above, the coordinator-station is practically a router and its job is to control the input and output flow of data and instructions between the sensor station and central station. In many cases, two XBee wireless transceivers are sufficient for the communication between two devices. However, the limitation of ZigBee is its transmission range (proximately 120 m outdoor/line-of-sight and 40 m indoor/urban range). Digi offers two different versions of ZigBee wireless modules: the XBee and Xbee-Pro. Both modules have the same set of instructions and operate in the same manner. The XBee-Pro module is capable of providing a much longer transmission range than the normal Xbee module (90 m indoor/urban range and 1500 m outdor/line-of-sight). This is a huge step up from the previous XBee products in terms of transmission range and power. However this is its maximum potential and its range cannot be improved with additional help from a high gain antenna. Therefore, Stand-Alone RF (SARF) modems were used instead of Xbee modules to provide a long range wireless communication between the coordinator station and the central station. The SARF modem used in this project is a 19200 baud 2.4 GHz XStream-PKG wireless modem provided by the Digi Company. This SARF modem is capable able of providing long range transmission (over 1 km with a normal antenna and over 16 km with a high gain antenna) at low power consumption (less than 50W). Both Xbee and XStream RF modem communicate with C8050F020 via UART interface, therefore it is required to have at least 2 UART serial ports to make this possible. The C8051F020 comes with two UART serial ports; therefore it was possible to interface both wireless modules without having to include additional circuits to the design. The system data flow of the coordinator-station is shown in Figure 5-17.

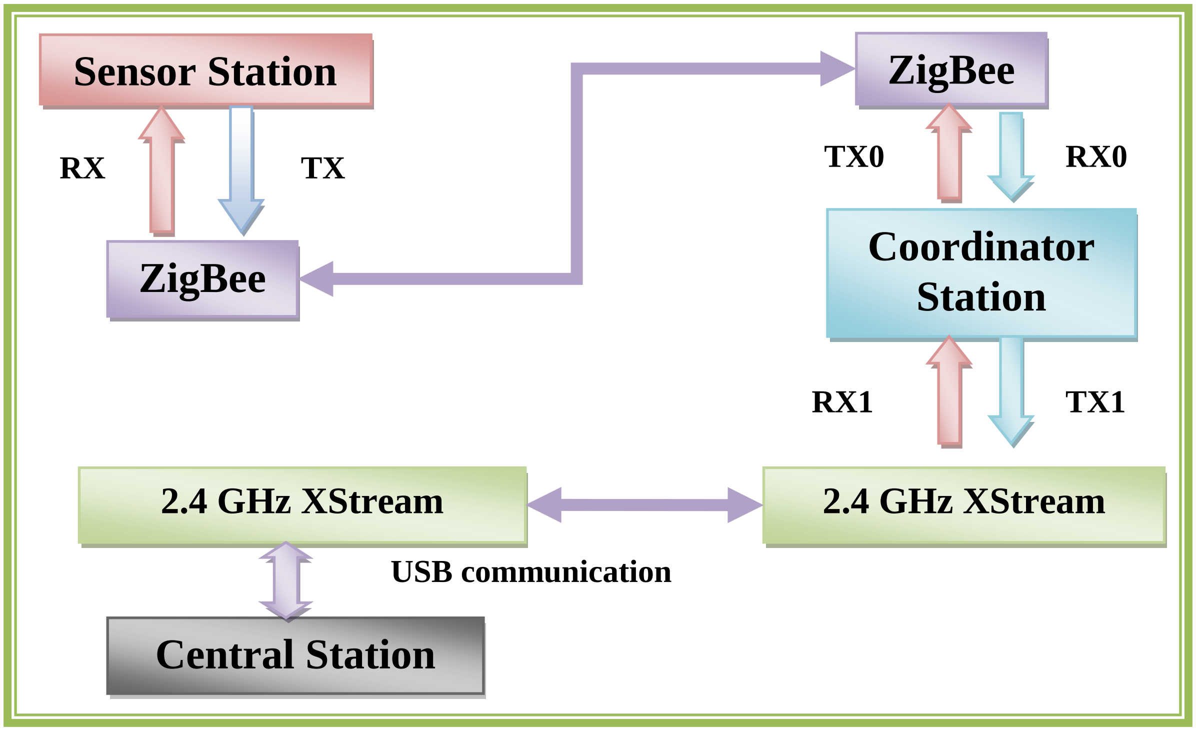


Figure 5-17: System data flow of the coordinator station

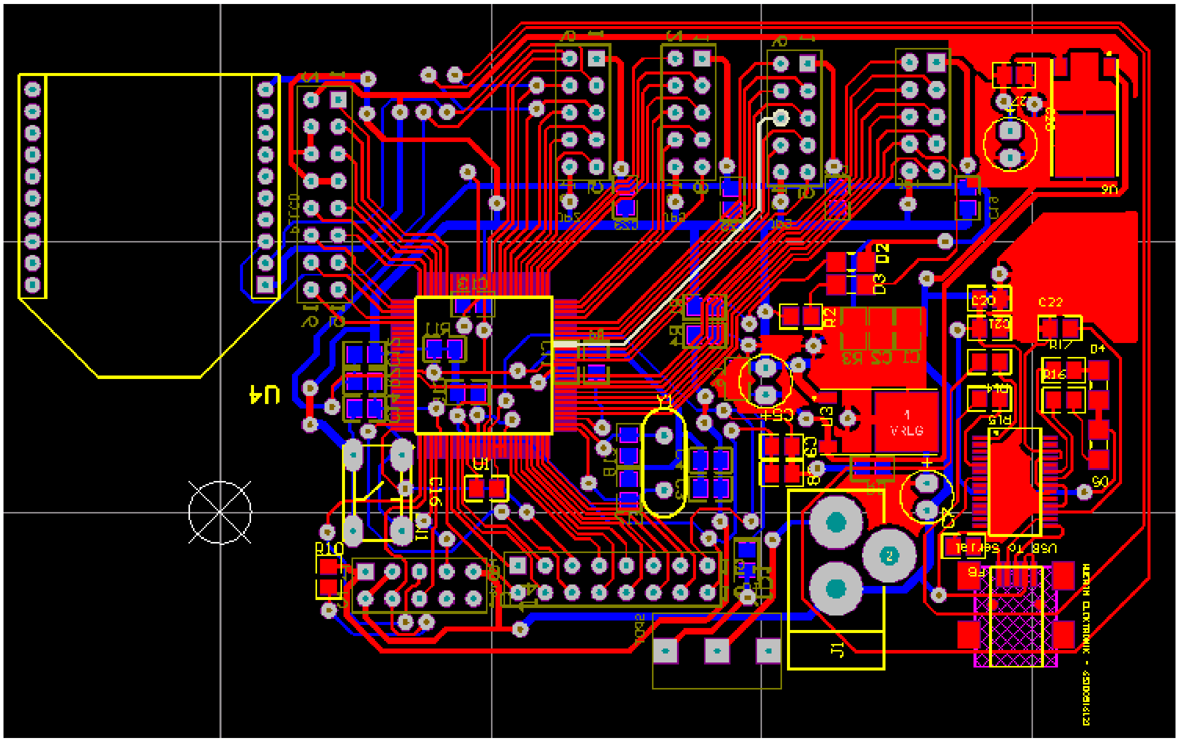


Figure 5-18: PCB design of the coordinator station

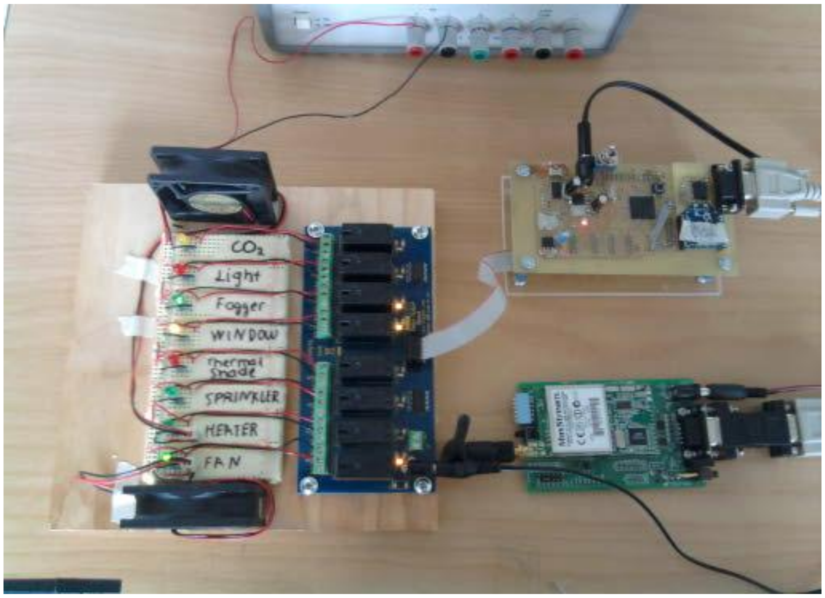


Figure 5-19: Final design of the coordinator-station

A relay circuit is also incorporated into the coordinator station to allow for the control of greenhouse equipment such as a heater, exhaust fan, lighting etc. The relay circuit is connected to the coordinator station via a ribbon cable. The final design of the coordinator station connected to a relay circuit via ribbon cable is shown in Figure 5-19.

5.4.4 Hardware design of the Central Station

The central station is the main controller of the system. It is in charge of controlling greenhouse climate, data collection, data processing, and data presentation. The central station implemented in this work has the following components to carry out its tasks:

- Personal Computer
- 19200 baud 2.4 GHz XStream-PKG’
- USB cable

The design of the central station is very simple in comparison to the sensor station and the coordinator station. The purpose of not having a microcontroller at the central station is that the PC can be used as the processor in place of microcontroller. In fact, a PC is a better choice than a microcontroller in terms of processing power, speed, capability and functionality. Interfacing the XStream RF modem with the PC is fairly simple. The XStream wireless modem can be powered via a USB connection therefore no additional power circuit or power adaptor is required. Figure 5-20 shows the layout of the central station.

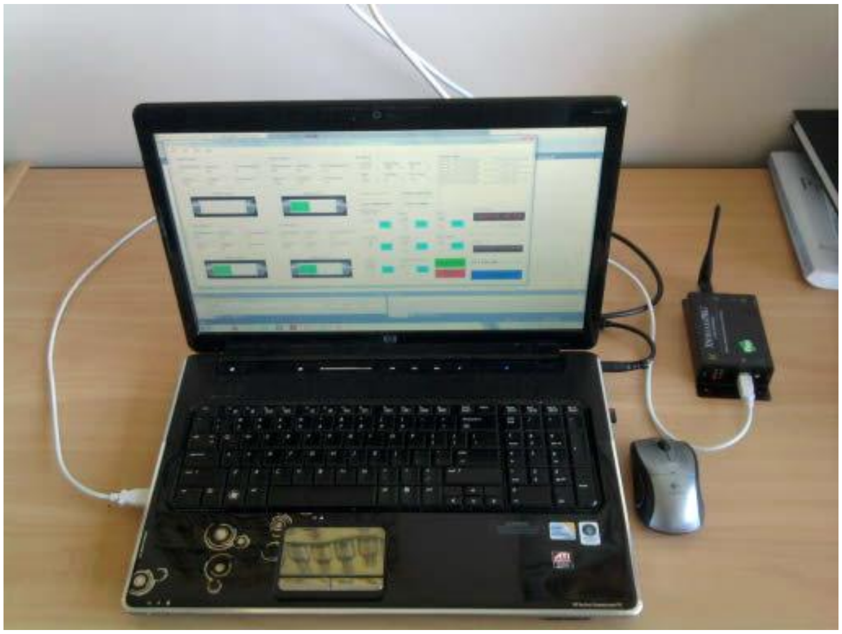


Figure 5-20: Layout of the central station

5.5 Software Design and Algorithms

5.5.1 Introduction

Several algorithms were written for the microcontrollers used, as well as software for the PC the user is connected to. The system software includes data acquisition, data processing and data transmission by wireless. This section explains in detail the design of these.

5.5.2 Software Design of the Sensor Station

The sensor station is used to collect greenhouse environmental data and to send them to the coordinator station. Figure 5-21 shows the software flow diagram of the sensor station.

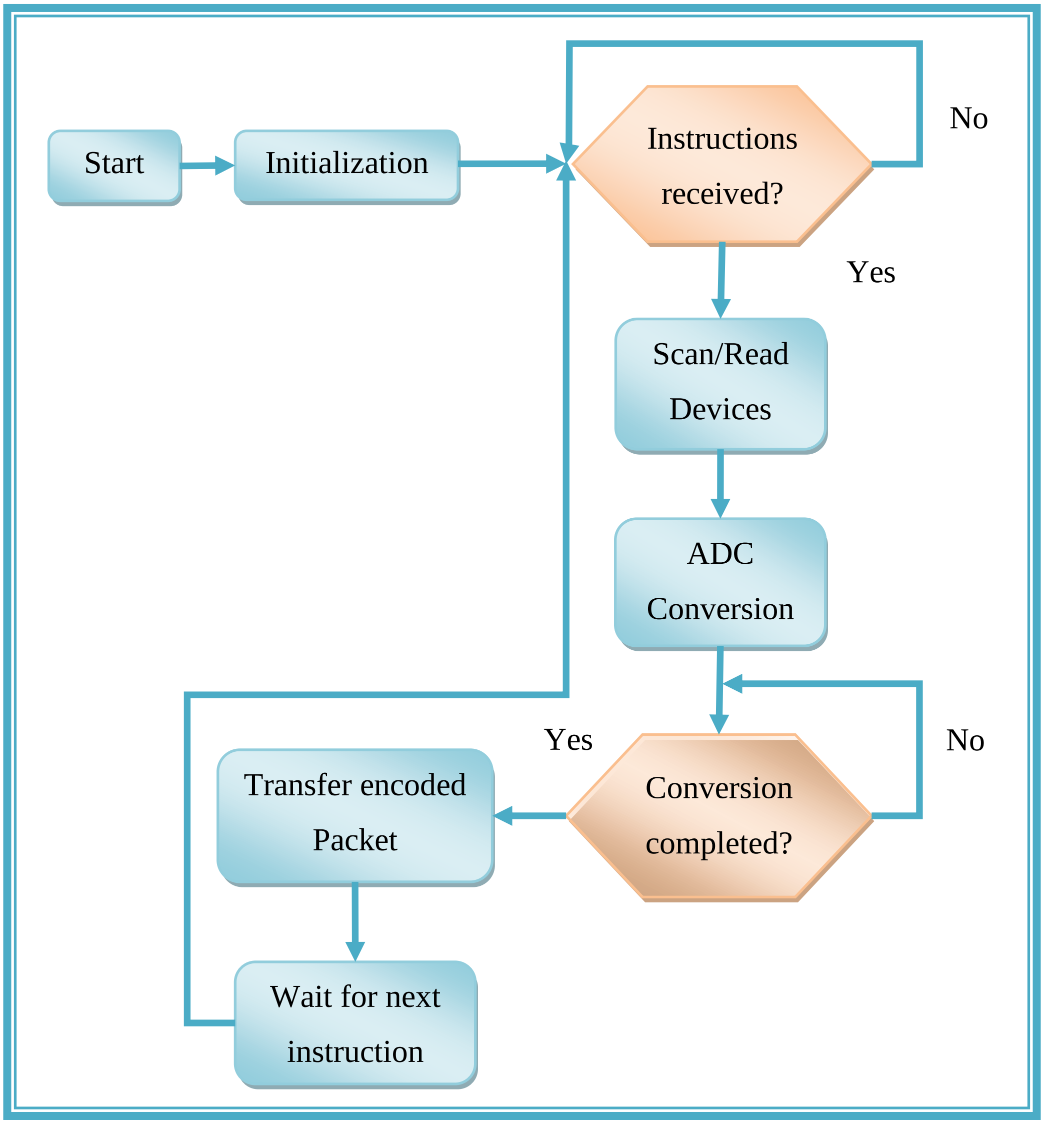


Figure 5-21: Software flow diagram of the sensor station

Parameters initialization is done first in the code. Depending on the type of application, not all parts of the microcontroller are required to be initialized. As mentioned previously, the main function of the sensor station is collecting greenhouse environment data and sending them to the coordinator station via XBee wireless module. Therefore there are two main components that need to be initialized:

- ADC initialization – Allows the microcontroller to convert an analog signal to a digital signal.

- UART initialization – Allows the microcontroller to perform parallel-to-serial conversion or serial-to-parallel conversion

The program does not need to collect environment data in a timely manner. Therefore it does not need to use any on-chip timers to initiate ADC conversion but AD0BUSY was used instead. AD0BUSY allows the program to freely sample and perform ADC conversion without any restrictions. AD0BUSY gives the programmer full control over the data collection and conversion process. The written algorithm for ADC initialization is shown in Figure 5-22

```
//-------------------------------------------------------------------
void ADC0_Init (void)
//-------------------------------------------------------------------
{
   REF0CN = 0x03;       // internal VREF
                        // Internal Temperature off
   ADC0CN = 0x80;       // ADC0 enabled; continuous tracking
                        // mode, conversion initiated on every
                        // write of '1' to AD0BUSY
                        // ADC0 data is right-justified

   AMX0CF = 0x00;       // AIN inputs are single-ended (default)
   AMX0SL = 0x00;       // Select AIN0.0 pin
   ADC0CF = 0x88;       // PGA gain = 1 (default)
}
```

Figure 5-22: Algorithm for ADC initialization

At the end of the initialization process, the program goes inside the while loop and waits for a data request. If a data request is received, the program will quickly scan and read the sensors' output and perform an analog to digital conversion on the collected measurements. When conversion is completed, the data is encoded into a data packet and sent to the coordinator station.

5.5.3 Software Design of Coordinator Station

The coordinator station is basically a router and its job is to control the flow of data and instructions between the Sensor Station and Central Control Station. Therefore it doesn’t require ADC initialization. It is however required to initialize both UARTs to allow for the implementation of both XBee and XStream modem. The written algorithm for UART initialization is shown in Figure 5-23.

```
//Set up the UART0
PCON |= 0x80;           //SMOD0=1 (UART0 baud rate divide-by-2 disabled)
SCON0 = 0x50;           //UART0 Mode 1, Logic level of stop bit ignored
                        //and Receive enabled
IE |= 0x10;
IP |= 0x10;             //set to high priority level
RI0 = 0;                //clear the receive interrupt flag
                        //ready to receive more
TI0 = 0;

//Set up the UART1
PCON |= 0x10;           //SMOD1   =   1(UART1   baud   rate   divide-by-2
disabled)
SCON1 = 0x50;           //UART1 Mode 1, Logic level of stop bit ignored
                        //and Receive enabled
EIE2 = 0x40;            //Enable UART1 interrupts
EIP2 = 0x40;            //Make UART high priority
SCON1 &= ~0x01;         //clear the receive interrupt flag; ready to
                        //receive more
SCON1 &= ~0x02;
```

Figure 5-23: UART0 and UART1 initialization

Figure 5-24 shows the software flow diagram of the coordinator station. Upon the coordinator station being started, the first action of the application is the initialization of the hardware and application parameters. At the end of the initialization process, the received instruction packet is analyzed to determine the type of instruction it received. If the instruction is a data collection request, it will automatically forward the instruction to the sensor station and wait for the respond packet. If the packet is a climate control request, it will send out a signal to activate the relay circuit letting it know which relay should be on or off and for how long. A timer is set for each transmission, if no response is received when the timer is expired, it will retransmit the request packet. If, by the end of the second retransmission no response is received, an error packet will be sent to central station letting the operator know something is going wrong and that immediate attention is required

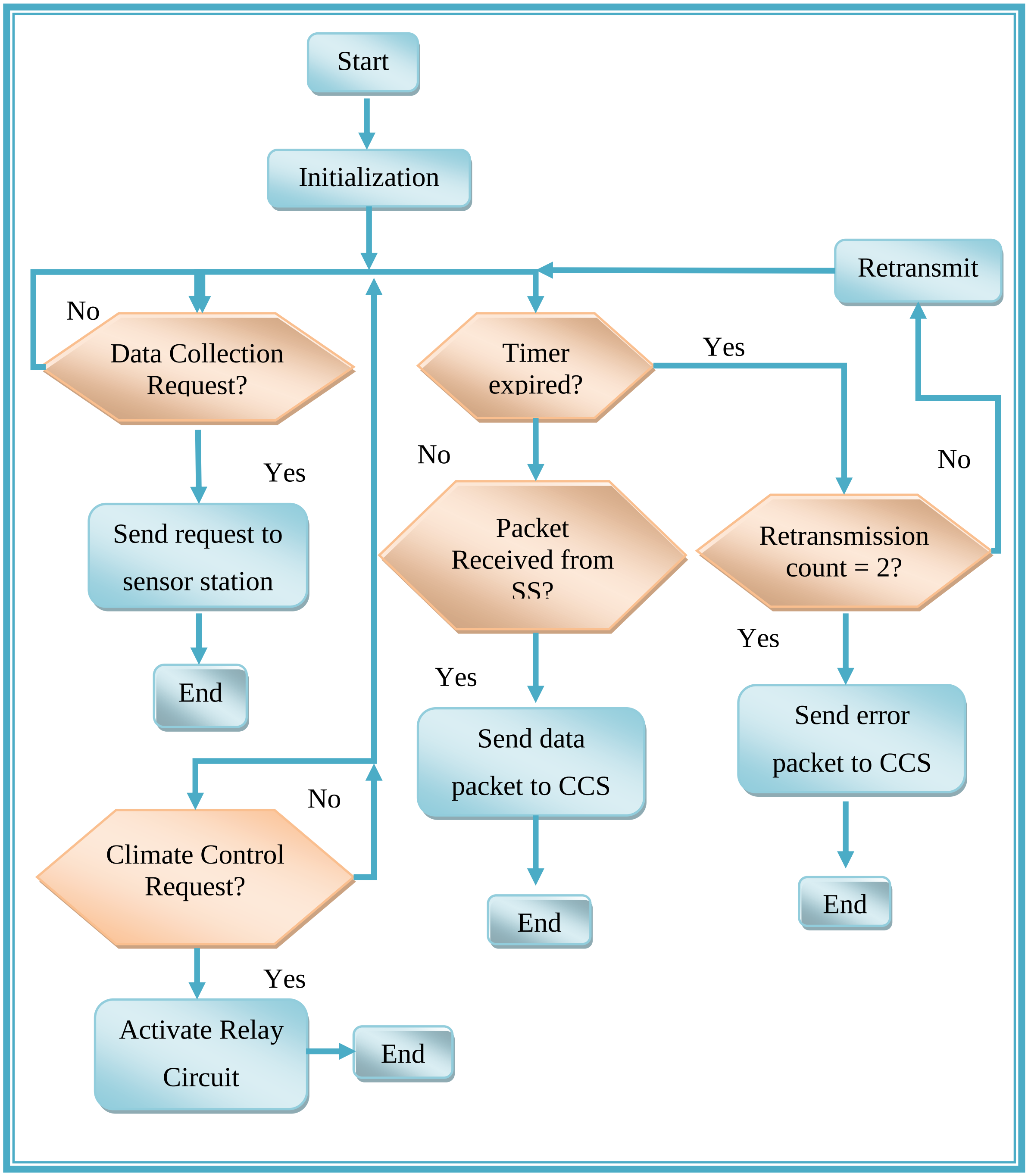


Figure 5-24: Software flow diagram of the coordinator station.

5.5.4 Software Design of Central Control Station

The Central Control Station is the main controller of this system. It is used for data control and storage. Figure 5-25 shows the software flow diagram of the central station.

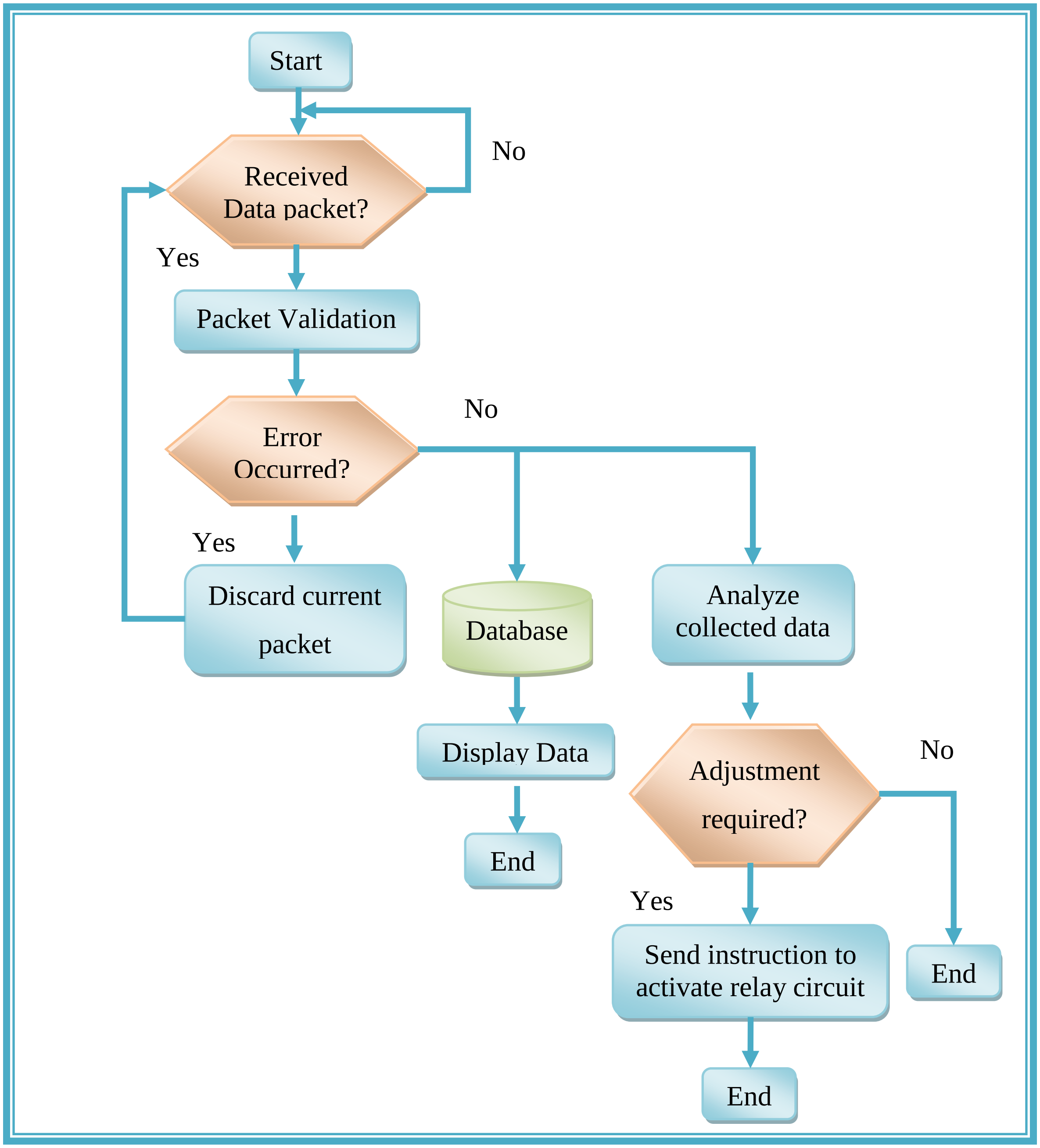


Figure 5-25: Software flow diagram of the central station

The software of the central station is designed in Visual C#. It consists of 3 main components that allow the program to effectively assess and process incoming data packets:

- Data packet validation – allows the system to determine the status of a received data packet based on its header bytes (Unicode character "&" is assigned to the first header byte and "$" is assigned to the second header byte).
- Data packet identification – allows the program to determine the identity of the data packet. There are two types of responses; data-collection-response and climate-control-response. Each response is identified by a Unicode character: "&" represents "data_collection-response" and "!" represents climate-control-response.
- Data packet handling – handles the information extracted from the received packets:
    - Store collected greenhouse data in a local database for research and analysis in the future
    - Run control algorithm
    - Display collected greenhouse data in real-time

5.5.5 Data Acquisition Algorithms

The densor station employs both sensor categories: Analog and digital sensor. Analog and digital sensors are different in both functions and the way they are implemented. Due to this, two different data acquisition algorithms were written.

5.5.5.1 Data Acquisition Algorithm for Analog Sensor

Figure 5-26 shows the algorithm written for collecting data from analog sensors. A variable called 'ANALOG_INPUTS' is assigned with a value of 4. This variable represents the number of sensors that are currently connected to the analog port of the microcontroller. There are many different methods that can be used to collect data from several analog sensors, some are more effective than others. However it is all comes down to the size of the algorithm and how easy it is for the next user to follow. Three most common programming statements that appear in almost every algorithm are:

- WHILE loop
- DO WHILE loop
- And FOR loop

Any one of these loops can be used for data acquisition, therefore it is up to the programmer to decide which loop is more appropriate and easy to implement. FOR loop was chosen for this particular algorithm based on a number of reasons:

- The number of iterations is known
- It is easier to implement

```
//-------------------------------------
void Data_Acquisition(void)
//-------------------------------------
{
      unsigned char j;
      for (j=0; j<ANALOG_INPUTS; j++)
      {
            AMX0SL = j;
            small_delay(10);
            AD0BUSY = 1;
            while (!(ADC0CN & 0x20));// Poll for AD0INT-->1
            Result[j] = ADC0;
            ADC0CN &=~(0x20);
      }
}
```

Figure 5-26: Data acquisition algorithm for analog sensors

The sampling function is activated by writing “1” to the AD0BUSY bit of register ADC0CN. The WHILE loop is placed after bit “1” is assigned to AD0BUSY to provide waiting time for the completion of ADC conversion. The ADC value is stored in an array called “Result” and is ready to be sent to the coordinator station. At the end of the conversion process the AD0BUSY bit is set back to 0 to allow for more ADC conversions.

5.5.5.2 Data Acquisition Algorithm for digital sensors

The digital sensor used in this project is the SHT75 Sensirion’s family of humidity and temperature sensors. The sensor comes with 4 pins; VDD, GND, SCK and DATA. The SCK pin is used to synchronize the communication between the microcontroller and the sensor itself. The DATA line is a tri-state pin and it is used to transfer data in and out of the sensor. Pin SCK is fed to pin #0 of port 1 and DATA pin is fed to pin # of port 1. To initiate a transmission, a special transmission start-up sequence must be issued to the sensor. This transmission start-up sequence wakes up the sensor and allows it to be ready for any incoming instructions or commands. The algorithm used to initiate the start-up transmission is shown in Figure 5-27.

```
//-------------------------------------
Void Transmission_Start (void)
//-------------------------------------
       ______            ______
// DATA      |_______|
//
        ___     ___
// SCK: ___|   |___|   |______

{     DATA = 1;               SCK = 0;
      small_delay (50);       SCK = 1;
      small_delay (50);       DATA = 0;
      small_delay (50);             SCK = 0;
      small_delay (100)       SCK = 1;
      small_delay (50);             DATA = 1;
      small_delay (50);       SCK = 0;
      small_delay (50);
}
```

Figure 5-27: Algorithm for start-up sequence

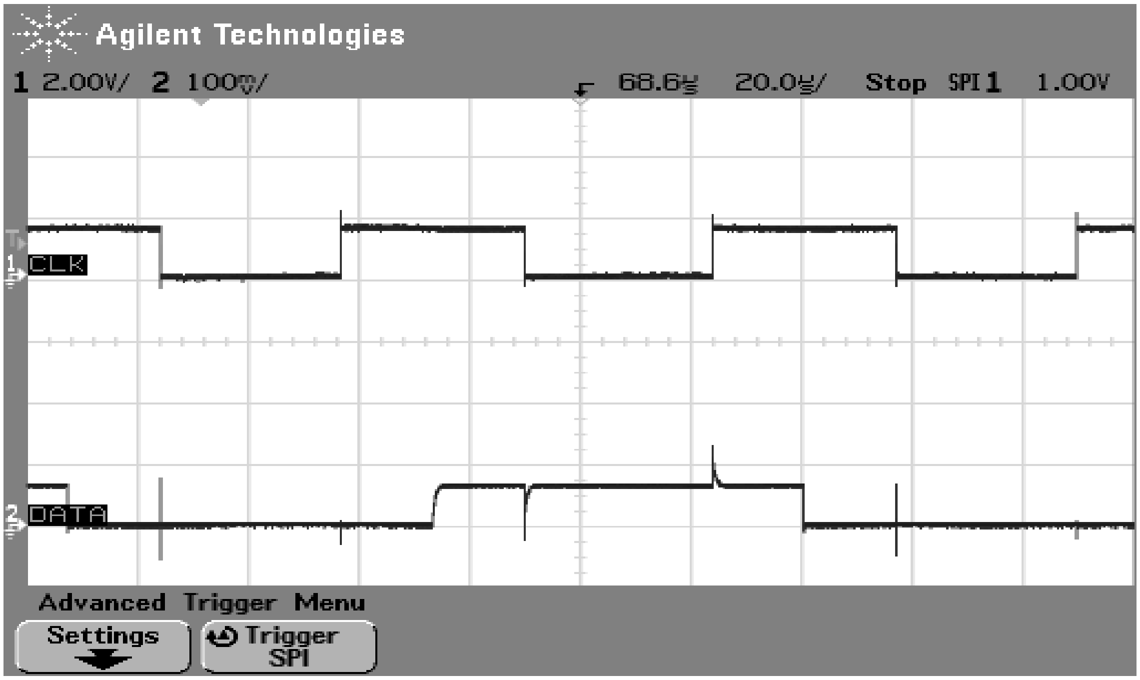


Figure 5-28: Start-up transmission output signal

Figure 5-28 shows the signal output generated by the start-up algorithm. The program lowers the DATA line while the SCK line is high, followed by a low pulse on SCK line and raising DATA line again. The start-up transmission is followed by a series of command bits. The subsequent command consists of three address bits and five command bits (‘00000101’ for relative humidity, ‘00000011’ for Temperature). Figure 5-29 displays the algorithm used for sending commands to the SHT75 sensor.

```
Humidint= Measure(MEASURE_HUMI);          //Measure the environment
                                          //Temperature
Tempint = Measure(MEASURE_TEMP);          //Measure the Humidity
                                          levelof the environment
```

Figure 5-29: Algorithm for sending command to SHT75

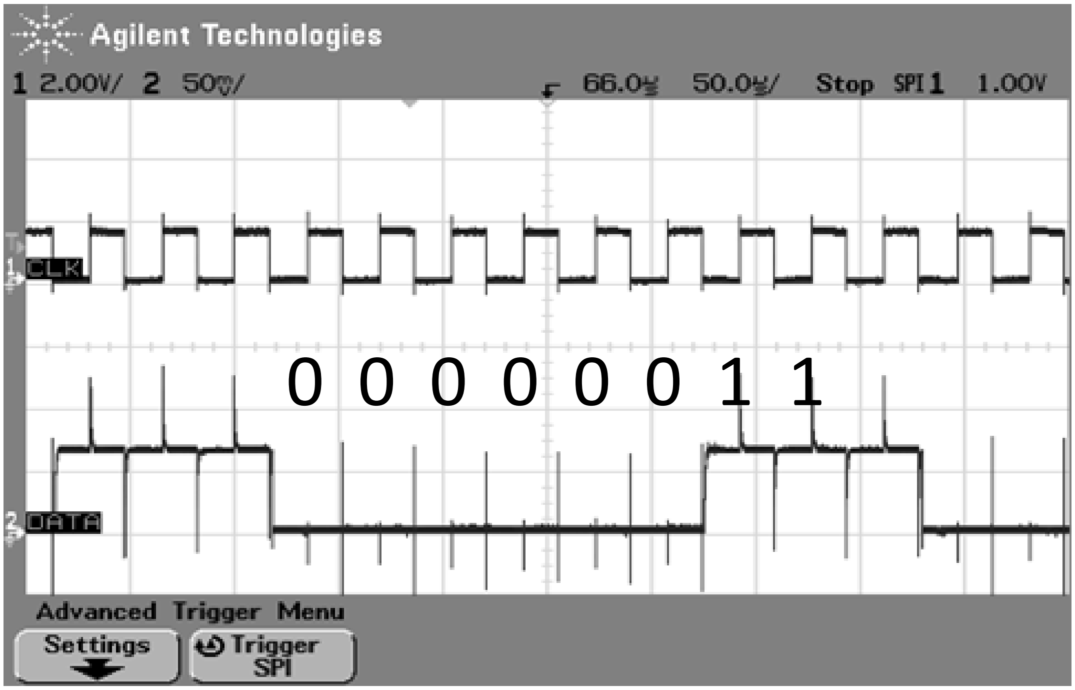


Figure 5-30: Temperature command ('00000011')

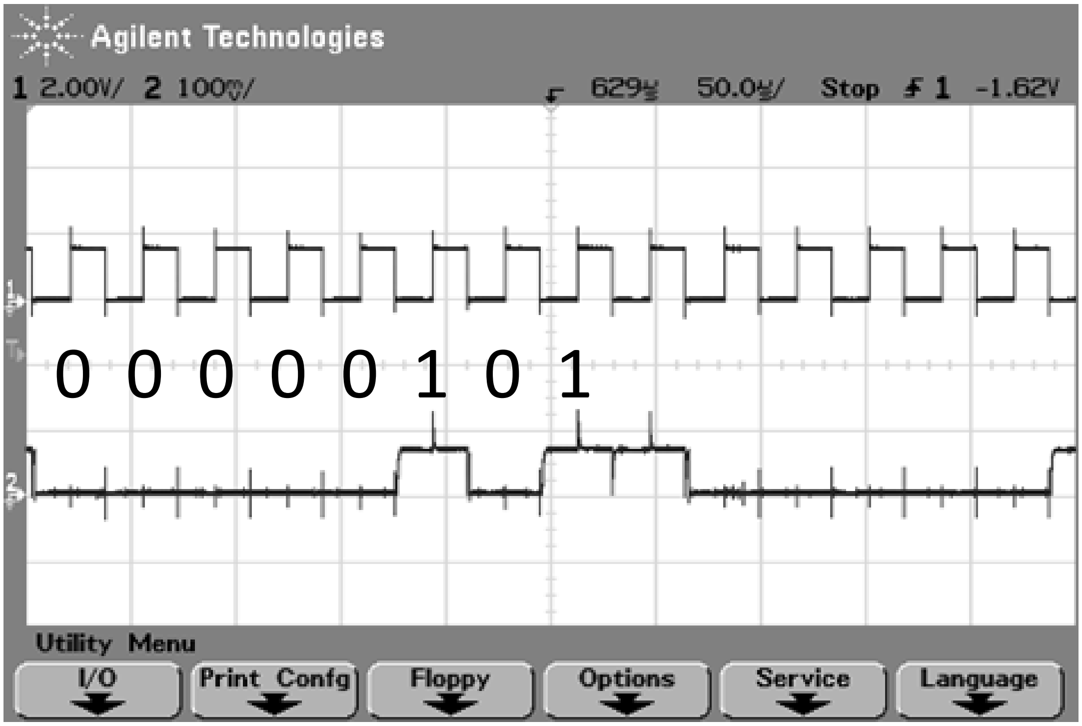


Figure 5-31: Relative humidity command ('00000101')

After sending the command to the sensor, the microcontroller has to wait for the measurement to be completed (the conversion process takes approximately 320 ms). When the conversion process is completed, the sensor sends out a signal to let the microcontroller know that the data is ready for collection. The “WHILE” loop used in the following algorithm is used for the detection of this signal.

```
//-----------------------------------------------------------
unsigned int Measure(unsigned char command)
//----------------------------------------------------------
{
      Unsigned int I;
      Write_Byte(command);
      small_delay(20);        // (6.8 us) wait for the dataline to //
                              stabilize
                              // (it takes approximately 5.4 us
                              // for the data to stable)

      //Now wait for the measurement to be ready. It can //take up to 320ms
      //now wait for the DATA line to go LOW (measurement //complete)
      //proceed if waiting time exceeds 2s
      i = 0;
      while (DATA && i<10)
      {
            huge_delay(10);               //wait for approx.  //200ms
            i++;
            if (i>10) break;
      }
            msb = Read_Byte(ACK);         //read the first 8 bits //(MSB)
            small_delay(50);
            lsb = Read_Byte(ACK);         // read the second 8 bits //(LSB)
            small_delay(50);
            CRC = Read_Byte(noACK); //read the check sum value
            Output = (msb<<8)+lsb;
      }
      return Output;
}
```

Figure 5-32: Data acquisition algorithm for SHT75

5.6 Prototype Final Design

5.6.1 Sensor Station Final Design

The prototype final design of the sensor station is shown in Figure 5-33. Four sensor stations are devoted to monitoring the greenhouse environment. Each sensor station is capable of measuring six different climate parameters: temperature, relative humidity, soil temperature, soil moisture, light and CO_2. The sensor station consists of two units: a sensing unit and processing unit. Sensors and Xbee wireless modules are mounted on the sensing unit to allow for data collection and wireless data transmission. The micro-processing unit contains a C8051F020 single chip micro computer and several voltage regulation circuits. The communication between two units is achieved via a ribbon cable. The power supply to the sensor station is provided by a 12V Lithium Polymer battery. The use of battery power allows for a low cost, portable and low maintenance solution for the end user.

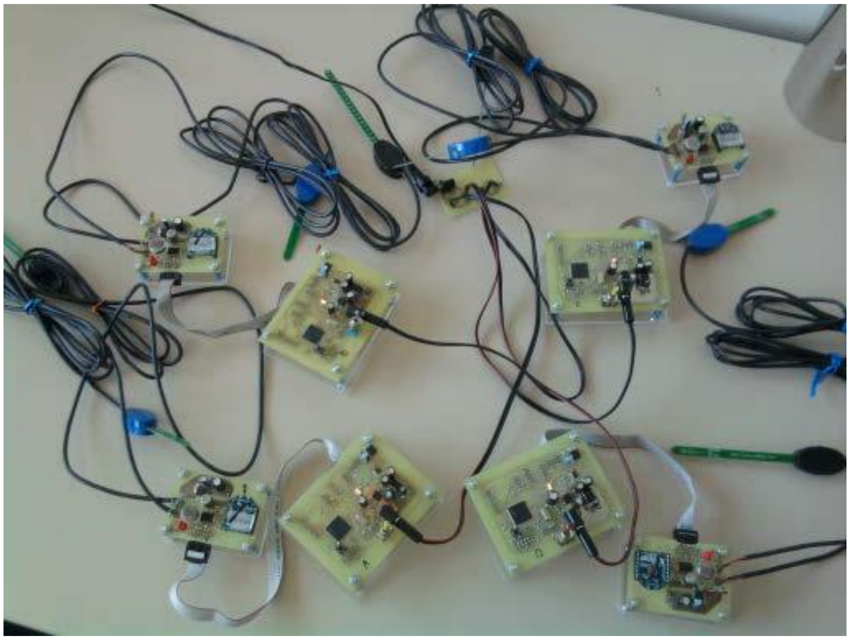


Figure 5-33: Final design of the sensor station

5.6.2 Coordinator Station Final Design

The final design of the coordinator station is shown in Figure 5-34. This station consists of three units: processing unit, transceiver unit and relay control unit. Similar to the processing unit of the sensor station, the coordinator station's processing unit also employs a C8051F020 single chip computer to allow for fast signal processing. Both UART0 and UART1 of the C8051F020 chip are used for interfacing both the XBee and XStream RF modem.

- XBee is used for the short range wireless communication between the coordinator station and sensor station
- XStream RF modem is used long range wireless communication between the coordinator station and central station

The Xbee wireless module is mounted directly on the processing unit to save space and lessen the complexity of design. XStream is a stand-alone RF modem therefore it was connected to the processing unit via an RS232 cable. The relay control unit used in this project is an IO relay control unit. Each relay can be activated using a TTL logic signal on the input pin of each relay. Port 1 on the processing unit was made available for interfacing with the relay unit. The connection between the relay unit and processing unit is established via a ribbon cable.

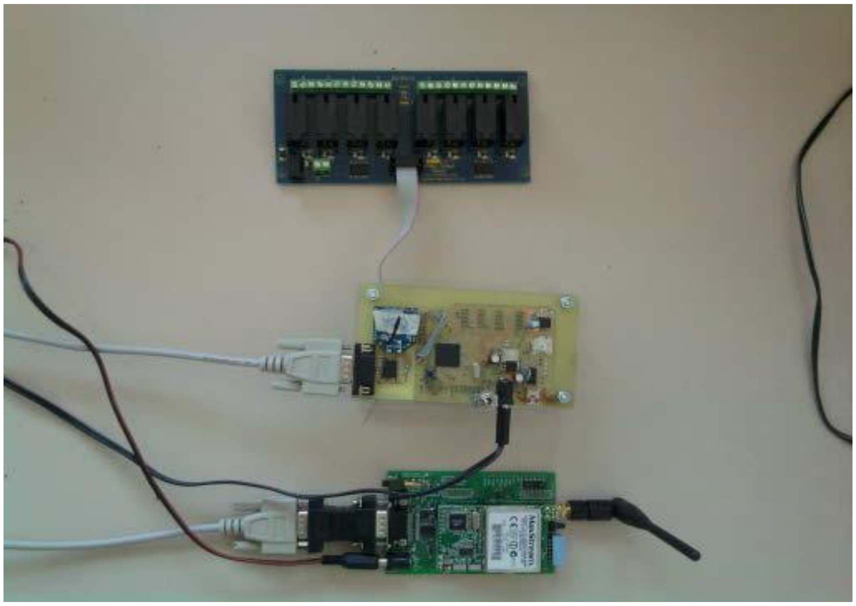


Figure 5-34: Final design of the coordinator station

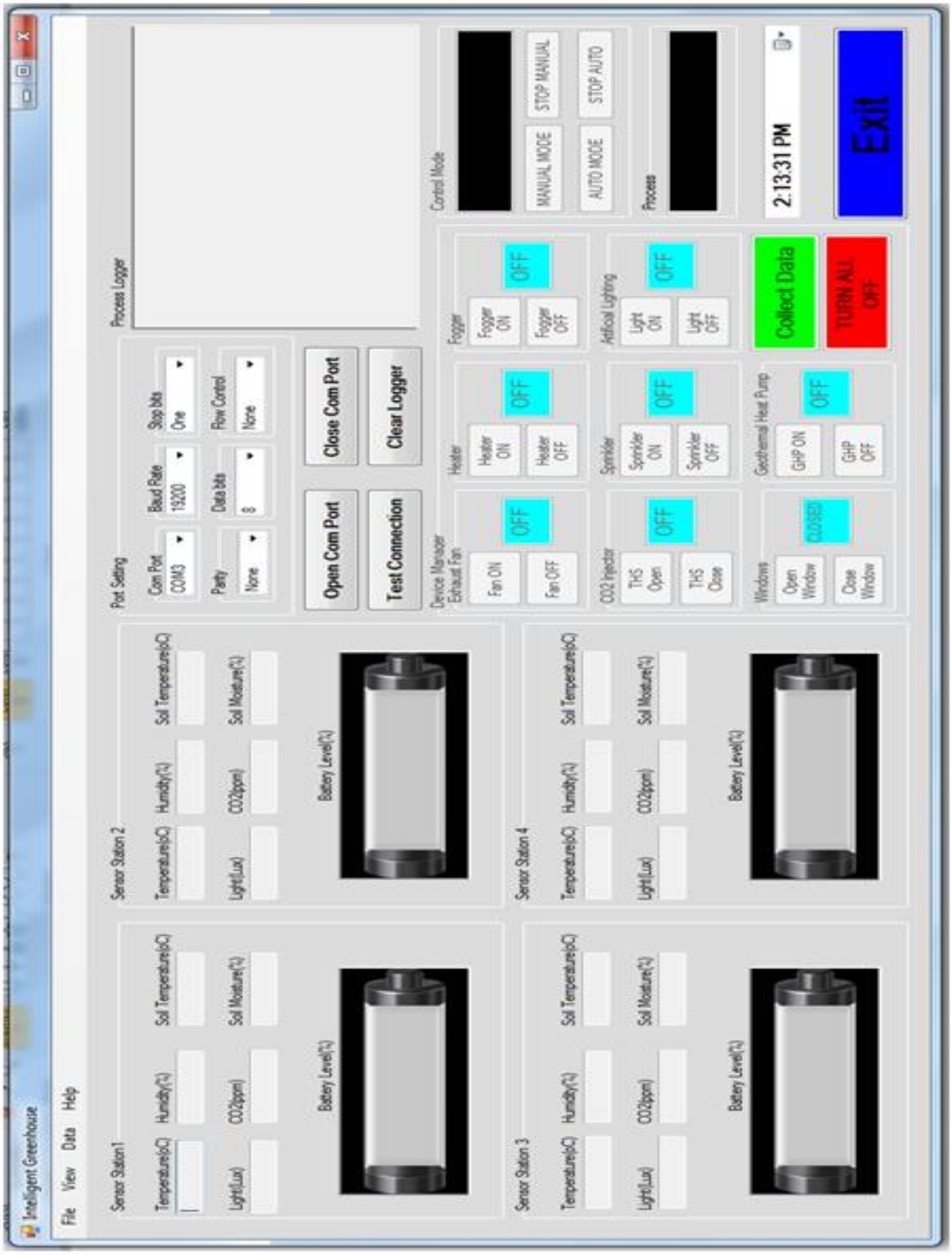
5.6.3 Central Station Final Design

The construction of Central Control is fairly simple. All it is required is a PC, an XStream RF modem and a USB cable. The RF modem is communicated with the PC via USB cable connection. The final design of the Central control Station is displayed in Figure 5-35.

Figure 5-35: Final design of the central station

5.7 Graphical User Interface (GUI) Final Design

The graphical user interface of the system is displayed in Figure 5-36. The GUI was designed using Visual C#. It was developed carefully to serve the purpose that the project has been set out for. Existing systems were designed mainly for skillful and experienced operators. New operators are often required to undergo an intensive training and education program before they are allowed to operate the system. Therefore, a simple but effective GUI was designed to tackle this problem. The designed GUI is so simple and convenient that even a beginner could effectively operate the system in a matter of hours.



Com Port: COM3
Baud Rate: 19200
Stop bits: One
Parity: None
Data bits: 8
Flow Control: None

2:13:31 PM

Figure 5-36: GUI of the developed system

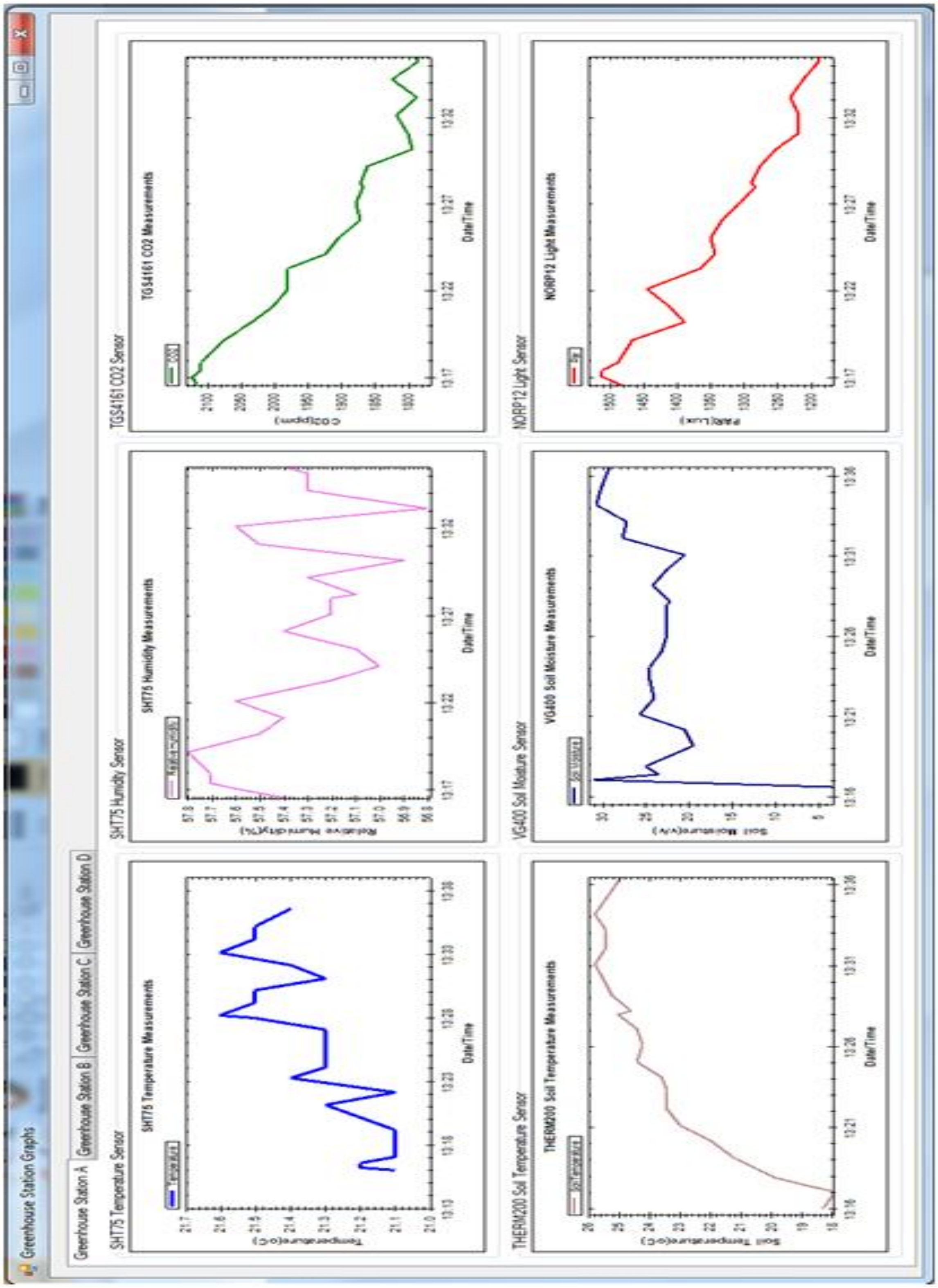


Figure 5-37: Real-time data plotting

The GUI’s key features are:

- Real-time monitoring: The user is able to monitor real-time information collected from the greenhouse environment.
- Transmitted and received instructions and response packets are recorded and displayed on the logger. This allows the user to keep track of any outgoing and incoming data and instruction packets.
- Real-time data plotting: any measurements retrieved are plotted and display in real-time. This feature allows the user to determine the trend and status of the greenhouse environment. This is shown in Figure 5-37.
- Historical data: Another one of the GUI attractive features is the ability to collect and store data in a local database. The program also records the time and date of when the data was collected and it save it into the database for future reference and analysis.
- Port Setting: This feature allows the user to configure the serial port such as selecting between com ports, changing baud rate, flow control etc.

5.7.1 MANUAL Mode

Initially, the aim of this project is to provide a fully automated greenhouse management system in order to make life easier for the growers. However in many cases growers are sometimes more interested in manual operation. Therefore a manual feature is also integrated into the design of the GUI. With the MANUAL feature, the operator is able to manually collect data, send a command to wake up the sensor station, check the status of the sensor station, control and operate local activates such as sprinkler, humidifier, heater etc. The layout of the MANUAL mode is shown in Figure 5-38.

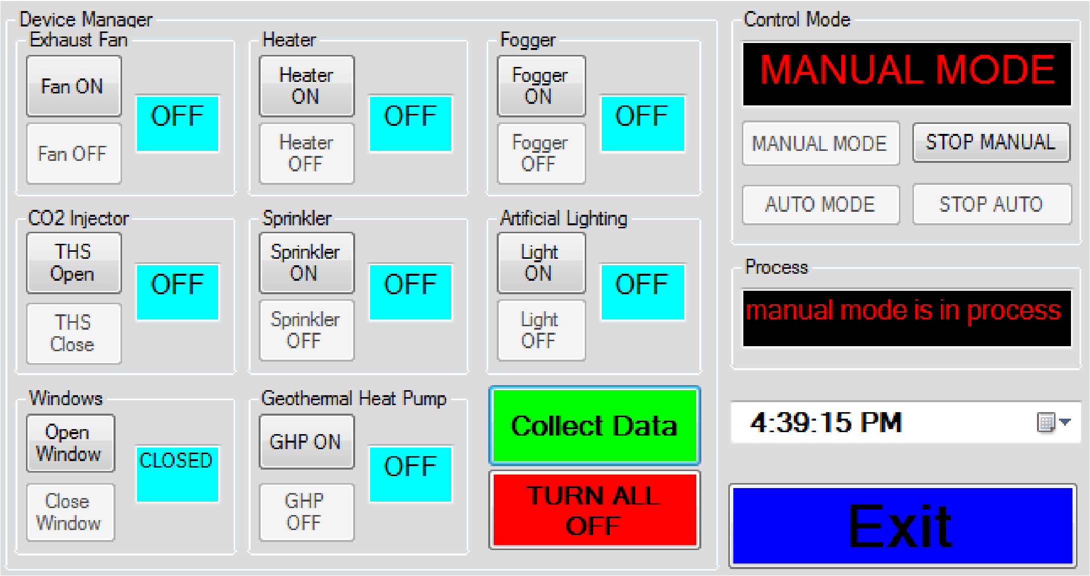
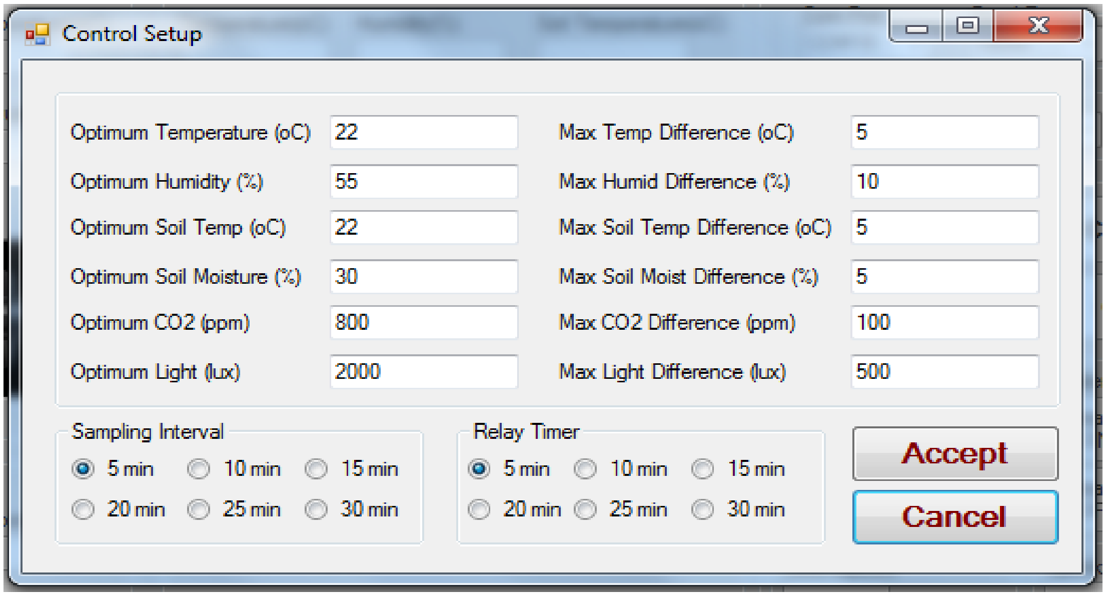


Figure 5-38: MANUAL Mode

5.7.2 AUTO Mode

AUTO mode makes life easier for the operator. It doesn't require instructions or human interventions but rather operates and controls the system in a preprogrammed manner. To use the AUTO mode, the operator needs to setup and configure necessary parameters and variables required for the control process. Figure 5-39 shows the layout of the AUTO mode



Optimum Temperature (oC) 22
Optimum Humidity (%) 55
Optimum Soil Temp (oC) 22
Optimum Soil Moisture (%) 30
Optimum CO2 (ppm) 800
Optimum Light (lux) 2000
Max Temp Difference (oC) 5
Max Humid Difference (%) 10
Max Soil Temp Difference (oC) 5
Max Soil Moist Difference (%) 5
Max CO2 Difference (ppm) 100
Max Light Difference (lux) 500

Sampling Interval
● 5 min ○ 10 min ○ 15 min
○ 20 min ○ 25 min ○ 30 min

Relay Timer
● 5 min ○ 10 min ○ 15 min
○ 20 min ○ 25 min ○ 30 min

Figure 5-39: AUTO mode

5.8 Database

The main purpose of using a database is to store historical data for future research and analysis. Therefore a designed database must be simple and easy to follow so that the user can easily retrieve recorded data in the future. The database design of this project is shown on Table 5-2.

Field	Descriptions
Record_number	Is used to keep track of recorded data
Sensor_Station	Displays the origin of recorded data
Time/Date	Displays the time and date of when the data was collected
Temperature	Temperature readings
Humidity	Humidity readings
Soil Temperature	Soil temperature readings
Soil Moisture	Soil moisture readings
Carbon_Dioxide	CO_2 readings
Light	Light readings
Battery_Status	Displays the battery status of each sensor station

Table 5-2: Database field description

6. Control of Operations and System Evaluation

6.1 Introduction

The development process of a plant is dependent on the environment. This is the main reason why a greenhouse is ideal for cultivation since it constitutes a closed environment in which climatic variables can be controlled to allow for an optimum growth and development of plants. Greenhouse climate control systems have been developed very quickly in the last few decades. In the late fifties, thermostats for temperature control were introduced as labour saving equipment and were later replaced by analogue electronics controllers [80]. Shortly after that more refined control systems and were developed and implemented in order to improve the overall condition of the greenhouse environment. Modern greenhouse and computerized climate control modules have become inseparable nowadays. Computerized climate control is an intrinsic part of present day modern greenhouse [81]. It allowed major advances and efficiency in product quality and maks the life of the growers a lot easier. The function of a computerized greenhouse climate controller [82] can be described as follows:

- It takes care of maintaining a protected environment despite fluctuation of external climate
- It acts as a program memory, which can be operated by the growers as a tool to control their crops.

The main advantages of using a climate control system in a greenhouse environment are:

- Energy conservation [83].
- Better productivity of plant [84].
- Reduce human intervention [85].

6.2 Development of the proposed Controller

The greenhouse climate is a complex system. It consists of many climate factors that affect the development of plants in a significant strong way. Various environment factors are interrelated and they cannot be considered singly without regard for the effect on the others as well as the total effect on the plant. Therefore, it is essential to define what the system inputs and outputs of a greenhouse system are and how they affect one another.

6.2.1 Input and output variables of greenhouse system

The environmental factors affecting the greenhouse climate are [1]:

- Temperature
- Relative humidity
- Soil temperature
- Soil water balance (or soil moisture)
- Carbon Dioxide (CO_2) balance
- Solar radiation (sunlight balance)

Based on the above information, the following greenhouse system inputs were proposed:

- Difference between the optimum temperature and the current temperature
- Difference between the optimum humidity and the current humidity
- Difference between the optimum soil temperature and the current soil temperature
- Difference between optimum soil moisture and current soil moisture
- Difference between optimum light intensity and current light intensity
- Difference between optimum CO_2 concentration and current CO_2 concentration

The system outputs are basically a series of actions required for adjusting the climate level inside the greenhouse in order to keep it at an optimum level. The following are the system outputs:

- Air heating system (ON/OFF).

- Humidification system (ON/ OFF).
- Thermal shade system (Open/Close).
- CO_2 generation system (ON/ OFF).
- Forced ventilation system (ON/ OFF)
- Window (Open/Close)

6.2.2 Control Rules

The control rules can be divided into four separate groups that are responsible for controlling different climate groups in the greenhouse:

- The first group focuses on controlling the temperature and humidity
- The second group focuses on controlling the greenhouse's soil condition.
- The third group focuses on managing the lighting level in the greenhouse through shading and artificial lighting.
- The fourth and final group is mainly concerned with the air quality in the greenhouse.

	Group 1		
Rule	*if Temp (in-Opt)*	*if Humid (in-Opt)*	*Heater/ ventilation/Humiliation*
1	**Low**	**Low**	Fogger On, Heater On, Window Close, Fan Off
2	**Optimal**	**Low**	Fogger On, Heater Off, Window Open, Fan Off
3	**High**	**Low**	Fogger On, Window Open, Fan On, Heater Off
4	**Low**	**Optimal**	Fogger Off, Window Close, Fan Off, Heater On
5	**Optimal**	**Optimal**	Heater Off, Window Open, Fogger Off, Fan Off
6	**High**	**Optimal**	Fogger Off, Heater On, Window Open, Fan On
7	**Low**	**High**	Fogger Off, Window Close, Fan Off, Heater On
8	**Optimal**	**High**	Fogger Off, Fan Off, Window Open, Heater Off
9	**High**	**High**	Window Open, Fan Off, Fogger On, Heater On
	Group 2		
	if Soil Temp (in-Opt)	*if Soil Moist (in-Opt)*	*soil heating/ irrigation/humidification*
10	**Low**	**Low**	Sprinkler On, GHP On
11	**Optimal**	**Low**	Sprinkler On, GHP Off
12	**High**	**Low**	Sprinkler On, GHP \Off
13	**Low**	**Optimal**	Sprinkler Off, GHP On
14	**Optimal**	**Optimal**	Sprinkler Off, GHP Off
15	**High**	**Optimal**	Sprinkler Off, GHP Off
16	**Low**	**High**	Sprinkler Off, GHP On
17	**Optimal**	**High**	Sprinkler Off, GHP Off
18	**High**	**High**	Sprinkler Off, GHP Off
	Group 3		
	If light(in-Opt)	*if Temp (in-Opt)*	*Light/Shading*
19	**Low**	**Low**	Light On, Shading Close
20	**Optimal**	**Low**	Light Off, Shading Open
21	**High**	**Low**	Light Off, Shading Close
22	**Low**	**Optimal**	Light On, Shading Close
23	**Optimal**	**Optimal**	Light Off, Shading Open
24	**High**	**Optimal**	Light Off, Shading Open
25	**Low**	**High**	Light On, Shading Close
26	**Optimal**	**High**	Light Off, Shading Close
27	**High**	**High**	Light Off, Shading Close
	Group 4		
	CO$_2$(in-Opt)		*CO$_2$ enrichment*
28	**Low**		Window Close, CO$_2$ Enrichment On
29	**Optimal**		Window Open, CO$_2$ Enrichment Off
30	**High**		Window Open, CO$_2$ Enrichment Off, Fan On

Table 6-1: Control rules

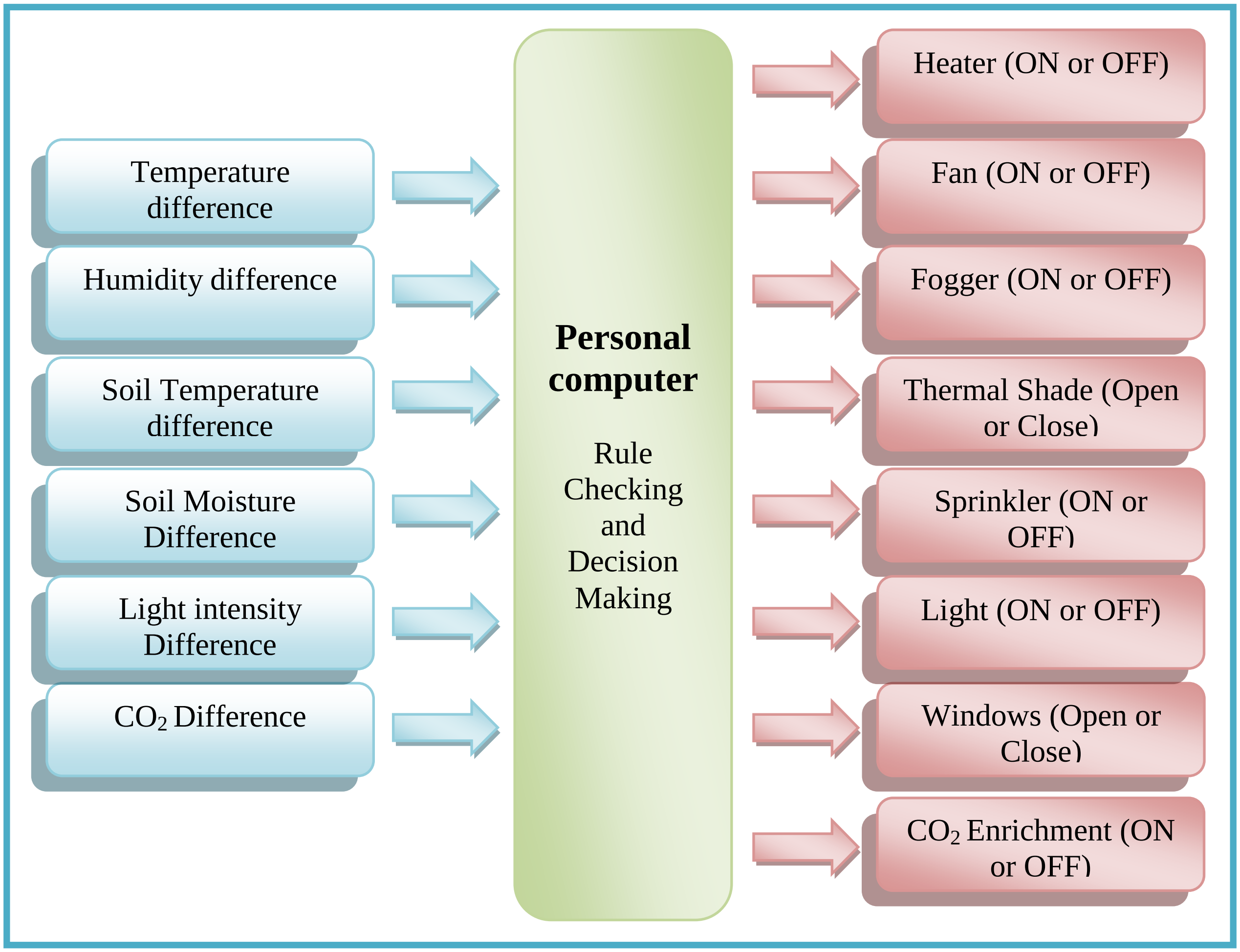


Figure 6-1: Tasks in greenhouse environmental control

A Block diagram describeing the tasks involved in the control system is shown in Figure 6-1. In the illustrated control system, the incoming data collected from the greenhouse environment is processed by a PC. The collected measurements are compared with a predefined optimal value and the result of the comparison is defined by one of the following terms:

- **Low**– this term is assigned if the difference between the current value and the optimum value is lower than maximum threshold
- **High** – this term is assigned when the difference is higher than the minimum threshold
- **Optimal** – this term is assigned if it is within the predefined limit

The computer assesses the result of the comparison and determines the suitable actions required for controlling the current climate condition based on the predefined control rules

6.3 Control Algorithm

The control algorithm for the controller is made up of two parts; comparison and rule checking.

6.3.1 Comparison Algorithm

The comparison algorithm allows the program to compare the collected measurement with a pre-defined optimal value. This comparison process is divided into 3 separate parts; Positive checking, Zero checking and Negative checking.

- Positive Checking is used to determine if the current measurement is greater than the sum of the optimum value and the maximum difference.
- Zero Checking is used to determine if the current measurement is within the predefined limit.
- Negative Checking is used to determine the status if the current measurement is smaller than the difference between optimum value and the minimum difference.

A sample code of the comparison process is shown in Figure 6-2

```
// Positive Checking
if ((Current_Temperature >(Optimum_Temperature+Max_Temp_Diff)))
{ temp_Status= 1;} // High
// Zero Checking
if ((Current_Temperature >=(Optimum_Temperature-Max_Temp_Diff)) &&
(Current_Temperature<=(Optimum_Temperature+Max_Temp_Diff)))
{temp_Status = 0;} // Optimal
// Negative Checking
if ((Current_Temperature <(Optimum_Temperature-Max_Temp_Diff)))
{temp_Status = -1;} // Low
```

Figure 6-2: Comparison Algorithm

6.3.2 Rule Checking Algorithm

The result from the comparison process is assessed and judged by the rule checking algorithm. The function Send_Relay_Instruction is used to issue instructions to the coordinator station. A delay of 100 ms was placed at the end of each transmission to slow down the transmission process and allows time for the coordinator station to react and respond to each incoming instructions. A sample code of the rule checking algorithm is shown on Figure 6-3.

```
if (temp_Status == -1 && Humid_Status == -1 )
{
      Send_Relay_Instruction(SENDING_INSTRUCTION[(int)PacketName_Instru
      ctrion.FOGGER_ON]);
      delay(100);
      Send_Relay_Instruction(SENDING_INSTRUCTION[(int)PacketName_Instru
      ctrion.FANHEATER_ON]);
      delay(100);
      Send_Relay_Instruction(SENDING_INSTRUCTION[(int)PacketName_Instru
      ctrion.WINDOW_CLOSE]);
      delay(100);
      Send_Relay_Instruction(SENDING_INSTRUCTION[(int)PacketName_Instru
      ctrion.FAN_OFF]);
      delay(100);
}
```

Figure 6-3: Rule checking Algorithm

6.4 Controller Implementation and Evaluation

The computerized greenhouse climate controller must be judged on the basis of its ability to react and respond to a set of given inputs with that of an expert in greenhouse management area. Therefore an experiment was carried out to test the reliability of the developed controller. Due to insufficient equipment required for the controlling of greenhouse climate, a simple simulator was created to simulate the control process instead. The simulator consists of a relay board with 8 relay outputs. The relay outputs are connected to LEDs and fans to represent the greenhouse equipment that need to be controlled (CO_2 injector, artificial lighting, fogger, window, thermal shade, sprinkler heater and fan). Two different case scenarios were introduced to the experiment. Figure 6-4 and Figure 6-5 show the controller's responses to each case scenario.

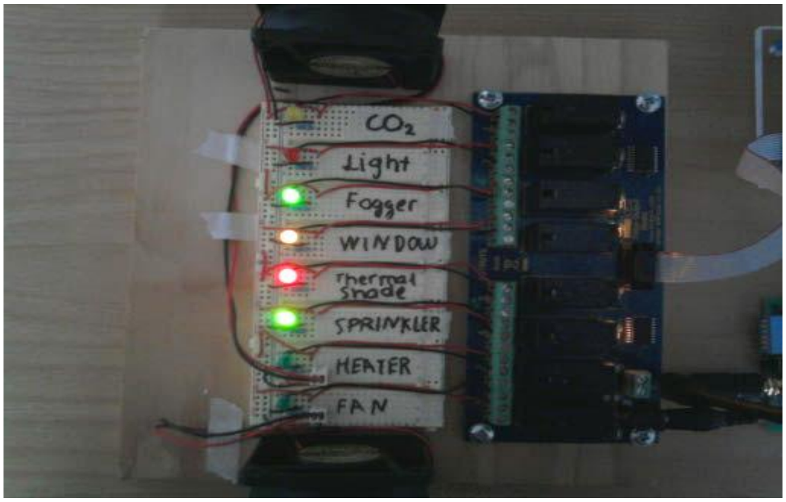


Figure 6-4: Case 1-simulation result (invoked control rules: 2, 11, 20 and 29)

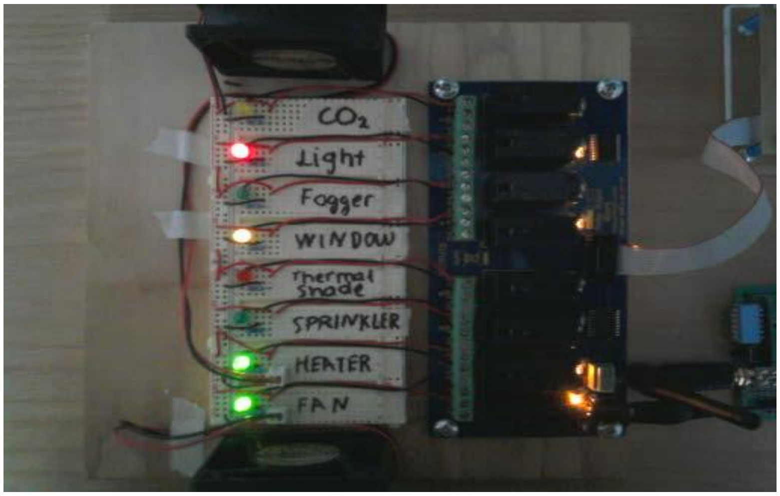


Figure 6-5: Case 2-simulation result (invoked control rules: 9, 17, 19 and 28)

The result obtained from each case scenario shows that immediate actions were taken to adjust the climate level in the greenhouse in accordance to the conditions given to the controller. No problem or delays were detected throughout the whole testing process, indicating that the developed control system worked satisfactorily. In future development it is recommended to have the system implemented in a greenhouse environment with sufficient equipment with the aim of verifying the obtained results in this simulation.

6.5 System Evaluation

6.5.1 Measuring Environment

Data reliability is a critical issue for a WSN, and it is necessary to ensure the system will not lose data packets during transmission. Therefore to assess the reliability of the developed system, an experiment was carried out in one of the greenhouses at the New Zealand Institute for Plant & Food Research Ltd. The experimental setup is shown in Figure 6-6

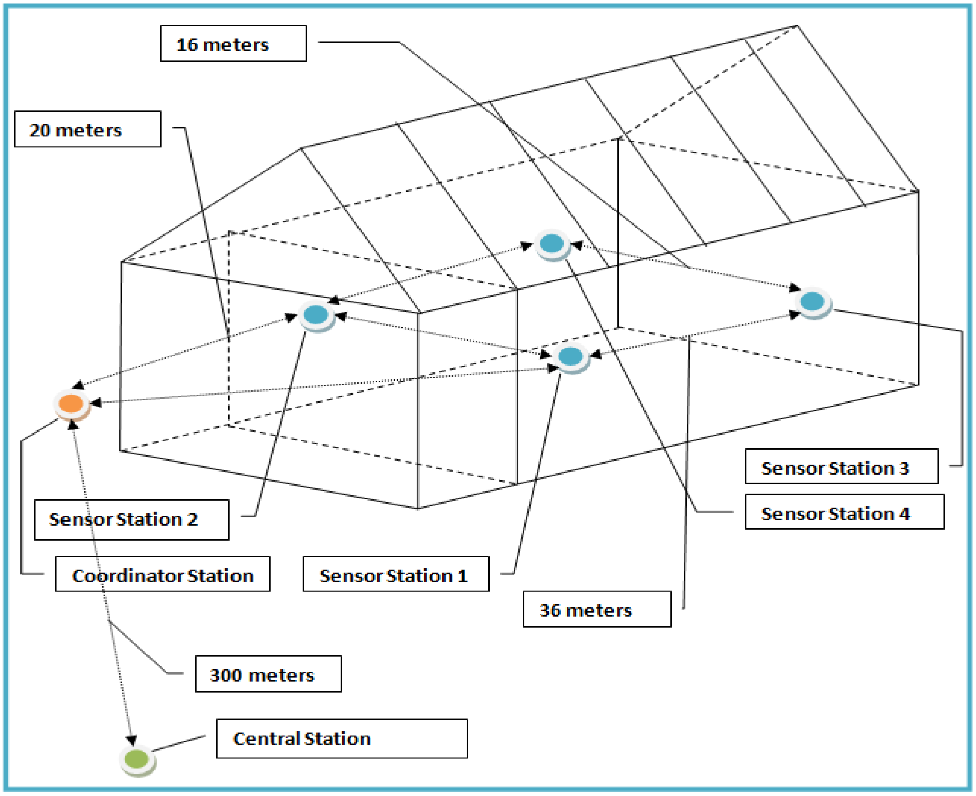


Figure 6-6: Experimental setup

The greenhouse used in the experiment has the following dimensions: length = 40m, width = 20m and height = 5m. In this investigation, the network setup is a basic star topology, where four sensor stations were used to measure the climate inside the greenhouse. The coordinator station is located near the greenhouse entrance. The distance between the location of the coordinator station and sensor station 1 and 2 is approximately 20m, and the distance between the coordinator station and sensor station 3 and 4 is approximately 56m. The central station is located in an office nearby (approximately 300 metres way from the coordinator station).

6.5.2 Network Throughput and ZigBee Feasibility

During the experiment, a total of 200 data requests were sent to each sensor station. The experimental results show that 4 packets with readings were either lost or were not received correctly (two packets were from sensor station 3 and 2 were from sensor station 4), which indicated a 0.005% data loss rate in terms of packets. Table 6-2 shows the network throughput of the system. The testing environment was thoroughly investigated and it was possible to conclude that the high humidity and dense flora factors of the greenhouse environment were the main causes of the missing data packets. An experiment was carried out to investigate the effects of these factor climate factors on the wireless range of the ZigBee modules. The maximum communication range of 50m was figured out in an individual test where the distance between the sensor station and coordinator station inside the greenhouse was increased until the connection was lost. It was discovered that the sensor stations needed to be placed no further than 45m away from the coordinator station to ensure reliable transmission. Despite the missing packets, the total throughput of 99.5% was an excellent result. Based on this result, it is possible to conclude that wireless ZigBee modules can be used as one solution to lower installation cost, increase flexibility and reliability and create a greenhouse management system that is only based on wireless nodes.

Initial condition					
	SS1	SS2	SS3	SS4	Total Throughput
Packet transmitted	200	200	200	200	800
Packet Received	200	200	198	198	796
Packet Loss (%)	0	0	0.01	0.01	0.005

Table 6-2: Network Throughput

6.5.3 Power Consumption

Table 6-3 shows the current consumption of the sensor station.

Sensor Station	current consumption (mA)
SHT57	2
VG400	0.5
THERm200	2
NORP12	3
ZigBee	35
TGS4161	50
C8051f020	10
Miscellaneous (LEDs, connector, cable etc.)	5
Total current	107.5

Table 6-3: Current consumption of the Sensor Station

As shown on Table 6-3 the calculated total current consumption of the sensor station is 107.5 mA. It was discovered that, at the sampling rate of one sample every 5 minutes, the lifespan of 4 AA batteries is approximately 33 days. This result indicates that the developed system is both energy efficient and is very cheap to operate. Of course, a better and longer life time can be expected by having a longer sampling interval or using larger capacity batteries. Furthermore, the result can be improved by replacing the TGS4161 CO_2 Electrochemical sensor with an NDIR CO_2 sensor. The reason behind this suggestion is because, unlike the electrochemical CO_2 sensor, the NDIR CO_2 sensor doesn’t required a heater substrate (which consumes a large amount of power) to maintain its sensing element. Therefore they consume less power than electrochemical sensors (typically 25 mA).

7. Conclusions

This report presents research on an application of a ZigBee-based wireless sensor network (WSN) in greenhouse climate monitoring and controlling. Unlike previous systems, which usually consist of two stations (a sensing station and control station), the proposed system consisted of three stations: a Sensor Station, Coordinator Station and Central Station. The sensor station acts like a data acquisition unit that is capable of measuring six different climate parameters such as ambient temperature, relative humidity, soil temperature, soil moisture, light intensity and carbon dioxide (CO_2). The coordinator station's functions are similar to that of a router. It is responsible for controlling the flow of data and instructions between the greenhouse station and the central station. It's also in charge of controlling the greenhouse climate via local equipment such as sprinkler, heater, exhaust fan etc. The central station is the main controller of the system. It carries out various tasks such as data collection, data storage, data processing and greenhouse climate adjustment. With three stations, the work load between each station is evenly distributed which will ultimately improve the system's performance, reliability and flexibility.

Each sensor used in this project was individually tested and the results were compared with calibrated commercial devices. ZigBee reliability and feasibility were also investigated. The signal strength of ZigBee wireless module was found to be slightly weaker when tested in the greenhouse environment. It was discovered that high humidity and dense flora factors of the greenhouse environment were the main causes of the diminished in signal strength. Despite the weakening in signal strength, it still shows an excellent result of 99.5% in total throughput. This result indicates that ZigBee can be used as one solution to lower installation costs, increase flexibility and reliability and create a greenhouse management system that is only based on wireless nodes.

Compact, portable and low power consumption are some of the most important key elements in the design of a wireless system. Therefore a carefully selection of sensing devices and circuitry components is also very important. Thanks to the rapid development and continual innovation in the electrical and electronics industry, sensing devices and circuitry components are now available in all shapes and sizes. Their power and capability have also been greatly improved. It depends on the type of the application; some are more suitable than others. Most sensing devices and circuitry components chosen for this system are fairly small, compact (most are made up of surface mount components) and have very low power consumption. These characteristics make the developed system superior to many existing systems in terms of size, maintenance requirements and power consumption.

Many existing greenhouse control systems often employed a “Time-driven” control method as one solution to solve greenhouse climate problem. This control method allowed major advances and efficiency in product quality and made the life of the growers a lot easier. However, in today’s dynamic greenhouse environment this control method was found to be insufficient and cannot deliver the level of automation and efficiency that’s required. A Sensor-based Event-driven controller was proposed to tackle this problem. In order to determine the controller’s reliability and capability an experiment was proposed. Due to insufficient equipment required for the controlling of greenhouse climate, a simple simulator was created to simulate the controlling process. The result obtained from the experiment shows immediate actions were taken to adjust the climate level in the greenhouse in accordance to the conditions given to the controller. No problem or delays were detected throughout the whole testing process, indicating that the developed control system is very reliable. However this assumption is made based on the simulation result and not the actual result. Future work is therefore to have the controller tested out in an actual environment to accurately determine its reliability and capability

In conclusion, greenhouse climate monitoring and controlling is one attractive application field to create a wireless automation system. This thesis can therefore be used as a good reference source for further integrating/developing or similar work/ projects.

7.1 Future Developments

This thesis has provided a comprehensive report on the design process and implementation of a ZigBee-based wireless greenhouse management system. Certainly, there is a need for further study to improve the system reliability and capability. The following are some recommendations for possible future work.

- Due to the lack in equipment necessary for the controlling of greenhouse climate, the developed controller was not correctly tested. Therefore it is recommended to have the controller tested out in a sufficient greenhouse environment to accurately determine its reliability and capability.
- TGS4161 is a solid electrolyte type sensor therefore it has similar characteristics to a battery. It was later discovered that the output EMF value of the sensor seems to drift slightly over time. Therefore in order to obtain a stable and accurate measurement of CO_2 a special microprocessor called a FIC03272 should be used with a TGS4161 sensor
- More sensors can be added to the sensing unit to monitor others environmental parameters such as soil pH level, air flow, carbon monoxide (CO) and oxygen (O) level
- GlGlobal System for Mobile Communication (GSM) and Short Message Service (SMS) can also be integrated into the system. These extra features will allow the system to directly alert the user of any abnormal changes in the greenhouse environment through the transmission of a simple short text message

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Publications

A. Proceeding and Conference Paper

1. V. M. Quan, G. Sen Gupta, S. Mukhopadhyay, "Review of Sensors for Greenhouse Climate Monitoring", Proceedings of the IEEE Sensors Applications Symposium (SAS 2011), Feb 22-24, San Antonio, USA, pp. 112-118
2. V. M. Quan, G. Sen Gupta, S. Mukhopadhyay, `Intelligent Wireless Greenhouse Management System', Proceedings of Electronics New Zealand Conference (ENZCON 2010), Nov 2010, Hamilton, New Zealand, pp. 129-134

B. Seminar/Presentation

1. V. M. Quan "Intelligent Wireless Greenhouse Management System ", of Electronics New Zealand Conference (ENZCON) Poster Presentation, 22th Nov, Waikato University, New Zealand.
2. V. M. Quan "Intelligent Wireless Greenhouse Management System ", Electronics, Information and Communication System (EICS) Seminar, 27th Dec, Massey University, New Zealand.

Appendix