Cell-Level Temperature and Hive State Monitoring for a Remote Smart Beehive System

by

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A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Department of Electrical and Computer Engineering

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Abstract

The designs of a temperature sensing and control board and a cell content detection board for use in a remote smart beehive system are presented in this thesis. These boards will help beekeepers to optimize their beehive management and allow researchers to better understand the environmental factors and stresses affecting the honeybee population. Simulations and experimental testing of a prototype temperature sensing and control board for use at the cell-level are presented. A temperature sensor was found to be capable of monitoring the temperature within a 2.5 cell radius and a heater was found to heat all cells within a 2.5 cell radius to temperatures hot enough to kill *Varroa* mites. The heat remained within the local area reducing the damage to other cells. The design and testing of an interdigitated capacitance sensor board for monitoring the cell contents in different regions of a hive frame is also presented. The relative permittivity of the material the electric fields pass though changes as the cell contents change, resulting in a change in capacitance. Simulations and experimental trials tested the designed sensor performance for measuring the level of water, honey, and various concentrations of sugar-water. The capacitance was found to increase with the liquid level and it could be determined if the cells are at least 30% or 60% full. The measured capacitance was inversely related to the sugar concentration of the liquid. Therefore, capacitance should be monitored over time because it will increase as the cells are filled with low sugar concentration nectar and then decrease as the water evaporates and the honey ripens. The final experiment presented in this thesis is an in-hive field test with the capacitance sensor boards. The system was capable of recording data and withstanding the hive environment for over a month. Due to the time of year, the bees were not actively building comb or making honey, but the capacitance sensors still worked and measured bee activity instead as the bees walked on the capacitance sensors.

Acknowledgements

I would first like to thank my advisor Dr. Cyrus Shafai for taking me as a graduate student and sharing his technical knowledge and insights into the many problems addressed in this thesis. I would also like to thank Dr. Rob Currie in the Department of Entomology for sharing his knowledge on bees and beekeeping as well as allowing me to test my sensors in his hives.

From industry, I would like to thank Al Campbell from Durston Honey Farms Ltd. for his suggestions and views from a beekeeper's perspective of what would be useful to the beekeeping industry and for large scale hive management. I would also like to thank Kurt Hildebrand and Bruce Hardy from Function Four for their support and expertise of the technology industry.

Thank you to the other graduate students working on the Smart Hive project, Colin Gaudreau and Nadia Khoshgoo, for their help and support, as well as the many other graduate students I have met during my studies. Thank you to Zoe Rempel from the Department of Entomology for helping me with the in-hive experiments.

Lastly, I would like to thank my family for their encouragement and support. Thank you to my parents for passing on to me their love of learning and my brother for his friendship and sense of humour.

This work was funded by NSERC, The University of Manitoba Faculty of Graduate Studies, and MITACS.

Table of Contents

List of Figures

List of Tables

Chapter 1 – Introduction

1.1 Motivation

In Canada, beekeeping and honey production is a multi-million dollar industry. In 2016 there were 9859 beekeepers maintaining 750155 colonies throughout Canada [1]. Eighty percent of the bee colonies in Canada are commercially operated and half of the honey produced in Canada is exported [2]. A study of the honey yields across the world in 1984 found that Canada yielded the highest amount of honey per hive in the world, with an average of 63 kg per hive while the world average was only 15.3 kg per hive [3]. In that same year Canada produced 43000 tonnes of honey and exported 19000 tonnes [3]. The amount of honey produced is similar today. In 2016, 41821 tonnes of honey was produced for a total value of $157.8 million with an average colony yield of 55.8 kg of honey [1]. Therefore, over the last 20 years the honey production has remained about the same for various reasons, so one goal of the research discussed in this thesis is to study how technology can be used within a hive to provide better hive management systems resulting in more productive colonies and higher profits for beekeepers.

One large problem with commercial beekeeping today is that the nature of beekeeping results in beekeepers with hundreds to thousands of hives placed throughout large areas. This allows for high honey yields, but makes monitoring and treating hives time consuming and labour intensive. Therefore, beekeepers want to be able to remotely monitor hive conditions and honey levels as well as remotely interact with their hives to minimize time spent visiting hives. A remote monitoring system will also provide beekeepers with up-to-date hive information instead of waiting for hive visits, allowing beekeepers to react in a timely manner to harvest full hives or solve any problems that may arise.

A remote monitoring system would also provide insight into hive health and bee behaviour from a research perspective. Bee populations are known to suffer stresses due to reasons that are complex and may arise due to a combination of different factors such as climate, *Varroa* mites, or chemicals. By creating a system that is able to monitor multiple hives over long periods of time, large amounts of data can be gathered about current internal and external environmental factors allowing for researchers and apiarists to gain a better understanding of the hive environment and how various factors impact the honeybees and honey production.

A system that is able to both remotely monitor and treat hives against *Varroa* mites, known predators of honeybees, would provide many advantages over current treatment methods. Existing methods are discussed in detail in Chapter 3, but a main disadvantage of existing non-chemical and chemical methods is that they can be highly labour intensive [3, 4], due to the need to travel to the hives frequently to apply treatment. This also limits when and how many times a hive can be treated allowing for periods of time throughout the season when the hive is not being treated allowing the mite population to grow.

1.2 Problem Definition

A remote monitoring and control system is needed for researchers and apiarists to gain a better understanding of the internal hive environment and how external factors impact honeybee colonies. The remote system should also provide a way for beekeepers to monitor the status of their hives remotely and possibly treat *Varroa* mite infestations allowing for better hive operation management. The designed system should be able to remotely:

1. Monitor and control temperature within regions of the hive frames
2. Monitor the cell contents within the hive frames

Both the bees and beekeepers place constraints on the system and have requirements that need to be met. Bees have many sensory organs are known to be highly sensitive to sound, light, touch, and chemical changes [5], and as quoted in [3], Lacher found that bee antennae are sensitive to differences in temperature, humidity, and carbon dioxide levels [6]. Therefore, the system should not include any components that interfere with natural bee behaviour.

The main requirement from a beekeeper is that the system needs to fit into existing hive structures, which in Canada and most other countries are Langstroth hives [3]. Similarly, the system needs to use some type of comb foundation because beekeepers only use foundation and do not allow the bees to build natural comb, and, like existing hive frames, they need to be easily removable. Further details on the Langstroth hive and hive frames and foundations are discussed in Chapter 2. With regards to selecting a treatment of *Varroa* mites, a non-chemical, low-labour intensive, remote method with a minimal impact on the bees' natural way of life is desired for reasons further discussed in Chapter 3.

1.3 Proposed Solution

Two components of the proposed system were studied in this thesis, the first provides a per-cell monitoring and control of temperature within the brood box and the second provides a per-cell monitoring of cell contents for use in both the honey super and brood box.

1.3.1 Temperature and Control

This part of the system consists of a printed circuit board (PCB) with temperature sensors and heaters to be placed inside of the brood box. It is known that the temperature in the brood nest is highly regulated by the bees and therefore by monitoring the temperature in the brood nest the beekeeper will be able to get a general idea of the hive's overall health. Heat is selected as a non-chemical method for killing *Varroa* mites so small heaters are also placed on the board to

provide beekeepers with the ability to selectively heat parts of the honeycomb to remotely kill *Varroa* mites.

As shown in Figure 1.1 the sensors are all placed on one side of the board and connected to the other side via heat pipes. This allows for the side without the sensors to be pressed flat against the base of the honeycomb. The temperature sensors can then be placed throughout the frame to allow for the temperature in all the cells to be measured so a temperature map of the frame could be developed. This can be useful to determine if certain regions of the hive are regulated more or less by the bees and how different external factors affect different parts of the hive. These sensors may also provide insight into the location of bees and larvae within the brood nest, as bees are known to sit on top and heat the cells containing larvae [3]. As discussed further in Chapter 3, many hive temperature monitoring systems that have been used in research only place a single temperature sensor in the brood nest area, therefore the proposed system will be able to provide more information on the conditions within the brood nest.

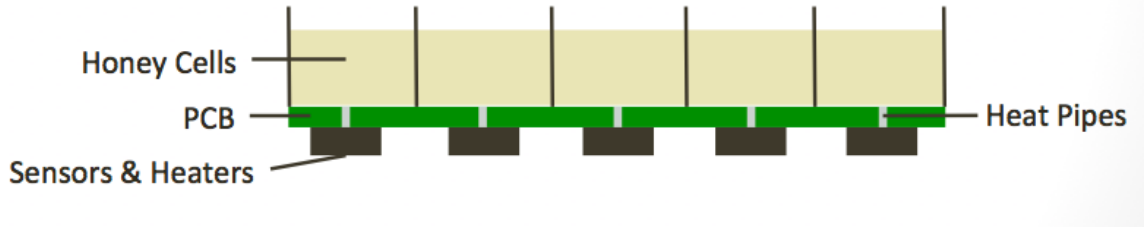


Figure 1.1 Proposed PCB, temperature sensor, and heater placement within a honeycomb

Heat was selected as the method to kill the mites over other non-chemical and chemical alternatives for reasons discussed in Chapter 3. Heat has been used as a non-chemical method of killing mites, however current systems are time consuming requiring either many short treatments [4] or a few long treatments [7], and in some cases entire frames of brood are killed along with the mites [4]. Therefore, by placing digitally controlled heaters throughout the hive

frames the temperature of individual cells can be controlled and cells can be heated locally to minimize the larvae loss. Another advantage to having the heaters controlled digitally is that the mites can be killed as soon as they are detected, thus supressing the mite population preventing it from getting a chance to grow, where as in the existing systems the time between treatments allows for the mite population to increase again.

1.3.2 Cell Content Detection

The second component developed for the system is the cell content detection system. This consists of a second PCB divided into regions each with an interdigitated capacitor (IDC) used for determining the contents of the cells above it. This system can be used in the honey supers to measure the honey levels and in the brood box to monitor the larvae growth. IDCs have been used for other similar uses in food applications such as determining milk water [8], bacterial [9], and fat [10] contents, sugar solution contents [11], and harvested honey sugar contents [12]. The board design is shown in Figure 1.2. This board has capacitors on both sides to allow for the honeycombs to be built directly on either side. The functional details of the IDC can be found in Chapter 4, but generally the capacitance measured by the system will change as the nectar and honey contents change or the larvae grows in the cells directly above the capacitor. This is a different use of the IDC than in [8-12] because the proposed system will focus on measuring the height of the cell contents (i.e. honey or larvae) above the capacitor over time as it changes instead of completely immersing the sensor in the solutions to take a measurement as was done in [8-12]. The proposed system will also monitor the capacitance over time to potentially detect the state of the honey as it ripens.

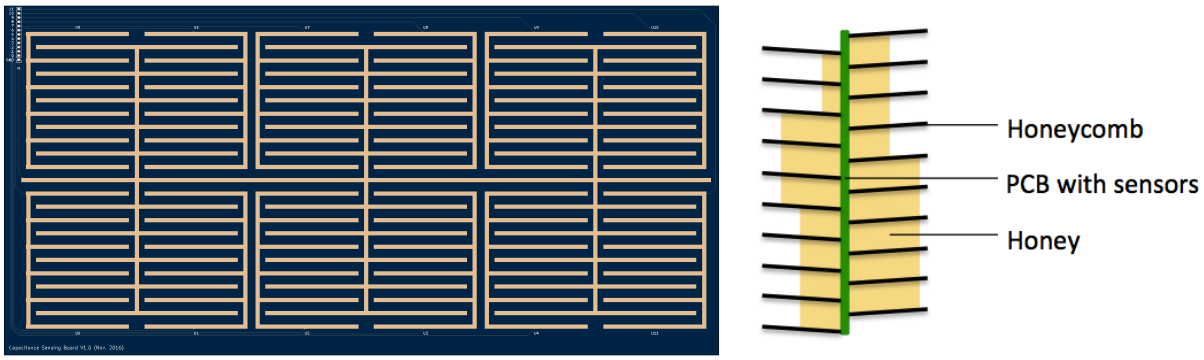


Figure 1.2 Cell content monitoring (a) capacitor layout and (b) placement within a honey comb

As further discussed in Chapter 4, bees are more productive when there is more space in the hive for producing honey because they can spread out the unripe honey, thus increasing the ripening rate. The presence of empty honeycombs has also been found by researchers to stimulate nectar collection and honey storage during strong flows [13]. Therefore, the sooner a beekeeper can replace full frames in their hive, the higher honey yield they can achieve. Currently beekeepers must physically go check the status of the honey frames to determine if they need to be harvested and as discussed previously this can be time consuming depending on the location of the apiary and costly if the honey is not yet ripened. Therefore, a remote honey level monitoring system would help to optimize operations by eliminating unnecessary trips to hives and maximize the honey yield by minimizing the amount of time a hive is sitting full.

A second use of the cell content monitoring system is in the brood nest to provide a way to estimate the larvae developmental stage within the capped cells, which could then be used to estimate the future colony population. Population estimation can be used as an indicator of queen health, colony health, indicate potential future swarming, or be used to ensure that there are going to be enough bees in a region to match the future nectar flows.

1.4 Thesis Formulation

The goal of this thesis is to determine the viability of a remote system for monitoring the temperature throughout the individual cells of a hive frame, killing mites within a local area of a honeycomb using heat, and monitoring the cell contents, specifically the honey level and larvae state, using an interdigitated capacitor. The usefulness of the system is also evaluated based on both the information about colony health and the hive environment that can be provided to researchers and the functionality it provides beekeepers for better hive management.

1.4.1 Thesis Objectives

The main objectives of this thesis are:

1. Study the possibility of measuring the temperature in each cell within a beehive by:
    a. Simulating the heat flow within a single cell to determine best location for measuring temperature within a cell
    b. Simulating the heat flow between cells to determine temperature sensor range

2. Study the possibility of using small heaters throughout a hive frame to kill mites by:
    a. Simulating the heat flow within the cell to determine the power needed to reach the required temperatures
    b. Simulating the heat flow between cells to determine the range of the heaters

3. Study the effectiveness of the use of sensors to measure the temperature in each cell and heaters to control the temperature in each cell by:
    a. Designing a prototype board
    b. Performing lab tests with the prototype board to verify the simulations

4. Study the feasibility of using an IDC sensor for the use of cell content monitoring by:
    a. Performing simulations to verify a measurable change in capacitance will occur as cell contents change
    b. Designing a prototype board
    c. Performing lab tests with the prototype board

5. Study the effectiveness of an IDC sensor for cell content monitoring as a case study within a real beehive by:
    a. Designing a PCB and system to be placed within a hive outside
    b. Placing the PCB within an existing hive to record capacitance measurements

1.4.2 Research Questions

Honeybees and their hive environments are extremely complex and many factors need to be understood and taken into consideration when designing a system to be placed within the hive. The following research questions and topics are addressed in this thesis:

1. How does heat flow within a cell and between cells in a hive?
2. Is measuring the temperature of small local areas within the brood nest possible?
3. Can small heaters placed throughout a hive frame reach temperatures capable of killing *Varroa* mites?
4. How can the use of an IDC sensor be used to monitor honey level and larvae growth?

1.5 Thesis Organization

Chapter 2 provides a background on bees and beekeeping including a general overview of beekeeping in Canada, the impact of climate on honeybees, the colony population and brood

rearing process, role of bees in crop pollination, current hive structures, and a summary of existing remote hive monitoring systems.

Chapter 3 focuses on the temperature monitoring and control board for use within the brood nest developed in this thesis. Background information on the physical impact of temperature on the bees and existing hive temperature monitoring technology, as well as background on *Varroa* mites and existing methods for treating hives is provided. This is followed by an overview of the simulations performed to understand the heat flow within the hive cells and this information is then used in the design of a prototype printed circuit board (PCB) consisting of temperature sensors and heaters. The results of the lab tests with the PCB are then shown and discussed.

Chapter 4 focuses on the capacitance sensor board for monitoring the cell contents within the hive. Background information is provided on the honey production process, the physical and electrical properties of honey, capacitance of the brood cells, existing capacitance sensor systems, and the details of an interdigitated capacitor sensor. This is followed by an overview of the simulations performed and the design and testing of a small prototype board. Based on the results of the small prototype board, a full-size 12-region prototype board is designed, built, and tested in a lab setting. The final sections of Chapter 4 discuss the design of a PCB and in-hive system as well as the results of an in-hive experiment.

Chapter 5 provides a summary of the conclusions that can be drawn from the work done in this thesis and summarizes the future work that could be performed.

Chapter 2 – Background on Bees, Beekeeping, and Existing Remote Hive Monitoring

2.1 General Background on the Beekeeping Industry

The beekeeping industry is built upon the races and strains of the honey bee, *Apis mellifera*, a temperate-zone bee native to Europe and is the most productive in regions consisting of large areas of accessible land with plants that flower at predictable times of the year and provide good nectar sources [3]. The Canadian Prairies provide excellent conditions for beekeeping. The provinces of Alberta, Manitoba, and Saskatchewan are the major honey producers in Canada with approximately 486 000 colonies [14] producing 80% of Canada's crop [2]. Some regions of the prairies are able to regularly harvest over 136 kg of honey each year [15], which is much higher than the Canadian average of 55 kg per hive [1].

Liquid honey is the main product from a beehive and can be eaten or used as an ingredient for other products. Honey has a history of applications in the medical field, however today the majority is used as a food and eaten in the form it is produced and sold [3]. Beeswax, propolis, and pollen are other products that can be obtained from the hive; however, the system developed in this thesis focuses on increasing the liquid honey yield of beehives.

2.2 Impact of Temperate-Zone Climate on Beekeeping

In temperate-zones there is less heat stress on the hive in the summer than in tropical zones, however the bees must survive cold winters with periods of no honey production. In [16], Gould explains that the changing seasons causes the bees to store honey in the summer, not just produce it as needed, making commercial beekeeping possible in temperate-climates [16].

The Canadian prairies provide an excellent climate for the honeybees to forage and for beekeepers to manage their hives. The prairies experience a temperate-zone continental climate consisting of four seasons with long hot days in the summer and extremely cold winters. While in comparison to tropical climates the foraging season is relatively short, only four months of honey production in May to August [2], the very long summer days allow for the rapid growth of both plants and honeybee colonies [3]. In temperate-zones many crops flower around the same time resulting in sudden large honey flows that only last a short period of time [3]. Because of the rapid growth of bee colonies and short growing season of plants, beekeepers need to monitor their hives more frequently to ensure that the bee colonies are healthy and ready to meet the nectar flows when the crops flower, therefore they need to react to problems within colonies quickly so they do not miss out on the honey flows.

While the summer provides excellent conditions for beekeeping in western Canada, beekeepers must protect the colonies over the winter. Hives can either be wintered inside sheds or outside by wrapping the hives in insulating materials [2]. To survive the winter, the bees naturally cluster together to create a layer of insulation and create heat by consuming honey and performing quick movements with their wing muscles [5, 16]. Therefore, the focus of the designed system in this thesis is for use during the summer months when the bees are actively producing honey and brood rearing and beekeepers need to carefully manage all of their hives, however it could be extended for use in the winter months.

2.3 Colony Population and Brood Rearing

Due to the seasonal cycles previously mentioned, a honeybee colony's population varies throughout the year in western Canada. A colony has its largest population at the end of July, the height of the nectar flow, and the smallest population at the end of March, after many of the autumn bees have died [3]. In the spring the colony is small with only 10 000–15 000 bees, but in the summer will have a population of 50 000–60 000 bees [15]

The larger the colony is the more honey it produces with little additional equipment and labour required by the beekeeper [3]. Naturally the colony population increases during honey flows resulting in a maximum population after the honey flow once the bees hatch, however as discussed in [3] beekeepers manage hives to get the highest population during the honey flow and then have the population decrease near the end of the flow so less honey is consumed after. Therefore, cell content monitoring in the brood nest can be advantageous economically for beekeepers.

The number of worker bees in a colony limits brood production as well as some of the following factors listed in [17]: not all eggs that are laid hatch; the harder bees work the sooner they wear out; the queen can only lay eggs at a certain rate; and both brood and adult bees are subject to diseases. Therefore, brood population monitoring could also provide insight into the overall colony conditions and hive health.

The brood rearing process follows a strict timeline with different stages of brood development that a system could try to detect. The queen bee lays her eggs in the empty cells of the brood nest, where after three days they hatch and are fed food and attended to by the worker bees until they are sealed with wax on the 8^{th} day [18]. As quoted in [3], an experiment performed by Lindauer found that before a larva is capped it is visited by bees about 2800 times

with a total time of just over 10 hours spent caring for that single cell and larva [19]. Therefore, the worker bees spend a significant amount of time tending to the larvae so the varroa treatment within the brood nest should minimize the damage caused to healthy larvae to avoid wasting the bees' energy and resources.

While the cell is being capped a larvae spins its cocoon, within which it develops into a pupae and eventually emerges as an adult bee on the 21st day [18]. Once worker bees have capped the cells they do not need to directly interact with the pupae any more, but still remain in the brood nest area inspecting cells and regulating the temperature. As is further discussed in Chapter 3, the brood nest is in the central most protected and thermally regulated part of the hive because the larvae must be kept at a temperature of about 35°C.

Therefore, the majority of the time the bee is growing inside a capped cell and its stage of development is not easily observed, so if the proposed system is able to detect the state of the bee inside the capped cell it could be advantageous for the beekeepers. Three advantages of monitoring the contents of the brood cells for population estimation are to monitor the queen's health and productivity, be prepared before swarming occurs, and ensure that there will be a sufficient number of bees in a region when the nectar flow begins.

The queen lays eggs at a rate determined by the frequency the workers feed her [3] and she may lay up to 2000 eggs per day in the height of the nectar flow [15]. Therefore, a decrease in the queen's egg laying rate may be an indicator of poor hive or queen health. Similarly, while some brood may die, if a large amount of the brood is dying the colony may be in poor health and unable to provide the required conditions for the bees to grow.

Swarming occurs when a colony grows large enough and is going to split into two or more colonies. Swarming is not a benefit to beekeepers as it often results in a loss of bees and a

decrease in honey production. Prior to a colony swarming there is an increase in egg laying and then a large portion of the colony leaves with the swarm [5]. If beekeepers are able to predict future swarming of the colony they can take action to prevent it from occurring.

2.4 Crop Pollination and Hive Transportation

A significant portion of the food in the world comes directly or indirectly from insect-pollinated plants. However, modern agriculture methods have reduced the number of wild pollinating insects, and therefore it is necessary to bring bee colonies to crops for pollination [3]. Well-pollinated crops produce two to eight times more fruit [2], and therefore there are benefits to both beekeepers and farmers working together. Hives are placed in crops when they are flowering providing the bees with an abundance of nectar and pollen increasing the hive's honey production, and in return the honeybees help pollinate the plants resulting in an increased yield for farmers. In Canada, honeybees are estimated to have a value over $2 billion annually due to their pollination of different crops, including hybrid canola seeds [2]. Therefore, the smart hive system proposed in this thesis provides a system to further study bees and monitor them more closely to allow for the hives to be more optimally managed to increase the honey bee productivity resulting in both higher crop and honey yields.

In [3], Crane discusses three reasons beehives must be transported throughout the year. The first reason discussed is that often an area covered by a crop is so large that many colonies are needed during the short flowering period for pollination, but during the rest of the year there is little or no forage to sustain the colonies. The second reason stated by Crane for transporting hives is that some crops, such as apples, pears, cherries, and almonds, only flower for a short period of time early in the spring when the bee colonies are small and the cool weather limits the their flight time [3]. The Canadian Honey Council states that it requires a colony of around 30

000 bees to pollinate one acre of fruit trees and a colony of honeybees only has 10000–15000 bees in the spring [15], so as explained by Crane extra colonies must be brought in to meet the pollination demands [3]. The last need for transportation discussed by Crane is that simply in some areas there are no wild bees such as greenhouses or areas where pesticides have killed them [3]. The total number of hives required in an area depends on the crop, but it has been found pollination works best when the bees are spread throughout the crop [3]. Hives may also be transported throughout the summer to find the areas with the highest nectar flows to increase honey yield. At the end of the season the hives may be transported again to either wintering yards or buildings.

The nature of beekeeping discussed above results in two outcomes affecting hive management. The first is that there may be a need for bee colonies to be transported many times throughout the spring and summer and the impact and stress that transportation puts on the hives is not very well known. Therefore, the use of a remote monitoring system allows for the hive conditions to be examined in closer detail to allow for any effects of transportation to be observed. The second outcome of using hives for crop pollination is that the transportation of hives to various locations, especially in large commercial companies, requires significant amounts of time and results in the beekeeper having many hives spread throughout a single or many large areas in a region. Therefore, the task of visiting the hives to check each colony's health and hive conditions as well as apply any needed treatments takes a significant amount of time resulting in hive management and monitoring to be very time consuming and expensive. Therefore, there is room for improvement in the area of hive management for more optimized operations through the use of a remote system to help reduce the time and labour costs of monitoring hives by minimizing the number of unnecessary visits to colonies.

2.5 Commercial Hive Structure

Due to the large number of existing hives in current use it is important that the designed system fits into existing hives to make it more economical for beekeepers. A few types of hives exist, however generally all beekeepers in a country use the same hive type [3]. The most common hive type used today globally is the Langstroth hive [3] and is based on the same movable frames invented by L. L. Langstroth in 1851 [16, 20]. The Modified Dadant hive is another hive that can be found in permanent apiaries [20]. It is the second most common hive used worldwide and consists of larger frames than the Langstroth hive [3]. However, in Canada, as in many countries, Langstroth hives are used almost exclusively [3], and therefore are the type used and discussed in this research, but the concepts can be applied to any removable-frame hive.

In [20], Dadant discusses three important inventions that helped the commercialism of beekeeping including the comb base developed by G. Kretchmer in 1843, followed by the production of comb foundation on a flat press in 1857 by J. Mehring, and finally the honey extractor in 1865 by F. vonHruschka. The honey extractor is based on a centrifuge principle and when used with the comb base allows for the comb to remain intact so it can be reused in the hive saving the time and honey that would be needed to construct the new comb [16, 20]. Therefore, by providing the wax foundations to hives and using the centrifuge honey extractor the combs can be reused, the colonies are able to store more honey making the hives much more profitable for beekeepers. Historically, hive boxes and frames were exclusively made from wood [3], however recently different materials have also been found to be accepted by the bees and have been used to create hive frames and foundation.

2.5.1 Hive Boxes

The hives consist of a series of boxes stacked on top of one another as shown in Figure 2.1. The bottom boxes are the brood boxes where the queen lives and lays her eggs. Hives may have between one and three brood boxes depending on the colony size [3, 20]. Above the brood boxes are the honey supers where the bees store the honey. As mentioned in [18], this division of the hive horizontally into separate regions exploits the natural tendency of the bees to store honey in the cells above the brood nest. The number of honey supers varies seasonally based on the amount of honey the bees can produce [3]. The queen's movement throughout the hive is limited to the brood boxes by the placement of a queen excluder, a screen that the worker bees can fit through but not the larger queen and drone bees, above the top brood box [16, 18]. The bees enter and exit through the hive entrance located at the base of the lowest brood box.

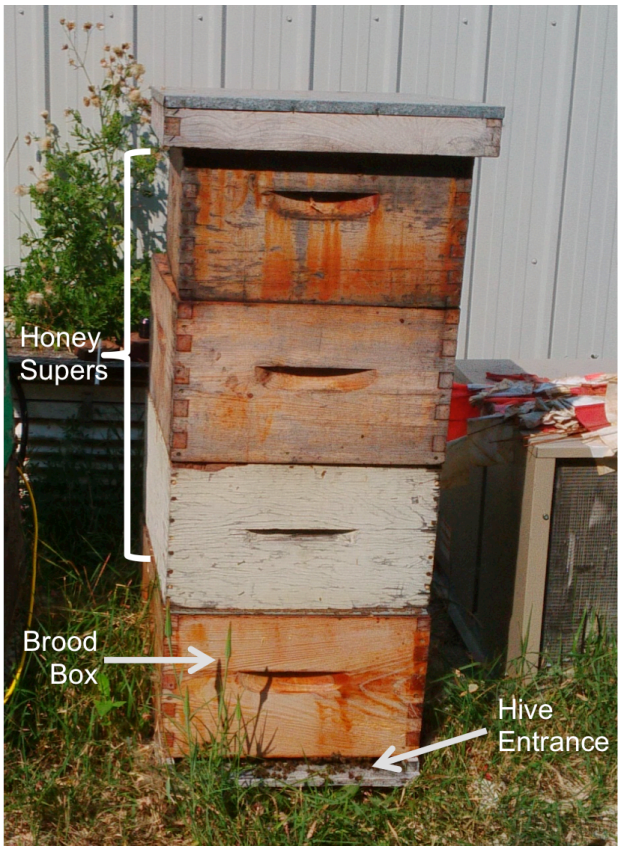


Figure 2.1 Example of hive setup with one brood box and three honey supers

Inside each of the hive boxes is a series of frames placed one bee-space apart as shown in Figure 2.2. Gould states in [16] that this bee-space was discovered by L.L. Langstroth in 1851 while studying an earlier hive model to determine why the bees only built a single sheet of comb in each frame and did not attach the frames to one another. He found that the natural spacing between adjacent combs in natural colonies is two bee-diameters allowing for bees to work on adjacent combs without interfering with each other [16]. The bee-space was found to be 3/8", and if the space is smaller or larger the bees will connect the frames to each other and the box [20]. The bee-space is applied throughout the hive including the space between the edge of the frames and the side of the hive boxes [3]. The correct spacing of the hive components is critical to ensure the frames are easily removed and replaced without needing to be cut out allowing the combs to be reused once the honey has been emptied. Therefore, these dimensions and bee-space are used in the designed system to ensure that the frames are just as easily removed as the existing frames.

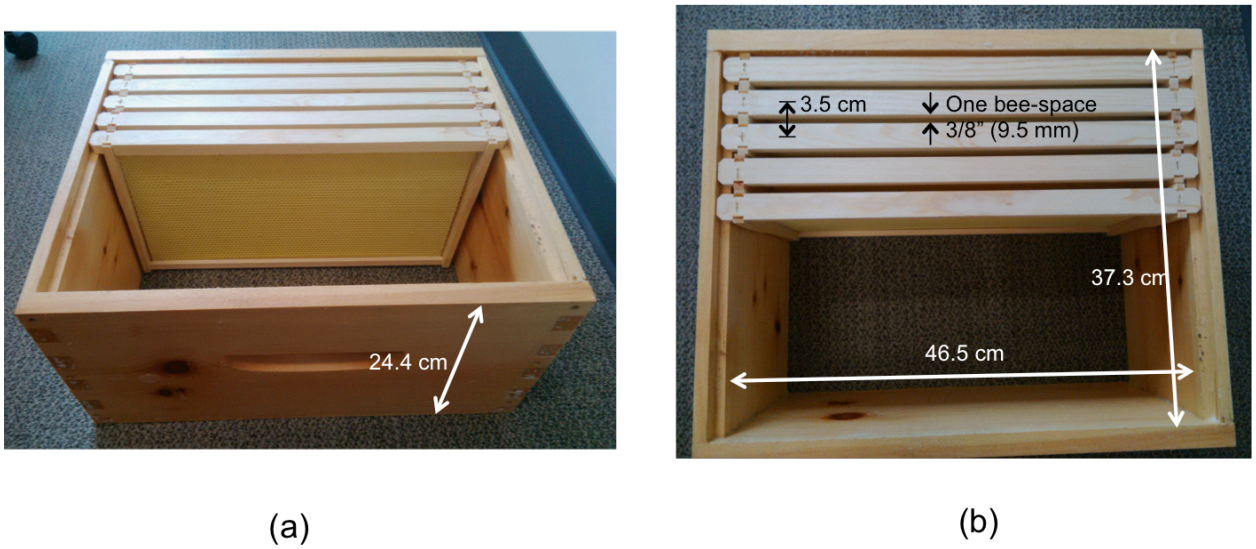


Figure 2.2 Sample hive box (a) front view and (b) top view with half of the frames and dimensions

The dimensions of the boxes and frames are shown in Figure 2.2. Each hive box holds 10 frames spaced 1-3/8" (35 mm) apart (centre-to-centre) [20]. The brood nest box will generally always have 10 frames, but the bees will tolerate a larger spacing in the honey supers where they extend the cell walls until only one bee-space is left between adjacent combs creating a deeper comb and providing a higher honey capacity than when 10 frames are used [3, 20]. Therefore, there are often only 9 or 8 frames evenly spaced in the honey supers [20].

In [20] it is stated that many beekeepers are concerned with standardization and exchangeability between the brood and super frames and boxes and therefore use a uniform box and frame size throughout the hive. However, Dadant also notes in [20] that another common set up is to have honey supers the same length and width as the brood box but a shallower depth. In this set up the honey supers are commonly half to three quarters the brood box depth [3]. The shallower boxes hold less honey making them lighter and easier to lift. In [3], Crane states that the choice of depth is generally up to the beekeeper and is based on availability, convenience, and how they can be handled mechanically with their other equipment, such as the honey extractor. The system discussed in this thesis is designed to fit within the standard deep frame, like the one shown in Figure 2.2, making it usable in both the brood box and deep honey supers, however the design can be easily altered to fit in a smaller frame without changing any design concepts.

2.5.2 Hive Frames and Foundation

Inside the hive box are the hive frames and comb foundations. The hive frame refers to the outer part of the slat shown in Figure 2.3 and they are mostly made from wood. The foundation refers to the sheet of honeycomb pattern placed inside the frame.

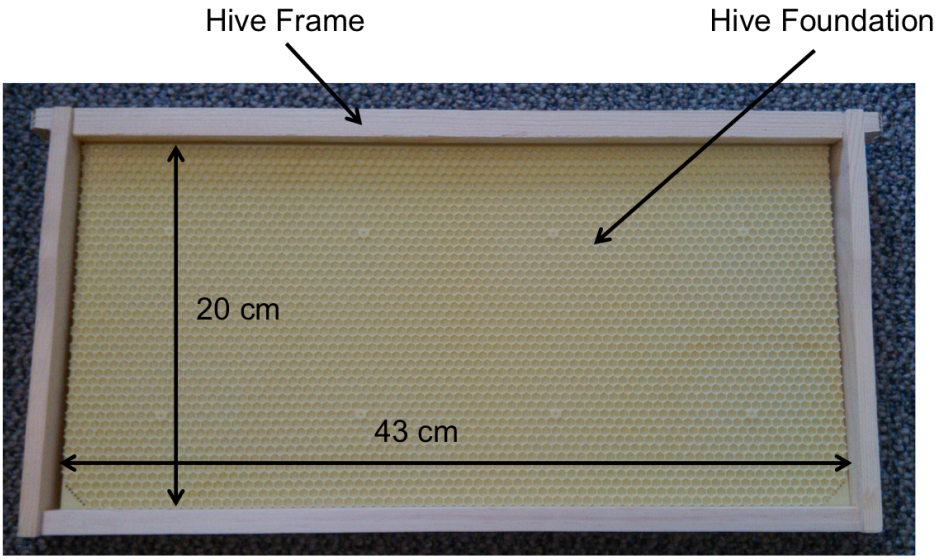


Figure 2.3 Hive frame and foundation

Bees generally start building their comb at the top and work their way down producing a comb with an average thickness of 1" [20]. The natural design of honey cells and comb produced by the bees is an efficient hexagonal grid that minimizes the use of wax [16]. The cells are hexagonal-shaped tubes with an inverted pyramid base, and are aligned with one another such that the centre of one cell is a connection point of three cells on the other side, as shown in Figure 2.4, and the cells also have an upward slope of 9°–14° to prevent larvae, pollen, or honey from sliding out [16, 20]. Naturally the comb walls can be extremely thin with a thickness of only 0.08 mm and a cell base of 0.2 mm but the comb is very strong and able to support many kilograms of honey [16]. Manufactured foundation cell walls generally have a thickness of 0.0635mm and they remain about that thickness as the bees draw out the comb [20].

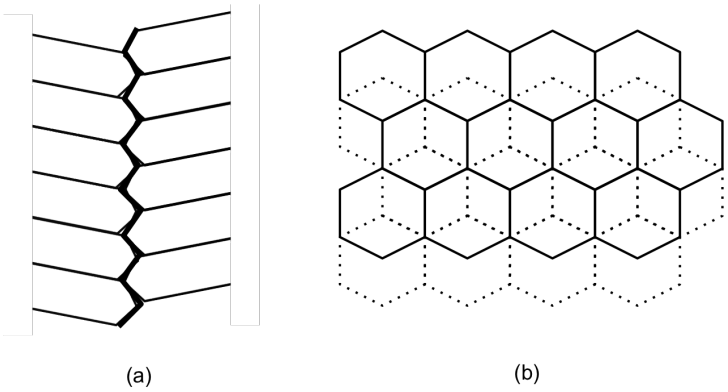


Figure 2.4 Honeycomb geometry from (a) the side showing the upward angle of 9-14° of the cells on either side and (b) the placement of the cells on one side of a comb relative to the cells on the other side indicated by the dashed line

Two different sized cells can be found in a hive. The most common cells are the honey cells which are used for producing and storing honey as well as for brood cells for the female worker bees, so they are found in both the brood boxes and honey supers. The honey cells have a diameter of 5.1–5.5 mm [3]. The second type of cell is a larger drone cell with a diameter in the 6.7–7.1 mm range that is found solely in the brood box for rearing the larger drone bees [3].

The original comb foundation, which is still commonly used today, was made from thin sheets of pure beeswax with the beginnings of cell walls embossed on both sides [16, 20]. These sheets are made from recycled beeswax and provide a starting point for the bees to draw out the full comb according to the size of the cells on it. One advantage stated in [20] of using wax foundation is that half of the honey and most of the labour is saved. Once the comb is built it can be reused multiple times within the hive. Wax is expensive for bees to produce because 1 kg of honey produces only 60 g of wax and approximately 7 kg of honey is needed to build the comb of an average sized hive in nature [16]. Previously 8-10% of the honey bees produced was used to build combs, but with the use of wax foundation and the reuse of honeycombs only 1.5-2% of the honey yield is used for wax creation [3], providing a higher honey yield for beekeepers.

A second advantage of using frames and foundations is that beekeepers are able to limit a colony's male drone population by limiting the number of drone cells within a hive. While a

small number of drones are required for colony stability and survival, they consume large amounts of honey and do not perform any work within the hive [20] and Gould states in [16] that by restricting the drone population a larger quantity of honey can be yielded. Bees naturally build more than 25% of the cells as drone cells, but by only placing worker bee foundation in the hive drone cells are only built as needed in the space along the bottom or corner of the frames [20]. This results in drones only comprising 3–6% of the population during the active season [3]. So while there may be 60 000 worker bees in the summer, there will only be several hundred drones [15]. Two other advantages off using foundation mentioned in [20] are that the bees are able to draw out the combs quickly and straight and uniform combs are obtained. Therefore for all these reasons, the system designed in this thesis should be able to work with some type of comb foundation.

Different types of frames and foundations can be used within hives. One popular frame type is a four-sided wooden frame with a central groove that a sheet of foundation fits into, as was shown in Figure 2.3. As previously discussed, foundation is typically made from recycled wax and the sheets are sold in various thicknesses and weights [3]. However in [3], author Crane lists some disadvantages of beeswax foundation including: its fragility, ability to be damaged by moths, breakage at high temperatures, and the difficulty of sterilization. In [20], Dadant states that other waxes have been tested, but it was found that the bees preferred pure beeswax, so that is what is commonly used. As quoted in [3], according to [21] other materials such as cellophane, cloth, paper, cardboard, aluminum, tin, zinc, metal foil, and wire cloth have also been tested in the past but either the bees did not use them, they were not structurally strong, had a disadvantage compared to beeswax, or gave no cost advantage over beeswax.

Some modifications have been made to the pure beeswax foundation to help increase its strength. Reinforced comb foundation, developed by Dandant & Sons in 1921, has nine or ten vertical crimped wires inserted through the wax sheet to prevent the thin fragile sheets from sagging in the frame [20]. In [3], Crane discusses similar beeswax foundation alternatives with tinned iron wires embedded either across it horizontally, vertically, or both, or in a zig-zag pattern through the wax. These wires may be either straight or crimped and the foundation may be sold with wires already or they may be inserted by the beekeeper [3]. Another foundation option used today is the plastic base comb foundation, developed by Dandant & Sons in 1963, and has a thin film of plastic in between two layers of beeswax, which is then embossed with the hexagon pattern [20].

Another option is a plastic frame-plus-foundation, which is a one unit plastic frame and foundation coated in a thin, layer of beeswax. As quoted in [3], Warren and Warren report in [22] that they operate more than 3000 hives with these frames and have found that perfect combs are easily obtained and drone combs can easily be removed. They also found that the honey extraction is faster and comb breakage, which can be up to 10% with pure beeswax combs, is not an issue and they have not found any disadvantages in comparison to the pure beeswax foundation [22].

The reusability of all types of combs is a large advantage to beekeepers and therefore, the system developed in this thesis should be able to work with existing hive frames and use some type of foundation for the bees to build their comb on top of. It should also be expected that the parts of the system with the sensors under the combs will remain there for a long period of time as the cells and combs are reused many times. From the research on various materials it appears as though the bees prefer working with wax foundations and therefore, similar to the one unit

plastic frames, the sensor boards will need to be coated in a layer of wax before being placed inside the hive so that they do not interfere with the bees.

2.6 Existing Remote Hive Monitoring Systems

Remote hive monitoring systems that are currently available on the market include Smarthives [23], Arnia [24], Hivemind [25], and B-ware [26], and APiS [27] is a system that is currently in development. All of these systems are very similar in their setup and the factors they choose to monitor with only slight differences between them. Smarthives, Arnia, Hivemind, and APiS all collect data that is then uploaded to a website where users can log in from anywhere on any Internet connected device [23-25, 27]. B-ware is a slightly different system. Originally, it was designed such that the data is all stored locally and then when a worker visits the hives they collect the data via Bluetooth to their personal device, such as a smartphone or tablet, and then uploads it to the internet when a connection is available [26]. However, this requires someone to visit the hive and does not provide remote real-time monitoring, and therefore they have started to introduce a system component that connects to a cellular network to provide real-time data and allows a beekeeper to set threshold values to indicate an alarm.

Arnia was started in 2009 in the United Kingdom and the system includes sensors to monitor the acoustics, brood temperature, humidity, hive weight, and ambient weather conditions [24]. The Arnia system is designed such that a single sensor is placed in the brood nest and the system watches for a constant temperature to indicate there is brood. If the temperature is fluctuating then it assumes there is no brood and the queen is not laying eggs [24]. To monitor the honey yield within the hive a weight scale is placed under the hive and a maximum weight threshold can be set to alert the beekeeper when the honey supers are full. The weight data is also tracked over time to map the nectar flows throughout the season [24]. Arnia also uses the weight

data to alert a beekeeper if a sudden daytime weight drop occurs indicating possible swarming or robbing. One difference between this system and the others is the use of an acoustic sensor to determine the activities of the bees including: how frequently the bees are flying and at what times of the day, if the bees are fanning to process the nectar, or to alert the beekeeper if the bees are being disturbed. This activity data is also compared with the weight data and environmental conditions to gain a better understanding of what is happening within the hive [24].

The Hivemind system was developed in New Zealand. It has a weight scale and temperature sensor under the hive, which reports the weight and ambient temperature every six hours. The inside hive temperature and humidity are reported every three hours and a bee counter reports the number of bees entering and leaving the hive in each three hour period. A rain gauge is also included and a sensor to detect hive theft that will alert the beekeeper [25].

A third available system, Smarthives, is similar to Arnia and Hivemind as it has a weight scale under the hive, a temperature and humidity sensor in the brood nest, and environmental sensors to monitor the conditions surrounding the apiary. It also has a motion detector sensor that alerts the beekeeper if hives are being disturbed by people or animals such as bears [23].

The B-ware system developed by Solutionbee is similar to the others but focuses solely on monitoring the honey levels of the hives. Once again a weight scale is placed under the hive along with a temperature sensor that measures the ambient temperature [26]. The weight and temperature measurements are taken every 15 minutes. Therefore, this system cannot provide as much information about the colony health as the other systems as there is no brood nest monitoring or activity monitoring within the hive.

APiS, the fifth system mentioned above, is a smart hive system that is currently being developed in Portugal, but is not yet available. Their system consists of one temperature sensor,

one humidity sensor, a weight scale, and optical sensors for bee counting at the entrance of the hive. They claim that they will be able to determine colony development, the colony's level of foraging, and if swarming is occurring from the bee counter measurements [27].

In summary, most of these existing systems measure temperature, humidity, honey level and some form of bee activity. Temperature and humidity is often measured with a single temperature sensor in the brood nest as in [23-25, 27], but as is discussed in Chapter 3 the temperature within the hive varies depending on the location and temperature changes within the brood nest can provide information about the colony health. Therefore, the system proposed in this thesis places many temperature sensors throughout the brood nest to monitor the health of the brood and colony more closely.

The honey level is measured by all of the systems discussed in [23-27] by a weight scale. However, as is further discussed in Chapter 4, whether the hive is ready for harvest or not depends on more than just the weight. While the weight provides a good estimation, it also need to take into account the fact that the number of bees in the hive changes throughout the day and once the cells have been filled with nectar it needs to ripen for a variable number of days. Therefore, the cell content detection component designed in Chapter 4 attempts to determine not only the amount of honey, but also the ripeness to help apiarists better plan when to harvest their hives.

A few of the systems have additional sensors to monitor bee activity using various methods. In [25] and [27] a bee counter at the entrance is used to count the bees as they enter and leave to determine bee activity, and in [24] they use an acoustic sensor to gain more information about the bee activity. While some of the systems inform a beekeeper when swarming is occurring, a disadvantage of the detection methods is that they only alert once something bad has

happened such as a sudden weight drop in [24] or large bee count exiting a hive as in [27] to indicate swarming. However, this may be too late for beekeeper to react. Therefore the system proposed in this thesis may be able to detect an increase in brood rearing to indicate possible future swarming giving beekeepers time to prepare and minimize their losses.

It should also be noted that in all the systems in [23-26] sensors are also used to monitor the environmental conditions surrounding the hive so that more information about the colony activity and health can be gained from the correlation between the sensors and the outdoor weather. The authors of [24] give the example that the sensor may indicate a few days of little foraging, which may be a concern but then after observing the ambient temperature it may have been cold forcing the bees to remain inside. Therefore, the components developed in this thesis should be integrated into a larger system with additional sensors so that additional information on the colony health and activities can be learned.

The components developed in this thesis provide different ways of measuring the temperature within the brood nest and the honey levels within the supers. The proposed temperature sensor system provides temperature readings from local areas within the brood nest instead of just a single reading from the brood box. Similarly, instead of measuring the weight of the entire hive, the proposed system is designed to measure the amount of honey in each region of the frames, allowing beekeepers to know exactly how much room is in the hive. Additionally, the proposed system is designed to not only determine how much empty space there is, but the ripeness of the honey within the frames. Another component of the proposed system that is different from the other systems is the ability to remotely heat local areas of the frame to treat colonies against *Varroa* mites. Further details on existing mite control are discussed in Chapter 3, but none of them are currently administered remotely.

Chapter 3 – Temperature Monitoring and Control Within the Brood Nest

Temperature was selected as an environmental factor to be monitored within the hive cells of the brood nest because bees are physically sensitive to temperature and regulate the temperature within the brood nest to maintain an almost constant temperature of 35°C. As quoted in [3], Ribbands states in [28] that the worker and drone bees have sensors on their antenna that are able to detect a 0.25°C temperature decrease. Therefore, the temperature within the hive and cells can be an indicator of overall colony health. The proposed system places both temperature sensors and heaters throughout a hive frame to locally heat different areas of the comb. The main application of the heaters discussed in this thesis is to kill *Varroa* mites, a honeybee predator that feeds on bee larvae, however it could be extended to aiding the bees with temperature regulation, especially in the spring when the outside temperature is cooler and the colony is smaller.

As is further discussed in section 3.1, the brood is very sensitive to changes in temperature, and so while the temperature within the honey supers can be monitored and controlled using a single temperature sensor and a simple heater or fan because of a larger range of acceptable temperatures, the brood nest is more delicate requiring more precise temperature control. A summary of the damaging temperatures to the adult bees, brood, and the comb itself from [3] can be found in Table 3.1. It should be noted that there is only a 7°C acceptable range of temperatures for the brood.

Therefore, the sensor board designed in this chapter based on the concept shown in Figure 3.1 is for use in the brood box, which can be used to give frame-level information and control. Section 3.1 provides background information on the impact of temperature on honeybees

and systems that have previously been used to monitor the temperature within the hive, as well as background information on *Varroa* mites and existing hive treatment methods. The simulations discussed in section 3.2 were performed to determine how heat flows within a honeycomb and the amount of power required to obtain the desired temperature increase. Section 3.3 used the results of the simulations to design a PCB, which was used for the lab tests discussed in section 3.4.

Table 3.1: Damaging Temperatures and their Effects on the Hive Environment [3]

Damaging High Temperatures	
47°C	Combs break down
45°C – 60°C	Workers Die
40°C	Damage to honey-producing enzymes
38°C	Damage to brood
Damaging Low Temperatures	
31°C	Damage to brood
26°C	Damage to emerging brood

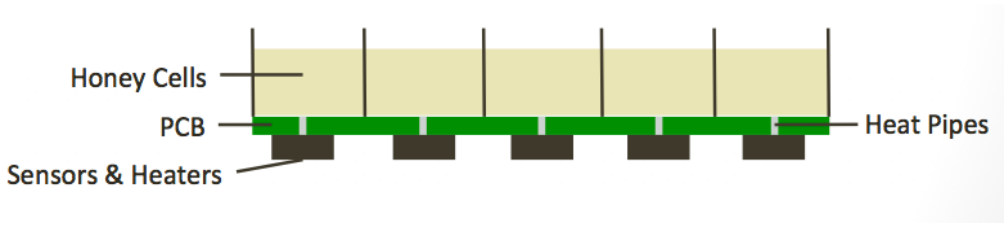


Figure 3.1 General board design indicating the placement of the sensors, heaters, and heat pipes in relation to the hive comb

3.1 Background

3.1.1 Physical Impact of Temperature on Honeybees

The honeybee physiology is such that ambient temperature affects the actions that a bee can physically perform. For example, bees are unable to fly at temperatures below 10°C and individual bees become motionless at temperatures below 7°C limiting their foraging time in the early spring or fall [5]. The temperature within the hive is also important. Bees are responsible

for many tasks within the hive and their capability of performing these tasks is partly dependent on temperature. Such tasks include producing and working with wax, which require temperatures of 33–36°C [5] and 30°C–34°C [3] respectively.

The eggs and young larvae are generally known to require a temperature around 35°C and it has been found that the brood nest temperature is highly regulated and seldom varies. In [29], Dunham performed a test recording the temperature within different parts of the hive each hour in a day and found that the central brood nest area of the hive experienced very little temperature change throughout the day, even when outside temperatures varied significantly. He also found that the area of the hive without the brood had the lowest temperature and varied more with the changing outside temperature. Many researchers have found that the bees are able to maintain this temperature of 35°C in the brood area by physically heating or cooling the area as required.

The bees are able to warm an area by clustering together over the larvae cells to provide insulation and shake their wing muscles to produce heat [3] and as discussed in [5], bees may arrange themselves within the hive and outside of the hive entrance and fan their wings to create a current of cooler outside air that passes through the hive. As quoted in [3], in [30] author Lindauer found that the bees also collect and spread water throughout the hive to reduce the temperature via evaporative cooling.

Monitoring the temperature within the brood nest can provide insight into the overall hive health because of the natural precise temperature regulation by the bees. Therefore, the proposed temperature monitoring system is designed for use within the brood nest area where the temperature does not fluctuate, so any temperature changes could indicate problems within the colony. The bees are extremely sensitive to temperature allowing them to properly regulate the

inside temperature because high or low temperatures can be damaging to the colony as was shown in Table 3.1. It can be noted that only temperatures between 31°C and 38°C are not damaging to the brood and temperatures greater than 40°C inside the hive can inhibit the bees' ability to produce honey. Therefore, the designed system needs to be able to detect the damaging high and low temperatures and the heating system should take the high temperatures into consideration to minimize the damage done to the brood, worker bees, and the comb itself.

3.1.2 Existing Hive Temperature Monitoring Systems

The concept of monitoring temperature inside a beehive has been addressed in [29, 31-33]. In [29] eight thermocouples are placed 4.5 inches from the top of the hive, to measure the temperature in different parts of the hive. It was found that different temperatures were measured depending on where the brood was located within the hive. The different areas were found to have a difference within 18°C, but the majority of the time the difference was only a couple of degrees [29]. In [31] the temperature was also measured with thermocouple wires, but this time they were placed at the entrance, periphery, and center of the hive. The center of the hive was found to remain around 35.5°C where as the periphery values varied more significantly [31]. A similar approach was taken in [32] in which seven sensors were placed inside the hive, one in the center of each wall, the top, and bottom of the hive, as well as one at the entrance. In [33] systems are designed to monitor multiple hives and only a single sensor is placed within each hive. However, in all cases it was found that the brood nest was the area of most interest because it is the area that is regulated by the bees, and in all cases only a single sensor was placed in that region of the hive.

Instead of placing a single sensor in the hive or a single sensor in the brood box, the system proposed in this thesis places multiple sensors throughout the brood nest cells allowing

for a more detailed examination of temperature within the brood nest. This will also allow for a heat map of a frame to be created, which may provide more information on the honey bees and their habits, as well as potentially the location and amount of brood within the hive, because the bees warm sealed brood cells until the bees hatch.

3.1.3 *Varroa* Mite Background

Varroa mites (*Varroa jacobsoni*) are a parasitic mite and a predator of the *Apis mellifera* causing the destruction in colonies over the past 37 years. Crane states that the presence of *Varroa* mites was first recorded on the Island of Java in 1904 as a parasite of a different species of honeybee, the *Apis cerana*, and by 1968 the mites had spread throughout many of the *Apis cerana* colonies in Asia [3]. The *Varroa* mites are not as destructive in the *Apis cerana* colonies because as Peng et. al. found in [34], *Apis cerana* worker bees are able to perform grooming and cleaning activities that remove and kill adult *Varroa* mites from worker bees and the brood while the *Apis mellifera* are unable to remove the mites. As discussed in [3], the mites are also less damaging to the *Apis cerana* colonies because the worker bee developmental stage is shorter, so the mites mostly reproduce in the drone brood, but the larval period is longer for the *Apis mellifera* worker bees so *Varroa* mites can reproduce in any brood cell. Thus, the mites are able to rapidly increase their population and cause damage to both the worker and drone larvae in *Apis mellifera* colonies.

As quoted in [3], in [35] it was found that by 1988 mites had spread to over 56 countries throughout the world and Griffiths and Bowman state in [36] that the spread of mites is entirely due to the transportation of bees. Mites are spread easily because hives may not show any physical signs of being infested until several years after they first become infested, by which time the mites have spread to many colonies in an area [3].

The *Varroa* mites were first discovered in the USA in 1987 and were found within many states within a few months, which resulted in the Canada–United States border being closed to all honeybee transport as of January 1, 1988 [37]. However, *Varroa* mites have since been discovered in Canada and are currently a problem. *Varroa* mites were first reported in New Brunswick in 1989 and have since spread across Canada [2] to all provinces except Newfoundland and Labrador [14]. *Varroa* mites can have a serious impact on honeybee colonies and beekeepers in Alberta, Saskatchewan, and Manitoba cited *Varroa* mites as the second largest cause of winter colony loss in 2016 [14]. In the fall of 2015 hives experienced high numbers of mites due to the very mild winter the previous year but many beekeepers realized too late to treat their hives causing a winter mortality rate of 30% or higher in some regions [14]. To be able to successfully manage the health of their hives, beekeepers want to be able to monitor the mite populations and take timely action to keep them under control [14]. Therefore, by designing a system that will allow beekeepers to monitor and treat their hives remotely, their hives can be checked more frequently and treatment can be applied to reduce mite populations before economic damage occurs.

3.1.4 Existing Methods for Treating Colonies Against *Varroa* Mites

Mites are visible by the unaided eye in an infested colony, mostly on the backs of young drones and workers where the wings attach, and also where the head attaches to the thorax and where the thorax attaches to the abdomen [38]. The mites are able to destroy a colony by attacking the larvae in the brood nest. Crane explains that the female mites enter the larvae cells before the worker bees seal them. Then mites then feed on the bee pupae and lay their eggs after the bee spins its cocoon [3]. As discussed in Chapter 2, the drone brood has a longer

developmental period than worker bees and therefore mites remain in the capped cells longer allowing more varroa to develop to maturity on drone larvae [3].

Many methods have been used to either kill *Varroa* mites or limit their population without losing honeybee colonies. If mites are ignored they will kill a hive within one or two years [39]. In Canada most beekeepers use a combination of non-chemical and chemical control measures. Some non-chemical methods are listed in [14] and include: trapping varroa with drone combs, using bees with genetic traits that increase tolerance of varroa, trapping varroa in screened bottom sticky boards, and splitting colonies.

One simple method is the use of drone brood combs to attract the female mites away from the worker cells. As was discussed in Chapter 2, beekeepers generally try to limit the drone population by having few if any drone cells in their brood boxes, however because mites prefer the drone cells beekeepers may place excess drone comb within the hive which can then be removed and destroyed once they have been sealed [3]. Walden explains that a lot of mites can be killed this way, especially if this is repeated many times throughout the year, however a large number of drone larvae are also killed in this method [39]. While not many drones are needed, a large amount of energy and honey goes into feeding and maintaining the larvae by the worker bees as was discussed in Chapter 2. While this method may help to limit the varroa population it does not prevent the mites from entering the worker cells or help the larvae in sealed infested worker cells and this method is labour intensive for a beekeeper.

Another method is to attempt to breed bees that are genetically more resistant to mites. In [39] the authors explain that this can be accomplished by learning what bees are suited to the local conditions of the hive and that bees more resistant to varroa can be observed as being more hygienic and seen brushing or biting mites off the backs of other bees. While this method may

work, it is more of a long-term solution and infested hives generally require an emergency short-term solution.

Similar to the method of trapping bees in drone combs, bees can be trapped in a screened bottom board with a sticky floor. This way instead of mites landing on a solid board allowing them to jump onto another bee when they fall off of one, they fall through the holes in the screen and get trapped [39]. The authors in [39] state that this method is able to reduce mite levels by 10–20% because while this method does kill some mites, the majority of the mites in the hive are not killed and remain on the bees and inside the brood cells.

Another less common alternative is to have a complete break in brood rearing so that there is no access to bee larvae for the mites, which will eventually die out [3]. However, this method is vey labour intensive for beekeepers and interferes with the normal bee population growth [3].

Another set of mite control approaches come from the use of chemicals and various methods of application. One of the methods discussed in [3] is to fumigate the hive with an acaricide. Crane states that while there are very few colony deaths after its use, it must only be used when there is no honey flow or contamination may occur. It is a specific process that needs to be repeated weekly four to six times and therefore the entire process will take over a month to complete. While, it is not to be performed during times of honey flow, honey contamination is still a large concern [3]. Another method of application discussed in [3] is the use of contact acaricide, which places plastic strips within the hive that bees walk over transferring it throughout the hive including inside the brood cells. A third method is systemic acaricide in which the acaricide, which does not harm the bees, is fed to the colonies in the winter and absorbed into their blood where the mites ingest it and die [3].

Registered miticides are available to beekeepers in Canada and the beekeepers select the best one based on the region, season, and operation [14]. However, in [14] the Canadian Association of Professional Apiculturists states that mite resistance to the chemicals is starting to become a problem and beekeepers are encouraged to rotate the use of different miticides. They also note that beekeepers are already reluctant to use two miticides previously used because of mite resistance to the chemicals. According to [14] Apivar™ is the most commonly used miticide in Canada but it is noted that mites will develop a resistance towards this miticide as well.

Many beekeepers want to avoid the use of chemicals within their hives due to the concern of honey contamination and because of mite tolerance towards the chemicals. Chemical treatments can also be very expensive and labour intensive with inconsistent results and may cause damage to honeybees if misused [4]. Therefore, beekeepers have looked for other alternatives to rid their hives of mites. While some non-chemical methods were discussed previously, they often only target some of the mites within the hive and often do not kill the mites within the sealed brood cells.

A more natural method of killing mites is through the use of heat. *Varroa* mites will be killed at temperatures above 47°C, so placing a hive within a heated chamber once a year may kill all of the mites within the hive [39]. However, while adult bees may be able to withstand the high temperatures up to 45°C the brood within the hive will die at temperatures above 38°C as was discussed in Section 3.1.1.

One existing system that has successfully treated *Varroa* mites in hives with heat is the German Bienensauna. This fully automated system treats the entire infested hive by controlling an inserted heater system and heating the hive for three to four hours during which time the

temperature and humidity are also carefully monitored [7]. This treatment is performed twice a year, once in early spring and once after harvesting the honey, without harming the bees [7]. The hive is slowly heated up to a temperature of 41–42°C over a period of 20–60 minutes so that no alarm signals are generated for the bees [7]. The Bienensauna produces optimal conditions inside the hive causing the bees to stop their heating activities and disperse throughout the hive [7]. The developers report that the *Varroa* mites are very sensitive to the heat but the heat does not cause any bad side effects for the bees. According to the developers of the Bienensauna, temperatures above 39°C affect the adult *Varroa* mites, but it is still safe for bees. At temperatures above 37°C irreversible damage is caused to the young mites in the brood cells and the longer they are exposed the greater the damage, and although they are not killed immediately enough damage is done so that within a few hours or days after the treatment the mites die [7]. Therefore, if the young mites and larvae are the target of a system the system only needs to raise the temperature to 37°C to kill the young mites and larvae without harming the bee larvae. The developers of the Bienenesauna found that 75%–85% of the mites were killed after a three hour treatment at 41°C–42°C, but for the system to work successfully the system needs excellent air circulation within the hive and therefore does not work well in crowded hives and the system requires a 48 V power supply [7].

The advantages of this system include the ability to treat the hive without interfering with the bee colony, the system is able to treat all mites within a colony, including the adult varroa on the bees and the varroa larvae inside the brood cells without the use of chemicals [7]. Some advantages of the use of heat over chemicals noted by the developers of the Bienensauna are that the *Varroa* mites cannot form a resistance to heat like they do towards chemicals and the system

does not have any damaging effects on the quality and lifespan of the queen as some chemical treatments do [7].

Another product available to beekeepers is the MiteZapper®. It is a combination of trapping mites in drone combs and killing mites with heat inside the brood cells. The MiteZapper® is an electronic drone foundation frame that is placed in the brood box like a regular frame and once the bees have sealed the brood inside the frame is connected to the control box which is connected to a 12V vehicle battery by the beekeeper [4]. Once it is connected, enough heat is produced to kill both the bee pupae and the *Varroa* mites. The frame then remains in the hive where the bees clean it out and use it again to produce new drone brood and this process is repeated every 18–23 days, so approximately four or five times throughout the brood rearing season [4]. This system has a shorter treatment time compared to the bee sauna because it only takes about eight minutes [4] to treat each colony, however it does require more frequent treatments throughout the season. This system immediately controls the mite population by killing a significant number of mites after the first zapping. Then mites that are still alive get trapped and killed in the second zapping, and so on so mites are progressively being killed [4]. The developers of the MiteZapper® found that it is 85–95% effective in the control of *Varroa* mites without killing the colony [4].

Heat has many advantages over the use of chemicals. The most significant advantages are that there are no harmful chemicals left on the bees, in the wax, or in the honey and the *Varroa* mites cannot develop resistance to heat the way they have to chemicals. A disadvantage of these existing heat systems is that they require beekeepers to physically interact with each hive. In the case of the Bienensauna, the heating system needs to be inserted into each hive and connected to the control system twice a year for three to four hours and the MiteZapper® in each hive needs

to be connected to the power source four or five times a year for eight minutes. If each beekeeper has hundreds of hives they need to visit and treat, this can take a considerable amount of time. Also, due to this limitation the hives are not being monitored and treated throughout the summer, providing periods of time when the mite population is free to grow. Another disadvantage of the MiteZapper® is that it kills all of the drone larvae in the frame. While a colony does not require a large drone population, the bees spend a significant amount of time, energy, and honey to rear the brood as was discussed in Chapter 2 and as was also discussed previously beekeepers prefer not to have drone comb in their hive as it is a waste of time and resources for the bees.

Therefore, due to the advantages of heat over the chemicals, the proposed system uses individually controlled heaters placed throughout a hive frame to heat and kill mites in a selected area. The localization of the heat allows for the amount of excess damage to the brood and comb to be minimized, killing only the infected larvae instead of all larvae in an entire frame. The remote controlled aspect of the system allows for the mites to be killed as soon as they are detected and the treatment can be applied at any time during the season, therefore there will not be weeks or months between treatments allowing the mite population to increase.

3.2 Simulations to Gain a General Understanding of Heat Flow within the Honey Comb

The results of the studies discussed in this chapter led to a PCB design and placement as was shown previously in Figure 3.1 with the components on one side of the board connected to the comb on the other side via a heat pipe. To gain a general understanding of how heat flows within a single cell and between the honeycomb cells the following studies were performed using COMSOL Multiphysics modelling and simulation software:

1. Modelling heat flow in a single 2D honey cell
2. Modelling heat flow between 3D honey cells focusing on:
    a. Heating Cells
    b. Heat source detection within a cell
    c. Time dependent studies

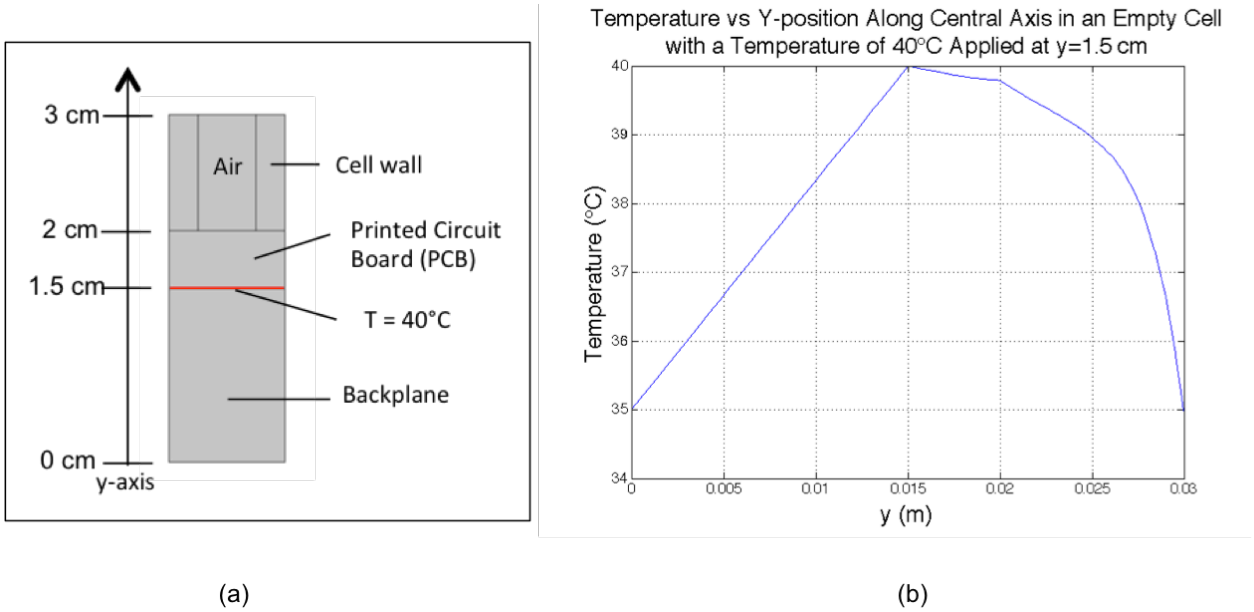
3.2.1 Modelling Heat Flow in a Single 2D Honey Cell

The first simulations were performed on the single empty 2D cell shown in Figure 3.2(a) and consists of polyethylene PCB, backplane, and cell walls. The cavity of the cell is 10 mm tall and 5 mm wide and is filled with air. A temperature of 40°C was applied at the base of a 5 mm thick piece of plastic, similar to a PCB board. To limit the contact of the system with the bees, the board should be designed with all of the electrical components on one side of the board, leaving the other side flat and able to be directly attached to hive foundation.

The results are shown in Figure 3.2(b) and it can be seen that there is a temperature drop across the plastic board resulting in a lower temperature at the base of the cavity. Therefore, it is possible to heat the base of the cell through the board, however some heat is lost in the board resulting in less heat transfer to the cell when the heater is placed on the other side of the board. Similarly, when trying to measure the temperature of the cell, measuring from the other side of the board will not be very accurate.

To address this problem, simulations were performed to study how the heat flows within the cell and viability of using a heat pipe to increase the heat transfer and accuracy of the temperature sensors. A copper pipe was added to pass through the board from one side to the other as shown in Figure 3.3(a). In addition to adding the heat pipe, the cell was also filled with varying amounts of water. Water was used for the initial tests as it has similar heat properties to

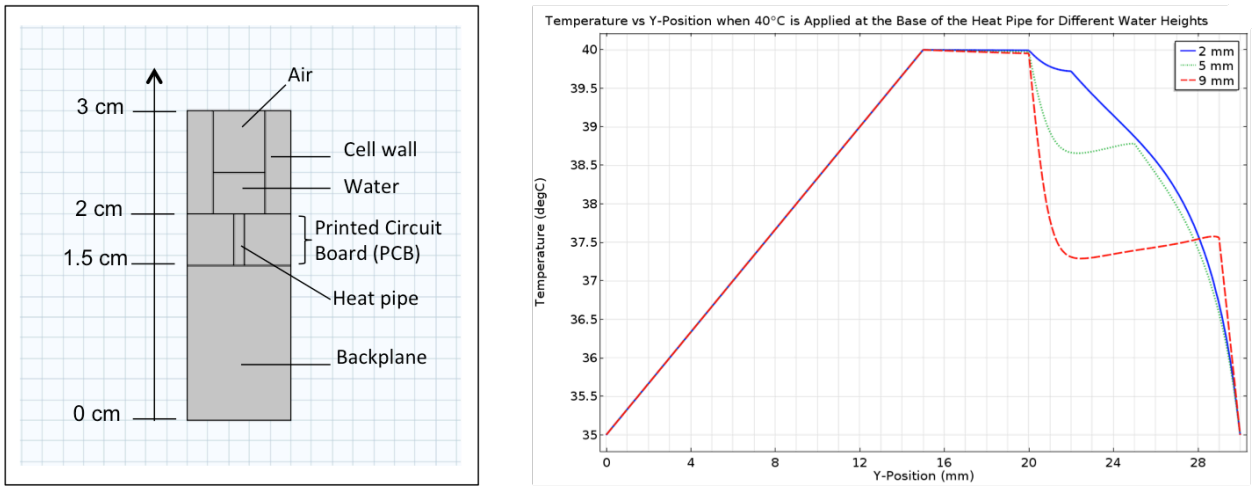
nectar and honey. In the following simulations both the water and air were treated as fluids and therefore convection is considered. All of the outer boundaries of the cell were set to a constant value of 35°C, except the top of the cell was set as an open boundary to allow heat to flow in and out with an ambient temperature of 35°C, to match the brood nest conditions.



(a) (b)

Figure 3.2 The diagram of the (a) model used and the (b) results of the simulation of heat flow along the center y-axis of a single honey cell when a constant temperature of 40°C is applied at the base

The results shown in Figure 3.3(b) were obtained when a temperature of 40°C was applied between the PCB and backplane for three different water levels of 2 mm, 5 mm, and 9 mm. It was found that the temperature decreased linearly through the solid backplane from 40°C to the boundary temperature of 35°C and for all water heights there was almost no temperature drop across the 5 mm long copper heat pipe, which through a PCB will be shorter resulting in an even smaller temperature drop. Therefore, as expected the copper heat pipe is a better heat conductor than the plastic resulting in almost the same temperature on either side of the board.



(a) (b)

Figure 3.3 The diagram of the (a) model used and the (b) results of the simulation of temperature along the center y-axis of a single honey cell with different volumes of water when a constant temperature of 40°C is applied at the base of the copper heat pipe

There is a temperature difference between the copper and water because the specific heat capacity of copper is only 385 J/kg°C [40] which is much less than the heat capacity of water which is 4182 J/kg°C [40] and therefore it requires more energy to heat the water than it does the copper. The temperature within the water appears to be approximately constant in the majority of the water as shown by the flat part of the graph. This is because the specific heat capacity of the water, 4182 J/kg°C, is greater than that of air, 1005 J/kg°C [40], and therefore a smaller amount of heat is transferred to the air and that is why the temperature of the air quickly drops from the temperature of the water to the ambient temperature.

It should be noted that the plots only show the temperature along one vertical line along the centre of the cell and due to convection, different parts of the cell are slightly different temperatures as the heat moves and therefore that is why the plot exhibits the shape shown with a minimum temperature in the middle of the water and the increase slightly as it reaches the top of the water.

From these plots it can be seen that measuring the temperature partway up the cell wall would not provide an accurate reading of the cell contents. Depending on the amount of water in the cell, the sensor may be measuring the air temperature instead of water which, as shown in Figure 3.3(b), varies quite a bit while the water temperature remains fairly constant in the cell. Therefore, to measure the water temperature it should be measured close to the base. It was also found that copper is a good choice for the heat pipe material to transfer a nearly constant temperature across it.

The next set of simulations was performed to gain a better understanding of the heat flow when a heat source is applied. In these models the base of the board and top of the water were set as open boundaries to be more realistic to the hive set up allowing the heat to flow in and out and the ambient temperature was set to 35°C once again to match the conditions of the brood nest. Heat sources of 10mW and 20mW were simulated. As shown in Figure 3.4 for the 10mW case some heat was lost in the board resulting an increase in the board temperature, however the desired outcome of increasing the water temperature was achieved. It can also be seen that there is a constant temperature across the copper heat pipe and an approximately constant temperature within the water as expected from the previous simulations. It can also be seen that the higher water levels reach lower temperatures when the same amount of power is applied. This is expected due to the increased volume requiring more energy to cause a temperature change.

The plot in Figure 3.5(a) shows the temperatures at the base of the cell (copper pipe) and the top of the water for various amounts of water when 10 mW is applied. It can be seen that for small amounts of water the values are the same, but for water levels between 2 mm and 9 mm water at the bottom is an average of 0.60°C warmer than the temperature at the top of the water. Therefore, the designed system will be measuring the temperature at the bottom of the cell,

which will be slightly higher than the rest of the water, but from Figure 3.5(a) this offset appears to be approximately constant. Similar results were found when 20 mW were applied, as shown in Figure 3.5(b), with a larger average difference of 1.05°C between the top and bottom of the water. In both cases the difference between the top and bottom increased with water height as expected because the distance between the two measurements was also increasing.

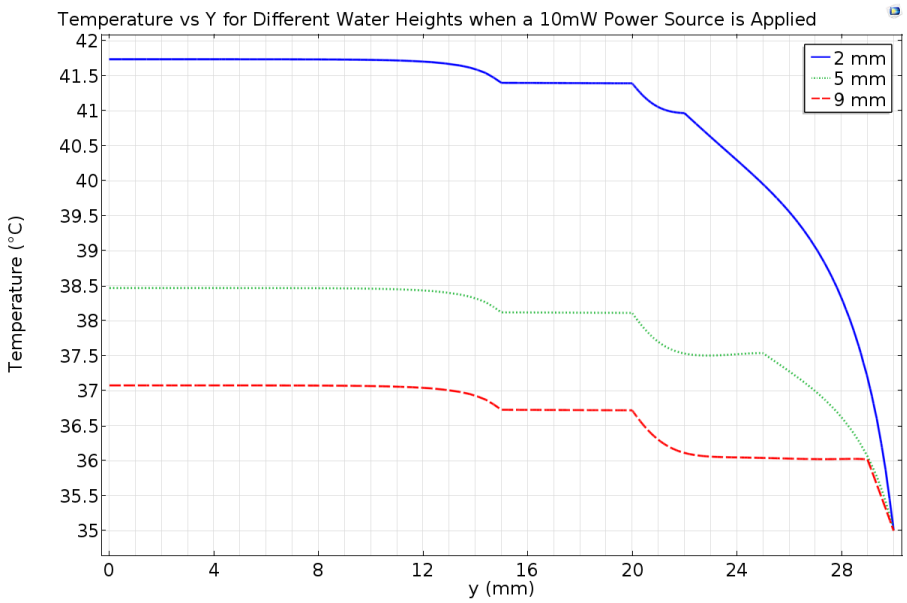
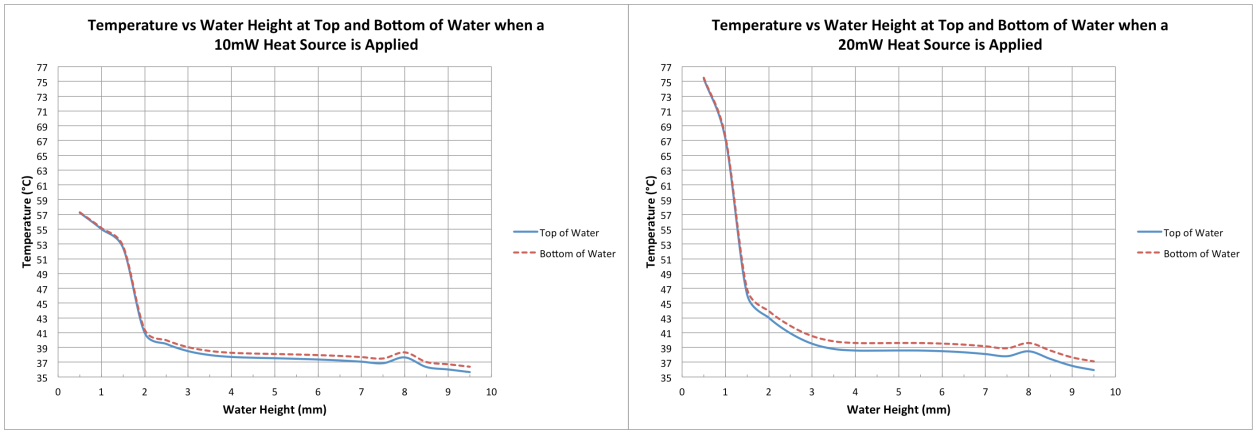


Figure 3.4 Simulation results of temperature along the vertical axis through the centre of a single cell filled with different amounts of water when a 10mW heat source is applied at the base of the cell



(a) (b)

Figure 3.5 Temperatures at the base and top of the water in a cell for water heights of 1mm to 10mm when a (a) 10mW and (b) 20mW heat source is applied

It can also be observed that for both power levels there is a large temperature increase in the water at lower water heights and then the temperature increase levels off when the water height reaches 3.5 mm resulting in a smaller difference in the temperature increase for the same power level at higher water heights. However, for all water heights up to 9 mm the temperature of all the water, as indicated by the top of water temperature, was still raised by at least 1°C, and even more when less water is in the cell. Therefore, even with only a 20 mW heat source a significant temperature increase can be achieved within the cell. This is not a lot of power and it can easily be increased to provide the required temperatures because as previously discussed in Section 3.1.4 a temperature increase of only a few degrees will kill *Varroa* mites. Therefore, from these simulations applying a heat source at the base of the cell to kill varroa larvae and mites is a viable option.

Varroa mites lay their eggs in the brood cells where they feed on the pupae and therefore the brood cells will only be partially full so it is assumed that the heat flow within those cells will be similar to a partially filled water cell. The temperature increase in a single half-full cell with 5 mm of water for different power levels was simulated and the results are shown in Figure 3.6. It can be seen that the temperature increases directly with the power level. Therefore, a 7.5 mW source will heat the water to at least 37.2°C and a 30 mW source would heat the cell to at least 39.4°C, with the bottom of the cells reaching temperatures of 37.6°C and 40.8°C respectively, all of which are hot enough to kill the mites.

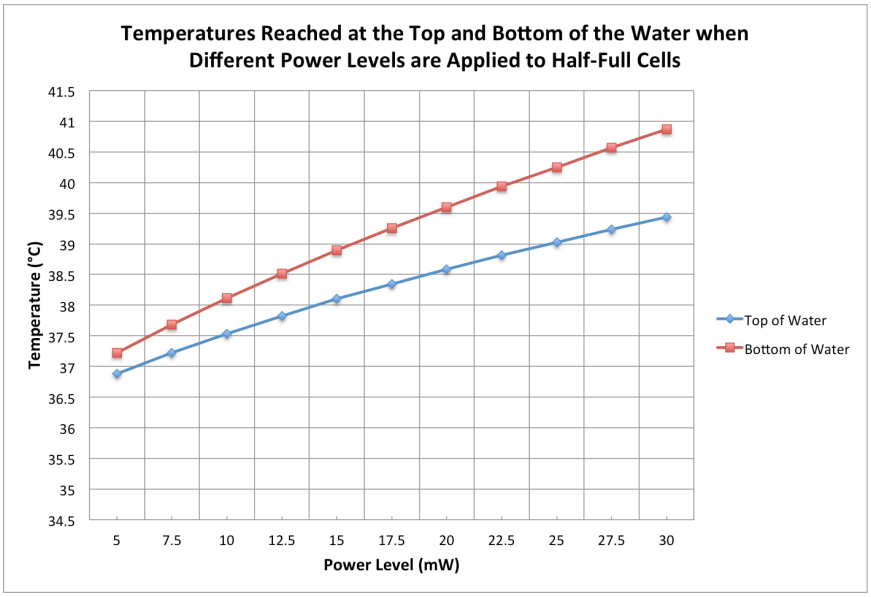


Figure 3.6 Simulated temperatures reached at base and top of water in half filled cells for different heat sources

3.2.2 Modeling Heat Flow Between 3D Honey Cells

3.2.2.1 Heating the Cells

The following simulations expanded the single 2D cell into a 3D cell to compare the results, and then 3x3 and 5x5 square grids were simulated to learn about how the heat flows between cells. Square grids of cells were used for the initial simulations to make the model simpler and to gain a general understanding. The simulations were performed with cells filled half-full with 5 mm of water, an acrylic base for the PCB, and 2.5 mm thick acrylic cell walls to be similar to some existing hive foundations. For all grid sizes, 1x1, 3x3, and 5x5, a 20 mW heat source was applied at the base of the copper pipe of the centre cell in the grid, to simulate a heater on the opposite side of the board from the honeycomb.

The initial and ambient temperatures of the model were set to 35°C and the results of the temperatures reached at the base of the cells is found in Table 3.2. It can be seen that as the board gets larger more heat is lost to the surrounding cells and therefore the increase in temperature in

the cell with the heater is lower, while the single cell experiences a nearly 5°C increase, the heater cell in the 5x5 grid experienced only a 1.7°C temperature increase for the same amount of power. However, as shown in Figure 3.7 for the 5x5 case the heater cell experienced the largest temperature increase at the base of the cell and the adjacent cell and the cell two cells away experienced 61.8% and 50% respectively of the temperature increase the heater cell did. Therefore, it will be possible to heat cells from an adjacent cell so a heater is not required in every cell. This simulation also shows that it is possible to locally heat an area of the frame without heating too many extra cells and damaging excess brood cells and honeycomb.

Table 3.2: Temperatures Reached at the Base of Cells Containing 5mm of Water with a 20mW Heat Source Applied at the Base of the Centre Cell

	Heater Cell	**Neighbour Cell**	**2 Cells Away**
1x1 Grid of Cells	39.90°C (4.90°C increase)	–	–
3x3 Grid of Cells	37.76°C (2.76°C increase)	37.13°C (2.13°C increase)	–
5x5 Grid of Cells	36.73°C (1.73°C increase)	36.10°C (1.10°C increase)	35.89°C (0.89°C increase)

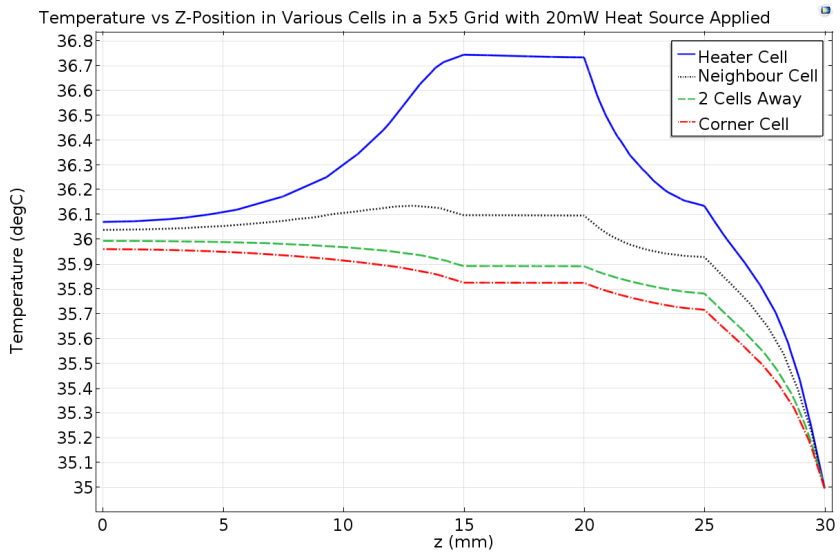


Figure 3.7 Temperature along the central vertical z-axis through cells various distances from a 20mW heat source

Table 3.3 shows the results of applying a 20 mW power source in the centre cell of a 5x5 grid of cells for different water levels. From the results it can be seen that as the water height increases the temperature in all of the cells decreases as expected because the larger volume of water the more energy needs to be absorbed by the water to increase its temperature. Therefore, more than 20 mW of power may be required to heat the cells if they are full, but a single heater can still be used heat a local area to the required temperatures.

Table 3.3: Temperatures Reached at Base of a 5x5 Grid of Cells Containing Varying Amounts of Water with a 20mW Heat Source Applied at the Base of the Centre Cell

	Heater Cell	Neighbour Cell	2 Cells Away	Corner Edge Cell
2 mm	36.85°C (1.85°C increase)	36.21°C (1.21°C increase)	35.98°C (0.98°C increase)	35.92°C (0.92°C increase)
5 mm	36.73°C (1.73°C increase)	36.10°C (1.10°C increase)	35.89°C (0.89°C increase)	35.83°C (0.83°C increase)
9 mm	36.43°C (1.43°C increase)	35.83°C (0.83°C increase)	35.63°C (0.63°C increase)	35.56°C (0.56°C increase)

Figure 3.8 shows the simulation results for the temperature at the top of the cells of a 5x5 grid filled with 5 mm of water for various amounts of power. It can be seen that the temperature increases linearly with power, and at 100 mW the heater cell experienced an increase of approximately 3°C above 35°C, where as the cell two cells away only experienced an increase of approximately 0.65°C. Therefore, even if the power needs to be increased to kill the mites the heating should remain in a fairly small local area of the frame.

It was also found that once again there is a difference between the temperature at the base of the cell and the top of the water but the difference is less than 0.5°C in the heater cell and less than 0.15°C in the other cells in the area. This is acceptable because this offset will stay approximately constant and only one of a temperature sensor or heater will fit in a single cell and

therefore the temperature will only be measured in the surrounding cells where there the difference is smaller.

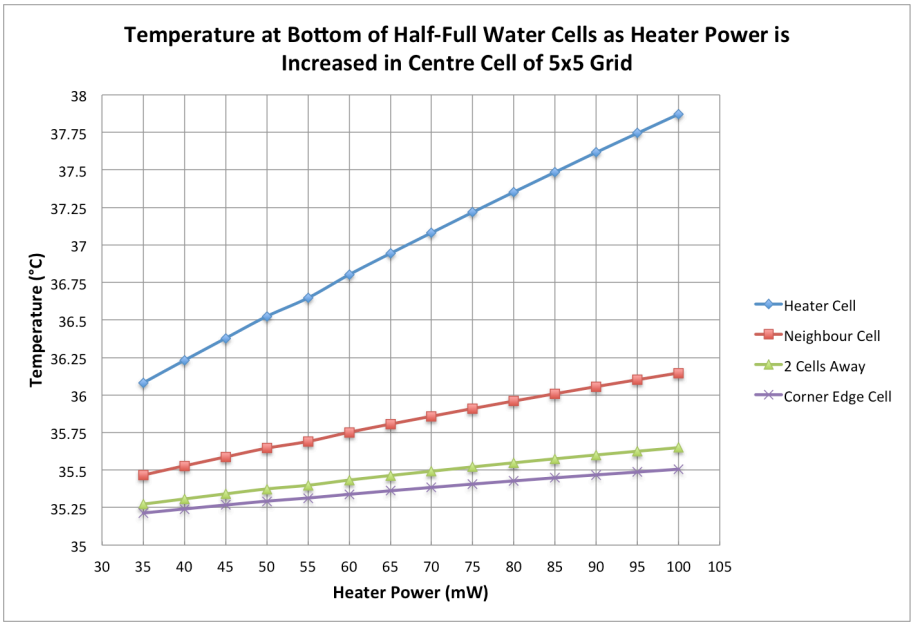


Figure 3.8 Temperatures reached at the top of the water in half-full cells at different distances from the heat source for different power levels

From these simulations it was also learned that while the majority of the heat is transferred through the heat pipe into the correct cell a portion of the heat from the heater is lost in the system as it is transferred through the board to other parts of the frame. That should not be a concern for the bees as they need to heat the brood nest to 35°C anyways which is higher than the outside temperature the majority of the time, therefore it may help to lessen their workload.

3.2.2.2 Detecting Heat Sources within the Cells

The simulations discussed in the previous section focused on verifying whether or not heaters would be a viable method of locally killing mites, however another function of this system is to locally measure the temperature within the cells of a hive frame. Therefore, simulations were performed to see if a heat source within a cell could be detected.

The first simulation consists of a 5x5 grid of cells each filled with 5 mm of water. Convection was turned off so all elements were treated as a solid and all of the outer surfaces except the top were held at 35°C. A portion, $1/8^{th}$, of the water was set as a heat source resulting in that portion of the water being 1°C hotter than the rest of the water. The distance of the heat source to the bottom of the cell was varied from 0 to 2.5 mm and the change in temperature detected at the base of the copper heat pipe is summarized in Table 3.4. Therefore, from the measurements it appears as though it is possible to detect a 1°C increase in part of the honey, but the measured increase will be significantly less than 1°C and a temperature sensor with a precision of at least 0.1°C will be needed. Only a 0.564°C increase was detected when the heat source was right against the heat pipe because some heat is transferred to the heat pipe and some is transferred to the rest of the water in the cell and cell walls. From the results it can also be observed that while the cell with the heat source detects the largest temperature increase, the neighbour cells also detect a temperature increase of a smaller magnitude. Therefore, if the presence of mites causes an increase in temperature within the cells a temperature sensor would not be required in every cell to detect the temperature change.

Table 3.4: Change in Temperature Measured at Base of the Cells with 1/8 of the Water 1°C Warmer than the Rest of the Cell Contents in the Centre Cell of the 5x5 Grid

Distance to Heat Source (mm)	**ΔT (°C) Heat Cell**	**ΔT (°C) Neighbour Cell**	**ΔT (°C) 2 Cells Away**	**ΔT (°C) Corner Edge Cell**
2.5	0.211	0.092	0.023	0.0054
1.25	0.328	0.120	0.029	0.0068
0	0.564	0.150	0.035	0.0082

3.2.2.3 Time Dependent Simulations

All of the simulations discussed in the previous sections have dealt with the stationary results of the system once it reaches a stable state, however the time dependent solution is also of

importance for the system because the system should ideally heat the cells within a few minutes, not hours. Therefore, the next set of simulations model the temperature within the cells over time.

The same 5x5 model as discussed in section 3.2.2.1 was used again with 5 mm of water in each cell and a 20 mW heat source applied at the base of the centre cell. From the stationary results shown in Table 3.2 the temperature reached a maximum of 36.7°C, however from the time dependent simulation it was found that it takes too long to reach that temperature. The cell only reached a temperature of 36.35°C after 50 minutes. This is too slow, the system needs to heat up the cell within a few minutes. Therefore, the 20 mW power source was replaced with a 60 mW power source which heated the cells at a much faster rate and was found to raise the temperature at the base of the heater cell 1°C in about 30 seconds and 2°C in about 100 seconds.

Simulations were then performed to investigate if the water level within the cells could be estimated by pulsing the heat source. The cells were all filled with the same amount of water and a 90mW heat source was pulsed with a 50% duty cycle and period of 40 seconds. The results are shown in Figure 3.9 and it can be seen that the temperature detected at the base of the cells where the temperature sensor will be placed will not detect a measurable difference in temperature, less than 0.1°C, with different liquid levels. This is probably due to the fact that, as seen in the previous simulations, the board is a better heat conductor than the water and therefore the board heats more than the water for all water levels and therefore adding a bit more water does not make a large difference in the temperature measured at the base of the neighbouring cells when the pulsed heat source is applied.

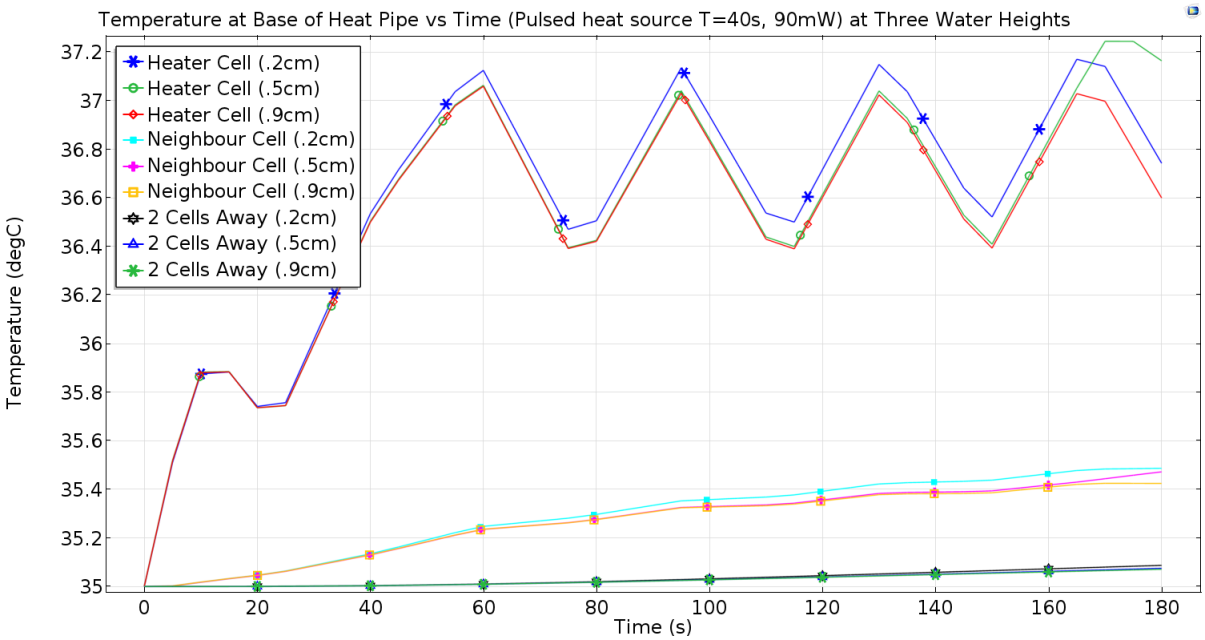


Figure 3.9 Temperature at base of heat pipe over time in different cells with different water volumes when a pulsed heat source is applied

3.2.3 Summary of Simulation Results

From these initial simulations it was found that to measure the temperature of the cell contents the temperature should be measured at the base to ensure the temperature of the cell contents is being measured, not the air in the cell which may be significantly lower. It was also found that the temperature drops significantly through the PCB. Therefore, a copper heat pipe should be used to connect the heaters and temperature sensors to the other side of the board allowing for better heat transfer to the cells and more accurate temperature readings at the base of the cells in the attached hive frame foundation. It was found that the temperature of the water at the base of the cell is higher than the temperature at the top of the water, but this difference is an approximately constant value around 1-2°C for all water heights in the 3-9 mm range, and therefore will not affect the detection of changes in temperature.

It was also found that temperature sensors were able to detect a change in temperature in the adjacent cell and cells two cells away, therefore a temperature sensor will not be required in

every cell. Similarly, heaters are able to heat cells in a local area therefore all cells can be heated in a frame without requiring a heater in each cell. It was also found that the required temperatures could be reached within minutes in a local area with power levels in the milliwatt range. It was also found that while the heaters are able to heat a local area, the heat remained within the local area of about a 2.5 cell radius minimizing the amount of damage done to the healthy larvae and comb in other areas of the frame. The possibility of using a pulsed heat source to measure the honey level within the cells was also tested, however it was found that the temperature measured in neighbouring cells did not change for different amounts of water and therefore another alternative must be considered for measuring the honey level within the cell.

3.3 Board Design

A general understanding of heat flow and board concepts were determined from the simulations discussed in Section 3.2. Using those results and those from further simulations a PCB was designed and tested within a lab setting to verify the simulation results. The prototype board is shown in Figure 3.10.

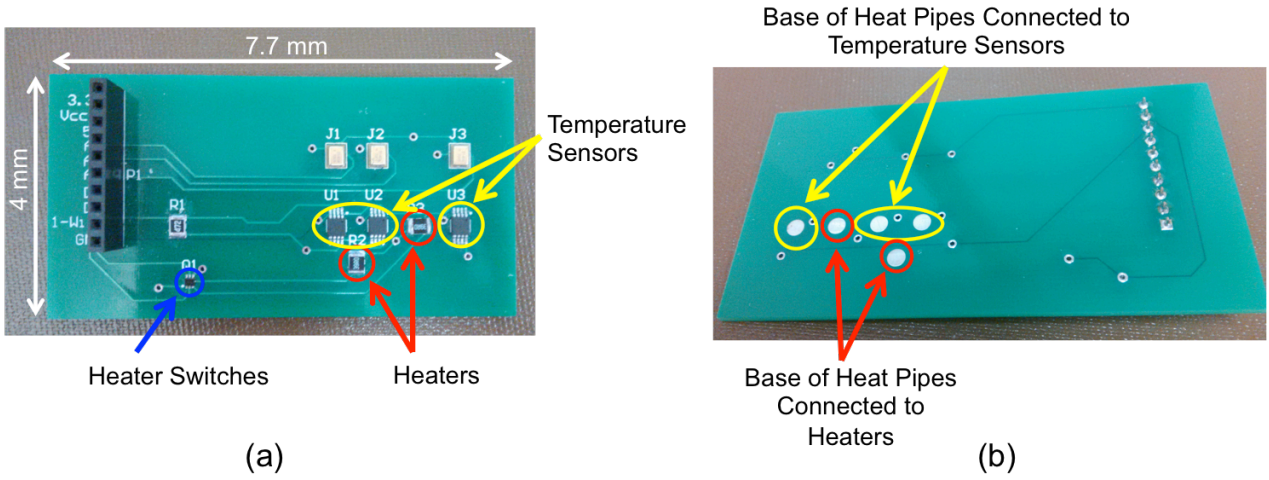


Figure 3.10 The (a) top side and (b) bottom side of the temperature sensor and heater PCB designed and tested

3.3.1 Further Models and Simulations for Determining Board Requirements

The simulation model discussed in Section 3.2 was updated to have cylindrical cells in a honeycomb layout to be more similar to the honeycomb to determine:

a) how much power the heaters need to provide

b) how the heaters should be placed throughout the comb

The model used in these simulations was built to be closer to the actual set up in the hive. The PCB thickness was reduced to a common value of 1.6 mm, which will also reduce the length of the copper pipe and thus the temperature difference between the two sides of the board. A 4x3 array of cylinders is used for the cells, even though in a hive the cells are hexagons, they are very close to cylinders and the results should not be significantly different. The wall thickness was set to 0.5 mm between the cells and the total diameter, including the cavity and wall, of the cell was set to 6.9 mm to match those on the drone foundation, because as discussed in Section 3.1 the mites prefer the drone cells.

Different power levels were measured over time to determine which power level would heat the cells hot enough in an acceptable amount of time. Figure 3.11 plots the temperature in the heater cell measured at the top of the water over time for each of the power levels. Therefore, the temperature in the graph is the minimum temperature of the cell contents. It can be seen that with 600 mW of power the entire cell reached a temperature above 45°C in approximately four minutes and the temperature increased linearly with time in the three to 10 minute range. Therefore, if the heater remains on, the temperature will continue to increase and after 10 minutes reach a temperature over 55°C. Therefore, the cell directly above the heater is able to reach the required temperatures to kill the mites throughout the liquid, and even temperatures much higher than needed at the base of the cell. Therefore, 600 mW of power should be enough

to kill mites in the heater cell within a few minutes. The power level could be reduced if the amount of time is lengthened, for example after about seven minutes the 400 mW power source reached a temperature above 45°C.

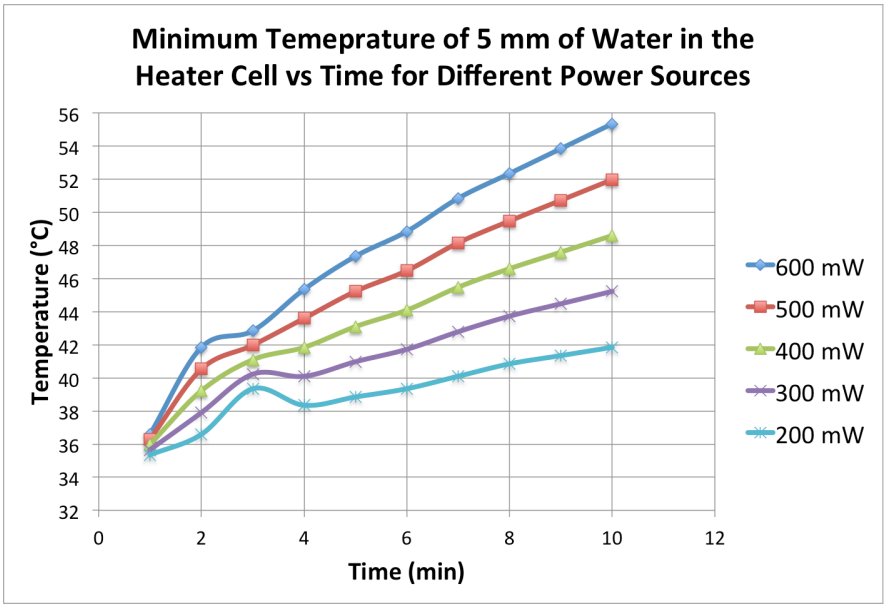


Figure 3.11 Temperature reached at the top of the water in the half-filled water cell directly above the heat source for different power levels over time

The next set of simulations tested the range of the heaters through a larger 6x4 array of cylindrical cells. The cells were half full with 5 mm of water and a 600 mW heat source was applied for 10 minutes. As expected the heater cell did not reach temperatures as high as before because more heat is lost in the larger board. The temperature at the top of the water in each of the four cells labeled in Fig. 3.12(a) after 10 minutes of a 600 mW heat source turned on in cell 1 is shown and the temperature along the central vertical axis in each of the cells is shown in Fig. 3.12(b). As was found previously, there is a large difference between the temperature at the base of the heater cell and the temperature at the top of the water. However, the other cells in the area experience a smaller difference between the base and top of the water, therefore the temperature

measured at the base of the cell should be very close to that of the majority of the water in the cell, and even the air temperature above the water is very similar. It can also be noted that the base of the heater cell gets significantly hotter than the rest of the board and cell contents and therefore, as desired, the high heat is localized to one small area. These results indicate that if temperatures between 37°C and 43°C are required to kill the *Varroa* mites [7], then a single heater could be used to heat 7 cells or possibly 19 cells as shown in Figure 3.13 depending on the required temperature and amount of time. This would help to minimize the number of heaters required for each frame while still keeping the heat within a local area.

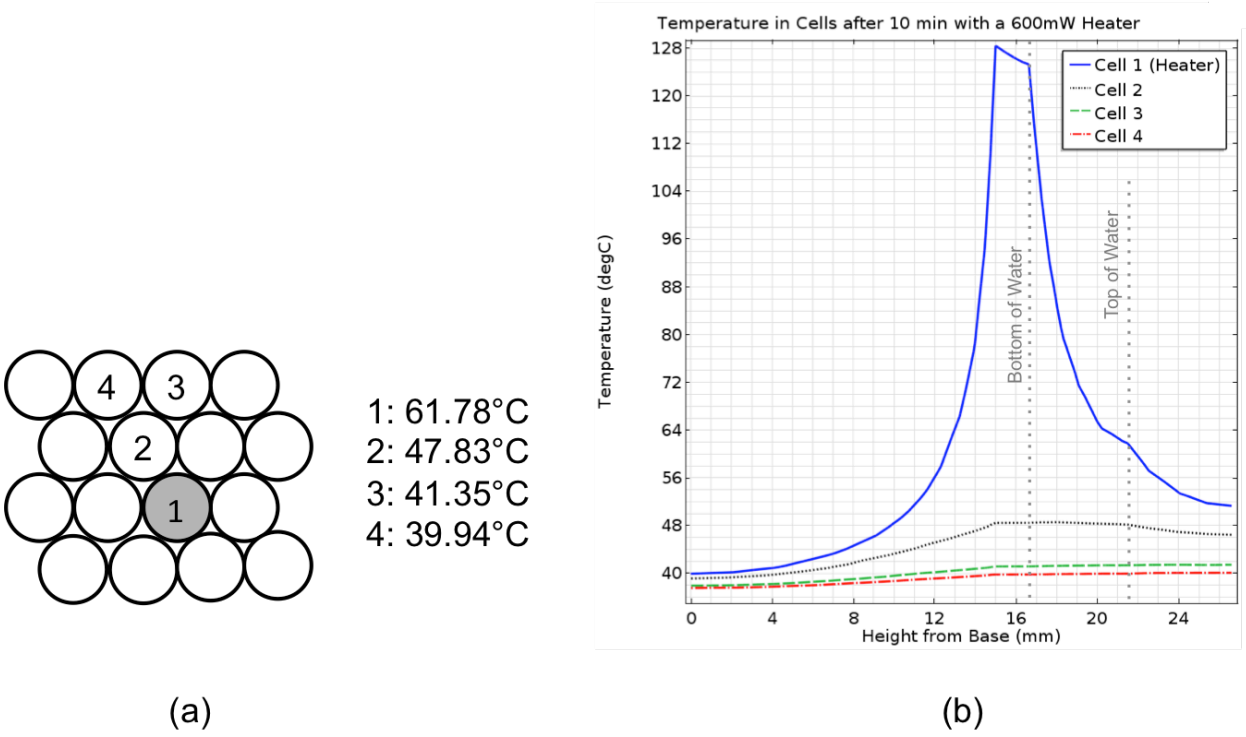


Figure 3.12 Simulation results including (a) cell numbers and temperature at top of water and (b) along central cell axis in half-full cells after 10 min with a 600mW heat source in cell 1

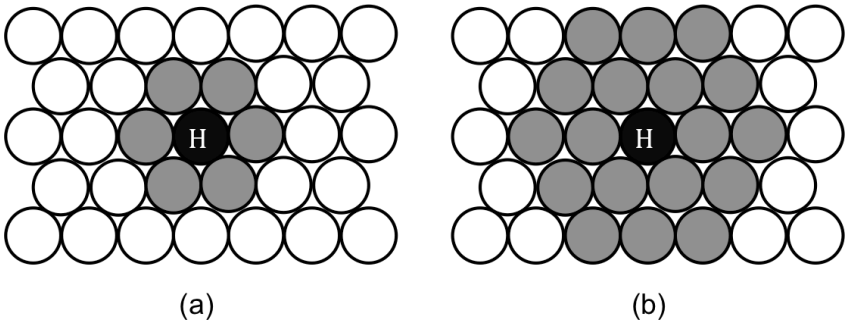


Figure 3.13 Cells required to reach high enough temperatures if a (a) 1 heater/7 cells or (b) 1 heater/19 cells layout is used

The effect of having two heaters turned on was also simulated. A 600mW heat source was placed in both cells H1 and H2 as shown in Figure 3.14 and the temperatures reached at the top of the half-full cells after 10 minutes are listed. As expected all cells are hotter with both heaters turned on because twice the power is being put into the system. The temperatures in each of the heater cells were about 2°C hotter than in the single heater case and the other measured cells were about 5°C hotter than in the single heater simulation. Therefore, if higher temperatures are required two heaters can be turned on to heat a neighbouring cell quite high. As a result, the heaters could be placed such that their range can be extended by having two heaters work together to heat the outer cells as shown in Figure 3.15, where the extended range of the heaters is indicated by the black cells. However, while this method of heater placement may minimize the total number of heaters on the board it will increase the amount of excess destruction within the frame as the local area is now twice the size because both heaters must be turned on resulting in all of the shaded grey area surrounding each of the heaters in Figure 3.15 to be heated. A drone comb has approximately 2400 cells, so using the one heater per 19 cells placement that was shown in Figure 3.13(b) would require approximately 126 heaters per frame, but if multiple heaters are used as shown in Figure 3.15 then only around 83 heaters would be required, a

decrease of about 34%. The decrease in the number heaters would come at the expense of less localized heating.

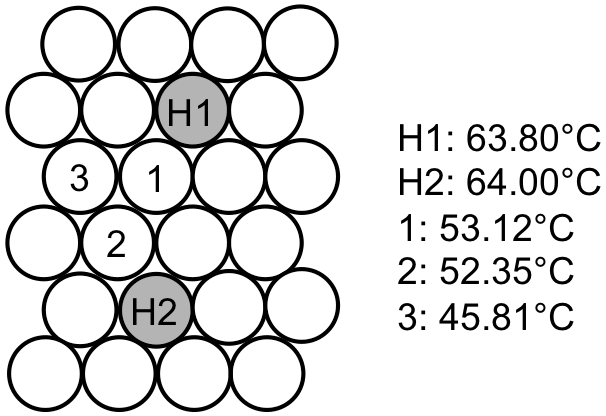


Figure 3.14 Simulation results including cell numbers and temperature at top of water in half-full cells after 10 min with a 600mW heat source in cells H1 and H2

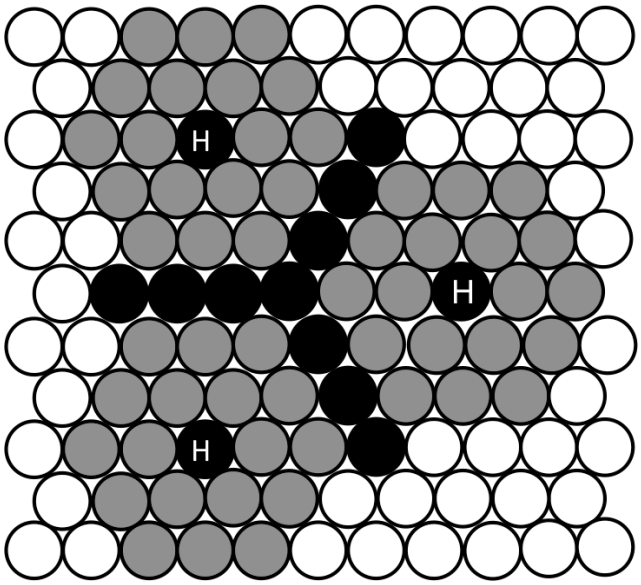


Figure 3.15 Heater placement to obtain an extended range (shown in black) with multiple heaters turned on

3.3.2 Board Requirements

The following requirements for the prototype board were developed based on the results of the previously discussed simulations and the nature of the bees and the hive environment.

Board Design:

- Board should be able to placed directly against existing hive foundation so that it:
    - Fits in existing frames
    - Gets the most accurate temperature measurements
    - Transfers the maximum heat from the heater to the desired cell
- Sensors should be spaced such that the sensors and heaters align with brood comb cells with diameter 6.9 mm
    - *Varroa* mites lay their eggs in the brood cells and prefer the larger drone cells as discussed in Section 3.1

Temperature Sensor:

- Measure temperatures in the 0°C – 100°C range
    - The brood nest temperature should remain around 35°C, however once the heaters are turned on the temperature may increase and from the simulations some cells reached temperatures close to 70°C at the base after the power source was on for an extended period of time. Lower temperatures also need to be measurable because if there is no larvae the bees may not regulate the temperature in the brood nest resulting in the temperature dropping to values less than 35°C which could also indicate important information about the hive health.
- Resolution of at least 0.1°C to detect temperature changes in adjacent cells
    - From the simulations it was found that a 1°C hotter object in one cell could cause a temperature increase of just over 0.1°C in the adjacent cell.

Heater:

- To be able to provide at least 600 mW of power

- The power used in the final design may be less, however from the simulations it was found that it still took four minutes to heat an entire cell to temperatures over 45°C. This is an acceptable amount of time because if less power is used it will take longer to heat up during which time the heat will spread to the surrounding cells and the heating will not remain in as localized an area.

3.3.3 Prototype Design

A printed circuit board, as previously shown in Figure 3.10, with three temperature sensors and two heaters was created to perform lab tests and verify the simulations. All of the components are placed on one side of the board and connected to the other side by filled via holes as shown in Figure 3.16. The components are organized within the cells as shown in Figure 3.17 and spaced such that the board should line up correctly within cells with a 6.9 mm diameter drone comb foundation within the brood nest where the temperature is regulated and where the mites lay their eggs.

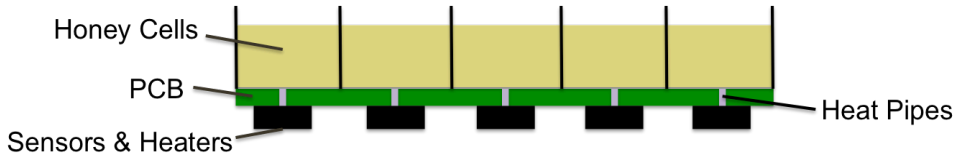


Figure 3.16 Sensor and heater placement relative to the honeycomb

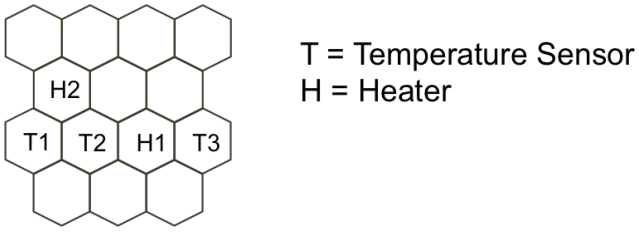


Figure 3.17 Location of temperature sensors and heaters within the honeycomb cells

For the prototype board the following components were selected:

- Temperature Sensor: DS1822 – 1-Wire addressable temperature sensor
- Heater: 39Ω resistor with a 750 mW rating
- Heater Switch: BSS84AKV – PMOS transistor

The DS1822 temperature sensor is part of the Maxim 1-Wire family of devices, which are designed to allow many devices to be connected to a single serial wire by giving each its own unique address [41]. This is ideal for the board we want to design because all of the required temperature sensors could then share three wires, a power line, ground line, and the single serial data line. The temperature sensor's specifications meet the requirements developed in section 3.3.2. It measures temperatures in the -55°C to 125°C range and has an adjustable resolution that varies between 0.5°C and 0.0625°C [41]. Therefore, the sensor covers the required temperature range and is able to offer a higher resolution than needed that will allow for the detection of smaller temperature changes which may increase the range of the temperature sensors to more than just the adjacent cells. The sensor only has a ±2°C accuracy [41], however it is the changes in temperature that are the most important, so this sensor is acceptable.

A simple heater was created with a resistor for the prototype board. The board is wired such that the resistors can be connected to an external power source separate from the 5V source connected to the temperature sensors to allow for different power levels to be tested. A resistor with a 750 mW power rating was selected as it meets the requirements and the resistors with even higher ratings are physically larger and may not fit within the cells. A 39 Ω resistor was selected so that when the maximum power of 5V is applied only 641mW are produced, which is more than required to heat the cells and less than the maximum power rating on the resistor.

The heater is controlled by a PMOS transistor as shown in Figure 3.18. The PMOS transistor configuration was chosen so that when the heater is off the heat pipe is at ground instead of Vcc. However, one disadvantage of the PMOS configuration is that the maximum Vcc is 5V because if it is higher the heater will remain on because the Arduino can only provide a 5V digital output to turn the transistor off. A 5V supply provides 641 mW of power, which is enough for the initial tests however to provide more flexibility in the future a NMOS configuration might be considered. The BSS84AKV transistor was selected and has a maximum current rating of 170 mA [42], which is larger than the 128 mA that will be passing through the transistor and 39 Ω resistor when the maximum voltage of 5V is applied.

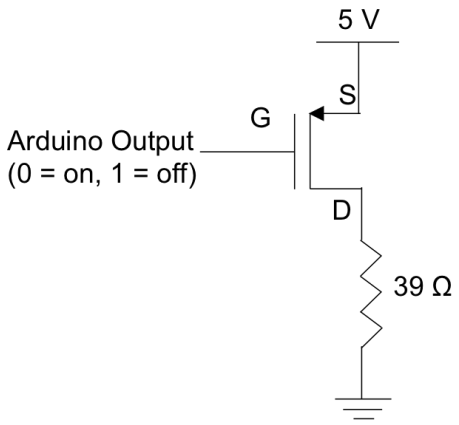


Figure 3.18 Heater circuit diagram

3.4 Lab Tests

The following lab tests were performed with both empty and water-filled cells to test the PCB and to verify the simulation results.

3.4.1. Purpose

The purpose of the lab tests was to determine:

a) How the heat spreads through the board and cells

b) If the heater power level is acceptable to reach the required temperatures

c) The length of time required to obtain the required temperature increase

d) How the temperature measured at the base of the cell compares to the temperature at the top of the water

3.4.2 Experimental Set-up

The following experiments were performed at room temperature, measured to be 24.9°C and 22.4°C for trials 1 and 2 respectively. Therefore, the absolute temperatures measured will not be the same in a 35°C hive environment, but the change in temperature should be. The on-board heater was connected to a 5V supply producing the maximum power of 641mW when turned on. A 1 cm tall acrylic 3D printed comb, as shown in Figure 3.19(b) with a 6x6 array of 6.9 mm diameter circular cells with 1 mm thick walls between cells was used for the honeycomb. One layer of clear plastic tape was placed across the board to prevent the liquid from directly contacting the board and two layers of the clear plastic tape were placed on the base of the 3D comb to keep the liquid inside the cells. The board was placed underneath such that the sensors and heaters lined up within the cells as shown in Figure 3.19(b). For these tests heater H1 was turned on and the temperature was measured at the base of the cells by the on-board sensors in two neighbouring cells, sensors T2 and T3, and the cell located two cells away, sensor T1. An infrared (IR) camera was also used to measure the surface temperature at the top of the cells by manually holding the camera above the cells and taking a picture each time the temperature was recorded by the on-board sensors. This allows for the temperature at the top of the liquid to be measured and compared to the simulation results. The IR camera also provides a method for measuring the temperature in the heater cell where there is no on-board sensor.

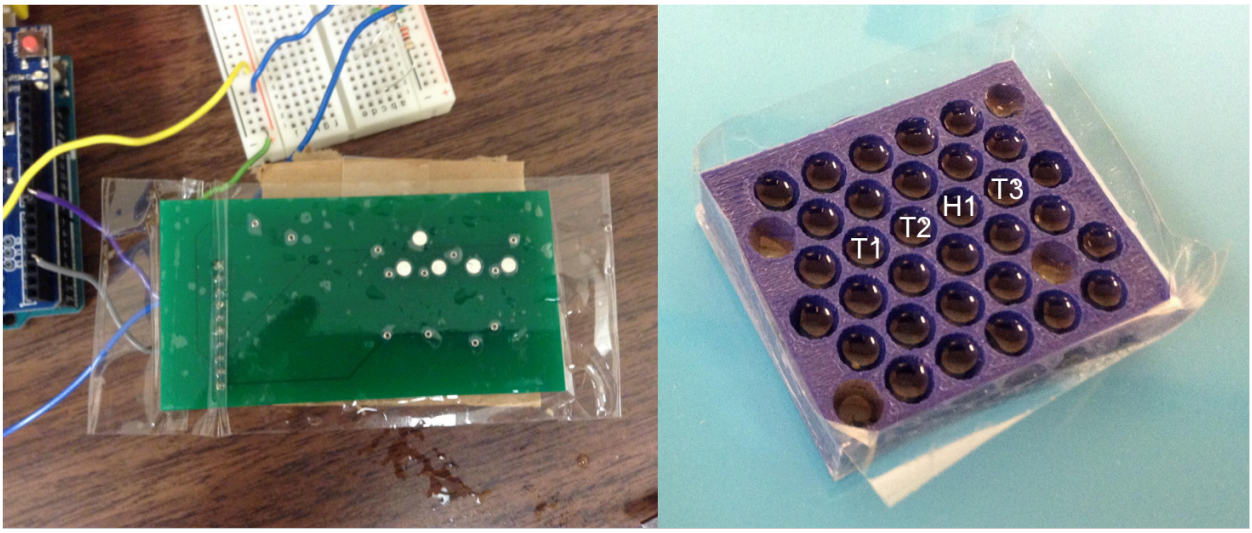


Figure 3.19 Lab heat test setup with (a) the PCB board and (b) the 3D printed comb placed such that the cells lined up as labeled with the components on the PCB

3.4.3 Trial 1 (Empty Cells) – Results and Discussion

In this test the cells were empty, therefore the on-board sensors measured the temperature on the heater side of the board and the IR camera measured the surface temperature on the other side. This allows for the accuracy of the temperature sensors to be tested and the amount of heat lost through the board to be observed and compared with the simulation results. The on-board sensors and IR camera measured the temperature every 15 seconds for three minutes after the heater was turned on. Table 3.5 summarizes the maximum changes in temperature measured in each cell by both the sensors and IR camera after 3.5 minutes and Figure 3.20 plots the temperature measurements over time.

From the values in Table 3.5 it can be seen that the heater is strong enough to significantly raise the temperature at the base of the cells within 3.5 minutes in a local area of at least a 2-cell radius because cell T1, two away from the heater, experienced a 10°C increase. Therefore, a heater is not required in each cell. From the values in Table 3.5 it can also be seen

that cells T2 and T3, which are adjacent to the heater and one cell closer than T1 to the heater, experienced a temperature increase about 2.4 times as large as cell T1. This indicates that some heat is spread through the board, but as desired the majority remains within the local area of the heater.

Table 3.5: The Maximum Change in Temperature Measured in Each Cell by the On-Board Sensor and IR Camera within 3.5 minutes of Turning the Heater H1 On

	T1		**T2**		**T3**		**Heater**
	Sensor	IR	Sensor	IR	Sensor	IR	IR
ΔT_{max} (°C)	10.00	9.6	23.25	26.0	23.31	17.8	46.5

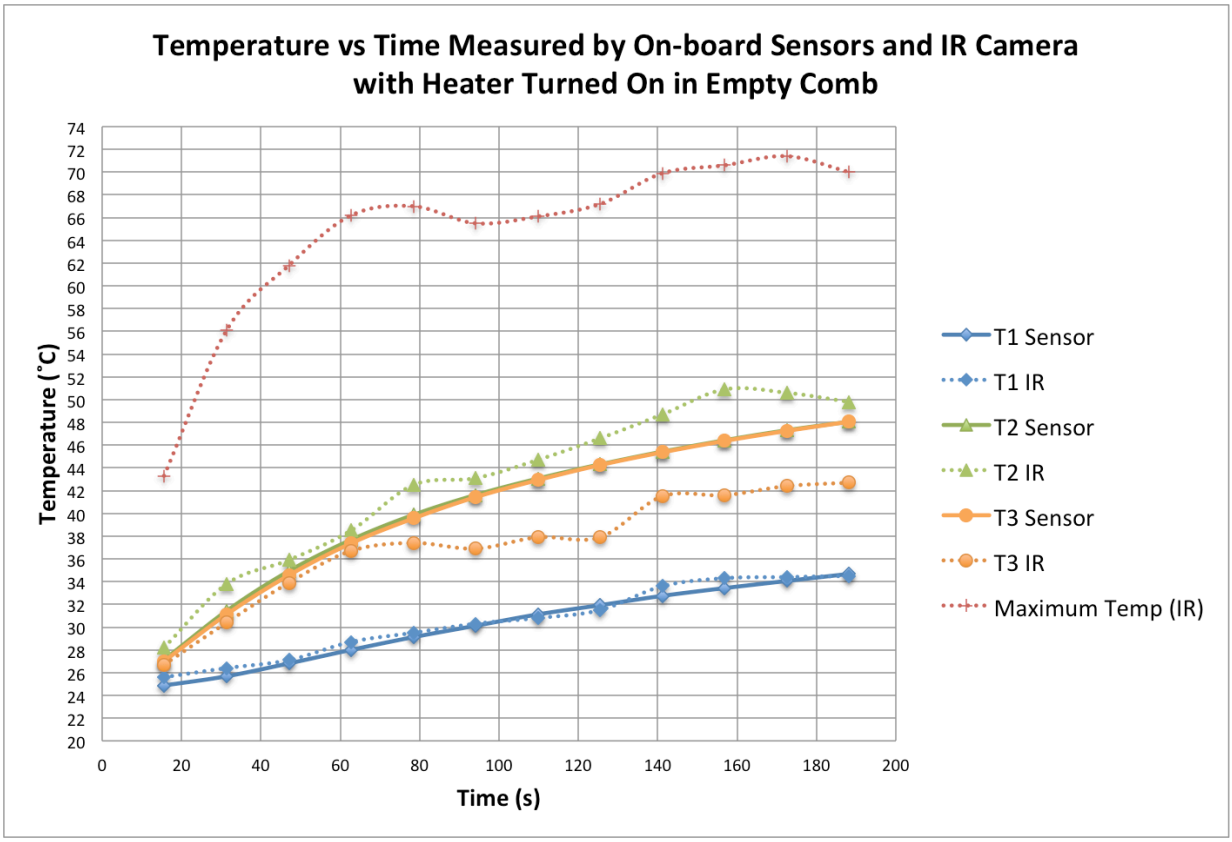


Figure 3.20 The temperature measured by on-board sensors and IR camera with an empty comb

From the plot in Figure 3.20 it can be seen that temperature sensors T2 and T3 have almost identical readings as expected because they are both positioned adjacent to the heater cell. Sensor T1 measured a lower temperature than T2 and T3 as expected because it is located further away from the heat source. It can be seen that cells T2 and T3 heated at a fast rate soon as the heater was turned on but then the temperature increase became more linear after about 90 seconds. The temperature increase in cell T1 was observed to be approximately linear the whole time the heater was on, probably because it is further from the heater and therefore does not receive much heat initially and then heats at a steady rate as the neighbouring cell warms. As mentioned previously the sensors measured the temperature at the base of the heat pipe on the same side of the board as the heater and the IR camera measured the temperature at the base inside the cells at the opposite end of the heat pipe. In Figure 3.20 it can be seen that in cell T1 the IR camera measured almost the same temperature as the sensor with an average difference of only 0.5°C. This matches the simulation results from before that indicated that there should be a constant temperature across the heat pipe. Therefore, the heat pipe is working as expected to allow the temperature sensors to measure the cell temperature from the other side of the board.

However, the two measurements were not as close in the cells closest to the heater. The average difference between the IR camera and the on-board sensor recordings for cells T2 and T3 were 2.17°C and 3.27°C respectively. The IR camera measured a lower temperature than the sensor in cell T3 and higher than the sensor in cell T2. It was expected that cells T2 and T3 would be the same however the IR camera measurements had an average difference of 5.61°C between the two cells, while the on-board sensors were almost identical as expected. The difference may have partially been caused by errors due to the positioning of the IR camera because it was held above the comb for each measurement and therefore was not always held in

the exact same spot. Another factor could have been that the camera may have been angled slightly instead of being directly parallel to the table causing some errors. This probably contributed to T3 being read at lower temperatures because it was the cell the furthest away from the centre of the comb where the camera was focused and therefore from the camera angle it may have been measuring part of the wall of the comb near the base instead of the board at the base. The repositioning of the camera for each measurement may have also contributed to the noise seen in the IR camera signal and why it varies up and down and is not smooth like the sensor readings. It should also be noted that the entire base of each cell is not a constant temperature and from the IR camera it was found that the temperature could vary as much as 0.5°C within a cell so the heat pipe in the centre of the cell was not necessarily the warmest part because often it was the part closest to the heater cell that was the warmest.

However, even with the errors in the IR camera measurements discussed above the general behaviour was as expected. Both cells T2 and T3 measured temperatures on both sides of the board that were hotter than T1, which was further from the heater, and lower than the temperature measured in the heater cell. As expected, the temperature measured at the base of the heater cell by the IR camera was much higher than all of the other cells. The temperature of the cell containing the heater was measured by the IR camera and although it is not strictly increasing as expected for the reasons discussed previously, it can be observed that the temperature appears to level off around 70°C, an increase of approximately 45°C, and therefore this could indicate that there is an upper limit on the temperature increase that can be achieved by the heater. As previously discussed in Section 3.1 temperatures of 70°C could be harmful to the bees and honeycomb, but this temperature is contained to the base of the single cell with the heater and therefore the amount of damage is minimized.

3.4.4 Trial 2 (Water-filled cells) – Results and Discussion

The brood nest cells will not be completely empty as they will have a wax base and either honey or bee larvae which quickly grow to fill the cell as discussed in Chapter 2. Therefore, in the second test the cells were completely filled with water, which should have similar thermal properties to larvae and honey. Because the cells were no longer empty, the IR camera measured the temperature at the top of the water in the cells while the on-board sensors still measured the temperature at the base. From the previous simulations and as was shown in Figure 3.3(b) the temperature at the top of the water should be close to the temperature of the majority of the water within the cell because all of the water was almost a constant temperature. Compared to the empty comb the temperature did not increase as rapidly so the temperature was recorded every 20 seconds for 9.5 minutes after the heater was turned on.

The temperatures measured over time are shown in Figure 3.21 where it can be seen that the sensors detected a spike in temperature initially but then the temperature decreased and followed a steady increase. A reason for this may be that the heat transfers through the board and wiring quickly initially heating the sensor, but is then dissipated into the water and air resulting in more of a steady-state behaviour. The results are summarized in Table 3.6, which includes the maximum temperature reached, the maximum change in temperature, and the average difference between the sensor and IR camera. The calculations in Table 3.6 only use the values recorded after 188 seconds, when the steady-state behaviour begins.

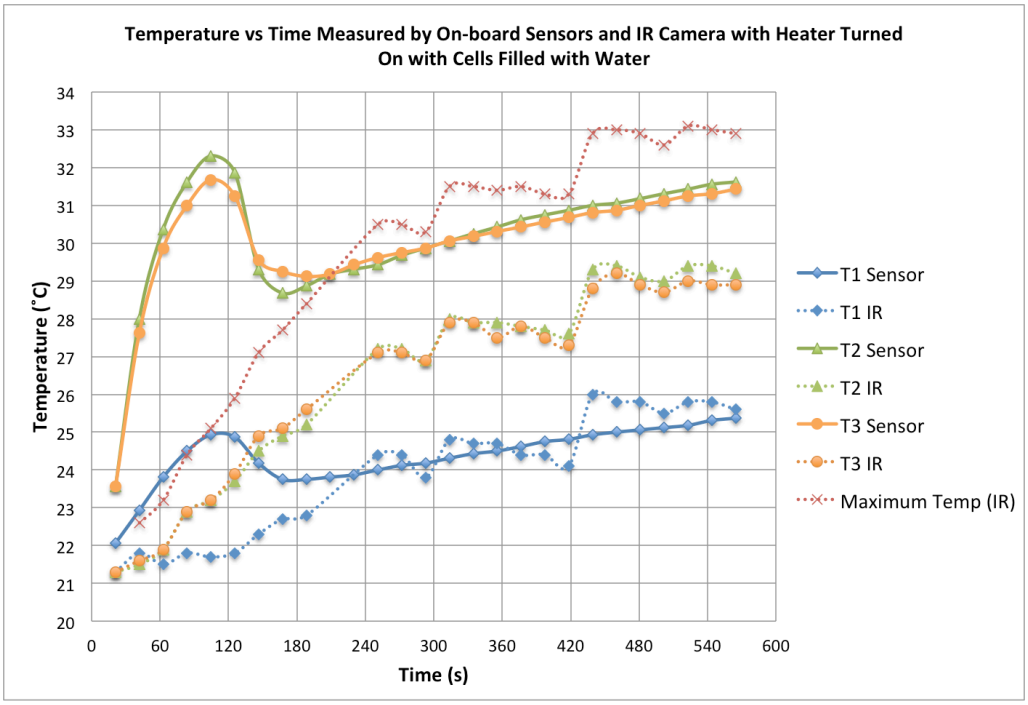


Figure 3.21 The temperature measured by on-board sensors and IR camera with full cells

Table 3.6 Summary of Results and Calculations from Temperatures Measured by On-board Sensors and IR Camera From Three to Nine Minutes After the Heater was Turned On

	T1		T2		T3		Heater
	Sensor	IR	Sensor	IR	Sensor	IR	IR
T_{max} (°C)	25.37	26.0	31.62	29.4	31.43	29.2	33.1
ΔT_{max} (°C)	3.37	3.6	9.69	7.0	9.37	6.9	10.7
Average difference between sensor and IR camera (°C)	0.99		3.74		3.69		
Temperatures reached if at ambient temperature 35°C (°C)	38.37 – 38.6		42.0 – 44.69		41.9 – 44.37		45.7

As expected the heater cell reached the highest temperatures, followed by the two adjacent cells T2 and T3, and T1 the cell two cells away reached the lowest temperature of the measured cells. Cells T2 and T3 were almost identical as expected because they are the same distance from the heater. In both cells T2 and T3, the adjacent cells to the heater, the sensor

measured temperatures a few degrees higher than the IR camera as expected, because from the initial simulations previously discussed there is a temperature drop from the base of the cell to the water because the water heats at a slower rate than the board. There is less of a difference, about 0.2°C, between the two measurements in the cell two away from the heater. As can be seen from the plot the IR camera and the sensor are measuring around the same value, which is what was also found in the empty cells test. This is probably due to the fact that at this distance from the heater, as was determined in the previous empty cell trial, the PCB heats up significantly less than at the base of cells closer to the heater, therefore more heat may be being transferred to the water from the neighbouring water-filled cells and walls than from the base of the board resulting in the water being about the same temperature as the base of the cell. Therefore, the further away the temperature sensors are from the heater the less their measurements will be impacted and the more accurate they will be at measuring the temperature of the cell contents. The noise observed in the IR camera readings are once again most likely due to the repositioning of the camera between readings as discussed previously for the empty-cell trial, especially since all cells seem to have the same noise pattern.

The temperatures listed in the last row of Table 3.6 and shown in Figure 3.22 are those that would be reached if the ambient temperature was 35°C instead of room temperature. These temperatures can be considered minimum temperatures because the brood cells with mites may not be full and therefore and may reach higher temperatures faster, as was the case in the empty-cell trial. The range is determined at the lower end by the temperature measured by the IR camera at the top of the cell, where from the previous simulations it was lower than at the base of the cell. The higher end on the range is determined by the temperature change measured by the on-board temperature sensors at the base of cell, where the mites may lay their eggs. As stated in

Table 3.6 it was found that after nine minutes the heater cell reached a maximum temperature increase of 10.7°C at the top of the water and it may have been even hotter at the base. The cell two cells away was able to reach a minimum temperature of 38.6°C in 9 minutes. According to [7] mites are instantly killed at 47°C, but damage is caused resulting in death at 37°C with a longer exposure time.

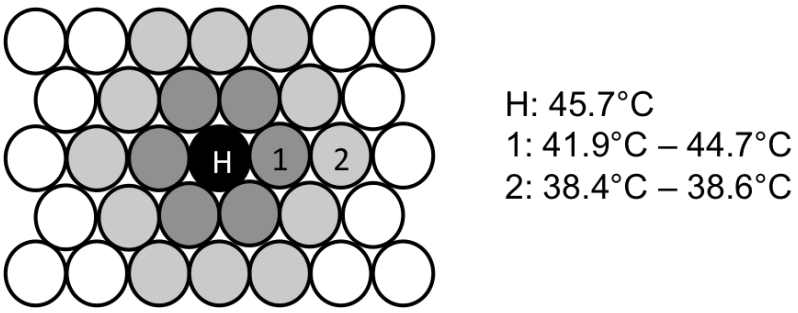


Figure 3.22 Temperatures reached within the water filled cells surrounding the heater after 9.5 minutes

Therefore, a 641 mW heater should be able to heat the cells within a local area with a two drone cell radius to temperatures over 38°C within ten minutes without harming the brood and comb in other areas of the frame, which from Table 3.1 can be damaged at the temperatures of 38°C and 47°C respectively.

3.4.5 Comparison of Trial and Simulation Results

The results of the two lab trials discussed above can be compared to the results of the simulations. For comparison the power level of the heater in the simulations was set to 641mW to match those in the lab test. Figure 3.23, shows the plot of the temperature at the base of the cell in the simulation, indicated by the dashed lines, and by the on-board sensors, indicated by the solid lines, in the empty-cell trial. It can be seen that the absolute temperatures reached were higher in the trial than in the simulation, but the behaviour was very similar with the

neighbouring cell reaching temperatures about 12°C hotter than the cell two cells away in both the simulation and trial after three minutes. Part of the difference in the absolute temperatures could be due to the materials used in the model not being exactly the same. As well the wiring and components on the PCB were not included in the model, which may have transferred more of the heat to the cells in the PCB trial.

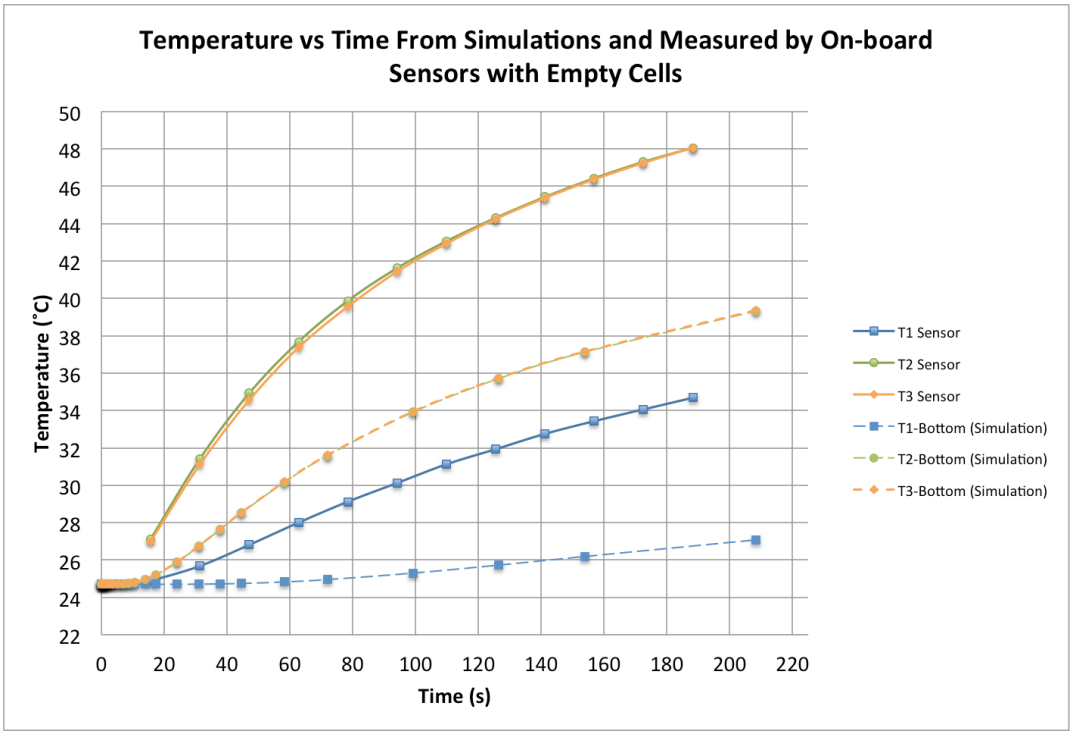
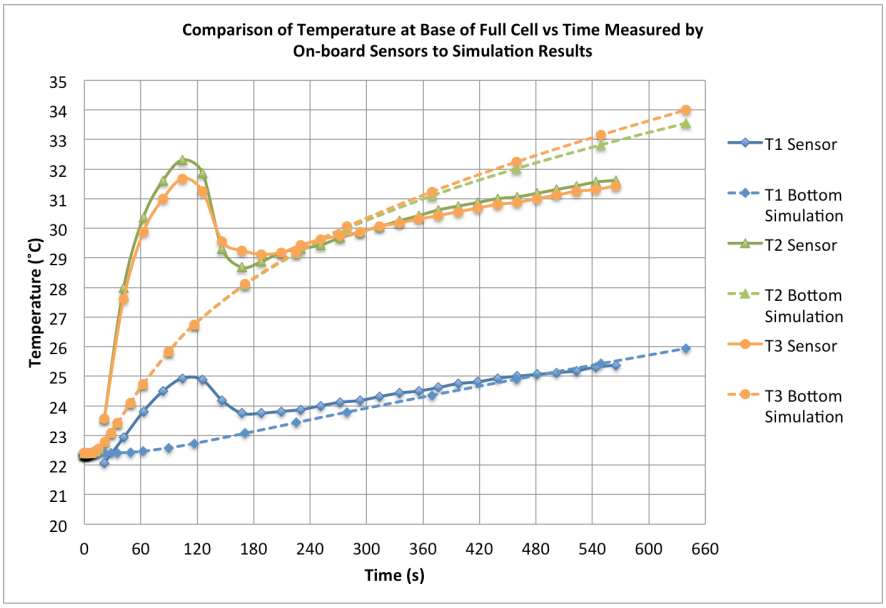
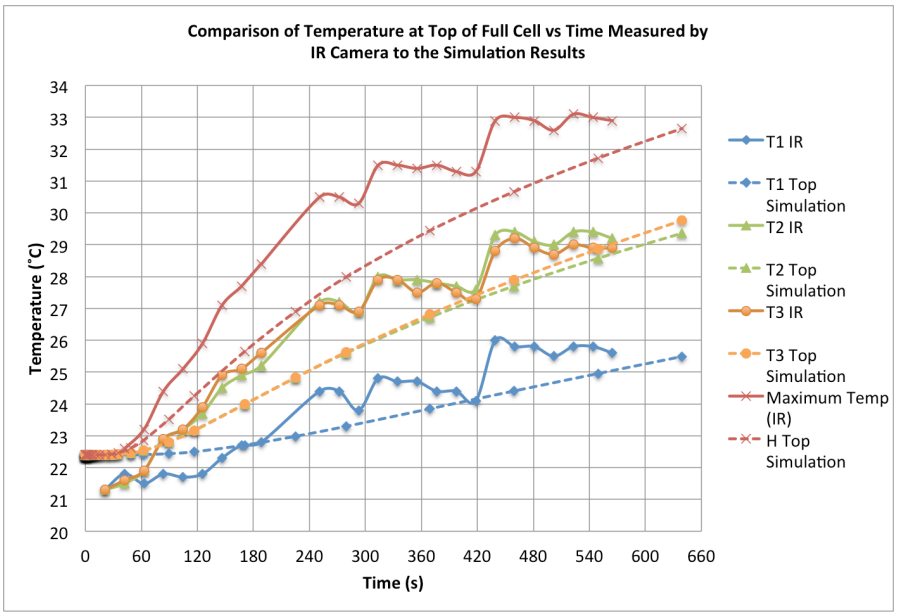


Figure 3.23 Comparison of temperature measured by on-board sensors to the simulation results

Figure 3.24 shows the results of trial 2 compared to the results of the simulation for water-filled cells. In Figure 3.24(a) it can be seen that the simulation temperatures at the base of the cell were very close to the measured values following the initial temperature spike detected by the sensors. The simulation did not indicate an initial spike and therefore the spike may be due to the circuitry and board as previously discussed. In both cases the rate of temperature increase was slightly lower in the lab test than in the simulation, probably because more heat was lost to the surroundings and larger area that was not included in the model.



(a)



(b)

Figure 3.24 Comparison of measured results to the simulation results for full cells at the (a) base of the cell and (b) top of the water

In Figure 3.24(b) it can be seen that the simulation temperature at the top of the water was lower than that measured by the IR camera in all of the cells, however the behaviour of the temperature over time follows the same behaviour. After about 9.5 minutes, the heater cell was found to about 3.5°C warmer than the neighbouring cell in the simulation and 3°C warmer in the

test. Similarly, the neighbouring cell to the heater was found to be about 3.5°C warmer than the cell two away from the heater in the simulation and 4°C warmer in the lab test after 9.5 minutes.

In summary, the simulations were fairly accurate in modelling the relative temperatures throughout the different parts of the board and cells, however the absolute temperatures appear to be offset by a constant in the empty-cell and full-cell top of water measurements. This offset could be due to external factors, such as humidity, that were not considered in the model as well the PCB was modelled with a single acrylic sheet that does not take any wiring or other materials of the PCB into account.

3.4.6 Conclusions

From the two lab trials performed some conclusions can be drawn. From the empty-cell trial it was found that the heat pipes work as expected transferring heat from the heater into the cell on the other side of the PCB and almost the same temperature was recorded on either end, so a heat pipe can be used to measure the temperature at the base of the honey cell from the other side of the board. From the empty cell test it was found that the PCB itself was a good insulator and only a small local area around the heater was heated and therefore damage to the surrounding cells will be small, only a few cells. Similarly, it can be concluded from the full-cell case that the heat will still remain within a local area and will not harm the brood and comb in other areas of the frame.

In comparing the results of the two trials it can be determined that the temperature of the contents is inversely proportional to the amount of liquid in the cells, therefore the cells will be heated hotter and faster when they are emptier. From the results of the water-filled cells it can be concluded that a 641mW heater should be powerful enough to heat the cells within a local area of a five drone-cell diameter to the temperatures required to kill the mites (over 38°C) and

therefore only one heater per 19 cells is required. The heater power is an acceptable level because it not only provides a good range, but also reaches the required temperatures in an acceptable amount of time. From the tests it was found that the system is able to reach temperatures required to kill mites within minutes because the top of the water experienced a 10°C, 7°C, and 3°C increase in the heater cell, neighbour cell, and cell two cells away respectively in 9.5 minutes.

In both trials the temperature sensors located further from the heater measured almost the same value as the IR camera indicating that the current PCB design is able to monitor the temperature of the contents within the cells from the other side of the board if it is just monitoring temperature, however if a heater is turned on then the cells closest to the heater may read temperatures higher than that of the contents due to the heat transfer through the board.

The model used, simulated the heat flow behaviour throughout the empty board and between the full cells fairly accurately and therefore can be used to model the heat flow within the comb.

3.4.7 Future Work

This initial design requires each heater to be controlled by a separate transistor and digital output from the Arduino, which would not be feasible when there are multiple boards in a hive and each board requires more than 80 heaters. There is a 1-wire addressable switch, however it has a maximum current of 20 mA [43], which is much less than the 128 mA currently passing through the heater. If the resistance is increased to reduce the current, then the power is decreased as well which, as from the simulations results in a much longer heating time which results in less localized heating as the heat dissipates through the rest of the board and the cells may never reach the temperatures required. Therefore, other options need to be considered.

The current design and tests only have honeycomb on one side of the board, when in the hive it will be on both sides. Therefore, the board may need to be modified to allow it to fit in frame with honeycomb on either side. Possible solutions are to place two boards back-to-back or to cover the side with the sensors in a material that will seal the board and allow the comb to be placed directly on both sides of the board.

3.5 Chapter Summary

Bees are known to be highly sensitive to temperature and the brood can be damaged if the temperature does not remain within the appropriate range. *Varroa* mites within the brood nest are also destructive resulting in larvae death or deformed bees. Therefore, the work discussed in this chapter was done to develop a PCB for use in the brood nest to monitor the temperature and heat the cells with local areas of a hive frame.

Simulations were first performed to determine how heat flows within and between cells. It was found that there was a noticeable temperature drop through the PCB from one side to the other and therefore to measure the temperature of the honey cells from the other side of the PCB, a copper heat pipe should be used to connect the temperature sensor to the other side. The copper heat pipe was a good heat conductor resulting in a constant temperature through the board. Similarly, a heat pipe is also more effective than just the PCB at transferring the heat from the heater. It was also found in the simulations that the temperature of the water at the base of the cell was slightly higher than the temperature at the top of the water, however the difference was very small and constant for all water heights so it will not affect the detection of changes in temperature. From the 3D modelling of the cells it was found that a temperature sensor is not required in each cell because a temperature change can be detected up to two cells away. Similarly, a single heater was found to heat all cells in a local area hot enough to kill mites, so

total coverage is achievable without a heater in every cell. Heaters with power levels in the milliwatt range were found to heat to the required temperature within minutes. It was also found that the heat remained within the local area minimizing the damage done to the comb and cell contents in other areas of the frame.

A prototype PCB was then designed with two heaters and three temperature sensors to verify the simulations. A 1-wire addressable temperature sensor was used and a 39 Ω resistor with a 750 mW rating controlled by a PMOS transistor was used for each of the heaters. When connected to 5V the heater had a power output of 641mW. Lab tests were performed with a 3D printed comb with circular cells placed over top of the board and the temperature measurements recorded by the on-board sensors and an IR camera were compared. The test was performed once with empty cells and once with water-filled cells. From the empty cell test it was found that the copper heat pipe worked as expected with an almost constant temperature across it allowing the temperature of the cell contents to be measured from the other side of the board. The PCB was also found to be a good insulator resulting in only a small local area of the board around the heater being heated, so the damage to the surrounding cells can be minimized. It was found that the rate and magnitude of the temperature increase is inversely proportional to the amount of liquid in the cells. The 641mW heater should be capable of heating cells to temperatures high enough to kill *Varroa* mites within minutes. The top of the water in the full cells experienced a 10°C, 7°C, and 3°C increase in the heater cell, neighbour cell, and cell two cells away respectively in 9.5 minutes. Therefore, only one heater per 19 cells is required.

The proposed temperature monitoring system is different from existing systems because the sensors will be embedded throughout each frame instead of just placing one or a couple within the empty area of the hive. The proposed heating system for the possible treatment of

Varroa mites is also different from existing systems because it allows for local areas of each hive frame to be individually controlled reducing the amount of wasted resources that occurs when entire frames or boxes need to be heated. Another difference is that by controlling the heaters remotely, beekeepers would have the ability to treat their hives at all times thus supressing the mite population by not giving it an opportunity to grow.

Chapter 4 – Cell Contents Monitoring within the Honey Supers and Brood Nest

In this chapter an interdigitated capacitance (IDC) sensor board is designed and tested for the following cell-content monitoring applications:

1. Monitoring the honey level and ripeness within regions of a hive frame to alert beekeepers when a hive is ready for harvest
2. Monitoring the state of the larvae in the sealed cells as it grows to allow for the possibility of future population estimation and to provide information about the queen and colony's health

The IDC layout and placement relative to the honeycomb is shown in Figure 4.1. The concept is based on the fact that as the cell contents change the electric field will pass through different materials with different electrical properties resulting in a change in the measured capacitance. Similar to the temperature sensor and control board designed in Chapter 3, this board will monitor the contents in local areas of a single frame.

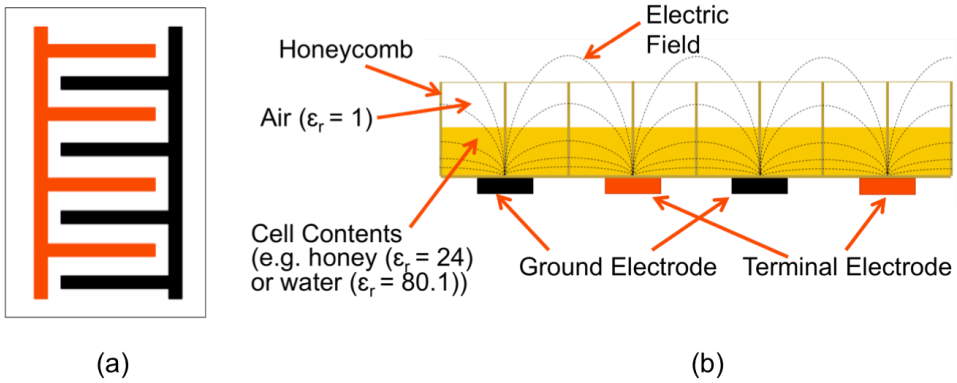


Figure 4.1 IDC layout (a) top view and (b) side view relative to the honeycomb

Section 4.1 provides background information on the bees' honey production process, the physical and electrical properties of nectar and honey, and how electrical properties of a cell will change as the brood grows. This is followed by a discussion of some existing capacitance sensor systems and an explanation of an IDC. Section 4.2 includes the results of initial simulations and the design and testing of a small prototype board, which were used as the basis for the full-sized 12-region prototype board designed, built, and tested in a lab setting in section 4.3. Section 4.4 includes the details and results of the in-hive test of the capacitance sensor board.

4.1 Background

Many factors need to be considered when designing a cell content monitoring system, including the honey making process and the larva growth stages. A capacitance sensor approach was selected due to its advantages over other options and its success in similar applications.

4.1.1 Honeybee Honey Production Process

The creation of honey from nectar is a multistep process. Nectar is first collected from flowers by the foragers and passed to house-bees that manipulate it [44] and add the enzyme invertase to it causing a chemical change in the sugar [3, 18]. The bees then place the unripe honey in cells in the honey supers where excess water is eliminated through evaporation [16, 45, 46]. The collected nectar may have a sugar concentration between 13% and 60%, however the bees do not usually collect very dilute nectars [3] and they are usually around 30% sugar [15]. The bees then work to ripen the honey by reducing the water content to obtain sugar concentrations of about 80% [45].

The rate at which the honey ripens is influenced by many factors including: weather, honey flow conditions, colony strength, concentration of nectar, available storage space, temperature, humidity, and ventilation [5]. As discussed in [5], two of the most influential

environmental factors affecting the ripening rate are temperature and humidity, because the rate of evaporation changes directly with temperature and inversely with humidity. The humidity within the hive can vary between 20% and 80%, therefore the bees increase the rate of evaporation by creating an air current by fanning their wings to pass dry air from outside the hive overtop of the honey filled cells [3, 5].

In [45], author Park found that the rate of water loss depends on three factors: the relative humidity, the amount of nectar in the cell, and the initial nectar concentration. Therefore, to increase the rate of evaporation the bees also spread out the nectar as much as possible throughout the honey super frames to allow for maximum surface area [45]. In [46] Park measured the ripening time for nectars with initial concentrations from 20%–60% in cells that were one-quarter full and three-quarters full. He found that higher sugar concentrated nectars ripened faster and the time to ripen was approximately twice as fast in cells that were one-quarter full than those that were three-quarters full with the same nectar concentrations [46]. He also found that if there was sufficient room the bees filled very few cells more than half full. Park found the ripening time for nectars with sugar concentrations of 20%–30% in cells one-quarter and three-quarters full to be about 2–3 days and 4.5–5 days respectively [46]. The very dilute nectars require significantly more water to be evaporated. Crane provides the example that to produce 1kg of honey, nectar that is 60% sugar only requires 0.3 kg of water to evaporate but nectar that is 20% sugar requires the evaporation of 3 kg of water [3]. Therefore, from these studies it can be seen that the ripening time of honey depends on a number of different factors making it difficult to predict exactly when the honey will be ripe.

Once the honey has fully ripened the bees store it in wax sealed cells to prevent the honey from absorbing any moisture from the air [3, 5]. Once a frame is filled with capped cells the

beekeeper removes the full frame from the hive, removes the wax caps, and collects the honey from the cells. The comb is preserved and can be reused multiple times within the hive. Replacing the full frames with empty ones as soon as possible allows the bees to spread out unripe honey to increase the ripening rate and in [13] authors Rinderer and Baxter found that during strong flows empty frames encouraged more hoarding. However, Crane also warns in [3] that the frames should not be removed until all or most of the cells are capped or the honey will absorb moisture from the air.

Therefore, the proposed system should be able to remotely detect when a frame is full and the honey is ready for harvest so beekeepers can monitor the honey status remotely and only drive out to a hive once it is full and ready to be harvested.

4.1.2 Physical and Electrical Properties of Honey

Nectars from different plants all consist of sugar and water, however the concentration of sugar varies across and within different species of plants and bees prefer the nectars with higher sugar concentrations [3]. The main components of honey are water and fructose, glucose, and sucrose sugars which together account for 99% of the ingredients in most honeys [3]. According to the Canadian Food Inspection Agency, Canada No. 3 grade honey must contain no more than 20% water, Canada No. 2 must contain no more than 18.6% water (20% if pasteurized) and Canada No.1 grade must have a water concentration less than 17.8% (18.6% if pasteurized) to be considered safe from fermentation [47]. In [3], Crane states that a sugar concentration of 80% or higher can only be achieved by the bees because of the chemical reactions with specific enzymes that take place at hive temperatures. As quoted in [3], in [48] it is stated that honey is hygroscopic and therefore should not be exposed to air over 60% humidity or it will start absorbing water reducing its concentration.

Therefore, due to its varying water concentrations, the electrical properties of honey also change along with the sugar concentration. A material's relative permittivity, ε_r, is an indicator of the amount of charge the material can hold compared to a vacuum [49]. Therefore, the amount of charge stored in a capacitor is directly related to the material between the two electrodes, and materials with a higher relative permittivity store more charge resulting in a higher capacitance across the capacitor [49]. Air is known to have a relative permittivity of 1, water has a relative permittivity of 80.1, and honey has a relative permittivity of 24 [50]. Therefore, initially when the cells are empty a low capacitance will be measured. Then, as the diluted nectar is added to the cells the capacitance will increase until the cells are full. Finally, the capacitance will decrease due to decreasing relative permittivity as the water evaporates ripening the nectar into honey. Therefore, by monitoring the capacitance over time, the beekeeper will not only be able to know when the hives have been filled with nectar but also observe the ripeness of the honey and be alerted when it is ready for harvest.

4.1.3 Capacitance of Brood Cells

Capacitance sensors can be applied to monitor brood growth in a in a similar way as monitoring the honey levels because as the bee develops it grows and changes the cell contents resulting in changes in capacitance. For example, when the egg is first laid in the cell the cell is mostly air. Then once it hatches it is fed and begins to fill the cell. Therefore, as the bee grows the relative permittivity in the cell will increase from that of air, which is 1, to that of the larva, which is not known but should be in the same range as water or honey, which is significantly greater than that of air, resulting in a significant change in capacitance. There may then be another change in the relative permittivity once the bee spins its cocoon and enters the pupa stage. Therefore, there could be three distinct phases in the capacitance measured over time that

correspond to the egg, larva, and pupa stages of the bee. While it is not known exactly what the capacitance function will look like over time, it should be fairly constant because the bees develop following a precise timeline. There are also fewer factors to be considered than when measuring the honey levels, due to the fact that the brood nest is a much more controlled environment than the honey supers and the majority of the time the bees are growing in sealed cells so the only changes in capacitance would be due to the growing bees.

4.1.4 Existing Capacitance Sensor Systems

Capacitance was chosen as the method to monitor the cell contents. As was discussed in Chapter 3, simulations were performed to determine if the temperature measurements varied when a pulsed a heat source was applied to cells with different honey levels. It was found that there was not a detectable difference in the temperature based on honey level and therefore another alternatives were considered.

In [51], author Spitzlei provides an overview of different methods that can be used for determining moisture content, which can be applied to the designed system because it will be measuring the amount of liquid nectar/honey in a cell or the size of the larvae, which both contain more moisture than the air in an empty cell. The methods Spitzlei considers are capacitive, infrared, microwave, and conductive. He notes that capacitance sensors can measure moisture through a pane of non-conductive material such as plastic or glass, so sensors will not need to come in contact with the honey or the bees. This is an advantage of capacitance sensors over conductive sensors because as Spitzlei points out a conductive sensor requires the placement of two electrodes directly in the material. He also notes that the capacitive sensors are able to detect the material's average moisture content, including both surface and core moisture [51]. This makes a capacitance sensor a good choice to measure the average moisture content

over a region of a hive frame, where as other sensors such as conductive and infrared only measure the surface moisture content in the small area where the sensors are placed [51]. The fourth sensor that is discussed by Spitzlei is a microwave senor, however these sensors require more equipment and space and therefore would not be feasible for placement inside the hive.

Capacitance sensors have been used in other food applications to determine various properties. For example in their paper, Phimphisan and Sa-ngiamvibool used an interdigitated capacitor placed inside a glass of milk to determine the water content of the milk [8]. In two similar experiments Felice et al. used capacitance sensors to measure the bacterial content of milk [9] and Lawton and Pethig used capacitance sensors to determine the fat content of milk [Lawton]. All three of these papers are based on the fact that the relative permittivity of milk changes when contents change. This applies to the honey monitoring problem because, as previously discussed, the water concentration of the honey decreases as the honey ripens changing the relative permittivity.

In [11], Angkawisittpan and Manasri propose a similar system to the one proposed in this thesis in which a low cost interdigitated capacitor is used for determining the sugar content in a solution. They place their interdigitated capacitor directly in a beaker with the solution and a first order high-pass filter is used to measure the capacitance. They perform a frequency sweep to determine at which frequency there is the largest difference in output voltages for the different concentrations to determine which frequency would give the best precision. Solutions with 10-50% sugar concentration by weight were tested and it was found that at all frequencies the output voltage decreased a measurable amount as the sugar concentration increased [11]. Therefore, even when a DC voltage is applied a measurable change in capacitance occurred.

Similarly in [12], Guo et al. studied the effects that water content had on the dielectric constant of three different types of honey. They tested water contents of 18-47% in each of the three types of honey and found that the dielectric constant increases linearly with water content in all three tested honeys when measured at the same frequency [12].

The chip that was selected to measure the capacitance applies a DC source instead of an AC source as was done in [11] and [12] and therefore it is the material's static relative permittivity that is affecting the capacitance measurement. However, as was found in [11] the capacitance should still decrease while the sugar concentration increases even at low frequencies.

4.1.5 Interdigitated Capacitor Sensor

An interdigitated capacitor (IDC) was selected for the capacitor design to monitor the cell contents in each region of the frame. As was shown in Figure 4.1, an IDC consists of a terminal and ground electrode each with a main line and electrode fingers that extend producing electromagnetic fields between each of the electrode fingers.

In their paper discussing the optimization of an IDC for gas detection, Endres and Drost developed the formula to calculate the total capacitance of an IDC based on a unit cell capacitance. The formulas from [52] are:

$$C_{IDC} = C_{UC}(N-1)L \qquad (1)$$

$$C_{UC} = C_1 + C_2 + C_3 \qquad (2)$$

$$C_1 + C_2 = \varepsilon_0 \frac{(\varepsilon_1+\varepsilon_2)}{2} \frac{K\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{K\left(\frac{a}{b}\right)} \qquad (3)$$

$$C_3 = \varepsilon_0 \varepsilon_3 \frac{h}{a} \qquad (4)$$

where,

N = total number of electrode fingers (ground and terminal)

L = length of the electrode overlap

C_1 = capacitance above the electrodes

C_2 = capacitance below the electrodes

C_3 = capacitance between the electrodes

ε_0 = free space permittivity constant

ε_1 = relative permittivity of the material above the electrodes

ε_2 = relative permittivity of the material below the electrodes

ε_3 = relative permittivity of the material between the electrodes

a = gap width between electrode fingers

b = unit cell width (gap width + electrode width)

h = electrode height

K( ) = complete elliptic integral of the first kind

From these equations it can be seen that the capacitance due to the material above and below the capacitor depends on the relative permittivity of the substances as well as the geometry of the IDC, particularly the ratio of the gap size between electrode fingers to the total unit cell length. Therefore, as the honey cells next to the capacitor are filled with nectar, honey, or larvae the dielectric constant in that region will change resulting in a change in the measured capacitance. In equation (3) the $\frac{K\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{K\left(\frac{a}{b}\right)}$ term is a constant based on the gap to electrode width ratio, and therefore changing the dimensions of the capacitor changes this factor. The plot in Figure 4.2 shows this constant value for different ratios. It can be seen that as the ratio of the

gap width to the unit cell width increases this factor decreases, resulting in a smaller impact of the capacitance above and below the capacitor on the total capacitance.

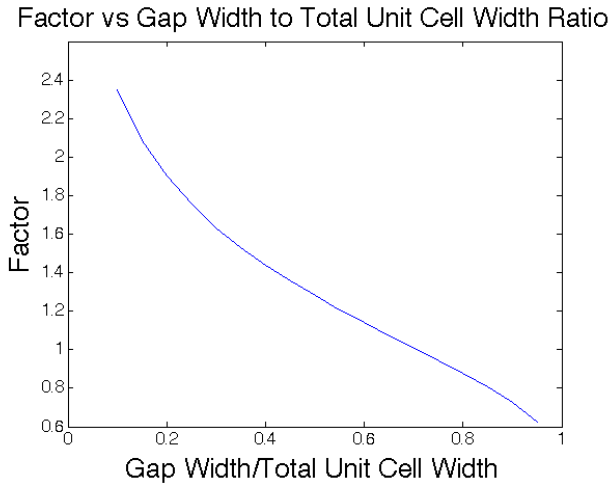


Figure 4.2 The constant factor in the equations developed in [52] as a function of the ratio of the gap width to the total unit cell width for an interdigitated capacitor

The goal of the system is to measure the changes in capacitance due to the fringing electric fields passing through the hive cells with changing contents. Therefore, the electric field should be limited to only pass through the honeycomb and not far past the top or else it will also pass though the empty space where the bees walk around or potentially the neighbouring frames. Therefore, the capacitor dimensions need to be selected to give a penetration depth that is large enough that the liquid height can be differentiated at heights close to the top of the cell without extending too far passed the top of the comb.

In their paper, Kim and Lee, develop a mathematical model and equation to determine the saturation thickness of the coating on an IDC. This determines the maximum height the electric field will penetrate into the substance above, and anything any higher will not affect the capacitance measured. The capacitance is considered saturated at 99.5% of its maximum. These equations only apply when the gap between electrodes is equal to the width of the electrodes, i.e.

the ratio of gap width to unit cell width as discussed in [52] is 0.5. The equations developed in [53] to determine the saturation thickness are:

$$t_{sat} = -\frac{L}{c_2} ln\left(\frac{0.005}{c_1}\right) \quad (5)$$

$$c_1 = 114.97G^3 + 28.85G^2 - 9.183G + 1.631 \quad (6)$$

$$c_2 = 1293.21G^3 - 164.87G^2 - 6.521G + 6.105 \quad (7)$$

where,

G = gap width, which must also be equal to the electrode width

L = unit cell length (gap + electrode width)

They also developed an equation for the unit cell saturation capacitance:

$$C_{sat} = 0.995\varepsilon C_0 \quad (8)$$

$$C_0 = -0.1962G^3 + 4.640\times10^{-2}G^2 - 3.739\times10^{-3}G + 4.545\times10^{-3} \quad (9)$$

These equations result in the saturation thickness increasing as the gap width and electrode width increase. Therefore, when comparing the two papers, in [52] it was found that as the electrode width became narrower in comparison to the gap width, the capacitance from the fringing fields above and below the capacitor decreased. Then in [53], the authors found that if the gap width to electrode width ratio is kept constant, then the larger electrodes and gap width will provide a higher saturation thickness.

Ong and Grimes apply both of the sets of equation developed above to build an inductor-capacitor circuit pair sensor whose resonant frequency changes in response to pressure and humidity levels. The capacitance changes in response to the electrical permittivity of the adjacent material and the IDC is coated with a thin layer of titanium dioxide, whose relative permittivity changes in response to humidity [54]. They use equations (1)-(4) from [52] above to calculate the capacitance, and equations (5)-(7) from [53] to calculate the desired thickness of the titanium

dioxide. It was noted in [54] that when the titanium dioxide layer was less than the saturation thickness, the relative permittivity of the region above the capacitor was not strictly equal to that of titanium dioxide but is partially determined by the remaining height of air. Therefore, in the designed cell monitoring system if the heights of the cell contents are not equal to the saturation thickness, then the relative permittivity in equation (3) will be a combination of the relative permittivity of each of the materials the electric fields are passing though. Therefore, the results from these papers were taken into account when selecting a capacitor design.

4.2 Initial Simulations and Prototype Board Design

As previously discussed many factors need to be considered when designing a capacitance sensor for honey level detection including the dimensions of the capacitor as well as the physical honey making process. Therefore, the first set of simulations and tests were performed to gain an understanding of whether an IDC is feasible solution for the cell content monitoring problem and how it can best be applied to the hive environment.

4.2.1 Simulations

The initial simulations were performed in COMSOL to test whether a capacitance sensor would be a feasible option for measuring the amount of honey in a honeycomb. The most important thing to determine if a measurable change in capacitance occurs as the liquid level increases. An IDC was used and aligned beneath the cells as shown in Figure 4.3. One electrode was grounded and the other was set to 5V. For these initial simulations the spacing between the electrodes was set to be equal to a cell diameter of 6.9 mm so there is an electrode every cell. Further tests and designs of the capacitor dimensions are discussed in later sections.

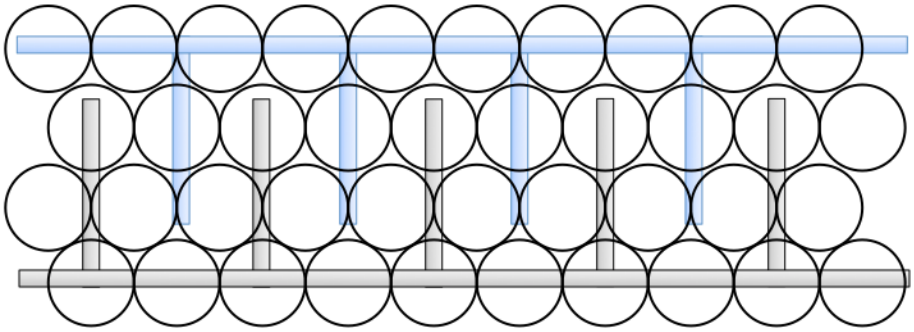


Figure 4.3 Interdigitated capacitor layout for measuring honey levels

The liquid level in all of the cells was increased from 1 mm to 1 cm simultaneously and the total capacitance was measured at each liquid height. The test was performed with both water ($\varepsilon_r = 80.1$) and honey ($\varepsilon_r = 24$) and the results are shown in Figure 4.4. From the results it can be seen that higher capacitances were measured for water than honey as expected due to its higher relative permittivity. Water also caused a larger total change of 1.95 pF in the capacitance between 1 mm and 1 cm of liquid, where as the honey only caused a change of 1.47 pF. Therefore, from the simulations it was learned that it is possible to determine the amount of honey in a group of cells based on the capacitance measured. It was also found that the change in capacitance is in the picofarad range, which is measurable by existing capacitance sensors. Therefore, a capacitor can be placed under the cells of interest to determine whether or not that section of the comb is full or empty.

From these simulations it was found that as expected the electric field is stronger closer to the capacitor, and therefore the impact of bees walking around above the comb will be smaller than the impact of addition of liquid within the cells on the capacitance measurement. That is also why there is a much larger change in capacitance observed when the liquid height is increased from 0 mm to 3 mm than when it is increased from 7 mm to 10 mm even though the same amount of liquid is added above the capacitor. Therefore, as was discussed in [54] when

the coating on the sensor is less than the saturation thickness the relative permittivity in equation (3) is a function of the relative permittivity of all of the materials the fields pass through, however as the liquid level in the comb increases the larger impact the liquid's relative permittivity will have. For example, at low liquid levels the strongest fields will pass through the liquid but a large number of strong fields will also pass through the air in the empty comb, but as the liquid level rises the electric fields will be passing more and more through the liquid, and therefore the relative permittivity used in equation (3) will become closer to that of the liquid. Therefore, from the increase in capacitance as the liquid fills the cells it can be determined that the saturation height of the simulated capacitor is higher than the top of the comb.

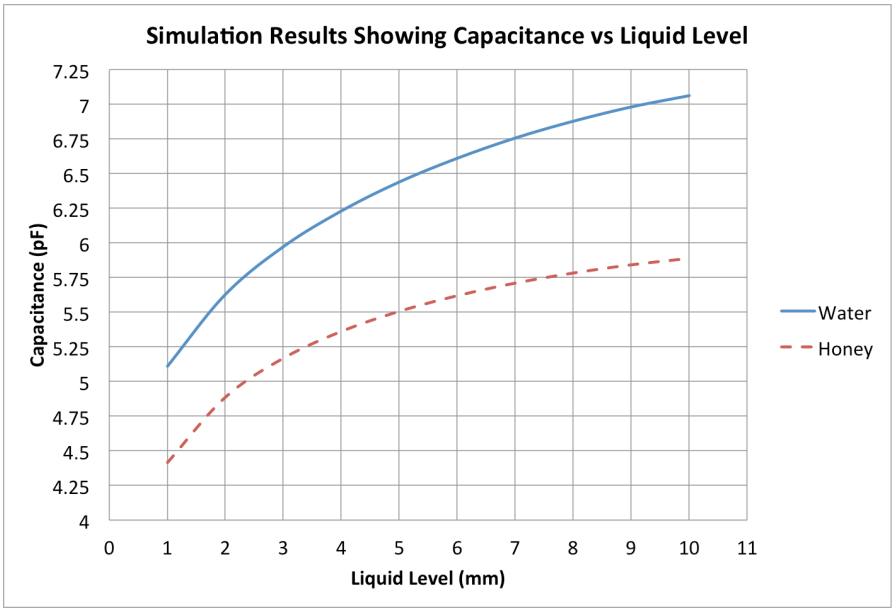


Figure 4.4 Simulation results showing capacitance vs liquid level for honey and water

In nature the honeybees will not fill all cells at the same time, instead they will fill cells in groups, and therefore the following simulations were performed to be more similar to how the honeybees will fill the cells. In a 4x10 grid of honey cells, the liquid height in two columns (eight cells) was increased by 1 mm each iteration until those cells were full. Once the two

columns were full the next two columns were filled until all 10 columns were full. So every 10 iterations the next set of cells begins filling. The simulation was performed once with water and once with honey and the results are shown in Figure 4.5. It can be seen that the change in capacitance is smaller when honey is used, but the behaviour is the same. Both water and honey were simulated to produce a minimum and maximum range for the capacitance because as previously discussed the water content is very high initially, but decreases as the honey ripens. Therefore, the resulting capacitance should be located between the two curves. It can also be noted that the capacitance increases linearly with the number of full cells. Therefore, each full cell contributes approximately the same amount of capacitance to the overall capacitance, and so the number of full cells can be directly calculated from the change in capacitance.

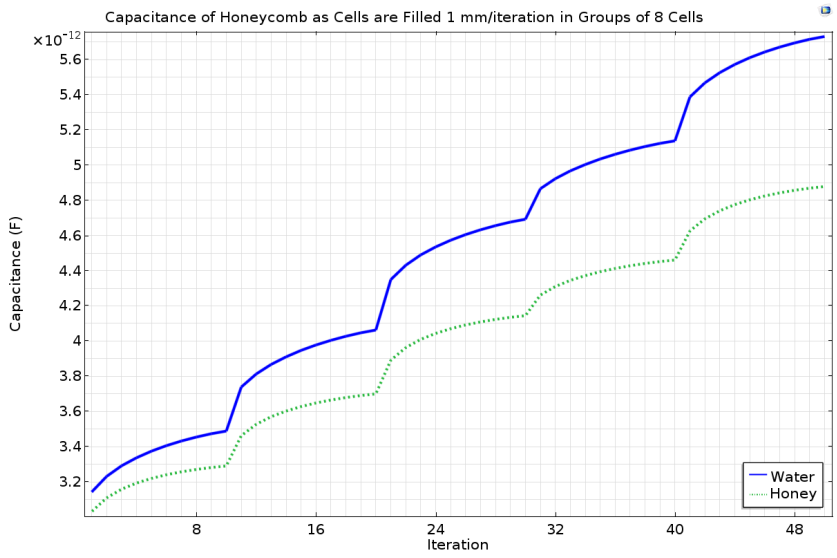


Figure 4.5 Simulation results showing the capacitance as a 4x10 comb of cells is filled eight cells at a time at a constant rate

Simulations were also performed to determine the impact of using various IDC dimensions. These simulations were performed using water but the relative behaviour should be the same as with honey but the change in capacitance will be reduced. The first test tested the effects of changing the spacing between the electrodes. It should be noted that because the

spacing was changed, but the electrode remained the same size (1.25 mm width), different numbers of electrodes were required to cover the same area. The results from the simulation are summarized in Table 4.1 where it can be seen that the closer the electrodes are together, the larger the change in capacitance, resulting in a slightly higher resolution of the water height. The final entry in the table is the case where there is only the main terminal and ground electrode line with no electrode fingers extending off of them, which measured a smaller change in capacitance and therefore the use of interdigitated electrodes extending under the cells gives a better resolution of the water level in the region.

Table 4.1 Total change in Capacitance from Empty to Water-Filled Cells for Different Capacitor Geometries

Separation (R = cell radius = 3.45 mm)	**# of Terminal Electrode Fingers**	**# of Ground Electrode Fingers**	**ΔC from 1 mm to 1 cm of water (pF)**
R	9	10	1.78
2R	4	5	1.62
3R	3	4	1.58
4R	2	3	1.57
8R	1	2	1.47
–	0	0	1.26

Capacitors with different electrode finger widths, but the same number of fingers, were simulated to determine the effect it has on the overall capacitance, as the simulations up to this point used a constant electrode width of 1.25 mm. The results for the different widths are summarized in Table 4.2 where it can be seen that the wider the capacitor, the larger the overall change in capacitance as the cells fill with liquid. The results of these simulations were used for the initial design of a prototype board for lab tests, and further simulations are discussed in Section 4.3 for selecting the dimensions of the capacitor while also taking the saturation height into account.

Table 4.2 Total Change in Capacitance from Empty to Water-Filled Cells for Different IDC Finger Widths

IDC finger Width (mm)	**ΔC (pF)**
1.75	2.08
1.50	1.98
1.25	1.91
1.00	1.85

Therefore, in summary from these initial simulations it was discovered that a detectable change in capacitance (picofarad range) across an IDC occurred when the water or honey level changed. It was also found that the IDC is more sensitive to changes at the base of the cells (i.e. when the liquid is first added to the cells), honey causes a smaller change in capacitance than water due to its lower relative permittivity, the measured capacitance should increase approximately linearly with the number of full cells, and the wider and closer spaced the IDC fingers are the more sensitive the sensor is.

4.2.2 Design and Testing of a Small Prototype Board

A small board, shown in Figure 4.6(a), was built to verify the design concepts and simulation results. Copper tape with a width of 2.667 mm was placed on a 6 mm thick piece of acrylic to create the electrodes. The main lines of the electrodes were placed 3.2 cm apart. Four electrode fingers that were about 2.7 mm long were extended off each the terminal and ground electrode lines and were spaced 8 mm apart. A 3D printed comb, shown in Fig. 4.6(b) was created to test the capacitor. The comb was made as a 9x17 grid of hexagonal cells to completely cover the capacitor. Each hexagonal cell had a cavity with a radius of 2 mm and a wall width of 1 mm between the cells, which was the minimum thickness required by the 3D printer, giving a total cell diameter of 5 mm, which is within the honey cell range.

(a) (b)

Figure 4.6 The (a) capacitance sensor prototype and (b) 3D printed honeycomb

Currently an Arduino is used to control all of the components in the smart hive, and therefore a chip is required to measure the capacitance on the capacitor and relay the information to the Arduino. The first chip that was considered was the AD7747, a 24-bit Capacitance-to-Digital Converter. This chip provides a ±10fF accuracy with a ±8pF range that can be adjusted to measure capacitances from 0–16pF or 9–25pF [55]. The chip has an I2C serial interface and can work with a power supply of 2.7–5.25V [55], and therefore is compatible with the Arduino. A disadvantage to this chip is that one will be needed for each capacitor in the hive frame or an analog switch may be needed to share one, therefore another alternative was found.

In order to reduce the number of parts required, a capacitive key sensor was used. The designed board will essentially be a large keypad covering the entire frame and each capacitor region is a key. Most keypad sensors are designed to just indicate either “pressed” or “not pressed” states based on a programmable threshold, however the cell content detection system requires the actual value of the capacitance. One sensor that is able to provide the raw capacitance value is the MPR121, a 12-input proximity capacitive touch sensor controller. It uses a 1.71 - 3.6 V supply and an I2C interface [56] making it compatible with the Arduino. The input

range is adjustable but can be set to read capacitances as low as 0.192pF and as high as 2.88nF [56].

The capacitance sensor works by applying a known current for a set amount of time and then measuring the voltage at that time. From the datasheet [56] the capacitance can be calculated as:

$$C = \frac{Q}{V} = \frac{I \times T}{V} \qquad (8)$$

where,

Q = charge

V = voltage

I = current

T = time

The range of the capacitance sensor can be adjusted by setting the charge current and charge time. From the application note [57], the low and high end of the ADC counts can be calculated as:

$$ADC_{low} = \frac{0.7}{V_{DD}} \times 1024 \qquad (9)$$

$$ADC_{high} = \frac{V_{DD} - 0.7}{V_{DD}} \times 1024 \qquad (10)$$

Which can then be used to calculate the measurable capacitance range using:

$$C = \frac{I \times T}{V_{DD} \times ADC} \times 1024 \qquad (11)$$

$$C_{low} = \frac{I \times T}{ADC_{high} \times V_{DD}} \times 1024 \qquad (12)$$

$$C_{high} = \frac{I \times T}{ADC_{low} \times V_{DD}} \times 1024 \qquad (13)$$

Therefore, the current and time constants were left at the default values of 60 µA and 0.5 µs respectively, which gives a range of 13.04 pF to 42.86 pF from equations (9)-(13) covering the capacitance range from the simulations.

The capacitor board was then connected to the capacitor chip, which was connected to the Arduino to measure the capacitance. In this test the cells were filled completely two columns at a time to see how the capacitance changes with an increase in water over the capacitor. The results of the three trials are shown in Figure 4.7 and the linear regression is plotted. It can be seen that the capacitance increased linearly as expected with a slope varying between 0.0036 pF/cell and 0.0046 pF/cell across the three trials. These differences may be due to not having the exact same placement of the 3D comb on the IDC for each trial. Similarly, the difference in the starting capacitance may also have to do with differences in comb placement or wire positioning between the trials.

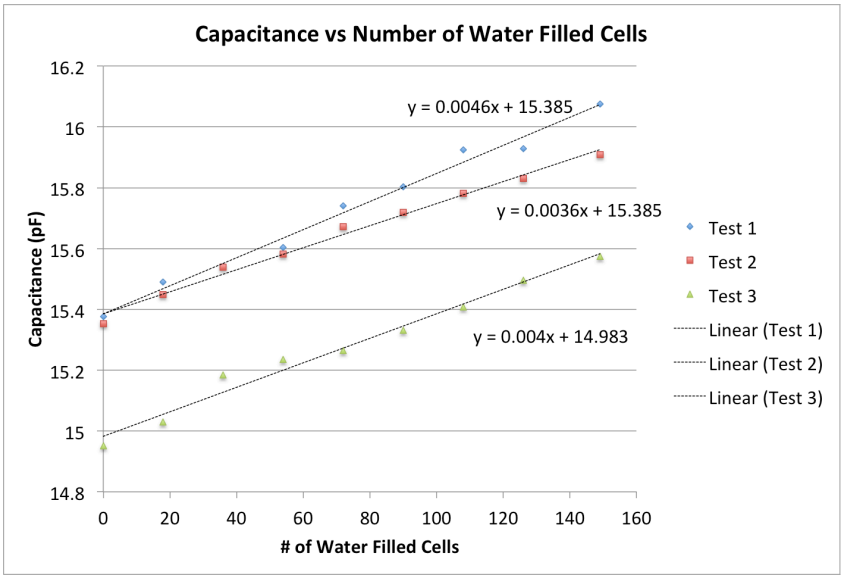


Figure 4.7 Test results for three lab trials with small prototype board

Figure 4.8 plots the average change in capacitance for the three lab trials as well as the results of three simulations with different overlay thicknesses. The overlay is the acrylic between

the IDC and the base of the cell, which in the lab test was about 2 mm. It can be seen in the plot that according to the 2 mm overlay simulation the slope should be higher for the lab tests, but was instead closer to that of a board with a 2.5 mm overlay. From the other simulation results in Figure 4.8 it can be seen that the slope can change significantly based on a small change in the distance between the base of the cell and the capacitor. The slope is also probably affected by the overlay material, and in the model it was set to be a solid piece of acrylic but the 3D printed board base may be a different plastic and not as solid. Some errors may have also occurred due to slight differences in the electrode dimensions and placement. Therefore, the overall behaviour was linear as expected and the slope was in the correct range, but slightly lower than expected due to differences between the model and lab set up.

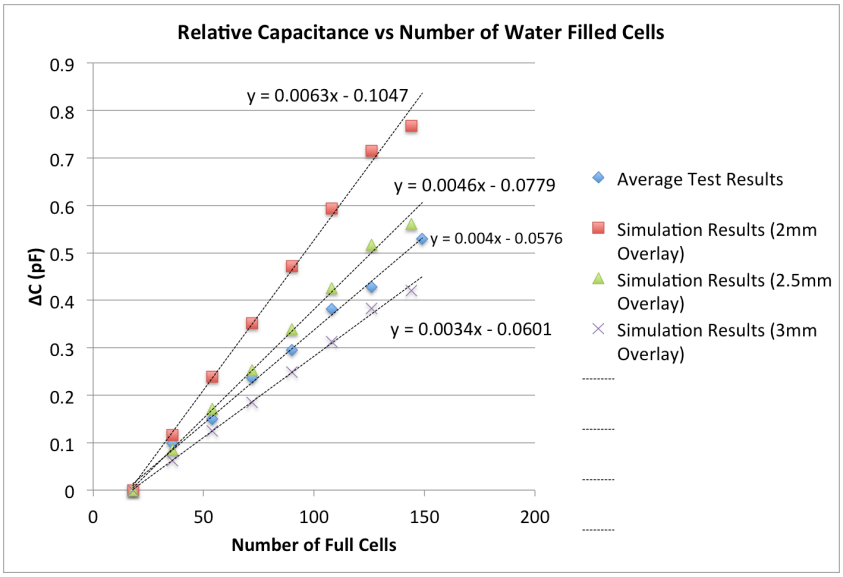


Figure 4.8 Simulation results with varying overlay thicknesses compared to the average of the test results

The difference between honey and water was also simulated to observe the difference in the capacitance measured and the results are shown in Figure 4.9. The slopes for water and honey were 0.0087 pF/cell and 0.0072 pF/cell respectively and therefore the water caused about a 21% larger increase in the capacitance than the honey, which was expected due to its higher

relative permittivity. However, the general behaviour is the same in both cases so water is a suitable liquid for the initial testing of the capacitance board.

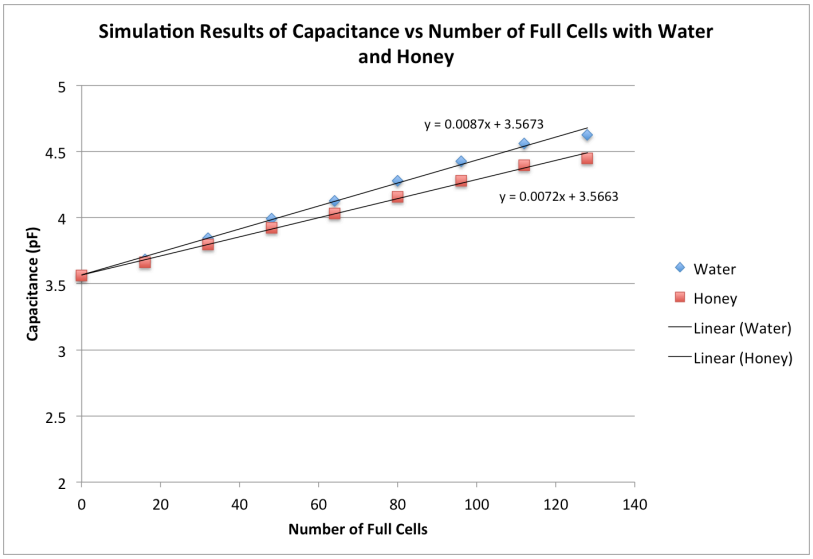


Figure 4.9 Comparison of simulation results for capacitance vs number of filled cells for water and honey

In summary, in all three test trials the capacitance increased linearly with the number of full cells and the slope varied between 0.0036 and 0.0046 pF/full cell across the trials. Therefore, the capacitor chip and copper tape electrodes were working as expected and the concept can be used to design a larger grid of capacitors to cover an entire hive frame.

4.3 Twelve-Region Capacitance Sensor Board Prototype and Lab Tests

4.3.1 Board Design

The previous prototype board was expanded to measure the liquid level in an entire hive frame. A 21x43 cm board was designed to fit inside a standard hive frame as shown in Figure 4.10. The board was divided into twelve 9x7 cm regions, one for each input on the capacitance keypad chip. All of the regions share a common ground electrode, but the terminal electrodes in each region are separate. The electrodes were wired to the capacitance chip in such a way that the wire lengths were minimized, however the wires have a large range in length, from about 7

cm to 57 cm, due to the fact that the wires must go around the outside of the board to avoid passing though other honey regions. Therefore, each region will have a different initial capacitance when the comb is empty due to the wiring causing a constant offset, but the overall change in capacitance should be fairly uniform across the regions. Once again the electrodes were made from copper tape placed on an acrylic board.

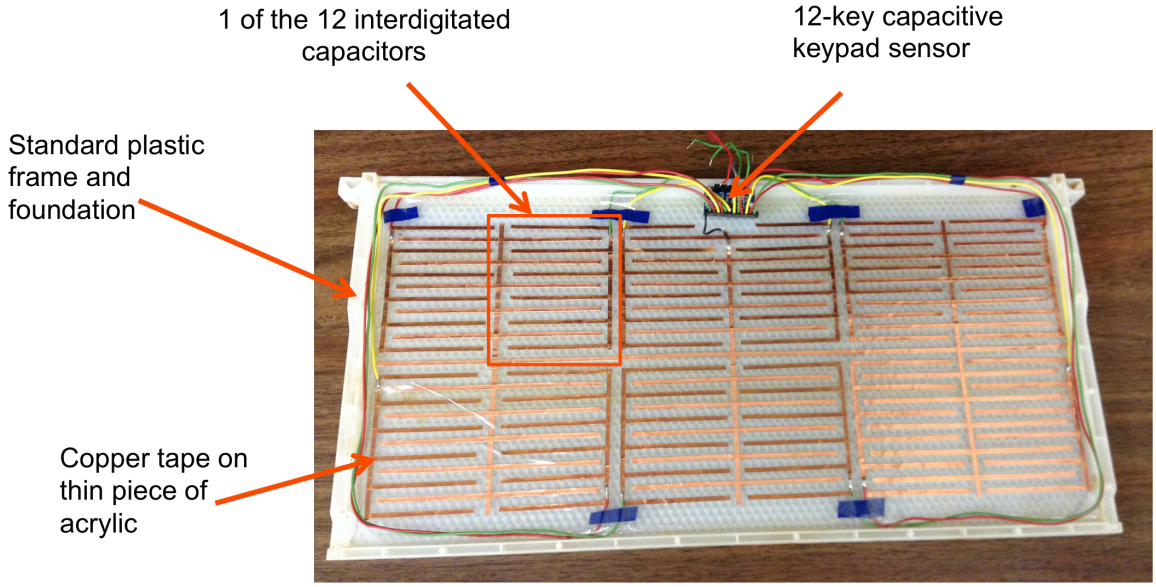


Figure 4.10 Twelve-region prototype board inside standard plastic hive frame

4.3.2 Purpose

The following lab tests were performed using the prototype board to determine:

a) How the capacitance changes with liquid height

b) How the measured capacitance compares to other regions

c) The differences in the measured capacitance between water and honey

d) How the capacitance changes with different sugar concentrations

4.3.3 Experimental Set-up

A thin plastic adhesive was placed over the board to prevent any liquid from coming in direct contact with the capacitors. During the following tests, the board was placed flat on a table

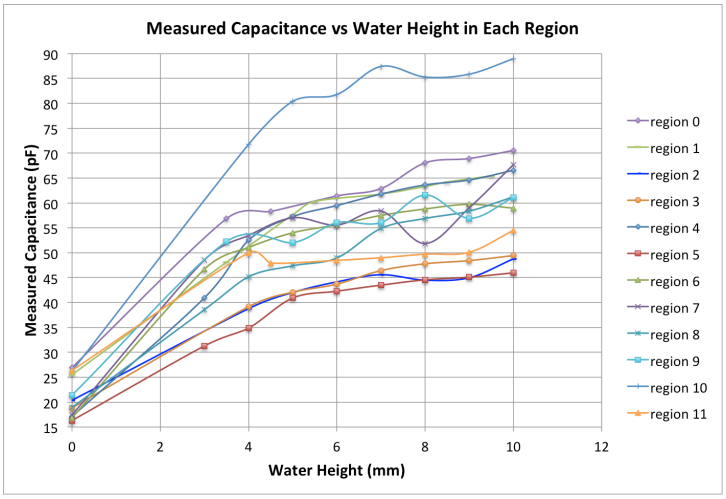
and cardboard walls were placed around the board with a plastic bag lining used to contain the liquid. So there was only a very thin layer between the capacitors and the liquid, similar to what will occur in the honey cells. No cell walls were used in these experiments, but as was previously discussed in Chapter 2, the cell walls are extremely thin and therefore do not occupy a large amount of the volume. The walls within a hive also remain constant so the capacitance due to the walls will not change with the increasing liquid level. Therefore, the addition of walls would probably reduce the change in capacitance by a small factor as the total liquid volume at each liquid height would be slightly reduced. However, this set up is acceptable for verifying the behaviour of the board.

4.3.4 Trial 1 (Varying Water Height) – Results and Discussion

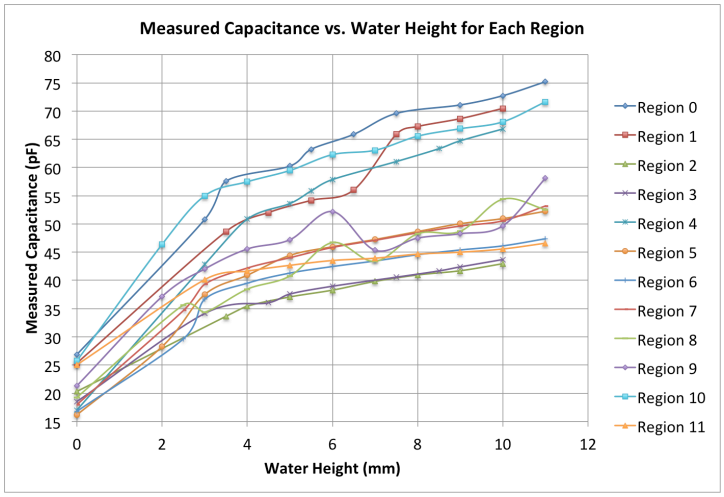
To test the behaviour of the capacitance sensor in each region the water height above the capacitor was increased from 0 to 1 cm. At each water level the capacitance was measured in each region every 3 seconds for about 2 minutes. Multiple readings were taken at each water height to observe the noise level, which was found to be less than 0.5 pF. The test was performed three times, each time increasing the water height from 0 to 1 cm. Due to the difference in wire lengths as previously discussed and other factors, the empty capacitance measured by each capacitor was different, therefore to compare the behaviour in each region the change in capacitance with water height was plotted. The results of the three tests are shown in Figure 4.11(a)-(c). It can be seen that the change in capacitance varies between the regions, with ranges of 28-63 pF, 21-49 pF, and 23-47 pF for each of the three tests. This could be due to the variations in the capacitors between the regions so they are not identical as well as any added capacitance from the different wires. The results show that while some of the regions exhibit the smooth increase in capacitance as expected, others tended to fluctuate up and down. However,

eight of the 12 regions had similar values for the change in the capacitance for all three tests and had fairly clean signals. Therefore, the capacitance sensor was working as expected in those regions. The other 4 regions had noisy signals, but because it was the same four regions in each test, the reason for the noise may have to do with the components. Some reasons for the noise may have been: the wires were not connected well to the electrodes or capacitance sensor, the copper tape joints on the electrode may not have been as solid as in the other regions, or the wires got bumped when water was added to the board, changing its constant offset slightly.

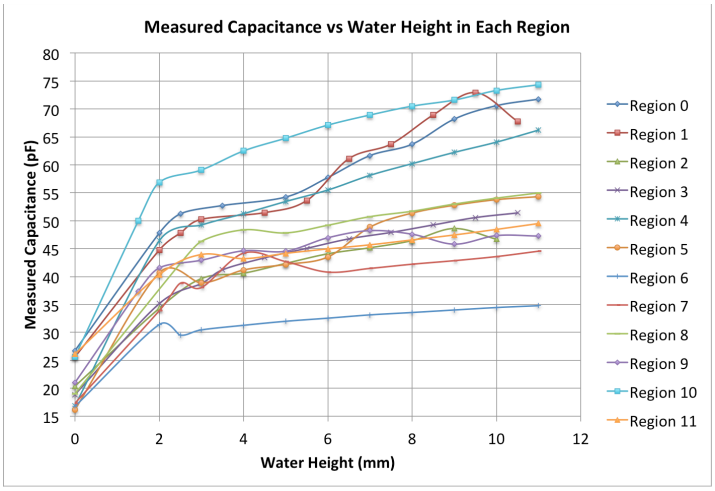
However, in all cases the general behaviour is that the overall capacitance increases with the water height above the board, and the sensors are more sensitive to changes in the first few millimetres of height. To remove any differences due to capacitance in the different wire lengths and the environment the normalized values, $\Delta C/\Delta C_{max}$, from test 2 (Figure 4.11(b)), were plotted in Figure 4.12 to observe the increase in capacitance at each height as a fraction of the overall capacitance change measured when each region is full. As seen in Figure 4.12 the majority of the curves are almost the same among the regions. However, in comparison to the simulation the capacitance values do not saturate as quickly with height. This may be due to some differences between the model and capacitance board because it appears as though the capacitance measured by the board is was increasing as the cells reach the top height, where as in the simulation the capacitance had started to level off. Therefore, the saturation height of the capacitance sensors built appears to be higher than it was in the simulation, which may be due to the added number of wires and overall size of the board.



(a)



(b)



(c)

Figure 4.11 Trial 1 capacitance measurements for 12-region prototype board with increasing water height for tests (a) 1, (b) 2, and (c) 3

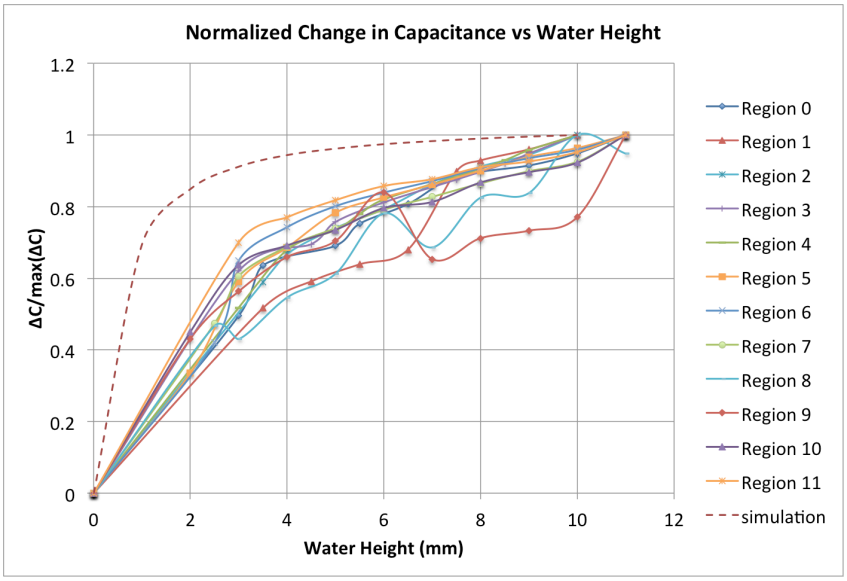


Figure 4.12 Normalized change in capacitance vs water height for all regions and simulation

4.3.5 Trial 2 (Varying Honey Height) – Results and Discussion

The second trial used honey instead of water to observe any differences in behaviour between the two liquids. The change in capacitance measured for different honey levels are shown in Figure 4.13. It can be seen that the readings seemed to fluctuate less than the water trials, but three of the same regions did. The change in capacitance measured with 1 cm of honey had a smaller difference between the regions with a maximum difference of 5.24 pF between the regions, where as the tests with water experienced a larger range in the changes in capacitance measured with the average range of 29.77 pF between the regions over the three trials. As expected, due to the lower relative permittivity of the honey the maximum change in capacitance was only 9.68 pF where as the average maximum change in the water trials was 53.4 pF.

Once again the results were normalized to account for the different constant offset capacitances in each region and as shown in Figure 4.14, it can be seen that with the exception of regions, 0, 8, and 9 the normalized curves all converge to almost the same value indicating that the regions all experience the same increase factor with each honey level increase. A simulation

was performed using the same sized capacitor comb as those on the board and the dashed line in Figure 4.14 indicates the normalized result. Once again as was the case with water, the simulation saturated sooner than in the experiment indicating that in the experiment the electric fields penetrated deeper into the liquid. This may be due to slight difference in the model such as the relative permittivity of the honey used or small geometric differences, such as the thickness of the overlay, which allowed the electric field to penetrate deeper into the honey.

Therefore, due to the measurement differences between the capacitors in each region the system may not be able to determine the exact liquid height, but thresholds can be set to indicate minimum amounts of honey in the regions. For example, Figure 4.15 shows the normalized values at 3 mm, 6 mm, and 10 mm, and how threshold values can be set to indicate the honey level is either in the 0-3 mm, 3-6 mm, or 6-10 mm range. This may be sufficient for beekeepers to indicate when a frame is getting close to full and will need to be swapped out soon.

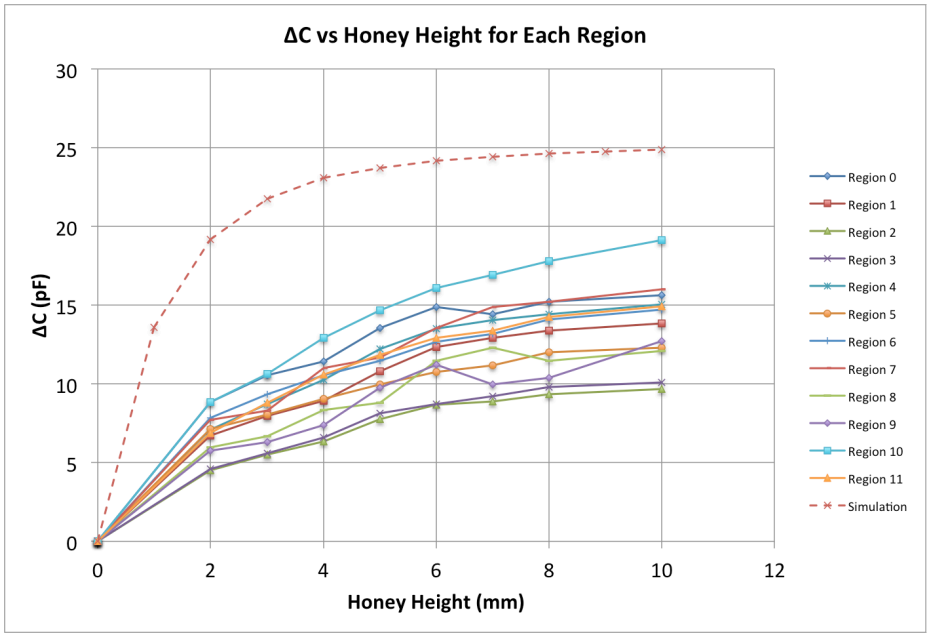


Figure 4.13 Trial 2 change in capacitance results for 12-region prototype board with increasing honey height

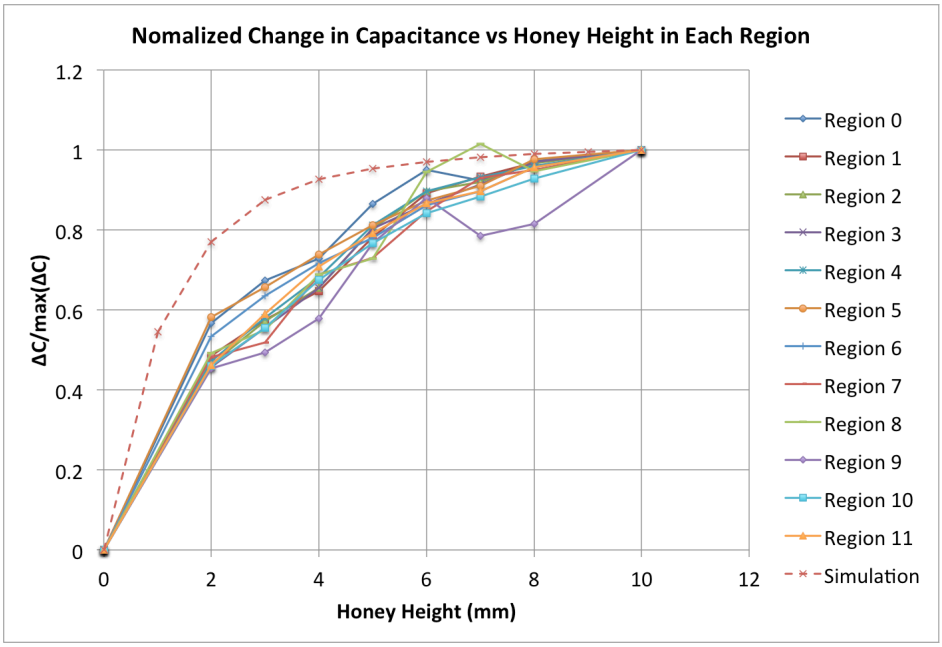


Figure 4.14 Normalized change in capacitance vs honey height measured in all regions and the simulation

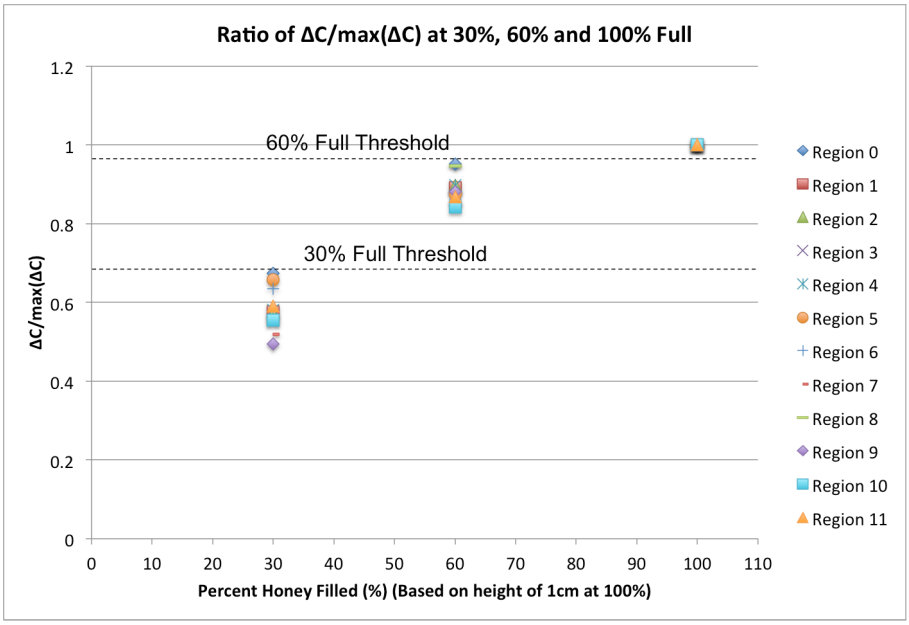


Figure 4.15 Normalized results at 30%, 60%, and 100% full of honey with threshold values indicated

4.3.6 Trial 3 (Varying Sugar Concentrations) – Results and Discussion

As previously discussed, it is advantageous for the beekeepers to empty their hives as soon as they are full and therefore the previous experiments focused on measuring the liquid height. However, as discussed in Section 4.1, the bees initially fill the cells with highly diluted

nectar that then remains in the cells for a few days as the water evaporates producing a high sugar-concentrated honey and therefore it may be even more advantageous if the system can detect not only when the cells are full, but when the honey has ripened. The following test was performed to observe how the capacitance changes with sugar concentration.

A single region of the twelve-region prototype board was used to measure the capacitance and a thin plastic container was placed on top to hold the liquid. Sugar-water solutions of 0%, 14.43%, 31.02%, and 44.04% by weight were created and tested, as well as pure honey, which has a sugar concentration around 82% [47]. The solution was then added to the container over the capacitor in 45 mL intervals, producing heights of 0, 3, 5.5, 8, 10.5, and 12.5 mm above the capacitor.

From the results shown in Figure 4.16 it can be seen that the capacitance measured decreased as the sugar concentration increased for the same liquid height. This behaviour is expected because the relative permittivity of water is 80.1 while the relative permittivity of honey is only 24, therefore as more sugar is added to water the relative permittivity decreases. This is consistent with the findings found by Angkawisittpan and Manasri in [11], in which it was found that the relative permittivity of sugar solutions decreased as the sugar content increased.

It can also be seen that the difference in the capacitance between the different solutions increases as the height increases. This is most likely due to the fact that the liquid height is less than the saturation height of the sensor and therefore as previously discussed the relative permittivity of the entire region depends partly on that of air and partly of that of the liquid. Therefore, at the lower liquid levels the majority of the electric fields are passing through air and only a few pass through the different liquids, but as the liquid height increases more and more

fields pass through the liquid with a varying relative permittivity causing larger differences in the capacitance, until the saturation height is reached and all of the electric fields are passing through the liquid resulting in the largest differences in capacitance. This is similar to the observation that was made in [54] when the titanium dioxide layer was less than the saturation thickness, the dielectric constant in the region above the capacitor is partially determined by the remaining height of air.

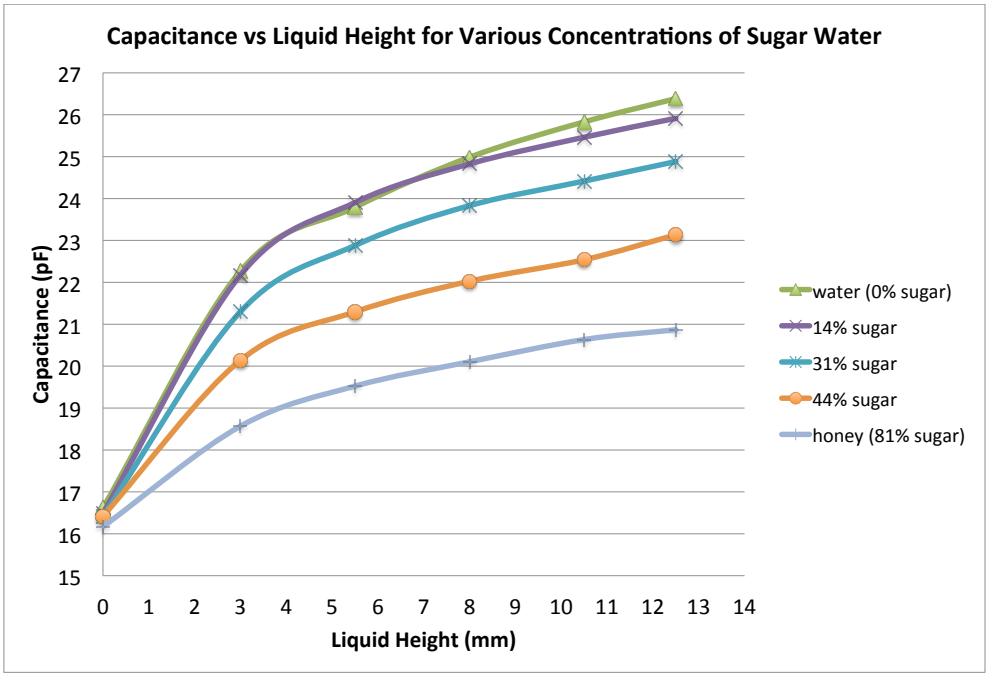


Figure 4.16 Trial 3 capacitance measurements vs liquid height for varying sugar concentrations

One important finding is that due to the large difference in capacitance for each of the different sugar concentrations it makes it difficult to determine the honey level from a single capacitance reading. An example of this is shown in Table 4.3, which shows the liquid level for each sugar concentration tested that gave the same change in capacitance as the full height of honey did. For example, a region that is only 22% full with a 31% sugar nectar will have the same capacitance as that of a full region of honey.

Table 4.3 Liquid Heights for Each Sugar Concentration Tested that Produce the Same Change in Capacitance as the Full Height of Honey

Sugar Concentration	Liquid Height (mm)	Percentage of cell capacity
Honey (~82%)	12.5	100%
44%	4.8	38%
31%	2.75	22%
14%	2.35	19%

Therefore, due to the changing relative permittivity and thus the changing capacitance at the same liquid level the capacitance will need to measured over time to better detect the contents of the cells. Over time a region may be filled with a 30% sugar nectar and therefore an increase in capacitance will occur due to the increasing honey height. Then over the next 2-5 days as the honey ripens the water will be evaporating increasing the sugar concentration until it reaches that of honey, and thus it is expected that the capacitance reading will decrease due to the decreasing relative permittivity. Therefore, if the system is recording the capacitance periodically over the ripening period there should be a large increase in capacitance as the low sugar concentration nectar is placed in the cells, then there should be a detectable capacitance drop as it ripens. Even at only half-full there is a 3.36 pF drop in capacitance as the solution goes from a 31% to 81% sugar. Then once the honey is ripe the cells are capped to prevent the honey from absorbing any moisture from the air, and therefore the capacitance in the area of full ripe cells should be higher than the empty comb capacitance and remain constant over time.

4.3.7 Conclusions

In conclusion, the twelve-region capacitance board worked as expected. Each region experienced an increase in capacitance as the liquid level increased, and as expected the change in capacitance decreased as the liquid level reached the saturation height of the capacitor. From the tests it was also found that while the capacitors resulted in similar capacitance readings they

did not behave perfectly uniformly. To reduce the difference between the regions the change in capacitance from the empty comb to the current state should be used, instead of the absolute value, to remove the constant offset capacitance caused by the arrangement of the wires and other external factors. However, even when only considering the change in capacitance there is still some variation among the regions, but if the results are normalized to the maximum change in capacitance measured in the region, the normalized curves from the regions are approximately the same. Due to the variations between the regions the sensor will not be able to determine the exact height of the liquid, but it is possible to set threshold values such as those to indicate when the cells above are empty or at least 30% or 60% full. It was also found that the overall behaviour is the same with water and honey, however due to the lower relative permittivity of honey it does not result in the same capacitance reading as the same volume of water. When comparing the results of measuring water height and honey height, the capacitance measured for honey was on average 81% of the capacitance measured for the same heights of water, and it was found that the capacitance is inversely related to the sugar concentration of the liquid due to the changing relative permittivity. Therefore, over time it is expected that the capacitance will increase as the bees fill the cells with low sugar concentration nectar and then decrease as the water evaporates and the honey ripens. Once the capacitance reaches the value for full cells of ripe honey, the system can indicate that the region is ready for harvest.

4.4 Design of PCB for In-Hive Experiments

The initial twelve-region board discussed in Section 4.3 was built using copper tape to verify the feasibility of the design, however a PCB is needed for placement within the hive. This will remove any human errors from the capacitors that were made and also provides the possibility to have copper pads of any size. The original prototype board was built using copper

tape with a width of 2.67 mm and spacing between electrodes of 5.33 mm. While this layout produced results that were usable as far as measurable changes in capacitance further research was done into determining the best capacitor sensor layout for the honey cell content monitoring.

4.4.1 Simulations

Further simulations were performed in COMSOL to test different capacitor sizes and geometries. A voltage of 3V was applied to match the MPR121 capacitance chip and a 0.4 mm acrylic plastic overlay was placed over the top of the electrode so that the liquid was not in direct contact with the electrode. The three different capacitor layouts shown in Figure 4.17 were tested with both water and honey ranging from 1 mm to 13 mm in height above the electrodes. The number of electrode fingers and dimensions were selected in the following tests such that the entire capacitor covers the same size region.

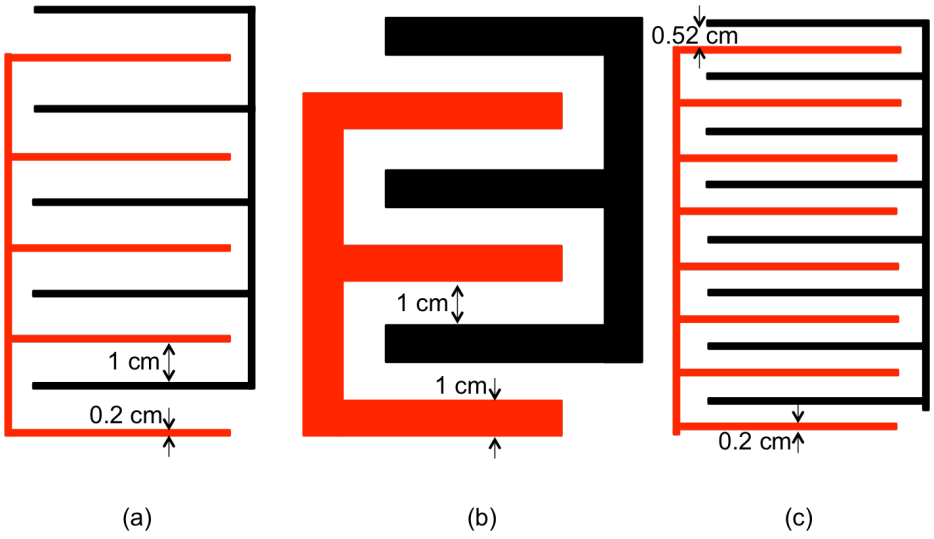


Figure 4.17 Three electrode geometries simulated to compare the effects of changing the electrode width and the gap width, (a) 0.2 cm width/1 cm gap, (b) 1 cm width/1 cm gap, (c) 0.2 cm width/0.52 cm gap

Figure 4.18 shows the simulation results for the capacitance of the three geometries shown in Figure 4.17. When comparing the results of the first two geometries to observe the

impact of the electrode width on the capacitance measurement, it was found that the electric field is stronger when the electrodes are wider resulting in a larger change in capacitance with the varying liquid levels, which could provide a higher resolution of the liquid height measurement. However, it can also be seen that the capacitance with the narrower electrodes is more saturated towards the top of the comb than with the wider electrodes and in the hive the electric field should not extend too far past the top of the comb or large amounts of noise may be added to the capacitance measurements from the bees moving around in that area. Therefore, selecting saturation height near the top of the comb will come at the expense of losing some resolution of the liquid height at the top of the cell.

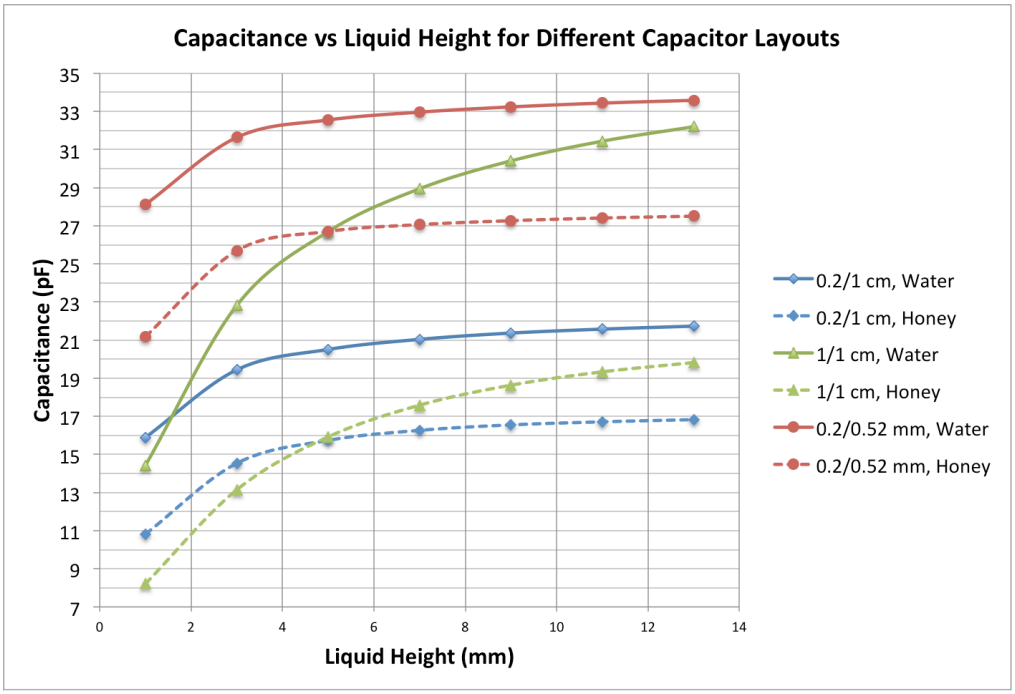


Figure 4.18 Simulation results of three different capacitor geometries to compare different gap and electrode widths

The comparison of the simulation results of the geometries in Figure 4.17(a) and (c) shows effects of changing the spacing between electrodes while the electrode width remains constant. From the simulation it was found that the electric field does not extend as far into the

liquid but as shown in Figure 4.18 the total capacitance measured was larger for the closer spaced electrodes. This was expected because there is a stronger electric field closer to the electrodes and there is less fringing due to the smaller gap. Therefore, the water height resolution will be higher at the lower water heights but slightly lower at the higher water levels as the capacitance saturates at a lower height. Therefore, the electrodes that are closer together measure a higher capacitance for the same liquid level, but both the 1 cm and 5.2 mm spaced electrodes are close to saturating at the top of the comb with the further-spaced electrodes having a slightly larger change over the last few millimeters of water height.

The calculated changes in capacitance from the simulation are summarized in Table 4.4 where it can be seen that the 2 mm wide and 1 cm spaced electrodes experienced a change of 0.28 pF over the last third of honey height and the 2 mm wide and 5.2 mm spaced electrodes experienced a 0.24 pF increase over the last third of honey. Therefore, it was found that there was not much difference between the different spacing for the same width electrodes, but changing the width of the electrode caused a more significant change. For the two simulations when the electrodes were spaced 1 cm apart, the 1 cm wide electrodes experienced a 1.19 pF increase over the final third with honey, where as the 2 mm wide electrodes only experienced a 0.28 pF increase over the final third of honey, which is only 23.5% of the 1 cm wide case.

Table 4.4 Simulated Change in Capacitance Over the Total, First Third, and Final Third of Liquid Height for Three Different Capacitor Geometries with Water and Honey

	0.2 cm Width, 1 cm Gap		**1 cm Width, 1 cm Gap**		**0.2 cm Width, 0.52 mm Gap**	
	Water	Honey	Water	Honey	Water	Honey
ΔC 1mm-13mm	5.84	6.01	17.77	11.62	5.47	6.32
ΔC 1mm-5mm	4.62	4.92	12.27	7.72	4.44	5.52
ΔC 9mm-13mm	0.36	0.28	1.79	1.19	0.35	0.24

4.4.2 PCB Design

Based on the simulations discussed previously a PCB was designed to have 3 mm electrodes with a 5 mm space between them in each of the 12 regions as shown in Figure 4.19. These dimensions were chosen to limit the electric field to be almost entirely inside the honeycomb while still providing a measurable difference in the final third of the liquid height. The 3 mm electrode is larger than the 2 mm electrodes simulated in Table 4.7 and therefore should provide a slightly stronger electric field resulting in a larger change in capacitance for all honey levels due to a higher saturation height. However, it is not too much larger that the saturation height will be significantly higher like it was in the 1 cm electrode case. The space between electrodes was chosen to be 5 mm because there was not a large difference between the 1 cm and 0.5 cm case in Table 4.7, and from the prototype board a spacing of 5.33 mm provided acceptable results and therefore a similar spacing was kept.

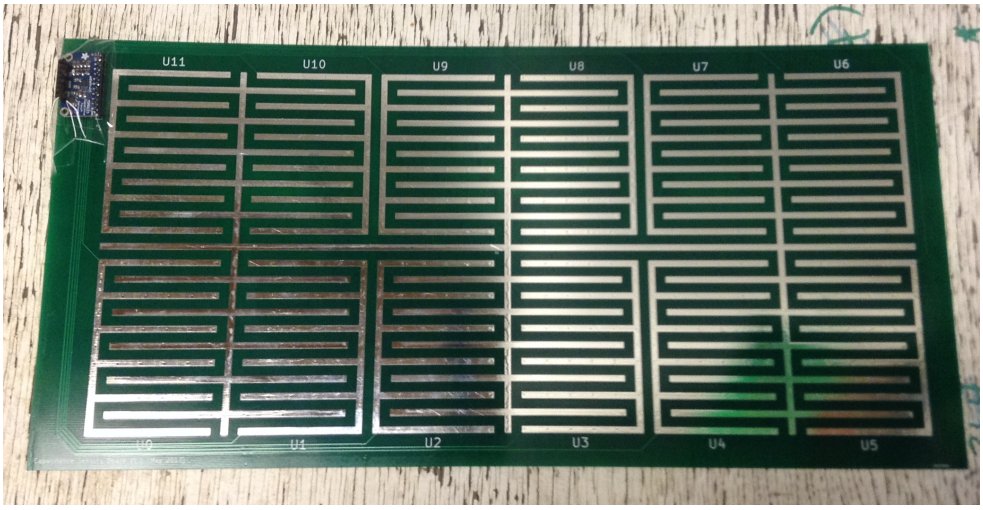


Figure 4.19 Twelve-Region PCB designed and built

The chosen dimensions were simulated for a single region with water and honey and the results are shown in Figure 4.20. The liquid level was increased higher than the comb height of

approximately 1.25 cm as indicated by the vertical dotted line, to a height of 4 cm to observe the approximate height the capacitor reached a saturation point. While the capacitor saturates at a height past the height of the comb, it cannot be selected much lower or resolution in the final third of the height will be lost. As shown in Table 4.8 there is only a 0.267 pF increase in capacitance from a 70% full cell to completely full cell of honey. Therefore, there may be some noise in the capacitance signal caused by the bees walking around on top of the combs but the change in capacitance due to the bees at heights above the top of the comb is relatively small compared to the capacitance change due to the changing liquid height within the cells.

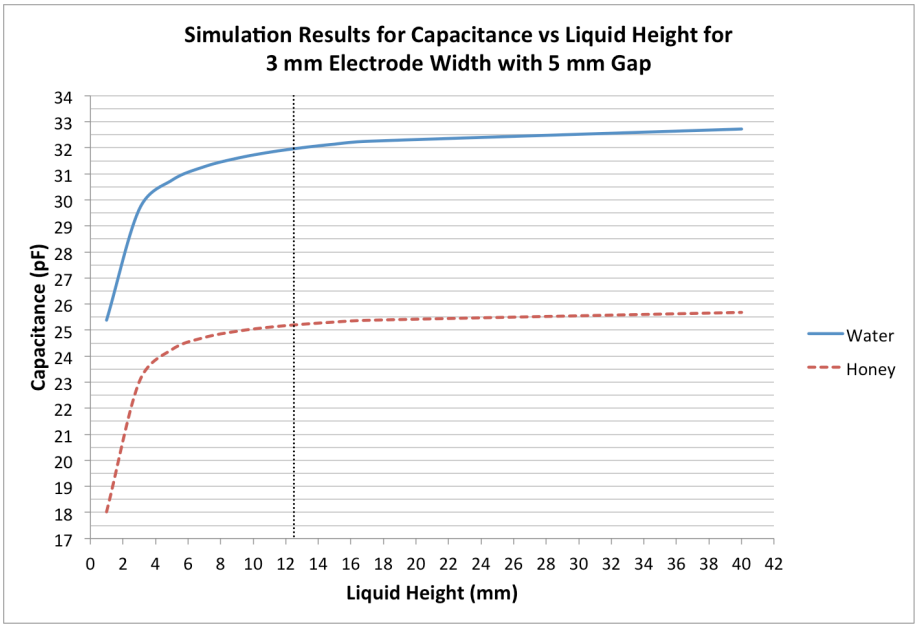


Figure 4.20 Simulation results for capacitor geometry selected for PCB

Table 4.5 Simulated Change in Capacitance Over the Total Cell Height, First Third, and Last Third for Selected PCB Geometry

	ΔC (1 mm – 13 mm)	**ΔC (1 mm – 5 mm)**	**ΔC (9 mm – 13 mm)**
Water	6.62 pF	5.37 pF	0.405 pF
Honey	7.20 pF	6.23 pF	0.267 pF

Once again, the decrease in capacitance due to the ripening of the honey will be larger than the increase due to the increasing height, especially at the higher honey levels. There is an average difference of 6.58 pF between the capacitance readings for water and honey from 3 mm to 9 mm. Therefore, initially there should be an increase in capacitance similar to the water curve as the cells are filled with low sugar concentrated nectar, then as the water evaporates the capacitance will drop by about 6 pF depending on the initial concentration and nectar height and then remain constant once the cells have been capped. Therefore, as previously discussed the capacitance will need to be measured over time to determine when the honey is ready for harvest.

The saturation height of the selected capacitor dimensions was estimated from the simulation. It was found that the capacitance saturated around 3.1 cm and was at 97% of the maximum capacitance when the water was at the top of the cell with a height of 1.1 cm and therefore the lower saturation height will reduce the noise from sources outside of the comb while still providing a high enough resolution at the top of the comb.

The PCB was designed with the same capacitor on both sides of the board connected with many vias through the board, because in the hive the board will be in the centre of the frame with a comb on either side. Therefore, the capacitance measured by each region will include the cell contents on both sides of the board and so it will detect changes twice as large as the simulations and the initial lab tests found. Having the capacitor on both sides reduces the error in reading the honey level on the other side of the board caused by the added distance through the thickness of the PCB, because as seen in all of the tests so far, the largest change in capacitance occurs within the first few millimeters of distance. The thickness of the PBC was selected to be 0.6 mm to minimize the distance between the two sides of the board. This also resulted in a board with a bit

of flexibility similar to the sheets of foundation that are usually inserted into the hive frames. The regions are numbered according to the input pin they are connected to on the capacitance chip and the numbering is printed on the board as seen in Figure 4.19. So region 0 is the bottom edge region below the chip and the regions are numbered consecutively counter clockwise around the board with the final region, region 11, being the top edge region adjacent to the capacitance chip.

4.5 In-Hive Experiment

Three of the PCBs designed and built in section 4.4 were placed in an existing hive for a field test as outlined in the following sections.

4.5.1 Preparation of PCB

Before placing the boards in the hive the electronics and wires needed to be covered and sealed to prevent the bees from placing wax and honey all over them. As was discussed in Chapter 2, generally a form of cell foundation is used in the hive frames to help the bees build uniform comb quickly, but bees will build natural comb if no foundation is provided. Therefore, the following options were considered:

1. Attach a piece of wax foundation to either side of the PCB
2. Put a layer of wax on the PCB and pass it through a roller press
3. Put a layer of wax on the PCB and allow the bees to build natural comb

The first option of attaching a piece of wax foundation to either side was considered, however the foundation sheets are two-sided and therefore there would be a gap between the board and base of the cell of a couple of millimeters. This is not ideal because from the simulations and lab tests discussed earlier in this chapter the first few millimeters is where the capacitance sensor is the most sensitive, and therefore a large amount of information may be lost. The section option, which would be the best for large-scale production, would be to cover the

boards in wax and roll them through the press. However, this option was not used because roller presses are not easily accessible due to the fact that almost all beekeepers buy foundation from suppliers and do not press their own. Further testing would also have to be done to ensure the PCB and press are not damaged in the process. Therefore, the final option of coating the boards in wax was selected to allow for the PCB to be placed in the hive quickly and natural comb built by the bees would be acceptable for the initial tests because it will still hold a similar amount of honey and larvae as the comb foundation.

The PCB was coated in wax by melting a brick of wax on a hot plate and then painting it on with a silicon brush. This produced a thin (~1-2 mm) and fairly even coating of wax on the board. There were some small variations in the thickness, however the bees move the wax around once they start building their comb, which may result in a thinner and more even comb base. The boards were then placed inside a wooden frame as show in Figure 4.21 and the capacitance sensor chip and wires were sealed using plastic tape and a plastic box to prevent the bees from directly contacting the chip and wires.

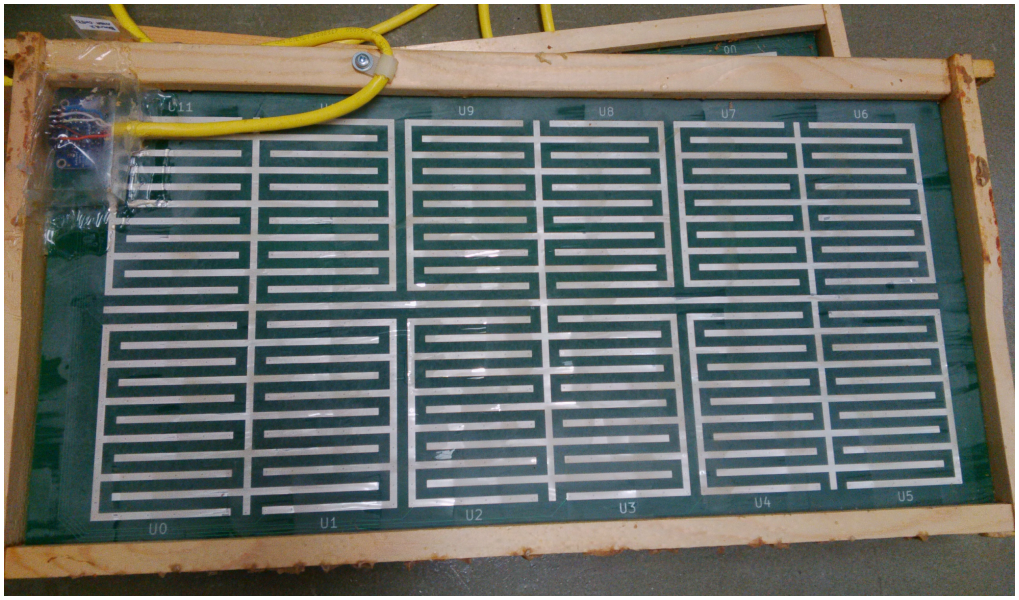


Figure 4.21 Wax coated PCB inside a wooden hive frame with a plastic box around the capacitor chip and wires

4.5.2 Hive System Set-up and Placement

Figure 4.22 shows the overall system set up and Figure 4.23 shows the placement of the sensor boards within the hive boxes, where it can be seen that the hive frames are inserted perpendicular to the hive entrance.

Figure 4.22 Field test set-up

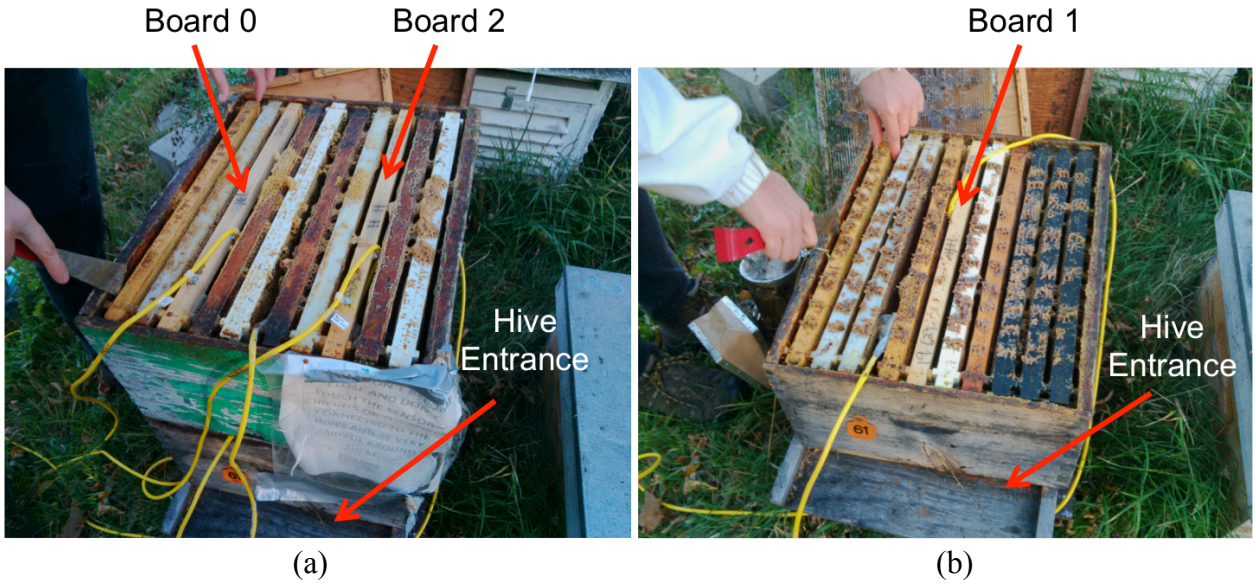


Figure 4.23 Board placement in (a) honey super and (b) brood box for field test

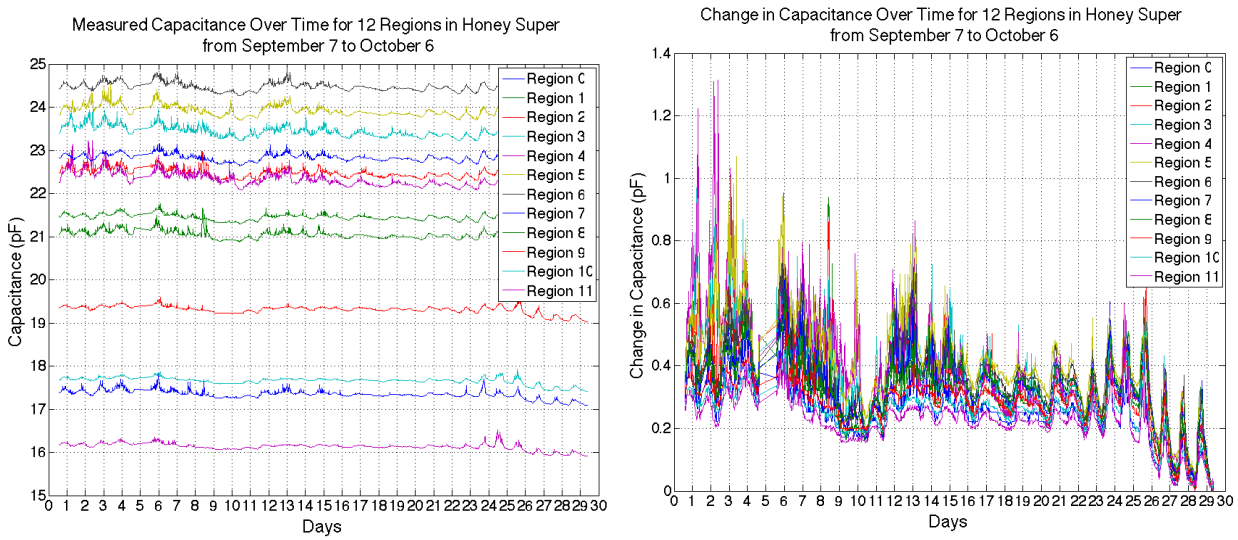
One capacitance sensor frame was placed in the bottom brood box and two capacitance sensor board frames were placed in the honey super directly above. For the current experiment each of the capacitance sensor chips were set to have a unique address so they could connect to a single Arduino and share the I2C lines. In future systems a multiplexor will need to be used so that all frames will be set to the same address allowing frames to be easily swapped or replaced. An Arduino data logger shield with an SD card slot and real-time clock is used for storing the data. The Arduino was programmed to record the capacitance of each of the twelve regions on each of the three boards every 30 minutes. The Arduino was placed inside a plastic container on the ground outside the hive and a USB power bank was used to power the system. The MPR121 capacitance chip on each of the boards has five I/O pins (SDA, SCL, power, ground, and an address line for setting the chip's I2C address) that were connected to the Arduino via an 8-wire Ethernet cable. The Ethernet cable was chosen because the wires are sealed so it can be left outside. It should also be noted that the analog-to-digital conversion of the capacitance measurements is performed by the MPR121 capacitance sensor, therefore it is a digital signal that is sent to the Arduino.

4.5.3 Results and Discussion

The results from boards 0 and 2, both placed in the honey super, are shown in Figures 4.24 and 4.25 respectively. The gap in data that occurred around day 5 is due to a loss in power from not replacing the battery, and therefore can be ignored. From the plots of the absolute capacitance it can be seen that while each of the regions behaved similarly, each had a different offset capacitance. It is also interesting to note that the offset capacitance of each region relative to the other regions on the board is almost the same for both boards. Therefore, the offset capacitance of each region is probably due to the geometry of the board itself and the placement

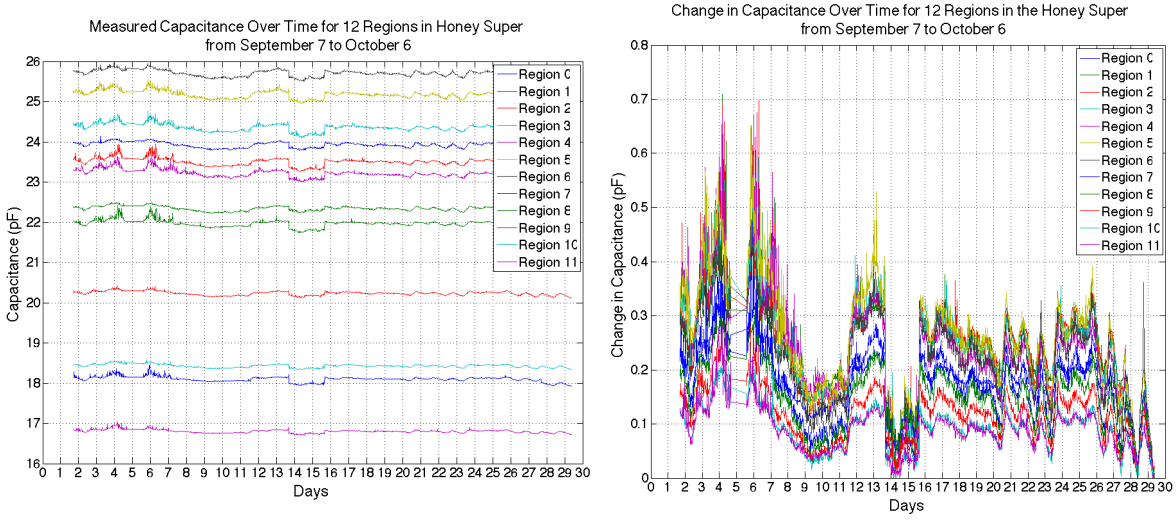
of the wires. In both cases regions 6 and 5 recorded the highest offset capacitances, which are the regions furthest from the capacitance chip and therefore required the longest wires. Similarly, region 11, which is directly beside the capacitance chip, recorded the lowest offset capacitance. Therefore, the wiring on the board and possibly placement within the frame adds different constant offset capacitances within an approximately 8.5 pF range to each of the regions. However, this value is approximately constant for each region from board to board because each region in board 2 experienced approximately a 1 pF higher constant offset than the corresponding region on board 0, indicating that the offset is most likely due to properties of the board.

Therefore, to eliminate the constant offset in each region the relative capacitance based on the minimum value measured was plotted as shown in Figures 4.24(b) and 4.25(b). From these plots it can be observed that the capacitance did not change very much over the course of 22 days. In both cases the change in capacitance remained under 1 pF indicating that the bees were not producing honey because changes in the 10-20 pF or higher range are expected from the lab tests when the comb goes from empty to full of honey. Upon inspection of the hive and frames it was found that the bees had not built comb or produced honey as seen in Figure 4.26 which shows the removal of one of the frames after about a month. Therefore, the system worked correctly in the honey super by indicating that there was no honey being produced. One reason that no honey was produced is that the sensors were placed in the hive at the beginning of September when the honey flow is finished for the year and bees are generally not producing honey.



(a) (b)

Figure 4.24 The (a) absolute and (b) change in capacitance measured over 29 days by board 0 located in the honey super



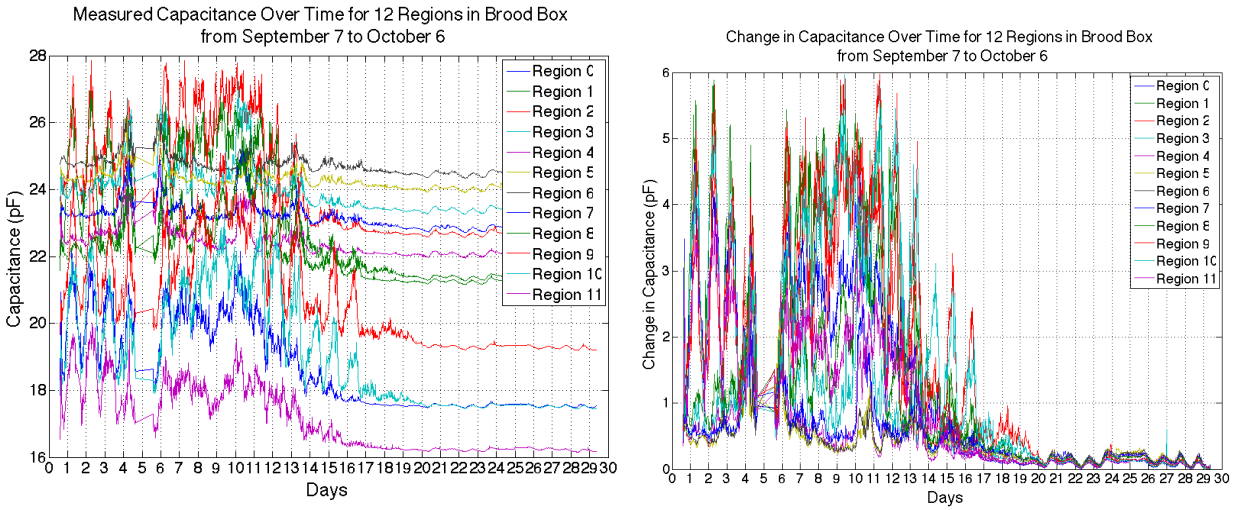
(a) (b)

Figure 4.25 The (a) absolute and (b) change in capacitance measured over 29 days by board 2 located in the honey super

Figure 4.26 Capacitance board being removed after 29 days inside the hive

While the capacitance in the honey super did not change very much over the month the boards were in the hive, the results from the board in the brood nest shown in Figure 4.27 show a significant change. It can be noted that the relative offset capacitances of each region, as more easily observed from days 21-29, were almost the same as those from the honey supers for the same regions. Therefore, this supports the fact that the offset capacitance in each region probably comes from the board itself. From the plot in Figure 4.27(b) it can be observed that for the first 16 days the capacitance fluctuates throughout the day, peaking in the morning and decreasing at night and the change in capacitance measured was around 5 pF, much higher than in the honey supers. The reason for this is most likely that the majority of the bees were located within the brood nest and were more active here than in the honey super. Even though they did not build comb on this frame, their presence walking around on the frame created an increase in the capacitance by changing the relative permittivity beside the capacitors to a value higher than that of air. In Figure 4.28 it can be seen that the regions near the back of the brood nest away from

the hive entrance experienced the largest changes in capacitance which could indicate that that was where the colony was mostly clustering together when in the hive.



(a) (b)

Figure 4.27 The (a) absolute and (b) change in capacitance measured over 29 days by board 1 located in the brood box

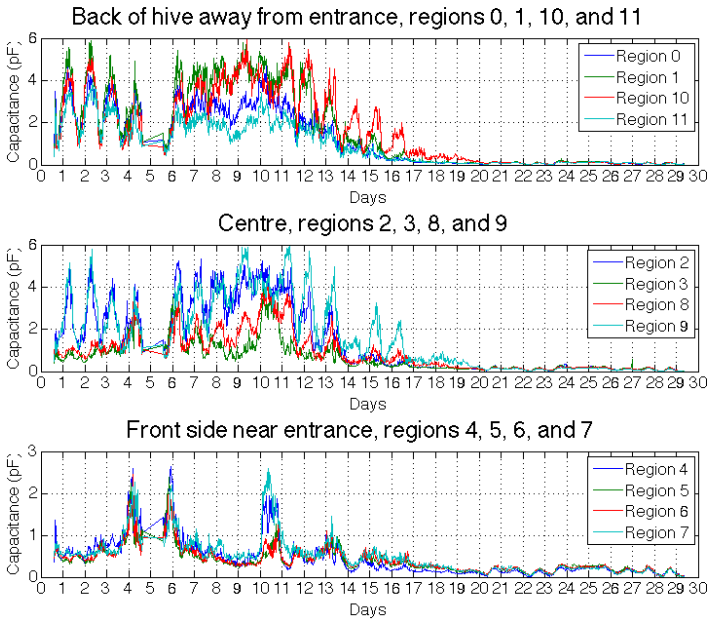


Figure 4.28 Change in capacitance measured at the backside, centre, and front regions of the hive frame in the brood box

One interesting observation of note is that from about days 13-17 the change in capacitance decreases from about 5 pF until it is less than 1 pF and remains less than 0.5 pF after day 20. Upon inspection of the hive on day 29 it was found that the colony had collapsed due to *Varroa* mites and only a few hundred of the original thousands of bees remained in the hive with the queen. It was not known when the colony collapsed, but the capacitance sensor within the brood nest may have recorded it if it occurred around days 13-17.

Therefore, because the bees did not build comb on the sensor board, most likely due to the time of the year and health of the colony, the capacitance sensor was instead measuring the bee activity and location within the brood box as the bees walked directly on the sensor. If the sensor did in fact detect the collapse of the colony, it occurred very fast, within a few days, and therefore this sensor would be useful for a beekeeper to detect the first signs of a collapse and either intervene to save the colony or take precautions to protect or treat the other colonies in the area. It should be noted that if the bees did build comb on the frame the sensor may not be as sensitive to the bee activity because the bees will not be walking as close to the capacitance sensor, however it should still detect some change and other changes may occur as well, such as no increase or change to the brood in the cells as the bees are unable to feed them or provide the required environment for their growth.

4.5.4 Further In-hive Experiment Results and Discussion

In order to test if the board in the brood box was in fact measuring bee activity, the three boards were placed back inside the hive in the brood box as shown in Figure 4.29 and the honey supers were removed. Boards 1 and 2 were placed on either side of the two frames with brood comb in the centre of the box and board 3 was placed as the outside frame where the bees store honey. A bee feeder was also placed in the hive due to the lack of nectar in the area.

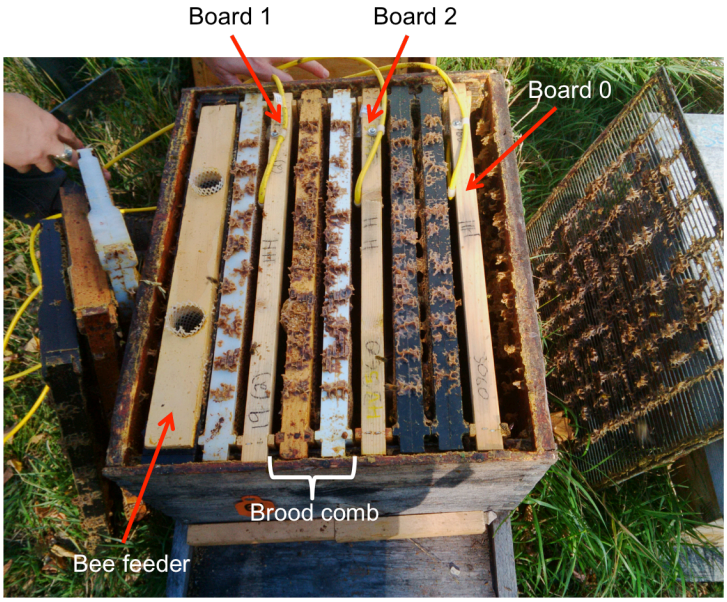


Figure 4.29 Sensor board placement within brood box for second hive experiment

More bees were added to the colony and the recorded results are shown in Figures 4.30-4.32. Once again, there was a day when the battery was not changed before it ran out of power, so the gap in data around day 33 should be ignored. As seen in Figure 4.30, there is some bee activity for the first three days as indicated by some regions experiencing a capacitance change in the 1-4 pF range, however the rest of the days experience a very small capacitance change, less than 0.5 pF. The fact that there was little bee activity could be expected because this frame was placed as the outside frame, and if the colony is very small and the outside temperature is getting cooler then the bees are most likely clustering together near the brood cells and not building comb or producing honey. Similarly, as shown in Figure 4.31, board 0 placed on the other side of the hive box experienced a change in capacitance in the 1-5 pF range for the first day, but the rest of the days experienced changes less than 0.5 pF. Once again this frame was closer to the outside of the hive box and although it is beside some brood comb frames it is closer to the outside than board 2 and therefore the bees may not have clustered in this area. As seen in Figure 4.32, board 2 located beside the brood combs in the centre of the box experienced

changes in capacitance in the 1-6 pF range for all of the days. It is also interesting to note that regions 5 and 6 on this board, which are located at the front by the hive entrance experienced the smallest change in capacitance compared to the other regions, which is expected as the bees probably clustered closer to the centre of the hive. The results from this board are consistent with the measurements taken previously in the brood box as was shown in Figure 4.27(b) before the colony had collapsed. Therefore, with the addition of more bees to the collapsed colony, the capacitance sensor measured a similar change in capacitance and followed the same daily pattern with the largest increase in the morning as it did before the colony collapsed and therefore, the capacitance sensor was most likely measuring the bee activity as the bees moved around the hive. The placement of the three sensor frames in the brood box also allowed for the location of the bees to be determined and it was found that the most activity was occurring in the centre of the brood box as expected.

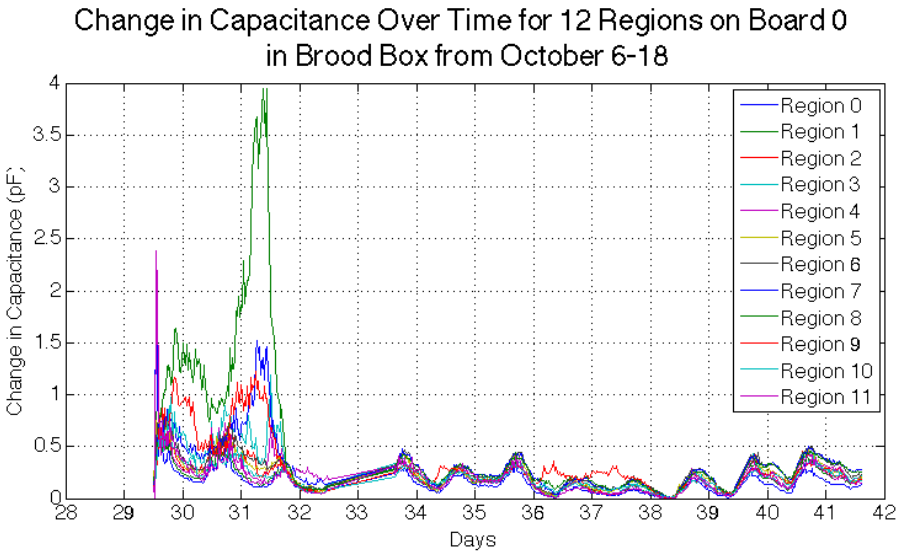


Figure 4.30 The change in capacitance measured from October 6-18 by board 0, the frame at the edge of the box

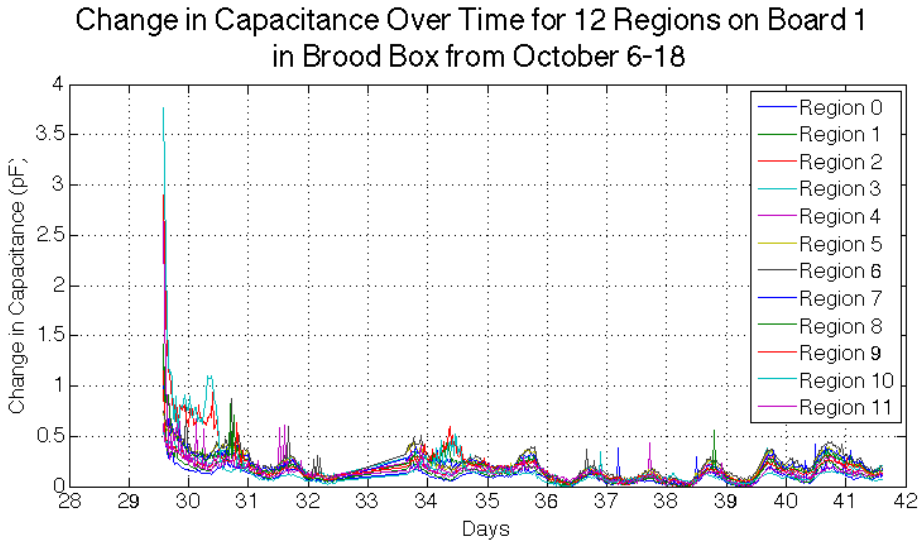


Figure 4.31 The change in capacitance measured from October 6-18 by board 1, the frame closest to the feeder side of the box

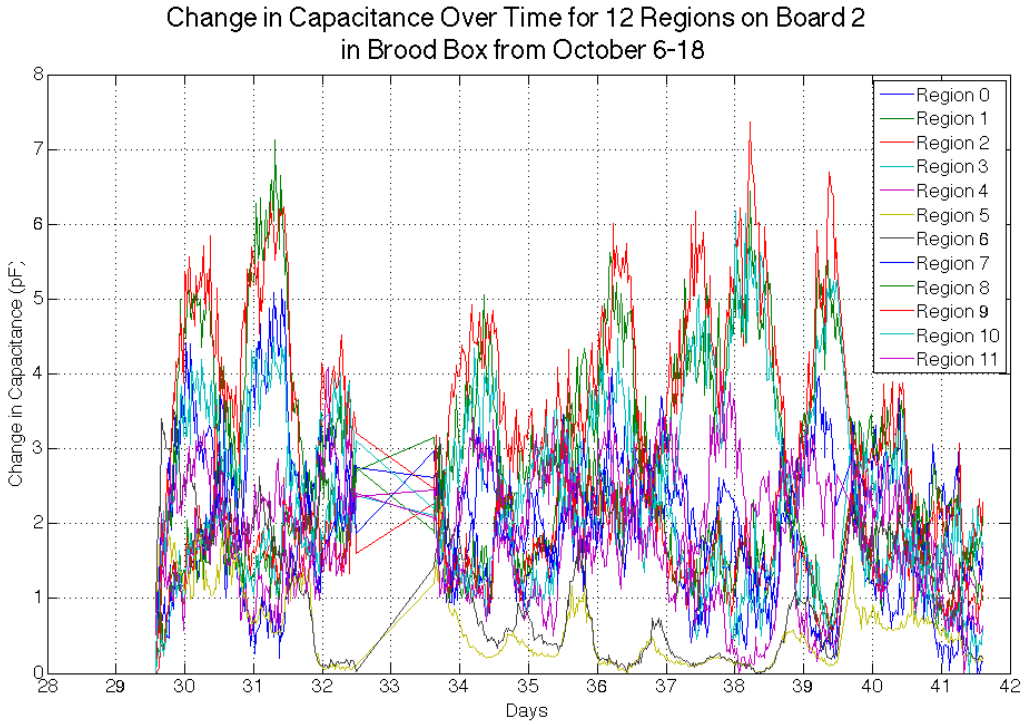


Figure 4.32 The change in capacitance measured from October 6-18 by board 2, the frame close to the centre of the box beside the brood comb

4.5.5 Conclusions

Some preliminary conclusions may be drawn from the in-hive experiments performed. It was found that there was a difference in the capacitance measurements between the honey super and the brood nest. In the honey super the capacitance remained almost constant indicating that there was not a lot of bee activity and probably just a small number of bees evenly distributed among the regions. In the brood nest there were larger changes in capacitance measured, around 5 pF, throughout the day indicating there were more bees and bee activity throughout the day. The capacitance tended to fluctuate in daily cycles with the highest capacitance being measured in the morning and different regions had larger changes than others, which could indicate the location of the bees and where they are clustering within the hive.

Because the sensors were placed in the hive in the fall after the honey flow, the bees did not build a comb or produce honey on top of the board. Therefore, the bees were walking directly on the sensor board causing the capacitors to measure the bee activity and location more significantly than it may if there is comb and the bees are approximately 1 cm away on top of the comb. However, this test does verify that the sensors were working as expected because the capacitance increased as the bees walked on top of the sensors increasing the relative permittivity of the area beside the comb to a value higher than that of air.

The sensor in the brood box was most likely measuring hive activity and able to detect a colony collapse due to *Varroa* mites. After being placed in the hive and measuring data for about two weeks there was a sudden decrease in the capacitance measurements over the course of a few days followed by very small capacitance measurements. Upon inspection of the hive the brood cells were filled with mites and only a few hundred of the original thousands of bees remained. The sensor boards were then placed back inside the brood box and more bees were

introduced to the colony resulting in capacitance measurements similar to what they were before the colony collapsed. According to the measurements the colony collapsed over about four days, and therefore by using this system a beekeeper could detect the first signs of a collapse and take the appropriate measures to minimize the damage to the affected colony and others in the area.

Another conclusion that can be drawn from the in-hive tests is that the designed capacitance sensor PCB was capable of being placed in a standard hive frame in an existing hive and withstand the hive environment and record data for over a month. The board appeared to be in the same condition as it was when placed in the hive and the wax placed over the capacitance sensors seemed to have sealed the electrodes well. The wiring and the board itself introduces a different offset capacitance to each of the regions and it is approximately the same on each board and therefore the change in capacitance should be observed instead of the absolute capacitance.

4.6 Chapter Summary

In summary, from initial simulations it was discovered that a detectable change in capacitance (picofarad range) across an IDC occurred when the water or honey level changed, the IDC is more sensitive when change occur closer to the capacitor, honey causes a smaller change in capacitance than water due to its lower relative permittivity, the measured capacitance should increase approximately linearly with the number of full cells, and the wider and closer spaced the IDC electrode fingers are the more sensitive the sensor is to changes in the cell contents. A small prototype board built using copper tape and the MPR121 capacitance sensor chip was selected to measure the capacitance across the IDC using an Arduino. The board was tested by placing various amounts of water in a 3D printed comb above the IDC. It was found that the capacitance increased linearly with the number of full cells in each of the three trials,

which was consistent with the simulation results. The three trials produced similar results with a linear increase of 0.00407 pF/full water cell. Therefore, the capacitor chip and copper tape electrodes worked as expected and the concept was used to build a full-size 12-region prototype board to fit in a hive frame.

Once again copper tape was used to build the electrodes in each of the twelve regions on a full-sized prototype board and the MPR121 and Arduino was used to measure the capacitance across each of the IDCs. Three tests were performed: varying water height, varying honey height, and varying sugar concentration. In all three tests the board worked as expected and the capacitance increased with liquid height and the sensor was more sensitive to changes in height at the lower levels than when the comb was getting close to full. As expected when testing with honey a smaller change in capacitance was recorded than with water due to its lower relative permittivity. It was found that plotting the normalized change in capacitance produced a more uniform result among the twelve regions and removed the constant offset capacitance caused by the arrangement of the wires and other external factors. From the results it was found that the system may not be able to determine the exact liquid height, but thresholds can be set to indicate the honey height within a range in a region, such as 0-3 mm, 3-6 mm, or 6-10 mm of honey, which may be sufficient for a beekeeper to plan their hive maintenance. A third test was performed with different concentrations of sugar-water where it was found that for the same height of liquid the capacitance decreased with an increase in sugar concentration, which is consistent to what was found in [11]. It was found that there is a detectable difference in the capacitance between the different sugar concentrations and the difference increases with liquid height. There is a drop in capacitance of about 16% from a cell full of 30% nectar to one full of honey. Therefore, due to this large change in capacitance it will be difficult to determine the

honey level from a single reading and instead the capacitance will need to be measured over time. Over time there should be an increase in capacitance due to increasing nectar heights, followed by a decrease in capacitance due to the honey ripening and sugar concentration increasing, and once the honey has ripened to about 82% sugar the cells are capped and the capacitance should not change.

Further simulations were then performed to determine the effects different IDC geometries had on the measured value, specifically the electrode and gap widths, to determine the electrode geometries for a PCB. It was found that with the same gap width, wider electrode fingers produced a stronger electric field within the comb which was more sensitive to the changes in liquid height, but was also less saturated at the top of the comb indicating that the electric field extends further past the top of the comb which would allow for external factors, such as neighbouring combs or bee movement to affect the measurement. When simulating geometries with the same electrode width and different spacing it was found that the closer spaced electrodes measured a higher capacitance value because there was a stronger electric field closer to the electrodes but had a lower resolution at the higher liquid levels because there is less electric field fringing due to the closer spacing. Overall, it was found that the electrode width had a larger impact on the capacitance than the electrode spacing and therefore the PCB was designed to have electrode widths of 3 mm spaced 5 mm apart. These dimensions were chosen to limit the electric field to be almost entirely within the comb while still providing a measurable change in capacitance in the final third of liquid height.

Three PCBs were built, coated in wax, inserted into a standard wooden hive frame, and placed into an existing beehive. The boards were able to successfully record data every half hour and withstand the hive environment for over a month. Because the sensors were placed in the

hive in the fall after the honey flow, the bees did not build a comb on the boards. Therefore, the boards did not measure the cell contents, but instead measured the bee activity as the bees walked directly on the sensors. It was found that as expected for this time of the year there was very little activity in the honey super. The sensor in the brood box recorded more bee activity and indicated in which regions of the frame more bees were clustering. After a period of two weeks the measured bee activity decreased quickly over a few days until the there was very little bee activity. Upon inspection of the colony, it was found that the colony had collapsed due to *Varroa* mites, and that is most likely what the sensor had detected. It was found that the colony collapsed quickly over about 4 days and therefore the sensor would be useful for beekeepers to detect early signs of colony collapse and take action to minimize the damage to the colony and others in the area. More bees were added to the colony and all three sensor boards were placed in the brood box. It was found that the board in the centre of the box measured the same bee activity that the board in the brood box did in the initial experiment before the colony collapsed and therefore it was most likely measuring bee activity. In the second test there was very little bee activity recorded by the other two boards, which were placed near the edge of the box. This was expected because the bees are not producing and storing honey and the temperature is getting cooler so they are clustering together near the brood comb, which was in the centre of the hive. Therefore, by placing the three sensor boards in the brood box the system was able to detect the location of the cluster of the bees within the box.

Chapter 5 – Conclusions and Future Work

A summary of the conclusions from the simulations, lab tests, and field trials discussed in the previous chapters is provided in section 5.1 and future work that could be performed to expand on these results is discussed in section 5.2.

5.1 Conclusions

The first part of the system discussed in this thesis was the design of a PCB for use in the brood box of a beehive to:

1. Measure the local temperature to within each area of a hive frame for use in monitoring colony health
2. Selectively heat small local areas of cells for *Varroa* mite control

Simulations were first performed to determine how heat flows from the board and within the honey cells. The PCB was designed such that the temperature sensors and heaters are all on one side of the board and the other side is flat to allow for the hive comb to be directly built on it. From the simulations it was found that a copper heat pipe was a better conductor than the PCB alone and was needed to provide a constant temperature through the board from one side to the other. This allowed for both the temperature to be measured and heat to be transferred more effectively from the backside of the board. From the simulations it was found that a temperature sensor is not required in each cell because a change in temperature within a cell can be detected up to two cells away. However, the magnitude of the temperature change may not be measurable as it decreases with distance from the heat source, but the detection of a change in temperature may provide insight into the colony health as the bees are known to regulate the temperature within the brood nest to remain around 35°C. From the simulations it was also found that a heat

source with a power level of 600 mW was capable of heating all cells within a local area of a 2.5 cell radius to temperatures over 39°C within 10 minutes, which is hot enough kill *Varroa* mites. It was also found that the heat remained within the local areal minimizing the damage to the comb and cell contents in other areas of the frame. Therefore, a heater is not required in each cell, only 1 heater per 19 cells is required, and the heat remains in a small local area making it possible for a beekeeper to selectively heat different regions of a frame.

The results of the simulations were then verified by designing a PCB to test the temperature sensors and temperature control in a lab setting. The PCB was designed with three temperature sensors and two heaters that were placed on the board such that they aligned within 6.9 mm drone cells in drone brood foundation. A 1-wire addressable temperature sensor was used and a 39 Ω (750 mW rated) resistor was used for the heater, which produced 641 mW of power when connected to a 5V source. A 3D printed comb was used for the comb in the lab tests and the temperature of the cells was measured by the on-board sensors at the base of the cells and an IR camera positioned above the cells. From the results of the test with empty cells it can be concluded that the copper heat pipes worked as expected resulting in a constant temperature through the board, which will allow for the temperature of the cell contents to be measured from the other side of the board. From the empty cell test it was also found that the board was a good insulator, so the heat remains in a small local area and thus minimizing the damage to the surrounding area of the hive frame.

When comparing the temperature results from the full cell and empty cell lab tests it can be concluded that the rate and magnitude of the temperature increase is inversely related to the amount of liquid in the cells. It was found that the top of the water in the full cells experienced a 10°C, 7°C, and 3°C increase in the heater cell, neighbour cell, and cell two cells away

respectively within 9.5 minutes. These are the minimum temperature increases that the cell contents will experience because the cells may not be completely full, in which case they will heat to higher temperatures, and the base of the cell reaches temperatures higher than the top of the water. Therefore, a 641 mW heater is capable of heating cells within a 2.5 cell radius to temperatures high enough to kill *Varroa* mites within 9.5 minutes confirming the simulation results that only 1 heater per 19 cells is required.

The proposed temperature monitoring system is different from existing systems because multiple temperature sensors will be embedded throughout each frame allowing for the temperature in different areas of the brood nest to be measured and studied, instead of just measuring a single value in the brood nest. This would be useful information to combine with other sensor readings, especially when locating the brood or colony cluster because as was discovered in the in-hive experiments the bee activity was not uniform throughout the brood nest, but instead the bees tended to stay in one area. Therefore, the temperature only in that one area would be regulated, allowing for the location of the bees to be detected by the temperature sensors as well as possibly provide insight into the size of the colony and the amount of brood.

The proposed heating system for the possible treatment of *Varroa* mites is also different from existing systems because it allows for local areas of each hive frame to be individually controlled reducing the amount of wasted resources that occurs when entire frames or boxes need to be heated. Another difference is that by controlling the heaters remotely, beekeepers would have the ability to treat their hives at all times thus supressing the mite population by not giving it an opportunity to grow.

The second component designed in this thesis was a capacitance board for monitoring the cell contents within both the honey supers and brood box. Simulations were performed to first

determine the feasibility of using an interdigitated capacitance sensor (IDC) for cell content monitoring and to determine an appropriate geometry for the electrodes. It was found from the simulations that a detectable change in the picofarad range occurred across an IDC as the liquid level within the cells changed. It was also found that changes occurring closer to the base of the cell (i.e. when liquid is first added to an empty cell) caused a larger change in capacitance than cell content changes near the top of the cell. The magnitude of the capacitance change also depends on the type of liquid because honey causes a smaller capacitance change than the same amount of water due to its lower relative permittivity. From the simulation of different capacitor electrode geometries it was found that the wider and closer spaced electrode fingers were more sensitive to changes in the cell contents. Therefore, from the initial simulations it was concluded that an IDC was a viable method for cell content detection and an initial prototype board was built with copper tape electrodes and a 12-key capacitive touch sensor was used to measure the capacitance. It was found from lab tests with a 3D printed comb and water that the measured capacitance increased linearly with the number of full cells, which was consistent with the simulation results. Therefore, the copper tape IDC was working as expected and a full size 12-region prototype board was built using copper tape and the same 12-key capacitive touch sensor for measuring capacitance.

Three tests were performed with the prototype: varying water height, varying honey height, and varying sugar concentration. In all three tests the board worked as expected as the capacitance increased with liquid height and the sensor was more sensitive to changes in height at the lower levels than when the comb was getting close to full, which was consistent with the simulations. As expected, when testing with honey a smaller change in capacitance was recorded than with water due to its lower relative permittivity. The normalized change in capacitance was

plotted to produce a more uniform result among the twelve regions and remove the different constant offset capacitances of each region caused by the arrangement of the wires and other external factors. From the results of the water and honey lab trials it can be concluded that the system may not be able to determine the exact liquid height, but thresholds can be set to indicate the honey height within a range in a region, such as 0-3 mm, 3-6 mm, or 6-10 mm of honey, which may be sufficient for a beekeeper to plan their hive visits.

A third test was performed with different concentrations of sugar-water where it was found that for the same height of liquid the capacitance decreased with an increase in sugar concentration, which is consistent to what was found in literature. There was about a 16% drop in capacitance from a comb full of 30% sugar nectar to a comb full of 82% sugar honey, so the same capacitance value was measured for a comb full of honey and a comb with cells only 22% full of nectar. Therefore, it can be concluded that it will be difficult to determine the honey level from a single reading and instead the capacitance will need to be measured over time. Over time, there should be an increase in capacitance due to increasing nectar heights, followed by a decrease in capacitance due to the honey ripening and sugar concentration increasing, and then once the honey has ripened to about 82% sugar the cells are capped by the bees so the capacitance should remain constant. The ability of the capacitance board to detect the ripeness of honey is an advantage over existing honey measurement systems, which generally consist of just a hive scale because it will give beekeepers more information as to whether or not the hive is ready for harvest. Similarly, the regional monitoring of cell contents within the frames will give beekeepers a better idea of how much space there is in a hive for the storage of honey so they can make adjustments to optimize their yield.

Further simulations were performed to determine the effects the different electrode and gap widths of IDC geometries had on the measured capacitance. It was found that with the same gap width, wider electrode fingers produced a stronger electric field within the comb which was more sensitive to the changes in liquid height, but was also less saturated at the top of the comb indicating that the electric field extends further past the comb allowing for external sources, such as neighbouring combs or bee movement to affect the capacitance measurement. When simulating geometries with the same electrode width and different spacing it was found that the closer spaced electrodes measured a higher capacitance value because there was a stronger electric field closer to the electrodes, but had a lower resolution at the higher liquid levels because there was less electric field fringing due to the closer spacing. Therefore, it was found that the resolution of the water height, especially in the final third of cell height, was determined by the saturation height of the electrode. Therefore, it can be concluded that if the electric fields are limited to remain within the comb to reduce added capacitance from sources beyond the comb, the resolution of water height within the comb, especially the final third of height, is lower. Overall, it was found that the electrode width had a larger impact on the capacitance than the electrode spacing and therefore a PCB was designed to have electrode widths of 3 mm spaced 5 mm apart to limit the electric field to remain almost entirely within the comb while still providing a measurable change in capacitance in the final third of liquid height.

Three PCBs were built, coated in wax, inserted into a standard wooden hive frame, and placed into an existing beehive. Because the sensors were placed in the hive in the fall after the honey flow, the bees did not build a comb on the boards and therefore the boards did not measure the cell contents, but instead were found to have measured the bee activity as the bees walked directly on the sensors. It was found that as expected for this time of the year there was

very little activity in the honey super. The sensor in the brood box recorded more bee activity and indicated in which regions of the frame the bees were clustering. After a period of two weeks the measured bee activity decreased quickly over a few days until the there was almost no bee activity. Upon inspection of the colony, it was found that the colony had collapsed due to *Varroa* mites, and that is most likely what the sensor had detected. From the sensor data it was found that the colony collapsed quickly over about four days and therefore, the sensor could be useful for beekeepers to detect early signs of colony collapse allowing them to take action to minimize the damage to the colony and others in the area.

More bees were added to the colony and all three of the sensor boards were placed in the brood box. It was found that the board in the centre of the box measured the same bee activity that the board in the brood box did in the initial experiment before the colony collapsed and therefore it can be concluded that the sensor boards were in fact measuring bee activity. In the second test there was very little bee activity recorded by the other two boards, which were placed near the edge of the box. This was expected because the bees are not producing and storing honey and the colony is small and the outside temperature is getting cooler so they are clustering together near the brood comb, which was in the centre of the hive. Therefore, by placing the three sensor boards in the brood box it was found that the bee activity is not the same throughout the box and the system was able to detect the location of the cluster of the bees within the box.

Therefore, from the in-hive experiments it can be concluded that the IDCs on the PCB measured capacitance as expected because the capacitance increased as the space beside the capacitors were filled with bees, which have a higher relative permittivity than air. It can also be concluded that the boards and system was robust enough to be able to successfully record data every half hour and withstand the hive environment for over a month. Therefore, the use of the

IDC board designed and built in this thesis can allow beekeepers to remotely monitor the cell contents in their hives and it can be placed directly into existing hive structures without requiring the hive to be modified.

The power consumption of a system consisting of both temperature monitoring and control boards and cell content monitoring boards would be determined by the microprocessor the majority of the time as the sensor boards would only be used periodically. The microprocessor board and heaters are the system components that consume the most power. For the tests in this thesis an Arduino that draws less than 100 mA when operating at 5V was used and each heater draws a current of 128 mA when connected to a 5V source. The majority of the time only the Arduino will be running consuming approximately 500 mW of power. Each heater that is turned on will increase the system's power consumption by 641 mW, however each heater may only need to be turned on once per week, or less, for about 10-20 minutes.

5.2 Future Work

The components designed and results from the lab and hive tests presented in this thesis can be used as part of the design of a larger smart hive system. The temperature sensor and heater board design concept could be extended to a full size board for placement within the brood box. This would allow for the temperature to be recorded throughout the frame to provide insight into the overall colony health according to how well the temperature is being regulated. It could potentially also provide an estimate of the overall hive population, especially if combined with the cell content monitoring capacitance board data because as the population decreases the size of the temperature regulated cluster within the hive will also decrease. Tests should also be performed with *Varroa* mites to determine the effectiveness of killing them with the small on

board heaters. As well, a method for *Varroa* mite detection, such as microphones or a camera, should be implemented to determine the location of the mites within the frames.

The capacitance board designed and built in this thesis should also be tested during a honey flow to observe the change in capacitance as the bees build their comb on the board and then produce honey within the cells. The hive tests could also be performed to verify that it is possible to measure the ripeness of the honey in the cells. Similarly, it would be interesting to record the capacitance as the brood develops from eggs to bees because a detectable change in capacitance should occur because a change was recorded when the adult bees walked on top of the sensor. This data could then be combined with the temperature measurements to determine the brood size and provide the possibility for future population estimation.

These components should then be incorporated into a larger remote system with many different sensors and placed in many hives. This would allow beekeepers to remotely interact with their hives and allow for large amounts of data from different sensors to be collected and correlated providing more information on honeybee hive health and how it is affected by different environmental factors.

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Appendix A – Component List and Prices

Table A.1: Component List and Prices [58, 59]

Component	**Price (CAD)**
Control Box Components:	
Arduino Uno	$32.00
Arduino Uno Data Logging Shield	$19.00
32 GB SD Card	$33.00
Capacitance Board Components:	
2-Layer PCB with Capacitor Electrodes	$12.00
Adafruit MPR121 12-key Capacitive Touch Sensor	$11.00
Temperature Sensing and Control Board Components:	
4-layer PCB	$20.00
DS1822 Temperature Sensor	$3.00
39 Ω, 750 mW Resistor (Heater)	$0.15
BSS84AKV PMOS transistor (Heater Switch)	$0.18