A Monitoring System for Honey Bee Colonies

by

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Abstract

In the recent decades, there has been an alarming rate of loss of honey bee colonies. Considering the important role that honey bee colonies play in crop pollination and preserving the environment, it is crucial to monitor the health of managed colonies. There is an increasing interest in continuous monitoring systems that can detect events in the colony, such as death or loss of the queen bee, the death of colony, etc. The purpose of this research is to design and implement a continuous monitoring system for honey bee colonies. Considering factors such as the effectiveness, cost, sensor placement, and known physiological behaviour of honey bees, a sensor array consisting of the following was developed: temperature, relative humidity, and sound. Furthermore, an algorithm is developed to process and analyse the collected data. The collective information gathered from these sensors and the ambient conditions are used to observe the state of the colony.

Keywords: honey bee (Apis-mellifera); precision beekeeping; monitoring; sensors

To the loving memory of my mom, *Nasim*,

my achievements are a celebration of your life.

To the cherished memory of my uncle, *Pouya*,

who had a great mind and an even greater heart.

And the three pillars of my life,

To my dad, *Farzad*,

who is my mentor, and ally.

To my brother, *Yashar*,

who is my forever best-friend.

To my love, *Bamdad*,

who inspires me to be a better me today,

and holds me steady as I venture my tomorrows.

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Who are you that I
so trustingly
confide my name to
hand the keys of my home to
share the bread of my joy with,
sit by whose side
on whose knees
so peacefully
I sleep?

Who are you that I
so solemnly
linger with,
in the land of my dreams?

-Shamloo
-From Aida in the Mirror, 1963

Many times, I ask myself the question: "What is my purpose"? A cliché that we all face at one point or another. And each time I have met people who have helped me define a set of values and goals, and each time I have been more than grateful. People come and go from our lives, and that is the inevitable; but their traces remain. I want to leave in print the memory of a few that I am thankful for.

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List of Acronyms

BCE	BCE/CE usually refers to the Common Era (the years are the same as AD/BC). That is, BC is usually understood to mean “Before the Common Era” and CE to mean “Common Era.”
BLE	Bluetooth Low-Energy
CCD	Colony Collapse Disorder
DSS	Decision Support System
JO	Johnston’s Organ
FAO	Food and Agriculture Organization of the United Nations
PB	Precision Beekeeping
PCB	Printed Circuit Board
RH	Relative Humidity
SPL	Sound Pressure Level

Glossary

Apilarnil	The entire content of the honeycomb cell where the drone larva lives (including the larva) until the 7th day.
Apis mellifera	The western honey bee or European honey bee is the most common of the 7–12 species of honey bee worldwide.
Chalkbrood (Ascosphaera apis)	A fungal disease of honey bee brood that infects the gut of the larvae.
Endothermic	(of an animal) dependent on or capable of the internal generation of heat.
Hygroreceptors	Structures, in many insect, that detect changes in the moisture content of the environment.
Metabolic Rate (BMR)	The minimal rate of energy expenditure per unit time by endothermic animals at rest.
Precision Beekeeping (PB)	A sub-branch of precision agriculture, is an apiary management strategy based on the monitoring of individual bee colonies to minimise resource consumption and maximise the productivity of bees.
Propolis	A resinous mixture that honey bees produce by mixing saliva and beeswax with exudate gathered from tree buds, sap flows, or other botanical sources. It is used as a sealant for unwanted open spaces in the hive.
Royal Jelly	A honey bee secretion that is used in the nutrition of larvae, as well as adult queens.
Stenothermic	A species or living organism only capable of living or surviving within a narrow temperature range.
Subgenual organ	An organ in insects that is involved in the perception of sound. The name refers to the location of the organ just below the knee in the tibia of all legs in most insects. It is associated with sensing ground movement and sometimes also of sound.
Superorganism	A group of synergetically interacting organisms of the same species.
Varroa mites	An external parasitic mite that attacks the honey bees. It can only reproduce in a honey bee colony. It attaches to the body of the bee and weakens the bee by sucking fat bodies.

Chapter 1.

Introduction

> *"Glowing with yellow scales and dazzling hue,*
> *Her body marked with golden bands we view;*
> *If safe, this king one mind abides in all —*
> *If lost, in discord dire and feuds they fall;*
> *Destroy their work, waste all their gathered store,*
> *Dissolve all bonds, nor are a nation more.*
> *If he but live ruling the glowing hive*
> *All are content the fertile race survive*
> *Him they admire with joyful hum surround*
> *While labour thrives and honeyed sweets abound."*
>
> *-Virgil, 35 B.C.*

Extracting honey from honey bee colonies is an ancient practice dating back to at least 10,000 years ago [1]. Beekeeping or domesticating honey bee colonies for honey is estimated to have started 3500 years ago in Egypt [2]. Many philosophers and scientists have delved into observing the honey bee colonies. However, it was not until the 18th century when biologists and scientists such as Swammerdam, Réaumur, Bonnet, and Huber started studying bees in more detail. Sensors were used to observe how the honey bees organize and communicate activities to sustain the colony.

Interest in honey bee colony monitoring peaked in the recent decade with the sudden increase in honey bee colony deaths all around the world. The concern and a clear awareness of the crucial role that honey bees play in the preservation of the ecosystem, agriculture and economics, motivated researches to develop monitoring systems. With the recent advancement in sensor technology and availability of various microcontrollers and microprocessors, the design and implementation of continuous monitoring systems has become more feasible. There are many remaining challenges in the design and implementation of the honey bee colony monitoring system. Data collection phase is a significant stage that needs to be expanded to various climates and subspecies of Apis mellifera. This can only be feasible if reliable data collection nodes are available to beekeepers and researchers. Colony health assessment can be performed utilizing collected data. The interdisciplinary collaboration of bee specialists, engineers, physicists, and mathematicians are crucial for the future of beekeeping and consequentially our lives.

1.1. Literature Review

The western honey bee or European honey bees (*Apis-mellifera*) are the most common species of managed bees. They are highly valued as pollinators for agriculture crops and preserving the ecosystem. The adaptive nature of honey bees has enabled humans to “domesticate” them in various parts of the world. The Ancient Egyptians (2600 BCE) were the pioneers in domesticated beekeeping. The practice was passed down to the Greeks, Romans and eventually spread through Europe [2]. The early European settlers transported honey bee colonies to the New World (Americas) mostly for their honey and bees-wax. The interest in the life of honey bee colonies began with naturalists such as Aristotle and Theophrastus and poets such as Virgil. It was only in the late 1800s that scientist such as Darwin (1876) and Müller (1879) realized the role of insects in pollination. The use of managed honey bees for pollination of crops only began after the modern form of beekeeping was established in 1895 [3].

Nowadays, beekeeping has become a major branch of agriculture. Honey bees have high economical value for their direct product, i.e. honey, and as pollinators of agricultural crops. It is estimated that honey bees perform more than 90% of commercial pollination services. More than 70% of the human consumed crops depend on animal pollination, where honey bees are the most significant contributors [4]. The use of domesticated honey bees as crop pollinators is a well-practiced industry. The added value of the pollinated crops is estimated to be $2 billion in Canada [5].

As the name implies, honey bees are commonly known for producing honey. Honey was the main sweetener known to man before the development of sugar refinement methods. Honey has antibacterial and antifungal substances and is rich in vitamins and minerals. As a medicine with a natural source, honey has a wide range of enzymes, peptides, organic acids, etc. which can be used in inflammatory, gastrointestinal, and cardiovascular treatments [6]. Besides honey, bees produce other products such as beeswax, propolis, apilarnil, and royal jelly that are used in cosmetic, medicinal and pastry products. According to the Food and Agriculture Organization of the United Nations (FAO), approximately 1.6 million tonnes of honey was produced in the world in 2013, a 30%

increase since 2003. The gross value of honey produced in the world was USD 7 billion in 2013 and the honey produced in Canada is estimated to have a value of USD 123 million [7]. However, it has long been established that the primary commercial value of honey bees is their role as crops pollinators. It has become a well-known practice for farmers around the world to rent various species of bees from beekeepers for pollination of their crops [8].

In the past decade, honey bee colony loss has increased at an alarming rate in North America and Europe. Colony collapse disorder (CCD), the sudden loss of adult honey bees, is not new to the apiculture industry [9]. However, recent losses have been a cause for concern for managed honey bee colonies [10]–[20]. Smith *et al.* studied both long-term (1947-2010) and annual losses of honey bees. In the long term, the losses have been associated to the political and socioeconomic factors leading to a 25% decrease of colonies in Europe since the mid-1980s and nearly a 60% decrease in the U.S. [21]. The environmental conditions and man-made pollution are also possible factors in the decline of the honey bee colonies. The recent cause of CCD has also been attributed to *Varroa* mites, a parasite that weakens the colony.

The main cause of the loss of honey bee colonies is not confirmed. However, it is evident that adequate monitoring of honey bee colonies before their decline is absent. Precision Beekeeping (PB) is a branch of precision agriculture that is dedicated to bee colony monitoring in apiaries. PB aims to develop real-time online monitoring systems for honey bee colonies that aims at “maximising honey bee productivity and minimising resource consumption” [22]. Currently, the popular method for honey bee observation and management is following the traditional methods of hive inspection. Traditional beekeeping involves training professional beekeepers to inspect the hives individually by visual examination. These methods are both time-consuming and expensive for beekeepers with a substantial number of colonies. The regular practices used by beekeepers, including opening the hive, are also intrusive for the bees and disturb their activities. Sensors provide a less intrusive method of monitoring for honey bee colonies. Effectively, the goal is to implement a monitoring system that can be used to understand and research honey bee colonies. It can also help beekeepers to continuously monitor their colonies without disturbing the colony and with less time and manpower expenditure. The monitoring system equipped with a decision support system (DSS) can recognize abnormal behaviour of colonies and alert the beekeepers accordingly. This allows for immediate response from beekeepers to minimise losses. The development and implementation of this monitoring and support system takes an extended amount of time, due to the nature of the study. The response of each colony is dependant on various factors such as seasonal changes, climate, colony health, type of the subspecies, access to food sources, and queen's health. Following the stages introduced in precision beekeeping, the system development will require three phases: data collection, data analysis, and application [22].

In this thesis, a monitoring system is designed and implemented to observe and process the data acquired using an array of sensors. Namely, the first and second stages of a monitoring apparatus introduced in PB are implemented. To effectively monitor honey bee colonies first the measurable variables and data collection methods are selected. The selection is made based on literature review and practical knowledge of the beekeepers. Then the collected are analysed considering the colony behaviour. For this purpose, it is imperative to understand honey bees in order to devise the right set of sensor arrays for monitoring.

1.2. Honey Bee Monitoring Variables

To design a monitoring system, it is essential to understand the physiological behaviour of the honey bees. This includes the response of the colony to external stimuli such as predators, infestation, and fungi as well as internal stimuli such as death/loss of queen bee, swarming and foraging. In the data collection phase of percision beekeeping, there are various types of variables to consider: a) apiary (ambient climate and video or in person observation), b) colony (temperature, humidity, sound, vibration, etc.), c) individual (forager traffic) [22]. This thesis is mainly focused on colony level observations.

"Honey bee communication" is a complex phenomenon that is yet to be completely understood. This intricate, yet organized form of interaction, leads to a self-sustaining society that communicates information on food sources, warnings and colony preservation. It has been observed that the bees communicate through a series of pheromones, tactical signals, substrate vibrations, and air born sounds. One form of communication in a colony is through chemical signals, such as queen mandibular pheromones (depicting the presence of the queen). The mechanical signals such as substrate vibrations and air borne sounds have a more prominent presence in the temporal changes of the response of the colony to various stimuli. Karl von Frisch first observed the first form of "bee communication," also known as the "waggle dance". Von Frisch observed that the bees that leave the hive to find food sources (foragers) perform body movements that where correlated with the direction and distance of their findings. Hence, observing these mechanical signals gives a more substantial understanding of the colony's condition [23].

The sense of "hearing," as we know it, is associated with humans and animals equipped with sound pressure receivers such as eardrums and similar membrane. Although it was clear that the sound produced in honey bee hives serves a purpose, it was not clear what it meant. Commonly, "ear"-like organs are associated to "hearing," whereas the bees' antenna has pore plate organs which are chemoreceptors [24]. Therefore, bees were considered "deaf" to airborne sounds until Autrum (1907-2003) a German zoologist and physicist verified that the hair-like structures on the body of some insects are used as sound velocity receivers [25], [26]. The way bees produce, transmit and perceive acoustic communication signals depends on their physiological and ecological limitations [23]. Studies have shown that most of the "sounds" produced and perceived in a honey bee colony are in low fundamental frequencies (100-600 Hz, various sources as described below) and its harmonics. To decipher the "sounds" made by bees we have to understand the *message* (provided by the sender) and *meaning* (motivation of the receiver)[27].

To go into the physiological details of bees is beyond the scope of this thesis. We refer the interested reader to the book on insect sounds and communication [28] and references therein. For our purposes, it is sufficient to understand how bees transmit and perceive signals and their characteristics. Historically the "hum" of the colony has given rise to the suspicion that the organized and united activity of honey bees is related to the sounds from the hive. It enticed many scientists to try and understand how honey bees communicate. Recently, the advancements in technology have enabled scientists and entomologists to look closer at the sound signals of honey bee colonies. It has not been clarified which of the discovered signals are the most prominent means of communication but it is established that the colony uses these mechanical signals as means of interaction. These signals can be divided into two types: 1) substrate vibrations, 2) airborne sound.

1.2.1. Substrate Vibration Transmission and Perception

Bees generate sound via vibration of the thorax, which is then transmitted to the comb by direct contact of the abdomen or through the legs. Due to the unique properties of the comb size and structure, the signal is transmitted to nestmates that are close by [29]–[31]. The tibia of the bee’s legs senses the vibration of the substrate. The subgenual organ located in the tibia translates the vibrations to nerve impulses [32], [33]. The sensory cells are able to detect vibrations in the range of 150 and 900Hz of 0.06 to 0.15 mm/s peak-to-peak [34] and the vibration produced by honey bees is indeed in the range of 100 to 500 Hz with amplitude of 0.08 mm/s peak-peak, up to 6 mm/s peak-peak [23], [30], [35].

1.2.2. Airborne Sounds Transmission and Perception

The airborne sound is the result of the bees' wings movement and the jet of air-pressure close to the abdomen of a bee. The airborne sound produced by honey bees is received through the vibrations of the flagellum of the antenna and sensory cells of the Johnston's organ (JO). Tsujiuch *et al.* studied the mechanical and neural response characteristics of the honey bees and how they perceive air particle displacements through their JO [36].

Beekeepers have also incorporated auditory inspection in their practices, mostly by experience. This shows that a comprehensive study of the signal details provides information about the condition of the colony. These mechanical signals are a means of communication for the colony that can be recorded using microphones. To better understand these signals, the literature is reviewed for records of honey bee communication signals.

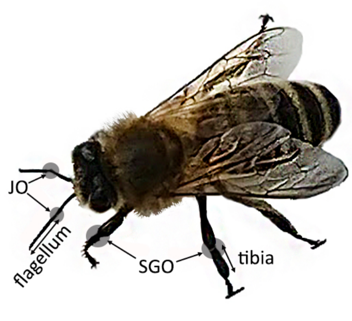


Figure 1-1 - Substrate vibrations are transferred through the tibia to the nerves in the subgenual organ (SGO). The neural response of the SGO is sensitive to low frequencies up to 500 Hz [37]. The airborne vibrations are sensed with the antennal flagellum. The sensory cells of the Johnston’s organ (JO) convert these vibrations to nerve impulses. The JO is sensitive to air particle oscillations of low frequency particularly in the range of 265-350 Hz [33].

1.2.3. Honey Bee Signals (Airborne and Vibration)

The requirements for monitoring the communication signals in the colony are gathered from previous observations in literature. One of the earliest communication signals distinguished was the queen's "*piping*" [38]. Piping is the signal that young queens produce during the swarming process. They are audibly louder and are distinguished by their fundamental frequencies. Other prominent signals are the "tooting" and "quacking" sounds that the virgin queen produces. "*Tooting*" signal consists of 1-second pulses followed by a number of short 0.25-second pulses. These pulses have a fundamental frequency of 400 Hz on the first day, rising to 500 Hz on the second to fourth day after emergence [24], [39], [40]. "*Quacking*" is also another observed signal produced as a response to the tooting sound. The mature queens that are confined in their cells and have not emerged yet produce the signal in response to other virgin queens. The signal consists of short pulses of 0.2-second duration with fundamental frequency of 350 Hz [39], [40]. Communication signals are also observed before swarming, i.e. when the new queen leaves the hive with the majority of the worker bees. The queen's piping signals let the other workers know that a new queen is present and they would stop chewing the cap of the other queens' cells. The tooting queen can assess her situation in the hive by the quaking signal from the other emerged queens and decide whether to swarm or stay [41]. The worker honey bees also produce a piping signal similar in frequency range of the queen's piping signal. However, these signals are in different context and have a different meaning. The piping signal produced by a worker bee aims to recruit more nectar foragers and also attracts the nest nectar receivers [30], [42], [43]. This signal is emitted as short pulses of 0.1 to 0.2 seconds at the fundamental frequency of 300 to 400 Hz [44].

Another observed characteristic of the colony's sound is their awareness of external threats. Protection of the brood (where the queen and larvae are) and the food resources are important in sustaining the colony. Honey bees relay certain signals to their nest mates to produce a collective response to threats. The colony responds to external physical attacks or the possible presence of a predator by producing a *hissing* sound through rapid wing movements. It is often referred to as the *shimmering* signal due to its visual impression produced by coordinated wing flaps of a large group of bees [45]–[47]. Sarma *et al.* showed that the scouting bees or the foragers would produce a signal upon seeing a potential danger upon arrival. The warning piping signal last 0.2 to 2 seconds and has a fundamental frequency of 300 to 480 Hz. The bees start hissing which propagates through the hive [47].

Another important signal for the colony is a series of signals that communicate the location of food sources. The "*waggle dance*" is a remarkable symbolic language that allows the foragers to recruit nestmates to food sources. The dance conveys different information and serves various purposes. These signals are used to gain the attention of nectar receivers and foragers [48]. Duration of the waggle phase may provide information about the distance of the food source and the temporal pattern can communicate the profitability of the food source [29], [49], [50]. The waggle dance has varying duration and timing depending on the direction communicated and has a fundamental frequency between 200 to 300 Hz [30], [36].

There are many unknowns about this intricate system of communication that coordinates thousands of bees in one colony. Nonetheless, it is evident that the vibration and sound produced inside of the hive is of importance when it comes to monitoring the health of the hive. The constant activity of the hive and the size of the colony evidently can be related to the frequency range and signal power. Table 1-1 summarizes the known honey bee (*Apis mellifera*) signal frequencies and their relating communication signal.

Table 1-1 - Sound signals produced by western honey bee (*Apis mellifera*) [23].

Signal	Fundamental Frequency (Hz)	Signal Pattern (Duration (secs))
Queen Signal		
Tooting [38], [39]	350 to 500	P (0.25)
Quacking [38], [39]	300 to 350	P (0.2)
Defense Signal		
Warning Signal [45], [46]	300 to 700	S (0.2 to 2.0)
Hissing [51]	300 to 3600[1]	S
Worker Piping		
Tremble dance[30], [42], [43]	300 to 550	S (0.1 to 0.2)
Swarming Signal [40], [52]	100 to 2000	S (0.1 to 0.25)
Recruitment Signal		
Waggle dance [49], [50]	200 to 350	P (0.1 to 0.2)

S (signal pulse or continuous signal), P (pulse sequence)

The information in Table 1-1 provides the frequency range and pattern of the signals that are expected to emerge upon constant monitoring of the hive. Information such as the frequency and duration of the signals, and colony's response time to events are decisive

[1] The observed signal also include the harmonics extending up to 5kHz [47], [51]. The signal is broadband and will last longer than a few seconds.

factors in the selection and design of monitoring hardware as well as methods for gathering data. However, relying on one form of information is insufficient in the study of the state of the honey bee colonies. Other studies have shown that other climatic factors in the hives such as humidity and temperature can also be used to monitor honey bee colonies [53]. The colony's response and motivation in regulating these elements are required to better understand the information that can be extracted from these measurements.

1.2.4. Regulation of Temperature and Humidity

The ability of honey bee colonies to withstand the colder months of the year enticed many researchers for further study. The abilities and motivation of the colony to maintain an average stable temperature, especially at the brood cluster, has been studied since the 18th century. Temperature measurements were one of the first studies performed on honey bee colonies using thermometers. Huber (1791), Root (1899), Gates (1914), Dunham (1926), and many more made measurements of honey bee colonies using thermometers and thermocouples [54]. With the advancement of technology, more studies were performed in the later 20th and 21st century [55]–[58] with continuous automatic temperature measurements. These studies lead to a better understanding of the colony's method of thermal regulations and the motivation behind it. The brood temperature has an important role in the development of the larvae and pupae. The stenothermic biology of the larvae and pupae compels the colony to regulate the temperature of the hive steadily at 33-36°C in the brood [59]–[61]. The temperature regulation of the hive has a direct effect on the development of the next generation of young bees. The eggs and larvae can tolerate lower temperatures for a short amount of time, but the sealed pupae are very sensitive to temperature variations. If the pupae remain at temperatures lower than 32°C, the chances of defects, such as shriveled wings and legs or malformed abdomen increases [62]. Adult worker bees perform the thermoregulation inside the hive since the young bees have low metabolic rates and therefore do not provide enough heat. Chemical signals and physical properties of the brood entice the adult bees to perform the warming or cooling activity. The warming of the colony is achieved through active heat production by thoracic flight muscles' movement [63], [64]. Conversely, during warmer seasons if the temperature exceeds the threshold of being overheated (above 37-38°C), the bees cool the hive by fanning and spreading water on the cells [65].

The honey bee colony as a whole has been described as a "superorganism" [66], [67], where the heating and cooling is the collective effort of thousands of individuals. The purpose of the colony is to maintain the colony's temperature in a range that is best for larvae and pupae specifically in the brood cluster. Conversely, the temperature closer to the sidewalls and in the super hive (usually where the honey is produced and sealed) is more affected by the ambient temperature [68]. The detailed regulatory mechanism of the colony and the physiological and genetic motives to maintain the hive temperature is out of the scope of this thesis and will not be further discussed. However, the importance of temperature measurement of the hive is evident in the literature [59]–[67], [69]. It should be noted that the placement of sensors is key to getting the best correlation of the condition of the colony and temperature fluctuations.

Humidity is another important climatic factor inside the hive. Unlike temperature, humidity is more correlated to ambient factors, but hive humidity levels can affect the health of the colony. It has been observed that the colony regulates the humidity to the best of their ability in sub-optimal levels [70]. Relative humidity (RH) is an important microclimate variable of the colony. The eggs need an RH level of more than 50% to hatch, where higher RH levels increase the chances of better development of the larvae [71]. However, it has been observed that the length of life for adult bees shortens at a higher RH level [72]. The RH of the hive also impacts the disease and infection rates of the hive. For instance, it was shown in [73], [74] that the brood mummification due to chalkbrood (*Ascosphaera apis*) increased when the relative humidity was increased from 68% to 87%. In case of *Varroa* mite[2] infestation, the reproduction of the mites increases at a relative humidity of more than 80% [76].

Humidity also plays a role in nectar concentration and nest thermoregulation. As was mentioned before, the bees sometimes use water droplets to regulate the temperature of the hive [65], [69], [77]. RH also affects the honey ripening, i.e., when the processed nectar transforms to ripe honey. During honey ripening more than 50% of its water content needs to be evaporated [70]. The evaporation rate is lower if the hive is too humid and a dryer environment is more favorable. Observations in the literature indicate that the relative

[2] Varroa mites are external parasites that attack both adult and developing brood by sucking their blood. They weaken the hive and lead to the death of the colony if not treated promptly. They also quickly infest colonies in the neighboring hives. Varroa mites have become a major problem of colony loss since when they were first found in 1980s [75].

humidity of the super hive is normally kept at 40% using evaporation and regular ventilation by the bees. The process and details of RH regulation is outside of the scope of this thesis.

In addition to what has been discussed so far, i.e., airborne sound, substrate vibration, temperature, and humidity there are other types of measurement that can be used to monitor the hive's condition such as forager traffic. Adult honey bees are foragers in charge of food collection. The forager traffic is defined as the number of bees exiting and/or entering the hive in a given time. Most of the data related to these activities were first observed visually and using a stopwatch [78], [79], obviously a non-optimal method due to fatigue and inaccuracy of the human observer. There have been several designs of entrance counters using photoelectric sensors, image processing, and RFID tags [53], [80], [81]. However, there are specific challenges associated with these counting systems: entrance counters often block the entrance and disturb the flow of traffic; image processing requires high processing power; and RFID tags are hard to implement at large scales.

Another effectively studied measurement method, in assessing the condition of the colony, is the weight of the hive. The continuous measurement of the hive's weight can help in observing the colony's size and activity during seasonal changes. The hive's weight has been correlated to the colony's food reserve and sudden or gradual changes in the colony's population, and swarming [82], [83].

Deciding on measurement variables and type of sensors used in designing the monitoring system is the first stage in precision beekeeping. The addition of a decision support system to the electronic system is the next stage. Zacepins *et al*. [22] propose a decision support system (DDS) for the electronic devices that categorizes the decisions to: individual rules (single colony measurements) and differential rules (colonies in an apiary or comparison of various apiaries). The role of the support system is to use computational methods and collective data analysis automatically to analyse and observe the state of the colony, and inform the beekeeper or researcher. This support system can be implemented after the primary data collection and analysis phases have been performed to set the rules for the DDS.

1.3. Honey Bee Monitoring Systems

In section 1.2, the existing studies on measurable variables for honey bee monitoring system were presented. In this section, existing observation methods in the literature are reviewed. The goal is to use this information in the design of the data collection system. The challenges and restrictions of these measurement systems are also discussed. There are other more specific restrictions that arise from limitations on sensor placement, cost, power, and remote access on a case-by-case basis.

Meikle and Holst [79] examined the recent studies and implementation methods of continuous monitoring. Their summary offers an insight into what has been done in the data collection and data analysis phases of PB, which also includes the information on sensors, wireless network, and power options. Zacepins *et al*. [22] also provide an insight into challenges and solutions that have been executed in PB. These studies provide us with information on the challenges of designing and implementing a continuous monitoring system. The challenges and advantages of each measurement variable are studied to decide the measurement variables and specifications of the monitoring system.

1.3.1. Challenges of Continuous Monitoring Systems

Continuous monitoring of honey bee colonies is still in the early stages of its development. Pioneers in the research of honey bee colony's phenology (study of natural seasonal phenomena) used sensors for direct monitoring. These research works mostly aimed to prove theories about the way the colony sustained and maintained its activities [84]–[86]. Recent advances in sensors with integrated interfaces and lower power consumption have made remote continuous monitoring more feasible. The main advantage of a remote monitoring system is that it eliminates the need for intrusive methods of colony inspections. Current beekeeping methods often involve opening and inspecting the hive. This method is disadvantageous since it disrupts the normal colony activity, aggravates the bees and can even lead to the loss or injury of the queen. Placing sensors that can monitor the colony without this intrusive inspection is highly desirable. The monitoring system will serve various services in both beekeeping and in progressing the research in PB. There is a great need for cost-efficient and reliable monitoring systems that utilize various sensors for diagnostic tasks in both colony and apiary levels. The ultimate purpose of the monitoring systems is to recognize events such as colony development during seasonal stages [55], swarming/pre-swarming, queenless, broodless, or dead colony, and disease or infections. This information can help the beekeepers increase the efficiency of their apiary management. The continuous tracking of colony information is also imperative to finding the causes of Colony Collapse Disorder (CCD)[3] by keeping a long-term record of the colony's health in a wider range.

The design and implementation of continuous monitoring systems and the advancements in PB have a great impact on the future of beekeeping and agriculture. This is still an emergent area of research with many future challenges. The main challenge in developing such systems is the slow processes of data collection and analysis stages [22]. In other words, correlating data and colony's condition to design a decision support system can be achieved using pre-defined models and expert knowledge. Continuous monitoring measurements can only be related to events that have been imposed on the colony, which would fall under "proof of concept" category, or they should be naturally occurring which can take a long time. However, the design and implementation of a system that can be used and replicated by researchers and beekeepers for effective data collection and analysis is a crucial step in PB that needs further contribution and collaboration.

Combination of various types of measurements can greatly improve the performance of monitoring systems. Optimal placement of sensors is a key factor in the design of continuous monitoring systems. Honey bees are known to cover foreign objects with bee wax or propolis [22]. This can cover the sensor surface and affect the accuracy of the measurements. Especially for sensors such as temperature and humidity sensors, the bee wax can affect the air flow across the sensor surface thus hindering the accuracy of the measurements [79]. Another challenge in sensor placement is finding the optimal location for the sensors and identifying the monitoring requirements for the hive. During seasonal changes, super hives will be added or removed from the colony. Therefore, placing the sensors in the brood hive will serve a long-term purpose compared to placement in the super hives. As we discussed previously, the honey bee colony regulates temperature and humidity of the hive by ventilation, and thoracic flight muscles' movement [55], [63], [64], [69], [70], [77]. Since the brood and super hive differ in their role for the

[3] Colony Collapse Disorder (CCD) is phenomena first recorded in 2007, when a large number of colony losses were reported. The signs of CCD are a lack of worker bees and dead bodies while the brood, queen and food sources remain [11], [87]. The lack of worker bees leads to the death of the colony.

colony, regulation of their temperature and humidity will serve different goals. This affects the monitoring requirements of each section of the hive.

Another placement issue to consider is sensors that may disturb the activity of the hive. As mentioned before, installing forager traffic measurement units requires modifications at the entrance of the hive. For example, counter sensors can cause blockage of the entrance which will hinder air flow, traffic and dead body removal [22], [53], [80]. Another issue with installing measurement sensors is the frequent transportation of commercial hives. The monitoring systems need to be robust and portable for fieldwork. This factor needs to be considered for sensors that will be installed on the body of hives such as weight or vibration sensors. These sensors are only useful in cases where the hives are stationary. However, a large number of commercial hives are regularly moved to various locations for pollination services. Therefore, these sensors either need to be removed and reinstalled on each hive after each move or require modifications of the hive, which is unfavourable in commercial beekeeping.

So far, the physical challenges of implementing a monitoring system have been considered. Other challenges in the data collection stage include memory usage, power requirements, and a wireless network connection. An important factor that should be considered in the data collection stage is finding the best sampling rate that will minimize the memory, power, and data transfer requirements. For instance, in the case of discrete data points such as temperature and humidity, it has been observed that the data has a sinusoidal pattern during daily cycles [70], [82]. Statistical analysis will be used to narrow down the frequency of the samples. In case of continuous data such as audio and vibration, where the sampling frequency and duration are important, signal processing and local assessment of data should be adopted into the system. This will decrease the data storage and transfer requirements for larger data formats. Concurrently, the system's power requirements should be taken into account. Since each section of the system has power requirements that need to be minimal. Sensors, microcontroller, microprocessor, as well as routers and/or Bluetooth devices require electricity. Most sensors today have very little power consumption and could go on for months on a small watch battery. But data loggers and storage devices along with the data transmission units require more power, specifically for data such as audio or vibration where processing is also required. Particularly remote and apiary level monitoring require portable power sources. Other sources of power such as solar or wind are effective candidates for this purpose [53], [82], [83]. There are still drawbacks to using these sources such as their inconsistency due to seasonal changes; nevertheless, they are the best forms of power sources that make the design of remote systems possible.

Based on [22], [79], a summary of previous studies and the challenges in the design of the system are as follows:

- Temperature sensors are well established in honey bee colony monitoring systems. Existing sensors are robust, economical, small and easy to install, and have minimal memory and power consumption. Sensor placement should be considered with respect to brood cluster, and ambient temperature effects should be considered.

- Humidity sensors are similar to temperature sensors except that they cost more and should be installed with care. Humidity sensors require direct contact with the water vapour in the air and should not be covered by bees wax [22].

- Gas sensors such as oxygen and carbon-di-oxide have also been used [88], [89] but they suffer from similar problems as humidity sensors and are often significantly more expensive.

- Weight sensors have been used to study nectar flow [82], [90], swarming, and forager traffic [91]. The weight of the hive can be useful information, but weight sensors can be expensive and have low accuracy. The industrial weight sensors have low resolution to detect the many interesting activities of the hive, such as forager traffic, nectar flow and other changes in passive months (winter). Also, the hive's weight can be affected by the moisture absorbed in the hive's body and other environmental factors such as precipitation and wind [22].

- Airborne sound recording and signal processing have been used in observing the colony's state [36], [92]–[94]. Sound recording and signal processing techniques are well developed; however, using this technology in colony monitoring can be challenging. Sensor location, environmental noises, power, and storage requirements need to be considered. The “buzz” or “hum” of the colony is a mix of complex and elaborate signals that require intricate computational tasks. Professional beekeepers often inspect their hives by listening [27], [79]. The analysis of frequency-time-amplitude components of the sound is useful in finding correlations between the recording and the condition of the colony. In particular, focusing on the amplitude of frequency bands that are known to contain honey bee communication signals is a promising direction [79].

- Substrate vibration is also known to give information about the colony's signals. Vibration signals have been studied using laser vibrometry [30], and accelerometer [95]. One issue with vibration data is that each bee sends an out of phase signal and at different frequencies. Therefore specific signal extraction from the hive is infeasible [95].

These challenges and advantages of each measurement method have to be considered in designing the monitoring system, data collection and data analysis stages. Next, we will look at some of the commercially available systems for continuous monitoring of honey bee hives.

1.3.2. Commercially Available Systems

Most of the measurement methods that have been discussed so far are largely developed and used by researchers. Few commercial colony-monitoring systems are available on the market. However, these systems are not widely used by commercial beekeepers due to cost or availability.

Arnia, United Kingdom, provides temperature, humidity, sound, vibration, CO_2, forager traffic, and weight measurements [96]. According to their reports, data such as sound are still in research phases. Arnia proposes that their system can distinguish between queenright and queenless colony based on the temperature and humidity of the hive [96]. BroodMinder [97] and SolutionBee [98] are also other available systems that provide weight, temperature and humidity measurements. There are a few more companies that also provide weight and temperature and humidity measurements [99]–[101].

It should be noted that although these systems are available, they are not regularly used by beekeepers. This can be due to cost, and availability of commercial monitoring systems. It has also been shown that honey bee genetic diversity [60] and regional environments affect the colony. Therefore it is important to have a larger and more diverse set of data. Supplying the beekeepers with a system, that is cost-effective, reliable, robust and easy to install, is the first step in creating a better database for the future of beekeeping and saving these pollinators.

1.4. Thesis Objective

Studying and monitoring the health of honey bee colonies has gained more attention in the past decade as the rise in colony losses has become worrying. Honey bees, as one of the main pollinators, play an important role in environmental sustainability and commercial crop production. With the advancement of technology is has become more feasible to design systems that can monitor the hives continuously. In this research the objective is to:

- Study the measurable physical variables that contain information about the health and state of the honey bee colony and review the challenges and benefits or each type of measurement.
- Examine different sensor placement strategies and collect relaible data with minimal disturbance of the colony.
- Design and implement a sensor array. Analyse and study the data gathered for the duration of the testing period.
- Develop and program a processing method to extract information from measured data.
- Examine the collective information from the hive and ambient climate for the development of future decision support systems.

1.5. Thesis Outline

In **Chapter 1**, the study of a honey bee colony and monitoring system is introduced. The literature review studies the known models of the honey bee physiological variables. Various monitoring and measurement methods are introduced.

In **Chapter 2**, the monitoring system design and implementation steps are described in more detail. The criteria for sensor selection and design steps for sensor placement are explained. Finally, an algorithm is developed for audio analysis.

In **Chapter 3**, the results for the testing period are presented. The temperature, RH, ambient conditions, and processed audio signal are shown.

In **Chapter 4**, results presented in chapter 3 are discussed. The design, testing method, and data gathered from the monitoring system are analysed and discussed for developing the support system.

Chapter 5 concludes the work and gives guidelines and closing remarks on the future work.

Chapter 2.

Method and Design

In this chapter, the design and implementation methods used for gathering data from the honey bee colony are described. Based on the literature review of Chapter 1 and expert knowledge and discussion with professional beekeepers, a monitoring system is designed and implemented that is capable of monitoring sound, temperature and humidity of the hive.

2.1. Monitoring Measurements

In Chapter 1, the physical measurements used in studying the colony’s condition were discussed. In this section, the sensory system’s requirements are specified and the overall design of the system is described.

2.1.1. Monitoring System Design

Relative Humidity (RH) and Temperature

As discussed in the literature review in Chapter 1, the colony regulates the temperature and humidity inside of the hive. The bees keep the brood cell’s temperature between 32°C and 36°C for better development of the pupae. During warm seasons they fan the hot air out, and during colder seasons they generate heat by collective metabolic heat [60], [61]. Therefore the brood cluster where the queen spends most of its time is the optimal place for temperature measurements.

The convenience of the current beekeeping methods is that the colony is often sectioned into the brood chamber and honey super (shown in Figure 2-1). The sections are separated using a queen excluder. This separation provides constant access to the brood cluster’s location and allows for relevant and convenient measurements. The brood’s health plays an important role in the health of the colony.

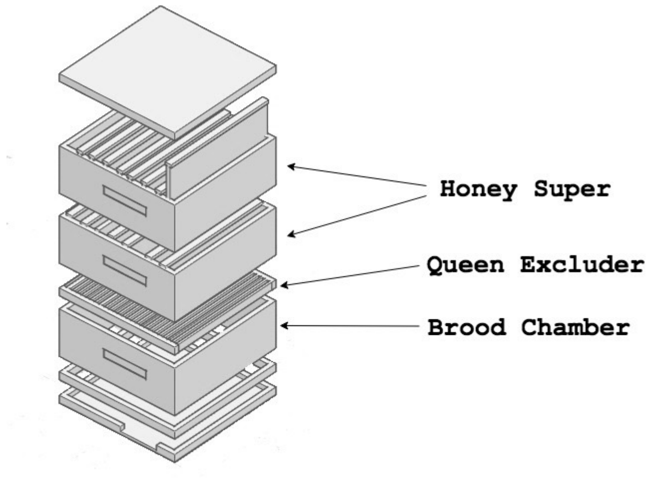


Figure 2-1 - Commercial honey bee hive structure.

Considering the measurement range, accuracy and cost requirement for temperature and RH sensor, the HIH8131 sensor (Honeywell HumidIcon™) was selected. The sensor takes temperature-compensated RH measurements and provides stand-alone temperature output. HIH8131 sensor with digital I^2C output, low power consumption, and high resolution is efficient for the monitoring of the colony. The sensor requires low voltage supply (3.3 V_{DC} is used). The sensor has sleep mode for when it is not taking measurements with 1 µA power consumption and 650 µA consumption for full operation. The sensor has a 14-bit output resolution for both temperature and RH measurements [105].

As mentioned before, bees cover foreign objects with propolis or wax, which could damage the sensors. Thus, the HIH8131 is outfitted with a hydrophobic filter and condensation-resistance that is ideal for use in the hive. A separate compartment is devised (as described later in Section 2.1.3) to enclose the sensors inside the hive and protect them from the bees.

The HIH8131 has a ±2.0%RH accuracy and ±0.5°C temperature accuracy. The monitoring system needs to detect changes in the humidity and temperature; therefore this accuracy is sufficient for the monitoring system. The operating range is between −40°C and 125°C and a humidity range of 0 to 100%RH. The sensor also has a 100 g shock and 20 g (10 – 2000 Hz) vibration resistance, which is reliable for when the hive is moved between locations [105]. Table 2-1 summarizes the sensor specifications.

Table 2-1 - Honeywell RH and temperature Sensor HIH8131 specifications [105].

Humidity Accuracy	Temperature Accuracy	Compensated Humidity Range	Compensated Temperature Range
±2.0 %RH	±0.5 %	10 – 90 %RH	5 – 50 °C

Airborne Sound

The literature review in Chapter 1 shows that researchers have performed measurements various measurements of the honey bee colony's activities. The objective of many of these research works has been the "proof of concept" of the social or individual characteristics of honey bees. The studies are used to support the design and integration of real-time monitoring systems for the future of precision beekeeping (PB). Considering the studies presented in Chapter 1, sound data was also collected in addition to RH and temperature as it offers a rich data structure that is indicative of colony health.

As part of the monitoring system, sound is recorded using an electret omnidirectional microphone with a frequency range of 20 Hz to 18 kHz (covering the human hearing range). These microphones are relatively inexpensive with low power consumption. The microphone has a sensitivity of -30dB ±2dB @ 94dB SPL. The microphone is connected to a Sabrent™ USB sound adaptor connected to a Raspberry Pi. Audacity™ software is used for continuous data collection. Due to cost or inaccessibility of other forms of observation such as a camera or in person, the sound data can also act as a form of observation, and it is used to determine outliers such as passing trucks or airplanes.

The Raspberry Pi 3 B+ (RPI) unit has the computational power for running onsite analysis tools such as the fast Fourier transform (FFT), power spectrum density (PSD), and band-power calculations. The analysis methods will be discussed in detail later in this chapter. For research purposes the sound of the hive was collected throughout the day, and it required more power and memory. The objective of this research is to construct a foundation for the future databases that could be used for diagnosis tools, so the higher costs of power and memory consumption at this stage of the research are justified.

In addition to what we discussed so far as part of the monitoring system, the ambient weather is also a factor that should be considered while analysing the colony's state. As discussed in the previous chapter, ambient temperature and humidity play a significant role in the colony's activities. The ambient conditions cause various colony states such as variation in the colony’s size during seasonal changes or outdoor and indoor activities. Noting these conditions, a weather station placed nearby to the hives is essential. Otherwise, data from a local weather station can be used.

2.1.2. Networking System Design

An imperative consideration in the development of the monitoring system is the access to real-time information of the colonies. Remote Access to hive’s information and onsite processing and analysis of these data is fairly new and has not generally been implemented in the beekeeping industry. The importance of such information has become more relevant in the past decade, and the recent technology advancements provides tools for performing remote data collection and transmission. The designed monitoring system was equipped with a mobile network connection via a USB modem, which was used for remote access and data transfer over a 3G network. The modem is compatible with the RPI unit out of the box. Then the measurement unit is accessed using a remote shell terminal via port forwarding with the Dataplicity™ client software.

2.1.3. System Overview

The system overview is described in Figure 2-2. The RPI is used as the main unit for data collection and processing. RPI is suitable as the central processing unit of the monitoring system as it has sufficient computing power and flexibility to record and process the measurements. Also, the onboard Bluetooth and Wi-Fi module can be used easily for communication. The GPIO pins on the RPI are used for powering the sensors and data collection. The sensors are wired to the main waterproof box that contains the RPI. The RPI is powered from a power outlet.

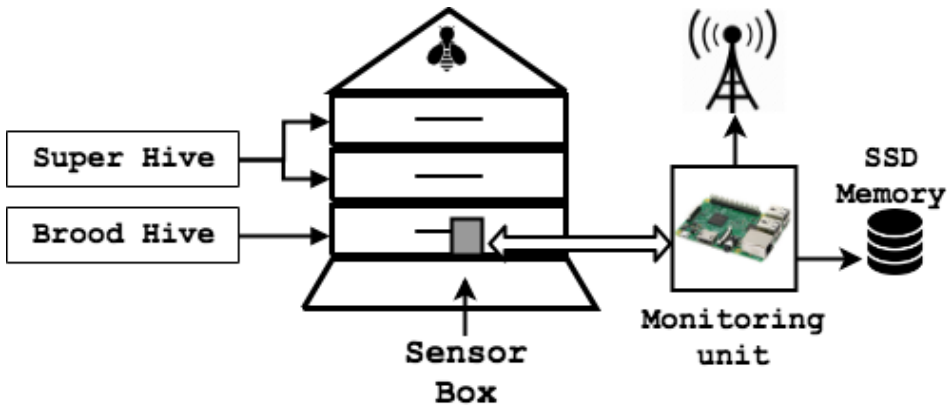


Figure 2-2 - Overview of the monitoring system.

The monitoring system unit's architecture implemented for this research is shown in Figure 2-3. The audio signal is collected using the electret microphone and is digitized using an audio adaptor. The data is collected by the RPI continuously at a sampling rate of 44.1 kHz and a 32-bit resolution. The HIH8131 temperature and RH sensor is placed inside the brood hive and the data is collected every 5 minutes using the RPI's I^2C port. As mentioned before, the RPI is connected to the 3G-network using a USB modem.

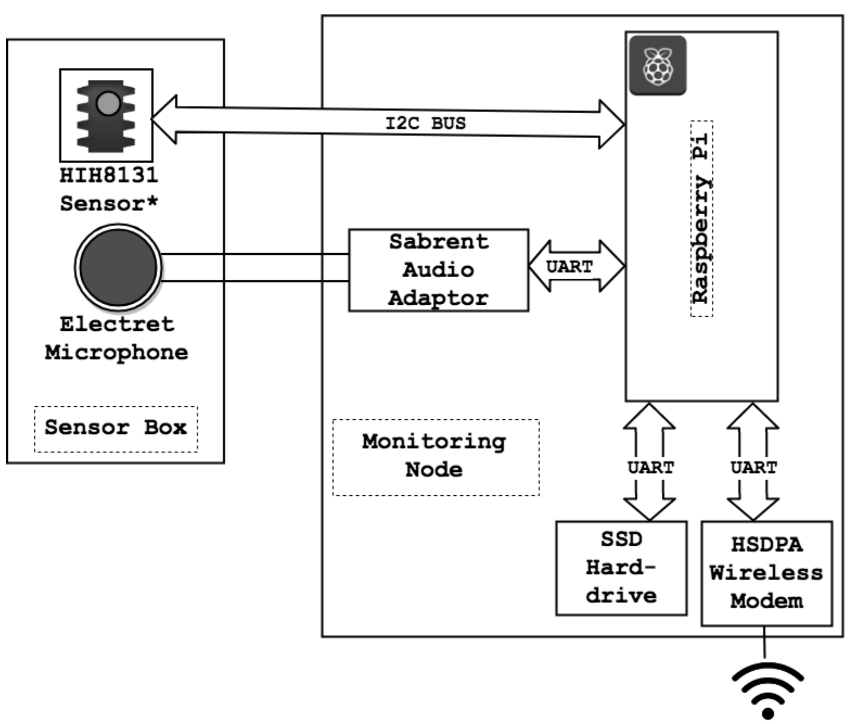


Figure 2-3 - Monitoring system unit installed on the hive.

As stated previously, honey bees tend to cover foreign objects with propolis (bees wax). This can cause obstructions to sensors that specifically depend on the airflow namely the microphone, temperature and humidity sensor. After experimenting with various methods of placing the sensor, it was evident that the sensors were seen as an intrusion by the colony. One of the tested methods of sensor placements was drilling a hole on the side of the hive and placing an external box (as shown in Figure 2-4) to encase the sensors. The side that is connected to the hive is covered with a mesh that will allow access to the hive but will prevent the bees from damaging the sensors. The problem with this design is that hives need to be modified which is costly for apiaries. Moreover, the temperature and humidity measurements are from the side frames of the hive. As discussed in section 1.2.4, the temperature and humidity of the hive are not as regulated on the sides. Especially during wintertime, the colony will only regulate the brood cluster. The brood cluster is usually kept in the middle of the hive, and it is kept away from the sides where the ambient temperature can affect it (sample is shown in Figure 2-5).

The second method of sensor placement was to place each sensor in a separate enclosure as shown in Figure 2-7. The new design was to enclose each sensor set separately. Noting that for this design each sensor is wired separately and placed inside the hive. The problem arises when the system is implemented on apiary level. This placement method disturbed the bees' activities and was interfering with a manual examination of the hive. The bees damaged the sensors and covered the ends with propolis (as shown in Figure 2-7 (b)) after 2 to 3 weeks of placement. Installing and removing the sensor proved to be difficult, and it caused damage to the brood cells.

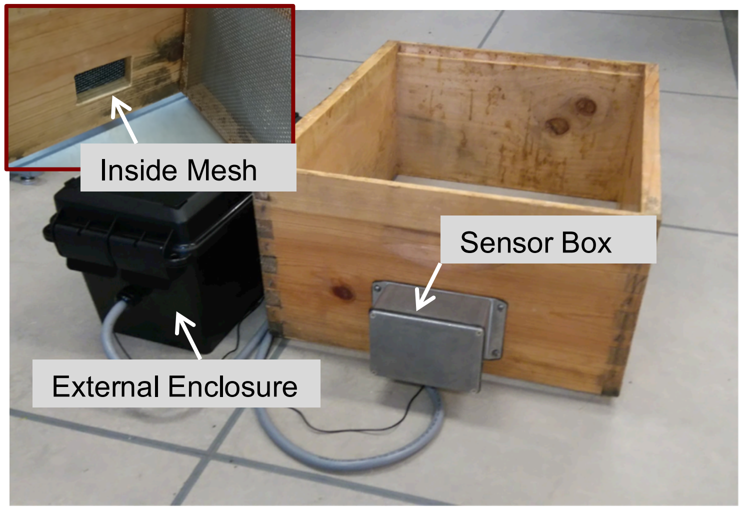


Figure 2-4 - Primary sensor placement. External enclosure includes the controller, power supply, and other hardware.

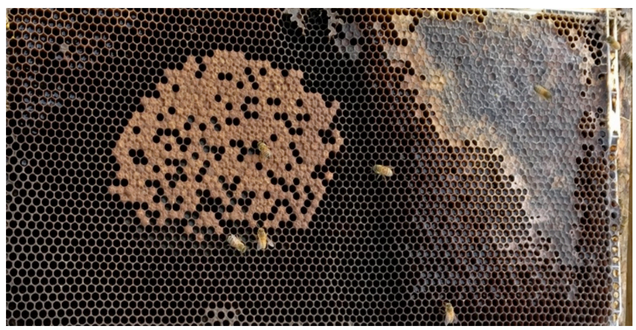


Figure 2-5 - Winter brood: The queen lays fewer eggs during this time, and the brood cluster is kept in the middle of the hive.

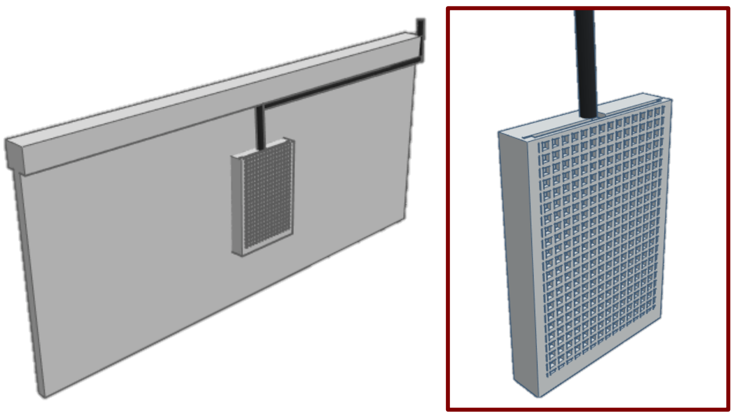
Figure 2-6 -Summer brood: There is more activity in the brood, the queen lays up to 1000-2000 eggs a day.

(a) (b) (c)

Figure 2-7 – a) Single wired HIH8131 sensor encosures. Placing a mesh on both ends will allow airflow through the sensor surface. b) Damaged sensors covered by propolis. c) 3D model design.

For the final design of the sensor placement, various factors are considered. First, a reliable mesh size was selected using the following criteria: 1) there is enough airflow that will not hinder the temperature and humidity measurements, 2) the bees will not cover the area with propolis or damage the sensors. Normal bee comb size is 4.9 mm; therefore a smaller mesh will prevent the bees from access to sensors. A mesh size of 3mm x 3mm was chosen as the cover for the sensors. In commercial hives the depth of the combs is standardized. And the opposing walls have enough space for the bees to move. Considering the structure of the frames used in commercial beehives, an enclosing case for the sensors was designed. The enclosure shown in Figure 2-8 is a 3D printed box that is approximately the same height of the regular honey bee combs (details appear in Appendix A.2). The frame with the sensors is placed inside the hive in the middle where it is closer to the brood cluster, especially during winter.

(a)



(b)

Figure 2-8 – a) The sensors are installed inside in a 3D printed box, and the sensor is covered with the mesh (*Left*). The sensor is placed on the middle frame in the brood chamber (*Right*). c) 3D model of the sensor placement box.

2.2. Data Collection Phase

In the previous section, the system's design and overview were described. In this section, the data collection methods and steps are described. A complete dataset is collected to help in the design of future Decision Support Systems (DSS). To narrow down the focus of this research, the data collection is performed at a higher sampling rate than is likely needed in the future to ensure no useful information is lost. Data collection can be optimized and adjusted to a suitable rate in later work.

The temperature, humidity and sound data are collected every 5 minutes for the duration of Spetember to November 2017. The data is collected from a single hive for this period; ambient temperature and humidity sensor was also placed outside the hive. In addition, data from the metrological station provided by Environmental Canada is used as a reference point for environmental conditions [107].

Various states of the honey bee colony can be related to the physical data collected from the hive. When collecting data from remote hives, the cost of data transfer both in size and power consumption are an issue. Therefore, it is best to find a processing and analysis algorithm that can be implemented on the remote processor. In our research work, the data collected from the hive are associated with naturally occurring events. The natural profile of the colony's activities in the circadian cycle is observed in temperature and humidity measurements and the sound level of the hive.

Also, from the month of September to November bees begin entering their wintering period in which the colony size reduces and the hive activity drops. The brood goes through a cycle during each year in varying temperate climates. The brood wintering starts when the ambient temperatures drop down to as low as 4°C on average. As the weather gets warmer in spring, the brood starts building up (spring brood rearing). Near the end of summer, the brood rearing decreases until it stops in fall [108]. During the seasonal changes from summer to fall and consequently winter, the life cycle of bees also changes. The lifespan of bees in summer is relatively short (~30days). However, starting in the fall, the bees have a longer lifespan of up to 8 months [108]. The role of these bees is more in sustaining the remaining colony and the queen. As studies show, the bees use their thoracic flight muscles to warm up the brood cluster to a temperature that is vital for their survival. Meantime, the population of the hive drops and activities change, which means there is an expected change in the sound of the hive. During the overwintering period, there is an increased chance of colony loss. In recent years the winter losses have increased due to *Varroa* mite infections. Events such as colony loss can be identified by examining the collected data [108]. Considering these conditions, one goal of the system in the future is to inform the beekeepers of the rearing period of the hive and winter loss of a colony.

Table 2-2 – Summary of detectability of hive state based on parameters (passive winter period – active summer period); I : Identified, U: Unclear [22].

Colony State	Sound	Temperature
Death	I – I	I – I
Brood Rearing	U – U	I – I
Broodless state	U – U	I – I
Queenless state	U – U	U – U

Table 2-3 - Summary of colony states, their importance and detection methods [22].

Colony State	Importance	Beekeeping traditional methods	Measured Parameter
Death	High	Dead bees, empty hive	Temperature, Sound
Brood Rearing	Medium	Seasonal *	Temperature, Sound, Weight
Broodless state	Medium	No brood, no eggs	Temperature, Sound, video
Queenless state	High	No Queen, no eggs, no Queen cells**	Sound, video

* Brood rearing state is highly dependant on the season. Detection can help beekeepers get their hives ready for winter passive period or know when the colony starts foraging. Traditionally the forager traffic and visible activity in summer or a lack of activity in fall are some indicators.
** Queen cells are cells that are specifically made for larvae that are being fed the royal jelly to replace the dead or swarming Queen.

Data analysis and decision-making have not been thoroughly studied due to the complicated behaviour of honey bees. Although many colony-based or apiary level observations have been made, there is a shortage of real-time monitoring systems. The result of such studies is highly dependant on the honey bee (*Apis mellifera*) species and the climate circumstances. Table 2-2 shows a summary of the studies on the bee colony monitoring diagnosis systems, as presented in [22]. As seen in Table 2-2, there is a lack of enough evidence that can decisively indicate the hive’s state. In Table 2-3, the importance of these states and their detection methods for the decision support system are indicated. In summary, it is possible to detect the state of the colony using a combination of sensors such as sound and temperature. However, such claims can only be made when an extensive study is performed on the response of the colonies at various states. The purpose of this research is to provide the tool and analysis methods for such studies. Preliminary observations have been made and studied, software tools have been implemented specifically for analysing the hive’s data.

The goal is to show that the measurement devices used in this research can be used as a tool for colony monitoring. The data gathered is a collection of sound, temperature, and RH from inside the hive. Also, the climate outside the hive is also considered: temperature, RH, weather condition, and sunrise/sunset time. The data for these external factors are gathered from databases provided by Pacific Climate Impacts Consortium (PCIC) [109], Government of Canada (Environment and Natural Resource) [110] , and National Research Council (NRC) Canada [111].

The sound data, however, requires processing tools that will extract information from the collected time series data. In the next section, data analysis methods and tools are briefly explained.

2.3. Sound Analysis

Sound data was processed in order to extract useful information about the state of the hive. In data collection, there is a trade-off between memory, power consumption, and data set size. At the prototyping stage, it is acceptable to pay higher power and memory costs in order to acquire a larger and richer data set. The audio signal-processing algorithm proposed in this section is part of the DDS but can be performed onsite. The following methodology, to the best knowledge of the author, is a new approach in observing the colony's sound data.

2.3.1. Audio Analysis

In analysing biological signals, spectrographic representations are used widely. The spectrogram is used to observe the components of the signal communicated in response to an event. The colony as a superorganism has a collective response, which is used as a tool of assessing its state. The spectrogram displays both the frequency components and the temporal changes in the audio signal by using windowed short time Fourier transform (STFT). In summary, the signal is divided into short time frames, and the discrete Fourier transform (DFT) is performed on each window to extract spectrum information. These tools are collectively useful for the visualization and inspection of the sound data.

Power Spectral Density and Band-Power

Another useful tool in audio analysis and the design of the DDS is the power spectral density (PSD). The power spectral density function computes the magnitude of power variations as a function of frequency. It is a well-known function in signal processing and is often used for finding the frequency components of a signal. Using the PSD function in MATLAB®[4], the "bandpower" function in MATLAB® integrates the PSD function for a defined frequency range. The band-power function computes the PSD using a Hamming window with the size of the sample. These functions are readily available in MATLAB® and an appropriate script has been developed to perform the PSD analysis in a post-processing stage after data collection. To later implement this algorithm in Python®, the NumPy library provides the PSD function, and the band power function can be developed using the same

[4] MATLAB is the registered trade trademark of Mathworks Inc.

method used in the MATLAB® library. The Python® implementation is advantageous as the script can run on RPI unit to perform onsite sound analysis.

Sound Data Processing

In the previous section, we discussed the advantages of spectrogram in data visualization and analysis. These tools are essential in proof of concept and exploratory studies and in analysing the characteristics of the audio signal. However, for a stand-alone system that is capable of computing and providing decision rulings, a different, automatic form of signal processing is required.

The temporal changes in the sound power level of various frequency ranges can provide better information on the activities of the colony. The patterns of daily changes in the sound level at different frequencies, comparative changes in sound level during seasonal changes, and conditional events can be observed using the temporal analysis of the sound level.

Before such an analysis can be performed filters are applied to the signal to eliminate various types of noise, such as hardware and ground loop noise. During field experiments a notable source of audio noise was the ground loop noise. The USB audio adaptor is directly powered via the USB hub on board the RPi, which is in turn, powered by the wall power. This introduces a 60 Hz (plus harmonics) noise in the data. This issue was discovered during system testing and was removed using a notch comb filter at 60 Hz and harmonics. This issue is expected to be less relevant when the system is battery powered.

In the case of this research work, audio signals were first collected, and processing was performed off-site. As mentioned above, the sound processing algorithm of this work can also be deployed onsite. Since the processed results have less memory requirements they can be easily transferred via a network connection to offsite computers for further processing, model generation and decision making. This can improve efficiency of the entire monitoring system. Put simply, the algorithm uses the band-power of the signal at different frequency ranges in order to analyse the audio signal of the colony. A flow chart of the algorithm is shown in Figure 2-9 and Figure 2-10. The different steps of the algorithm are summarized as follows:

- A 2-second sample of the audio signal is taken.

- The PSD of the signal is computed. The PSD is integrated for various ranges of frequencies. These ranges are selected based on previous studies in the literature as outlined in Chapter 1. Honey bees are known to produce sound in a range between 20 Hz to 1 kHz and the respective higher harmonics.

- The measured signal is then compared to the average computed for previous measurements (the number depends on the frequency of the samples taken). This comparison eliminates the outliers that could be due to hardware noise or the proximity of a single bee to the microphone. Therefore, an upper and lower bound is prescribed and signals outside this range are discarded and a new sample is taken.

- If the sample's power range is within the set boundary, the sample is accepted. Then a new mean is computed considering the new sample.

- The computed PSD and signal band-power is saved for each sample with a time stamp. This eliminates the need to save the actual audio sample.

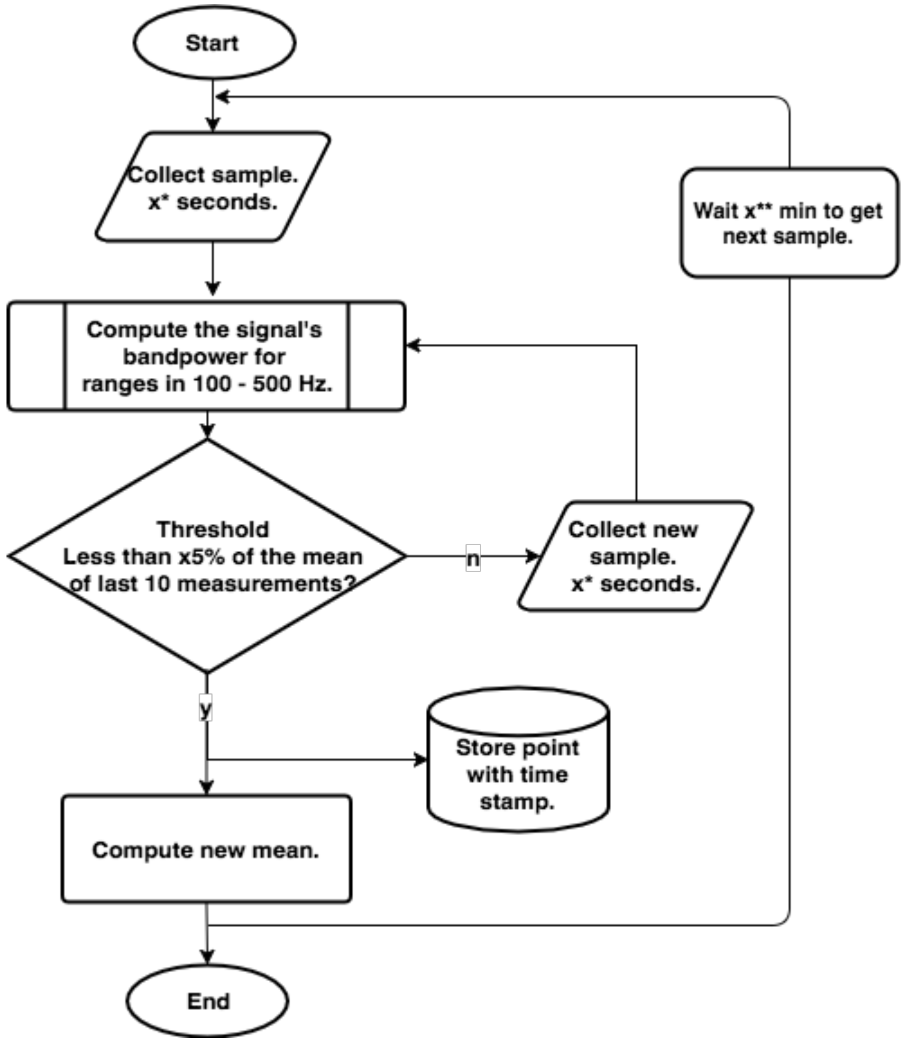


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Figure 2-9 - Flow chart for the algorithm of audio data processing (x* = 2 seconds, x = 5 mintues).**

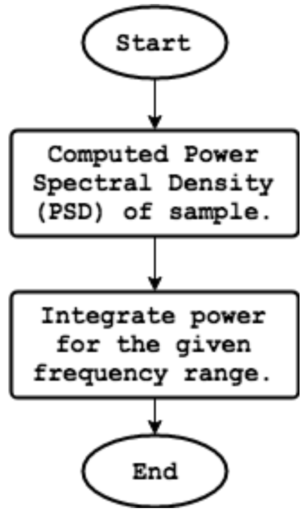

Figure 2-10 - The band-power computation subprocess.

2.4. Chapter Conclusion

In this chapter, the system design parameters are discussed. The monitoring system is designed considering the physical activity of the colony as discussed in Chapter 1. The system consists of temperature, RH, and sound sensors connected to an RPI unit that pre-processes measurements and transmits data over a wireless network for further processing. The placement of sensors and testing methods are also discussed, and the overall system structure and data collection and processing methods are described. Notably, an algorithm is developed for sound data processing and analysis. In the following chapter, the processed data is presented.

The response of the colony to certain events can be clearly observed in temporal changes in sound level and frequency. This can be used to further analyse the audio signals from the hive to extract meaningful information about the hive activity. As the literature indicates, honey bees have audibly detectable responses to events inside the hive. The hive is never completely quiet even in winter times when there are no flight activities.

Chapter 3.

Field Experiments and Results

In this chapter, the data from different collection methods and sensors for each measurement are presented. The data collected from the hives are plotted for various periods of the field experiments. The humidity and temperature measurements are observed on hourly basis. The data from weather stations and national database are also considered in analysing the hive's condition. The data is then analysed using the algorithm developed in section 2.3.1. Next, the processed data is used to infer meaningful information regarding hive behaviour such as the circadian cycles.

3.1. Data Collection Phase: Sensors Placement and Field Study

The research work presented here was conducted as a part of a MITACS cluster project in collaboration with HoneyView Farm (Now, Worker Bee Honey Company, BC, Canada) starting in May 2016. The company provided beehives and professional beekeeping expertise that helped this research in the design, and implementation of the sensory system. The hives were first kept on the company's grounds in Chilliwack, BC. Due to distance (120km from the research lab) regular testing and modifications were challenging and time-consuming. Collaborating with the city of Surrey (Park Development Department) and Worker Bee Honey Company, the hives were relocated to Cloverdale, Surrey (50km from the lab) in late November 2016. The closer distance to the lab made inspections, modifications to the hardware and replacing the sensors more accessible. The hives were fed before the move. During the overwintering and early spring (November 2016-May 2017), the hives were protected with covers (shown in Figure 3-1) to preserve heat and shelter from rain and snow. The colonies were inspected regularly every month during system design, and every 3 days during testing. The hives were placed near blueberry farms in Cloverdale and in spring the hives showed healthy growth. By the end of August 2017, one of the hives showed signs of weakness, and the colony perished soon after while the other hives remained unaffected. In October 2017, the three remaining hives were moved back to Worker Bee Honey Company for closer inspection, and feeding for winter. At this stage of the research, the proximity of the hives played an important role in the fieldwork that required regular visits, testing, and debugging. It was possible to install and test various sensors and data collection methods with the closer hive location. Due to the difficulty of working on site, the system had to be brought back to the lab at SFU several times for modifications and updates.

(a) (b) (c)

Figure 3-1 - (a) Hive cover for bee colony overwintering. (b) Hive inspection and sensor installment December 2016 (c) Hive Inspection and sensor installment February 2017 (Photograph by Oldooz Pooyanfar).

As it was described in section 2.1.3, sensor placement methods took several iterations of hardware installations until the latest placement method was developed (shown in Figure 2-8). The 3D-printed box was used to house the sensors with a mesh cover to prevent bees from destroying the sensors. The sensors were placed at the center of the brood hive, and the data was collected continuously from September of 2017 to end of November 2017. There were short periods when data was not collected, either due to hardware failure, memory storage problems (specifically for audio data) and hive relocation.

Nonetheless, due to distance, everyday inspections were challenging and resolving issues would take time. Software issues were easier to address after a 3G-network connection was added in August 2017. The data collected for the duration of this research is presented later in this chapter. The results show the monitoring variable's measurements and will be further discussed and analysed in detail in the next chapter.

3.2. Data Collection Phase: Measurements and Analysis

The primary stage after design and implementation of the monitoring system is data collection. The results presented and analysed in this research work are used to optimize the sampling rate, power and memory consumption. The data gathered at this stage was used to establish better methods of data processing, storage, and transfer for the extended future research. The first objective with audio data was to find information on frequency and amplitude range of the detectable honey bee communication signals. The frequency response of the audio signal produced inside of the hive was examined to adopt the optimal sampling rate, and resolution. The study of temporal changes in the audio data is deterministic in choosing the samples' duration and period. The optimized sampling rate, resolution, duration, and frequency of samples play an important role in the data storage and transfer requirements. The objective of developing the algorithm in Chapter 2 was to find signal processing methods that can be performed onsite using the RPI's processor. The temporal study of changes in the temperature and RH of the hive is also used to determine the sampling frequency. Using the results and selecting data collection variables is deterministic for the next stage of the research.

In the following sections, the humidity and temperature data collected are presented, as well as the ambient weather conditions. Then, the analysis of sound data using the algorithm from Chapter 2 is presented.

3.2.1. Honey Bee Colony's Temperature and RH

As outlined in Chapter 2, the temperature and RH of the hive are collected using a HIH8131 (Honeywell HumidIcon™) sensor. The samples were collected every 5 minutes. Then mean of the temperature for each hour is computed. The ambient relative humidity and temperature are taken from the Environmental and Climate Change database provided by the government of Canada. The hourly measurements taken by the weather station at the

Vancouver International Airport (YVR) [107] are used as the ambient weather conditions. Starting from October 2017, an HIH8131 temperature and humidity sensor was added at the hive side for ambient measurements. In addition to the hourly temperature and relative humidity, the weather condition of the day (i.e. rainy, cloudy, or sunny) and daylight time (sunrise-sunset) were gathered from online sources [112].

The average temperature measurements from inside the hive for every hour from September 21 to October 13 are shown in Figure 3-2. The hives were relocated after this period and so the measurements were discontinued. For each hour maximum and minimum measurements are also shown to observe the sensor's precision. The overall moving average of the measurements is also plotted. Daily weather conditions are included for observing the colony's activity. In the next chapter, the significance of these graphs is further discussed in details and in their relation to the state of the colony. The climatic measurements are also used to observe the effect of the ambient changes on the colony's condition.

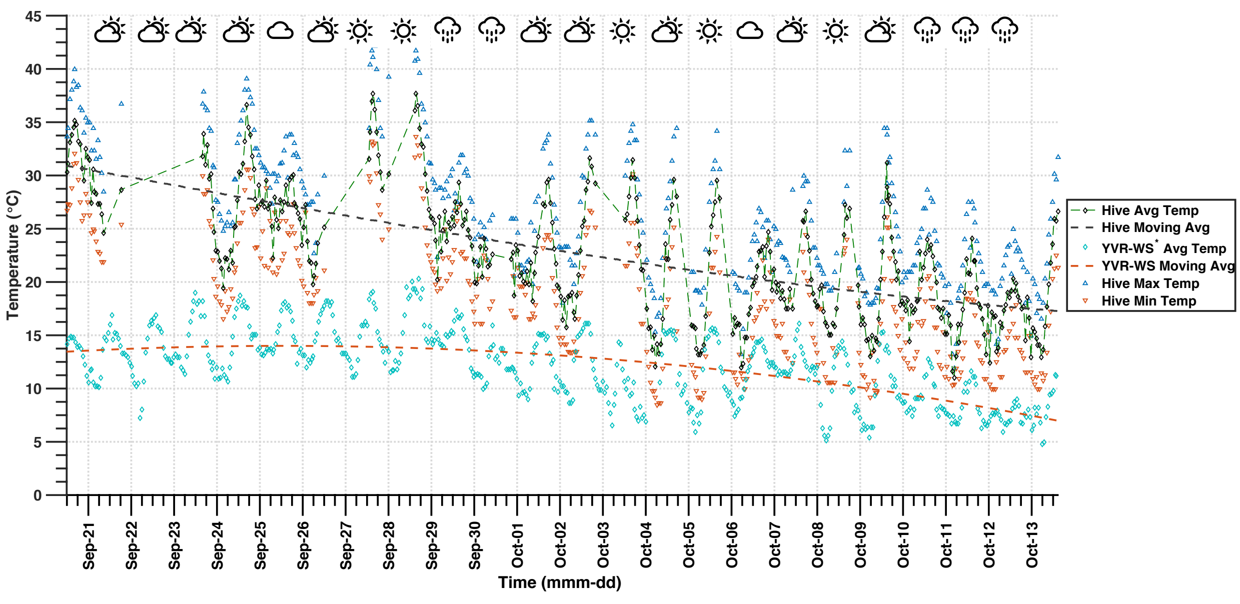

Figure 3-2 - The measured temperature inside a hive and the ambient temperature reported from YVR weather station; September 20th to October 13th, 2017.

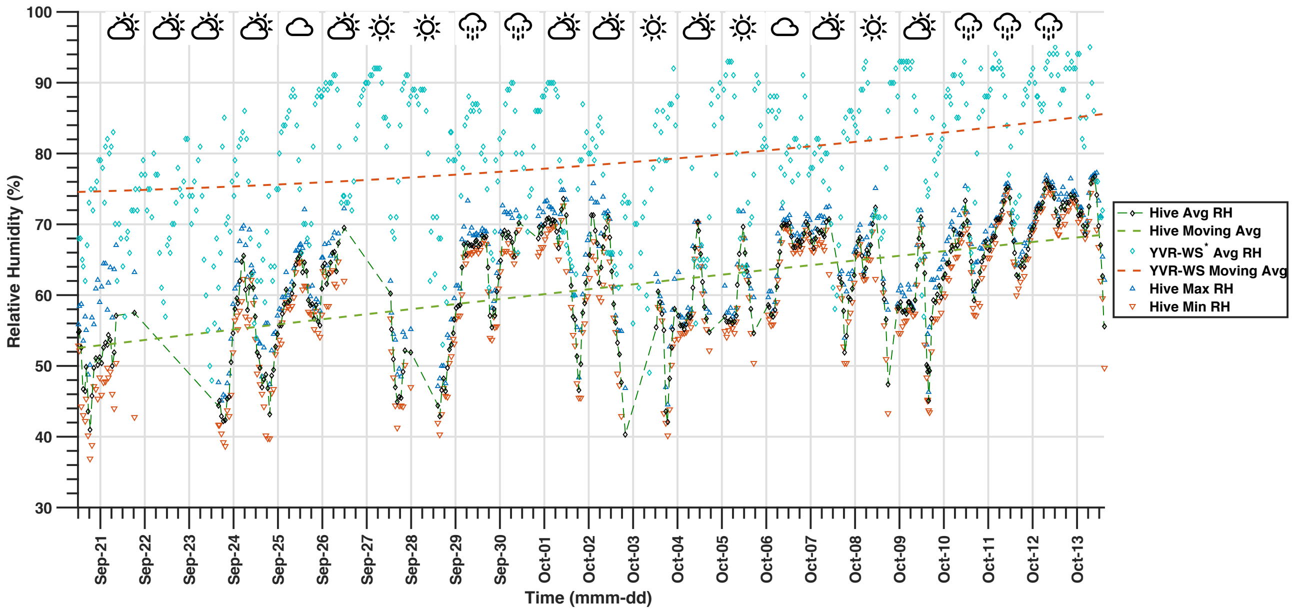

Figure 3-3 - The measured relative humidity inside a hive and the ambient relative humidity reported from YVR weather station; September 20th to October 13th, 2017.

3.2.2. Honey Bee Colony's Airborne Sound Data

As stated in Chapter 2, the sound data offers various types of informative representations that need to be considered. A known factor about the honey bees is the frequency range that they produce and hear airborne sound. As honey bee communication studies indicate, the honey bee communication form, which can be directly detected, are airborne sound and substrate vibration. The change in the sound level in various frequency ranges should be considered as the hive's population and activity varies. In summary, the amplitude-frequency-time components of the sound recorded are analysed collectively and as pairs for assessing the colony's condition.

The sound data was collected continuously for the duration of mid-August to end of November 2017. An omnidirectional microphone with a sensitivity range between 10 Hz-15 kHz was connected to a USB audio adaptor. The recording was done using Audacity software at 44100 samples/sec (Hz) and 32-bit resolution and saved on a SSD hard-drive. Due to storage issues the recording had to be collected every three-four days. The location of the hives and remote access problems caused problems on the data collection at times. The sound was recorded at highest rate (44.1 kHz) as a means of monitoring, i.e. since there was a lack of human observer onsite at all times, listening to the sound recorded helped as a tool of audio observation. After analysing the data, observing the sound spectrum and considering the Nyquist theorem, a lower sampling rate was established for data collection (8000 kHz), which sufficiently includes all the useful information regarding the colony's communication signals.

As discussed in Section 2.3.1, to analyse the sound data gathered from the hive first the frequency-time-amplitude components of the sound should be observed. To observe the signal frequency components, the best tool is the fast Fourier transform (FFT) of the signal. The frequency-amplitude pair is a great tool for investigating the components of the data. However, the temporal changes of the data are not visible in the signal FFT. Therefore, the spectrogram of the data is used to show all three components of the data, i.e., frequency-time-amplitude. These types of visualization tools are sufficient for proof of concept and observation of the sound signals.

Communication Signals: Single Bee Piping

The airborne signal transmission and perception by honey bees have been studied as a single bee or as a colony through various methods, such as sound recording [40], [113], and laser vibrometer [33], [36]. These studies mostly involve analysing bee communication signals, such as waggle dance, swarming, piping, and other bee signals that we looked at in Chapter 1. For instance, the following is a signal that was recorded when a single bee was performing her dance close to the microphone inside the hive. The spectrogram and the frequency response of the recorded signals are displayed.

The first recorded sound, shown in Figure 3-4, is a honey bee piping sound produced by a scout. The piping signal recorded consists of six distinct signals with an average length of 1.1 seconds repeated every 5 seconds. The signals have a fundamental frequency 430-470 Hz with higher harmonics. The spectrogram of the recorded signal is plotted using a Hamming window with 2000 samples (45.4 msec). The FFT of each piping signal is taken separately and is shown in Figure 3-5. The characteristics of each pipe are summarized in Table 3-1.

Table 3-1 - Characteristics of piping signals A-F shown in Figure 14.

Signal	Duration (sec)	Fundamental Frequency Bandwidth (Hz)
A	1.06	420-490
B	1.01	450-470*
C	1	440-460
D	1.3	450-480*
E	0.7	420-440*
F	1.2	450-480

* Signal was noisy for lower frequency and was calculated based on higher harmonics.

The piping signal communicates different information. For instance, Schlegel *et al*. obsevered the piping signal produced by scouts before swarming [40]. Generally, detecting this type of signals in a colony is not the aim of the monitoring system, since it is nearly impossible to distinguish single bee's signals in the colony's sound. Even when Schlegel et al. collected their data they had to follow the honey bee scouts individually and record their piping sound. Their method was helpful in understanding the honey bee's communication signals, however it will be difficult to utilize in colony monitoring, and it does not serve our purpose.

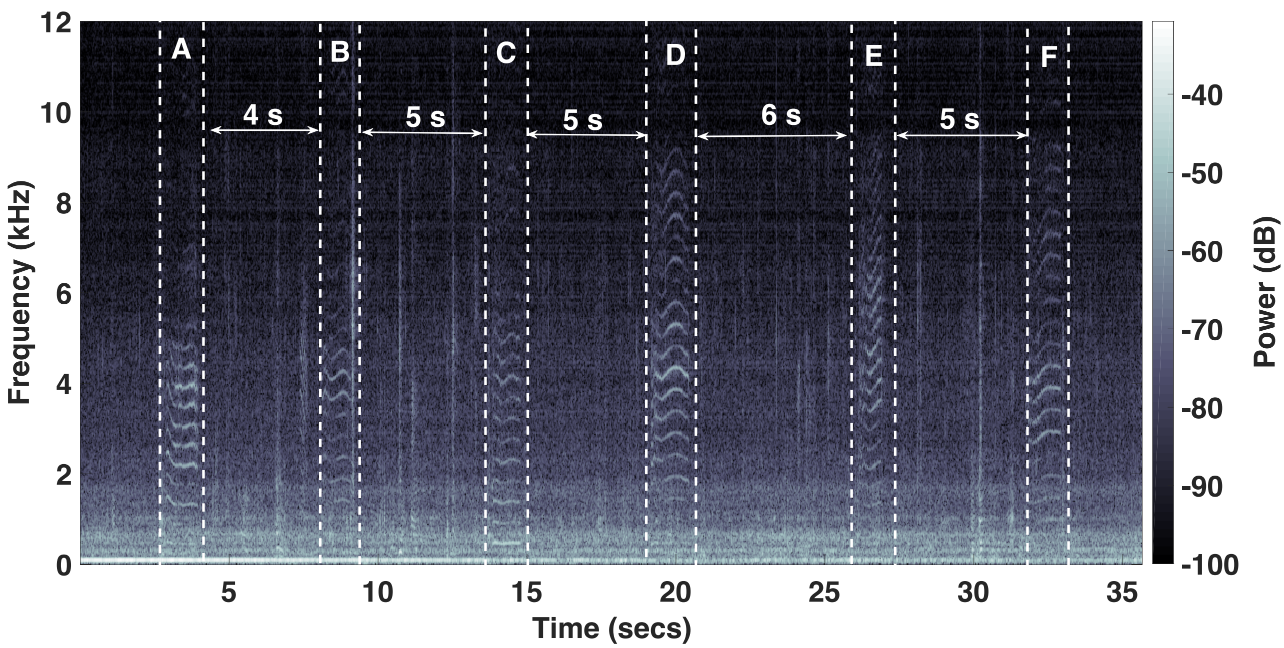

Figure 3-4 – Spectogram of the recorded piping signal of a single bee.

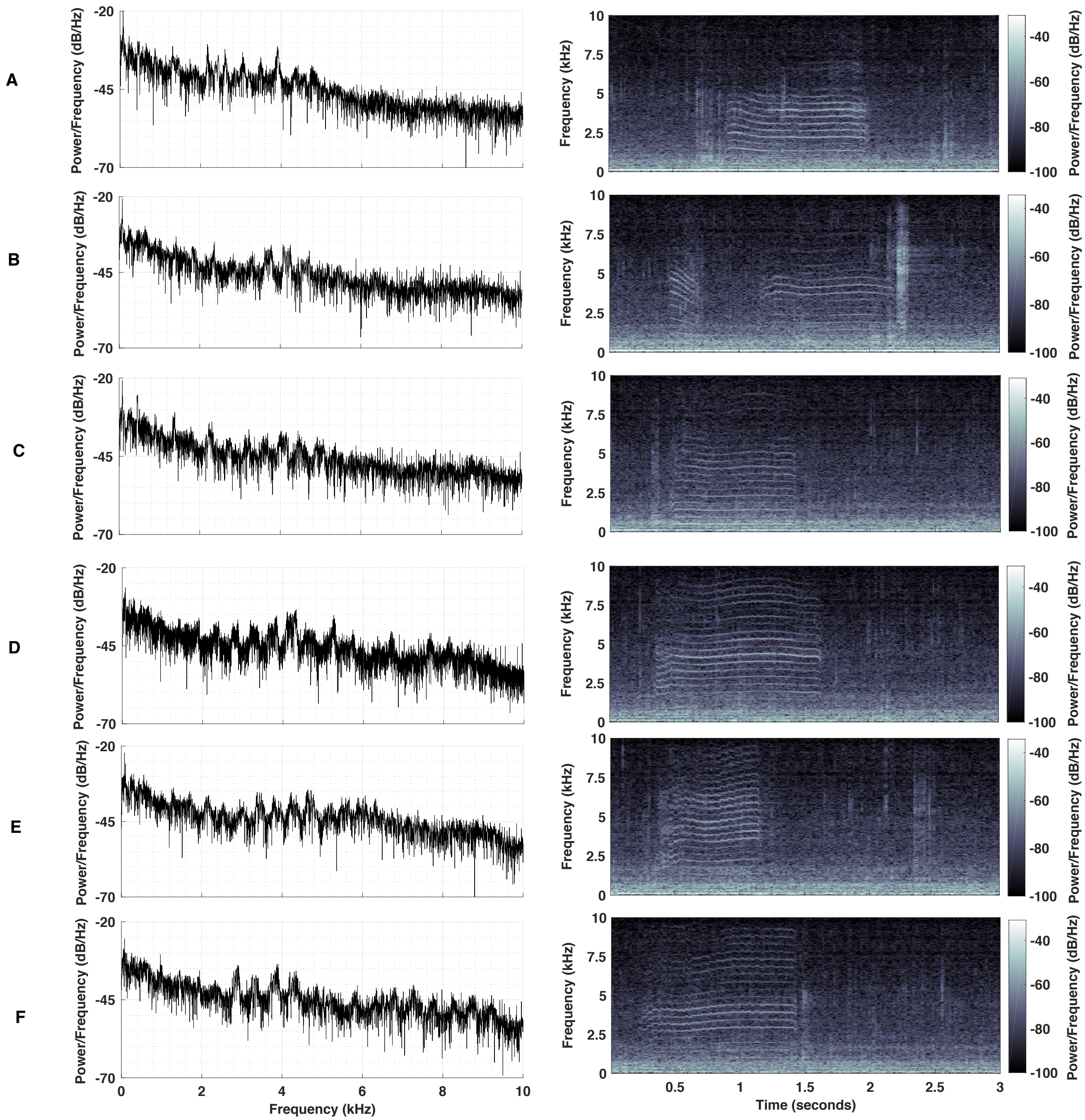

Figure 3-5 - Spectogram and FFT of piping signals A-F.

Finding this type of singular signals is difficult when collecting data from the hive. Nonetheless, plotting the FFT and spectrogram of the signal for various samples shows the hive's audio signal range. Upon inspection, it is clear that most of the signal power in between 100 and 500 Hz. From models in literature, it is understood that the majority of signals have a frequency between 100 -1000 Hz range, with higher harmonics. Therefore, to find the circadian rhythm of the sound produced by the colony or their responses to an event, it is better to focus on the temporal changes in the amplitude of the signal for these frequency ranges. The method introduced in the previous chapter for sound processing is used to observe temporal changes of signal power in various bandwidths.

Audio Signal Power Analysis

The temporal profile of the sound data's power spectrum is needed to study the state of the colony. The sound data is analysed based on the suggested algorithm in Chapter 2. The data was collected continuously for this period, and it is sampled according to the algorithem, presented in Section 2.3, at various time intervals. In the next chapter, the optimal period between samples are examined to reduce power and memory consummation while maintaining important information.

The signal power was computed for various bandwidths of each sample. After close observation, it was clear that most of the signal power was in the lower ranges (10-500 Hz) as literature models suggest. Higher harmonics of the signal are not shown here since they do not provide any new information. The signal power of various frequency ranges was computed for 2-second samples of every 5 minutes. Then the sample is processed using the proposed algorithm after a comb notch filter (at 60 Hz for ground loop noise). The samples average for every 10 sample is computed, and the new sample is only considered if it is within 5% range of the latest computed mean. The respective processed data are shown in Figure 3-6 to Figure 3-11.

The data presented in these plots show the signal power for various bandwidths. The frequency range between 10-500 Hz is broken into 100 Hz bandwidths. These plots also include sunset and sunrise times. In the next chapter, the results are discussed in more detail.

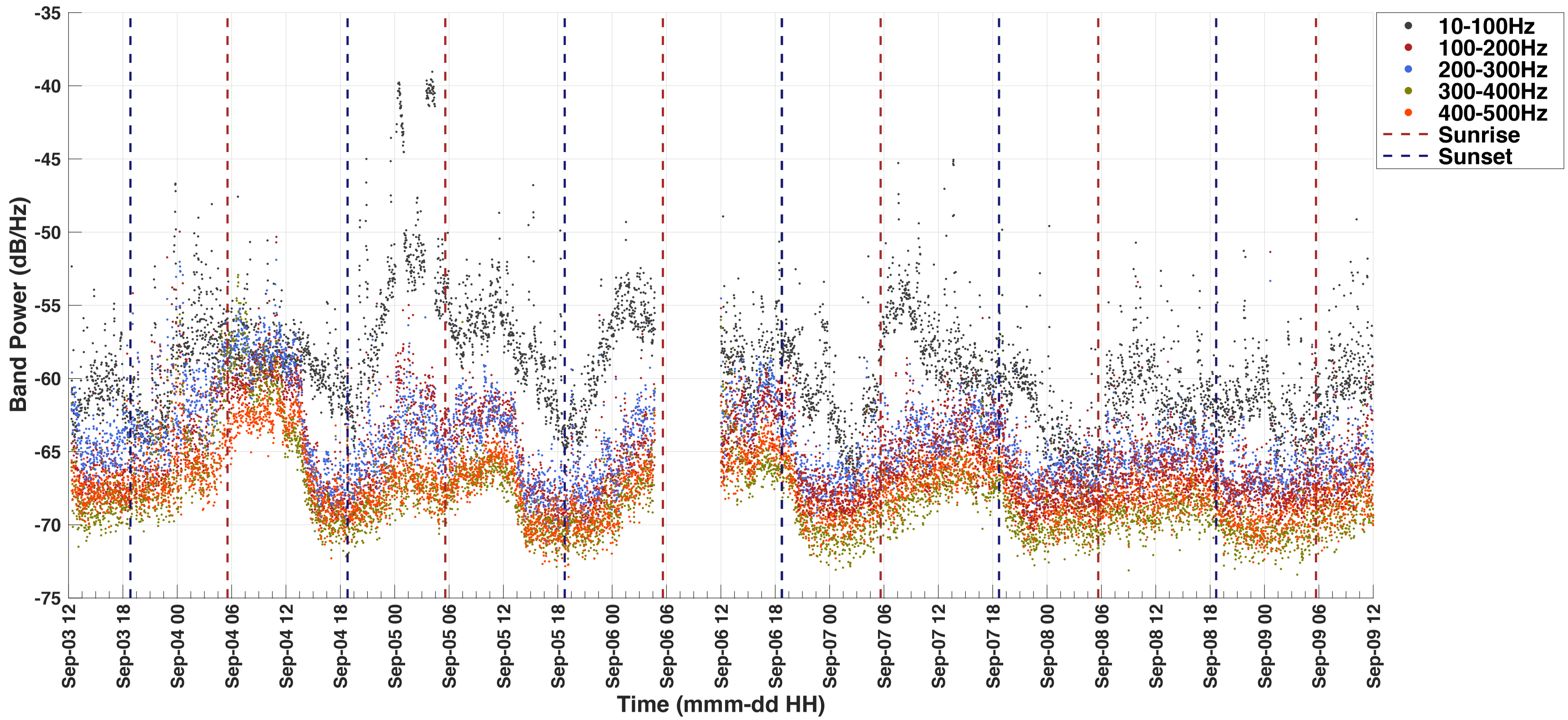

Figure 3−6 - Sound power profile of various bandwidths (September 3-9).

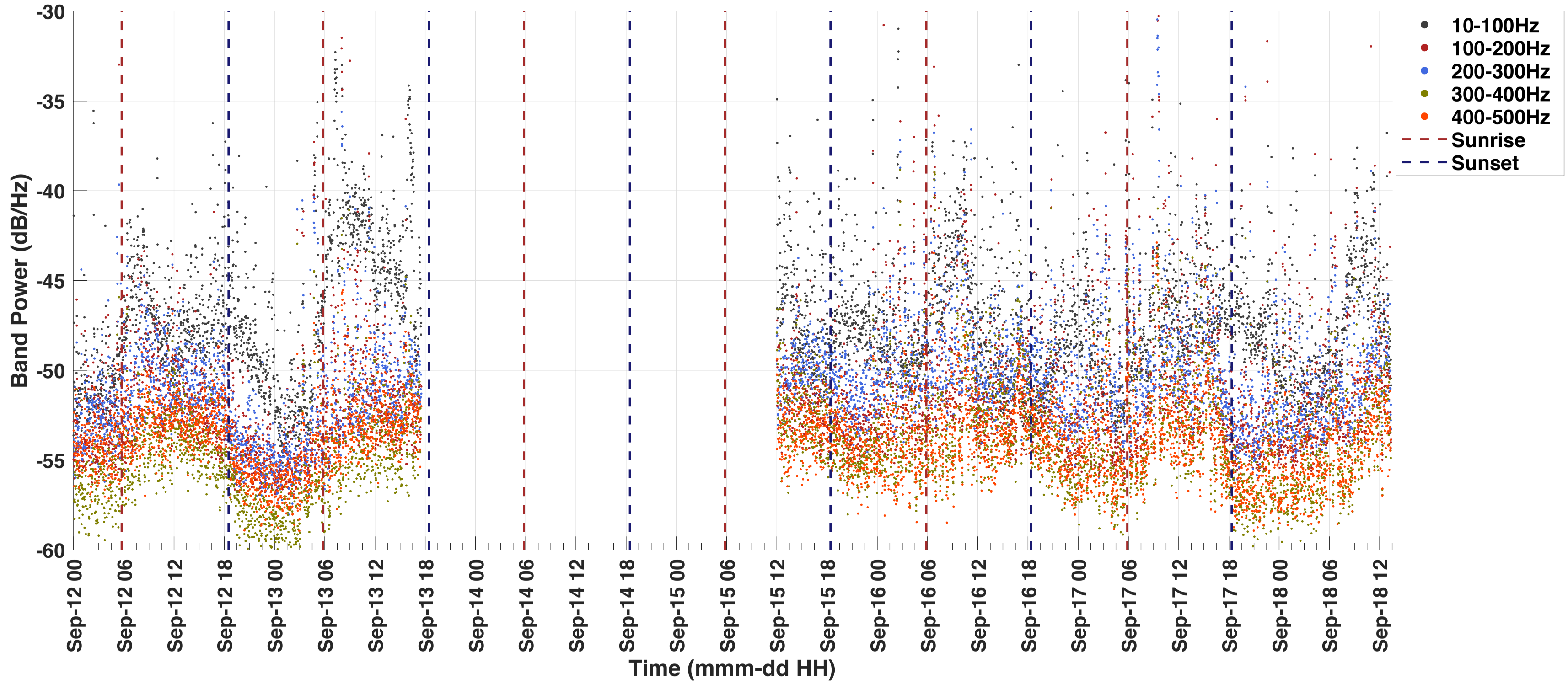

Figure 3-7- Sound power profile of various bandwidths (September 12-18).

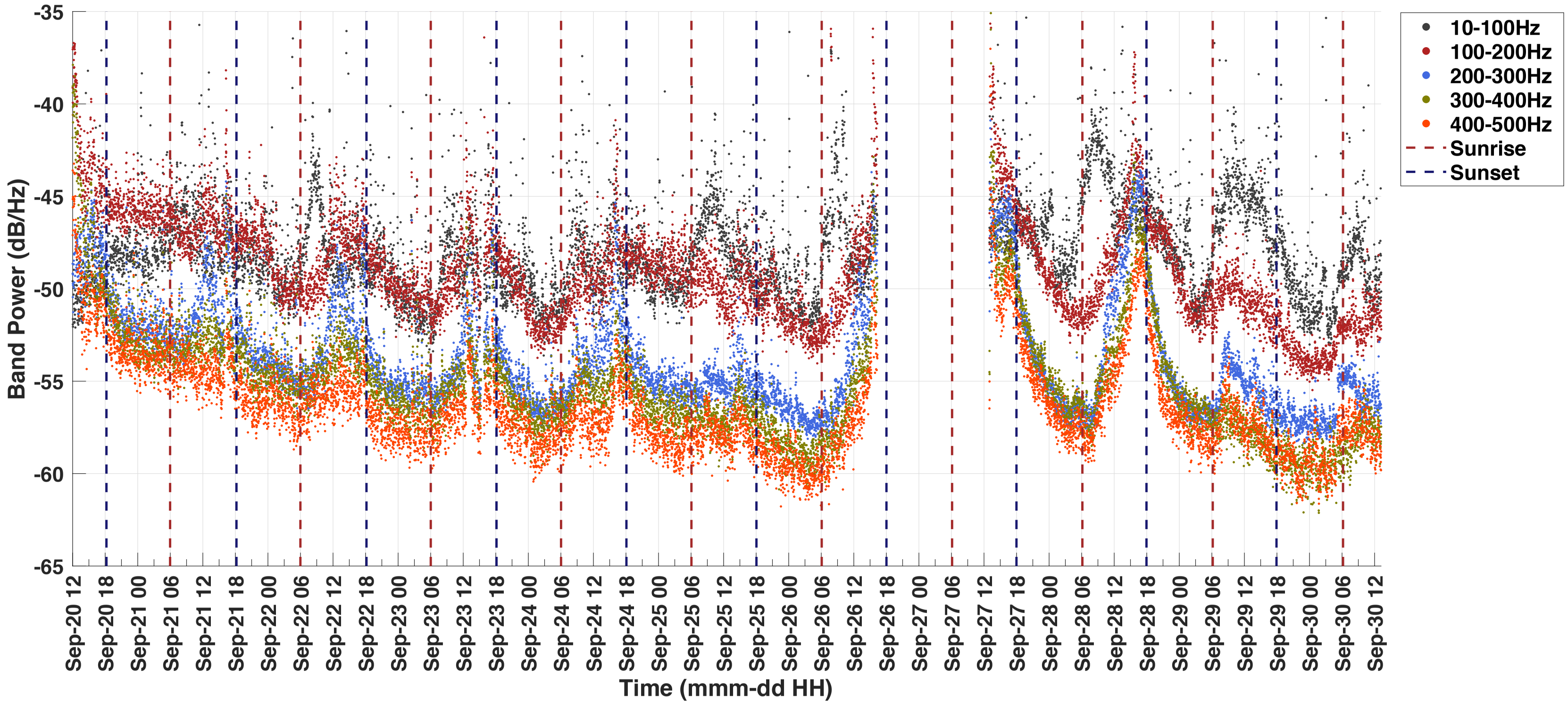

Figure 3-8 - Sound power profile of various bandwidths (September 20-30).

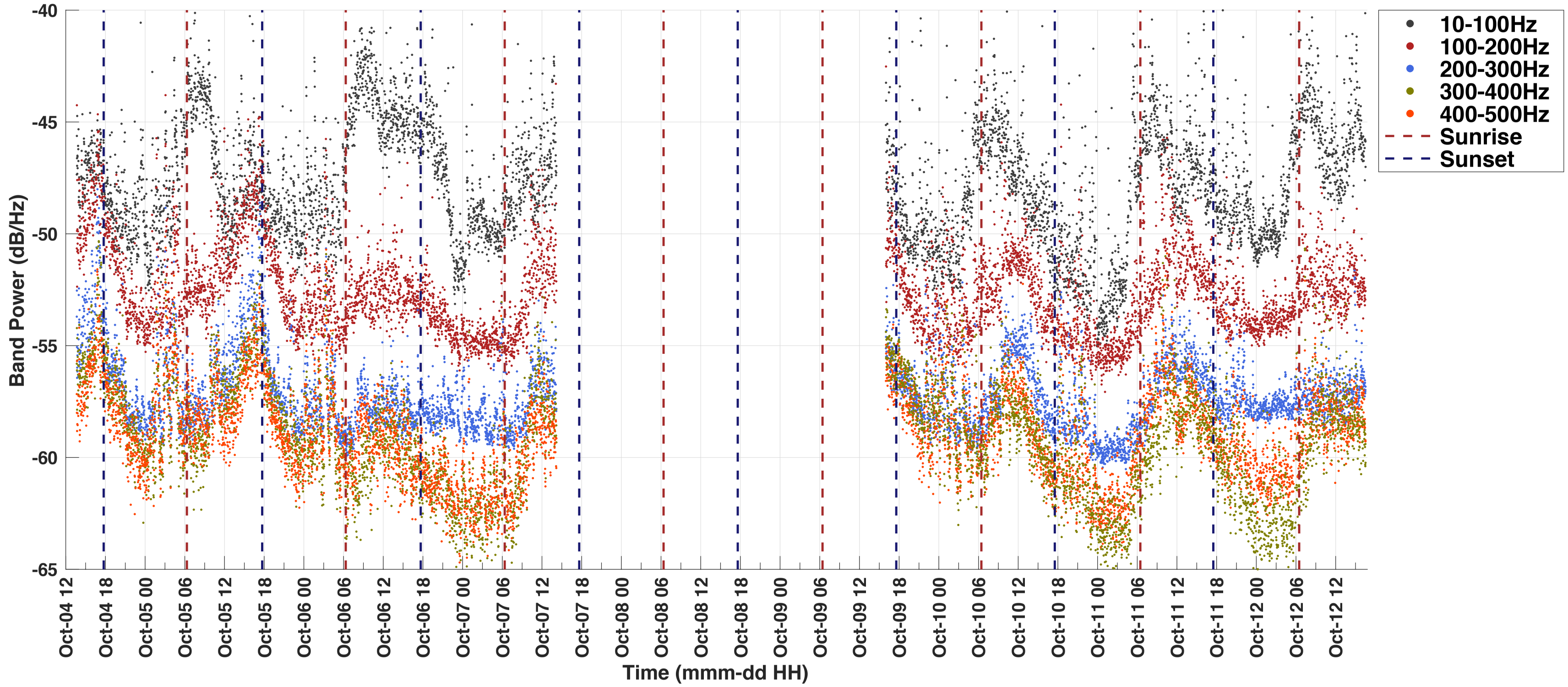

Figure 3 - 9- Sound power profile of various bandwidths (October 4-12).

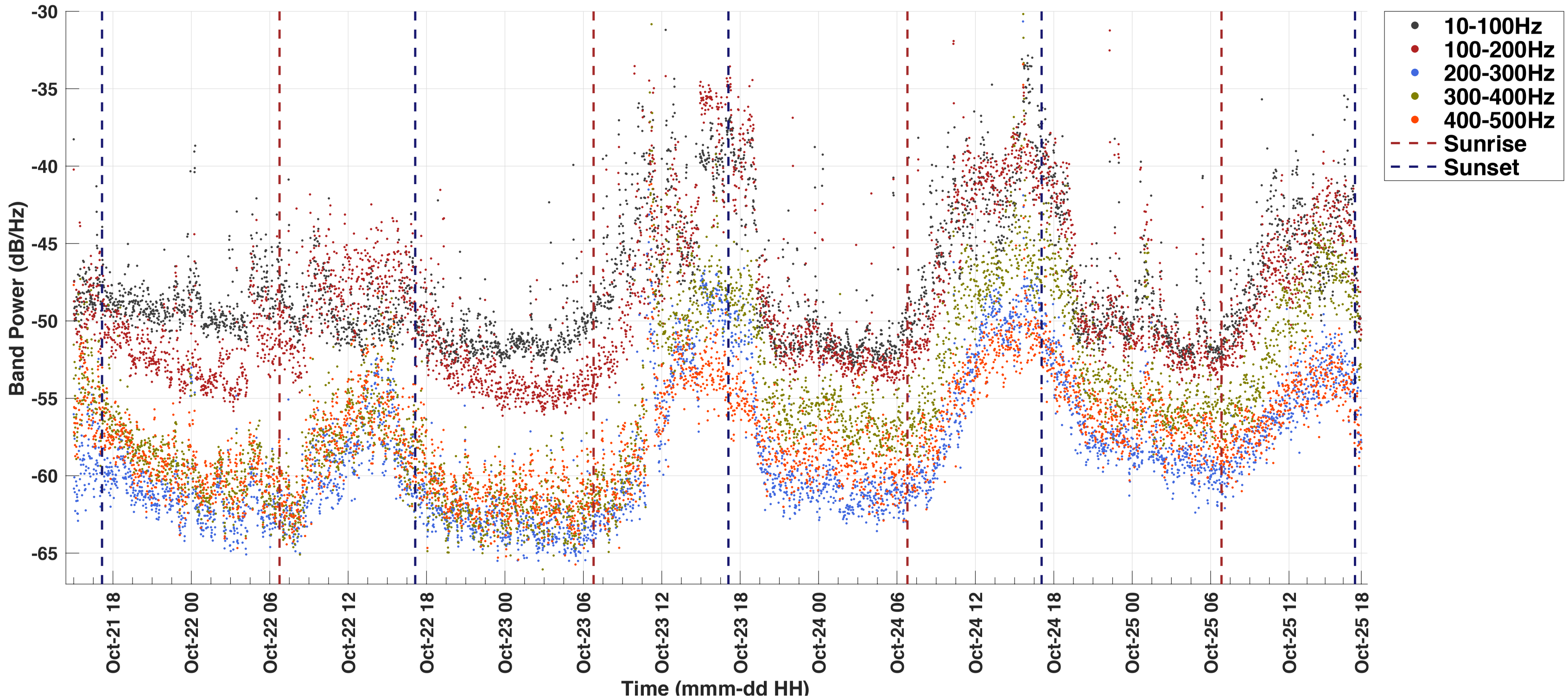

Figure 3 -10 - Sound power profile of various bandwidths (October 21-25).

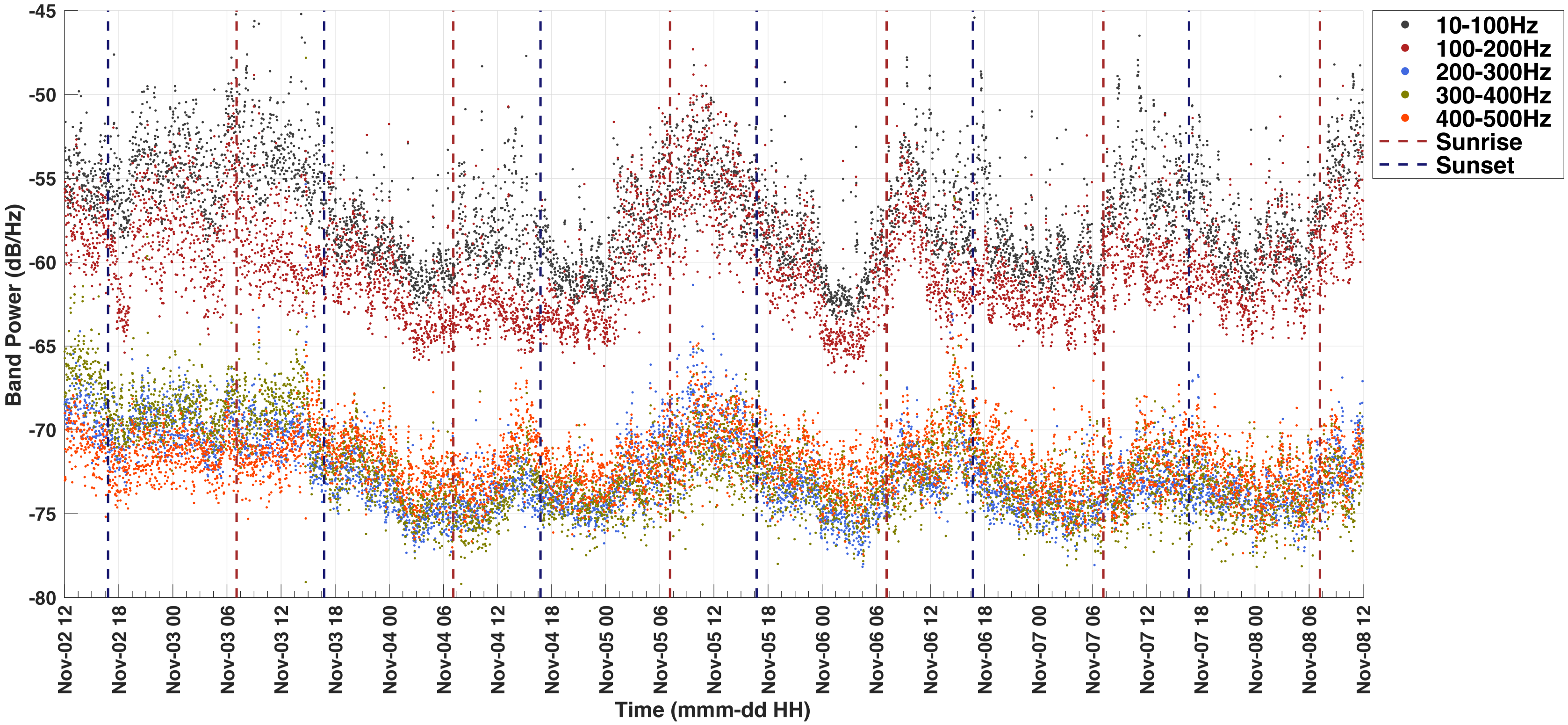

Figure 3 -11 - Sound power profile of various bandwidths (November 2-6).

3.3. Chapter Conclusion

In this chapter, data collection results are presented.

- The temperature and RH data for each day was plotted with an hourly rate. The plots also include the daily weather condition (i.e., cloudy, sunny, rainy), as well as the reported ambient temperature and RH by the YVR weather station.
- Audio data is presented for a single bee's piping signal.
- Audio data is processed using the algorithm developed in section 2.3.1. Sound data is presented for known frequency ranges of honey bee's communication signals.
- Sound data frequency range is consistent with the literature. Frequency range of the collected data is lower than 1 KHz and higher harmonics.

In the next chapter, the data presented in this chapter are further discussed. The honey bee colony's state is examined based on a collective observation of sound, temperature, RH, and ambient weather.

Chapter 4.

Discussion

In this chapter, the data presented in Chapter 3 are systematically examined. These observations will help in the future development of the honey bee monitoring system. The analysis discusses both the temporal and frequency changes in the sound data of the colony, and the temperature, and RH inside the hive. It also indicates the ambient factors such as temperature and RH, plus the weather conditions such as rain, or sun. The daylight duration based on sunset and sunrise times are also considered. First, the characteristics of the temperature and humidity plots are studied. Next, the sound data power level profiles are discussed. Finally, the correlation between combinations of these data and any external stimuli are examined in relation to the response and state of the colony.

4.1. Temperature and RH

In the temperature measurements shown in Figure 3-2, there are various factors that need to be considered. First noticeable observation is the circadian rhythm. The temperature of the hive follows the ambient temperature in a sinusoidal pattern. The same pattern is also visible in the RH measurements in Figure 3-3.

In Figure 3-2, it is evident that the colony has a higher temperature than the ambient measurements. While the ambient temperature drops below 10°C, the hive's temperature is kept a few degrees higher. This fact is evidence of the colony's activity inside the hive. It should also be noted that the average temperature of the hive does not exceed ~35°C and it does not drop below 10°C. The thermoregulation of the hive highly depends on the hive population. However, the hive's temperature is always within the expected range for honey bee thermal models described in [59] and [67]. The measurements during winter are below the expected values reported in literature (between 32-35°C). However, it is expected that the proximity of the sensor to the brood clusters, especially in winter when the brood size shrinks, affect the measurements.

The moving average of the temperature is also shown for this period. It can be seen that the hive's average temperature decreases more rapidly from September to October compared to the drop in the ambient temperature. This is attributed to the seasonal changes and the change in the colony's formation and activities when wintering of the brood begins.

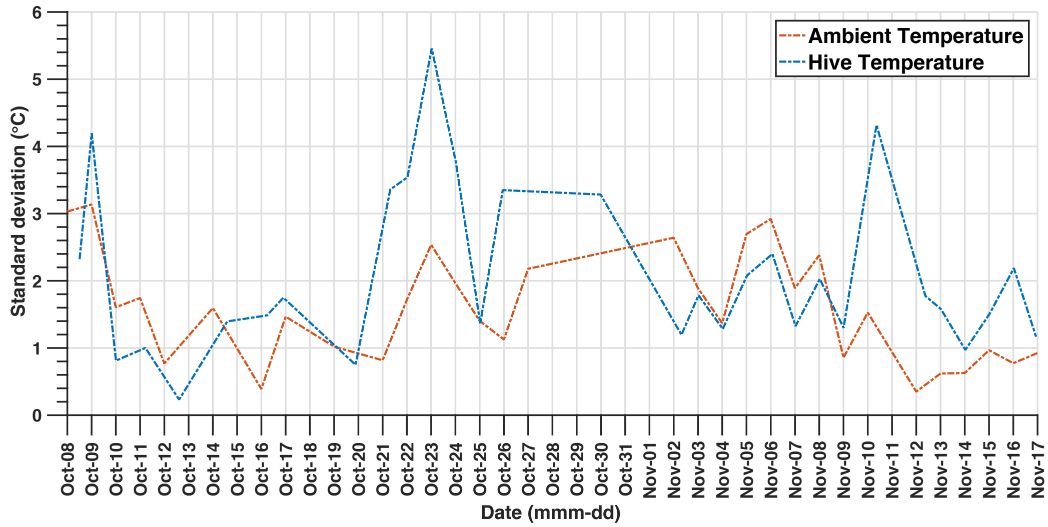

Figure 4-1 - Comparison of daily standard deviation inside the hive vs. ambient for temperature.

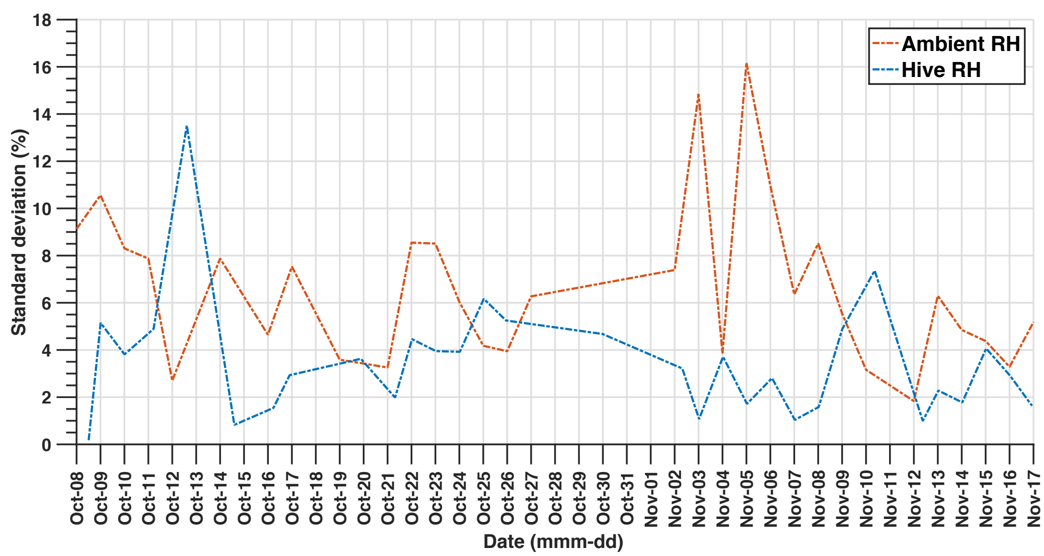

Figure 4-2 - Comparison of daily standard deviation inside the hive vs. ambient for RH.

In Figure 4-1and Figure 4-2, daily standard deviation of temperature and RH for the hive and ambient values are computed and shown respectively. The standard deviation of the hive's temperature differs slightly from the standard deviation of the ambient temperature. This difference is due to both measurement errors and the colony's activities. Most of the variation in the temperature between day and night is affected by the ambient temperature changes. At the same time, the hive's activities during the day increase the temperature inside the hive.

The standard deviation for the hive's RH is slightly less than the standard deviation of the ambient RH. The hive's RH peaks on rainy days. However, the hive is an enclosed space, and the temperature is comparably higher inside the hive. Subsequently the overall RH inside the hive is always lower than the ambient variations. In Figure 3-3, the hive's RH is within an expected range (between 40%-80%). However, as it was discussed in section 1.2.4, the humidity of the hive is not regulated as much as its temperature. The average RH has an overall increase from September to October as the temperature decreases and the rainy season begins. This is also an indication that the brood and colony are decreasing in size and the ambient factors are affecting the measurements inside the hive.

The temperature and relative humidity of the hive can be related to the colony's condition when more detailed observations of the colony are made by bee specialists. Considering the discussion on temperature and RH so far, clearly, there are a few aspects that need to be considered while making observations on the colony's condition. The following remarks should be considered while analysing the temperature and RH of the hive relative to known hive conditions:

- Effect of ambient temperature and RH on the daily activity of the colony
- Effect of seasonal changes on the colony.
- Effect of sunrise and sunset on the colony's activities.
- Effects of colony population.
- Sensor's position with respect to brood cluster.

In section 1.3, it was stated that using one type of measurement for monitoring the colony is not conclusive. There are many external attributes that can affect temperature and humidity measurements. Next, the sound signal data, presented in section 3.2.2, are discussed.

4.2. Airborne Sound

Sound data provides further insight into the state of the colony. The algorithm developed in section 2.3.1 and implemented in section 3.2.2 is used to observe this information. The colony's population, circadian rhythm, and special events directly affect the sound level variations and/or frequency shifts. Therefore, it is important to closely inspect the temporal change of the sound power level inside the hive. Daily and monthly variation relative to weather condition, seasonal changes and responses to human factors such as inspection, feeding, and treatments in winter are also observable.

After empirical analysis of the data presented in Figure 3-6 through Figure 3-11, it is evident that the hive's sound level has a repetitive sinusoidal pattern during the hive's daily activities. The sound power level of the hive increases rapidly until the late afternoon, and later it declines after sunset. Although the same pattern is observed in the colony's sound power level daily, the profile of these patterns varies. These differences could be attributed to a sudden change in the state of the colony but some of these factors are unclear at this stage. Adding a human observer will later help identifying these states and their conditions.

These similar and repetitive variations indicate that the implemented algorithm is presenting us with valuable information. For instance, on September 27, the hive was opened for sensor inspections. Meanwhile, the sound recording was continued while the hive was open. The sudden increase in the sound level inside the hive is the response to intrusion, which also continues to the next day (shown in Figure 3-8). As we discussed in Chapter 1, the colony activities are disrupted after inspection. In Figure 3-10, the profile of the sound during the wintering period is shown. On October 23rd, the hive was tested for Varroa mites, on October 24th it was fumigated with oxalic acid (used as a miticide against Varroa mites), and on October 25th the hive was fed with syrup. During all of the three days there is an increase in sound level compared to October 22nd. This increase in sound level is due to intrusion but any of the mentioned events can also be a trigger for the increase in colony activity.

In addition, following graphs show the approximate integral of daily signal power at each frequency range, computed using the trapezoidal method. As it can be seen in Figure 4-3, the signal power for all ranges except 400-500 Hz increases by 5dB from October 22nd

to October 23rd, and remains relatively high until in drops again on October 25th. As mentioned, these are the days that the hive was inspected and treated for Varroa mites.

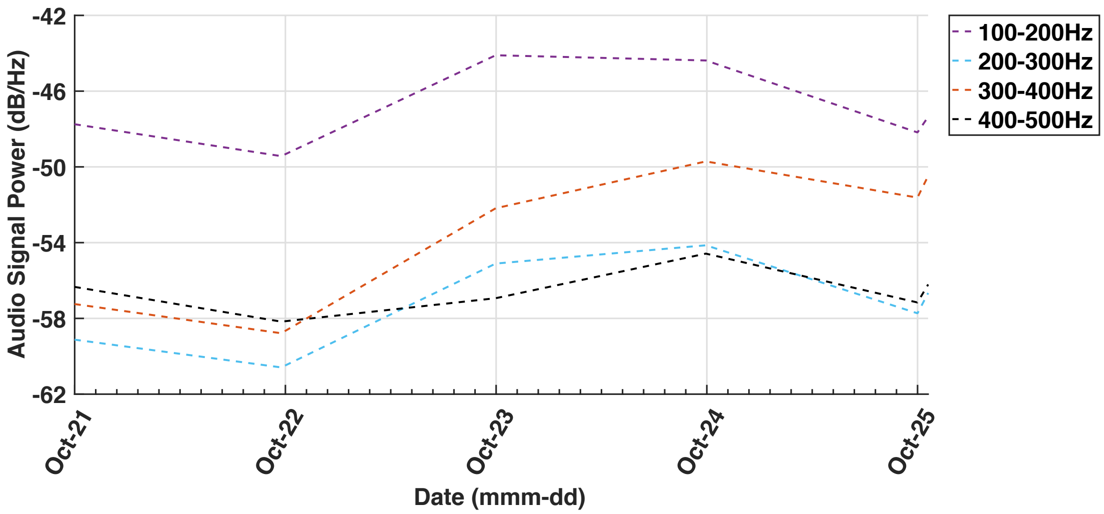

Figure 4-3 - October 21–25 : Daily signal variations for each frequency range.

Similarly, in Figure 4-4, the net power of each frequency range is shown for a week in September. The known stimulus is that the hive was opened on September 27th. The sudden increase in the net power compared to the days before shows the effect of intrusion on the colony's sound power level. The sound level, for the various frequency ranges, decreases and returns to the initial values. These observations of the overall sound level can be used as an indicator of colony's activity. The aim of the support system will be to connect the dots between how the colony's health and activity affects the changes in the sound power level.

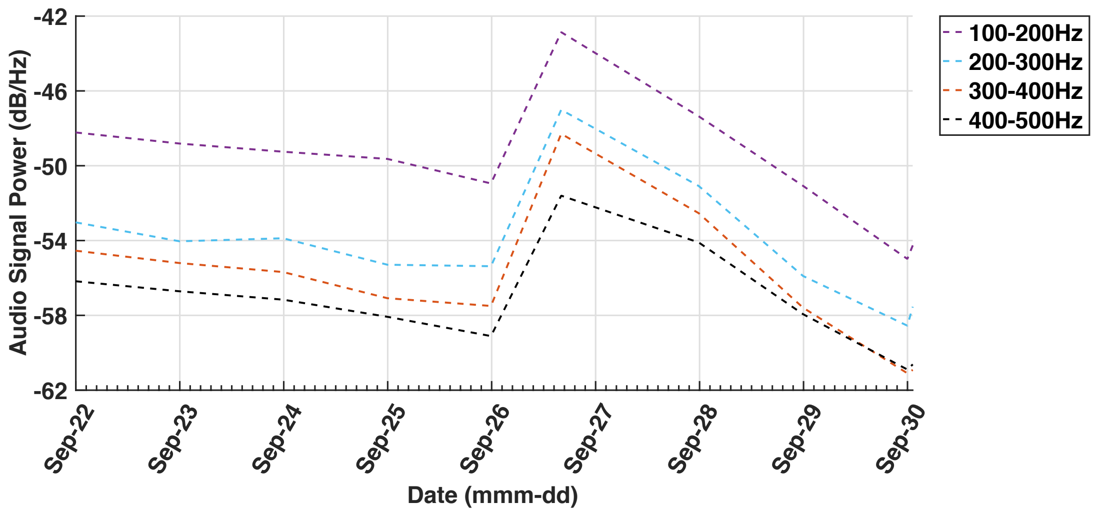

Figure 4-4 - September 22–29: Daily signal variations for each frequency range.

4.3. Collective Observations

Examination of each physical measurement shows compelling results. In the previous section, the empirical analysis of the monitoring variables was discussed. However, a combined observation of all the attributed data for each day provided a more comprehensive analysis.

In Figure 3-9, on October 5th the hive's sound power level increases and decreases similar to other daily profiles. However, the sound level on October 6th remains fairly the same, and has less amplitude variations. A close inspection of the temperature, RH and weather conditions reveals that on the 6th the hive's temperature is lower and the weather is cloudy (foggy), whereas the 5th is sunny. October 7th is partly cloudy, and similarly, the total sound power level is less than the days before. Meanwhile, on 8^{th} when it is sunny, the hive's total sound power level increases. The sound power level drops for the following days again when it is raining. This observation can be correlated to the hive's activity on cloudy/rainy days compared to sunny days. The seasonal changes are also present in the collected data. As described in section 4.1, the average temperature decreases, whereas the RH increases while the colony resizes for overwintering period. Concurrently, in Figure 3-6 through Figure 3-8, sound power level changes during the daily activities is more compared to a smaller winter brood Figure 3-9 through Figure 3-11.

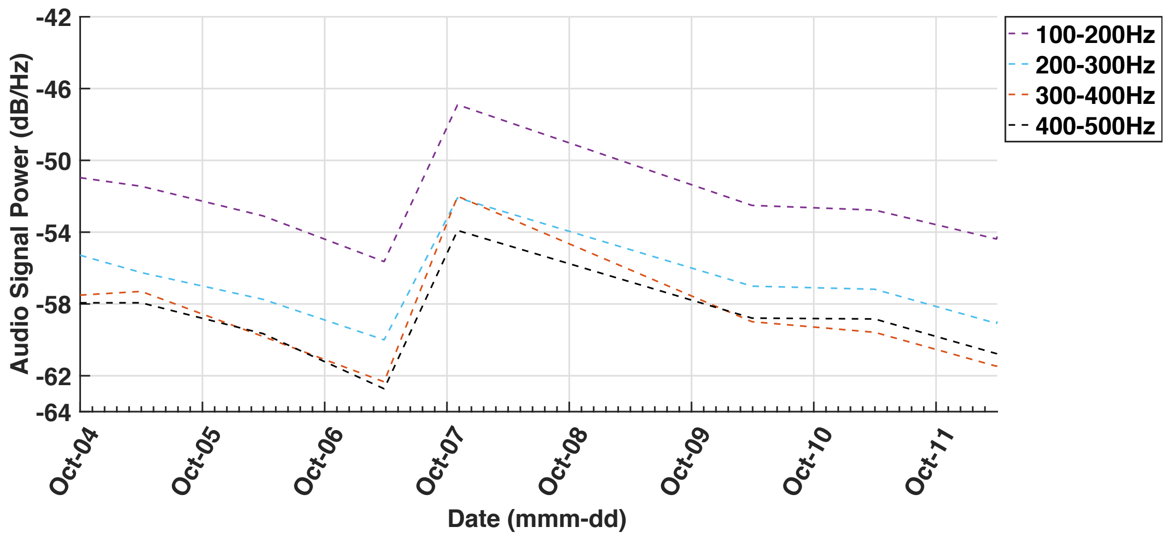

Figure 4-5 - October 5–12 : Daily signal variations for each frequency range.

The detailed analysis of the colony's state can be performed based on known models. Here we have only scratched the surface of understanding honey bee through physical measurements. Additional studies are required, utilizing the developed hardware, measurement, processing, and analysis in this research.

4.4. Data Collection Optimization

In order to reduce power and memory consumption, the data sampling rates should be optimized. In Figure 4-6, the signal's "band-power" for 200-300 Hz range is chosen for 2 consecutive days. The Gaussian Process Regression (GPR) of MATLAB® is used to create a mathematical model for the data pattern. The GPR reduces the noise in the profile of the sound band-power and gives a better view of sound power level variations. The time frame between samples is increased, and the model generated for each sample is shown for this set of data. Only a fraction of the data is used for this optimization task.

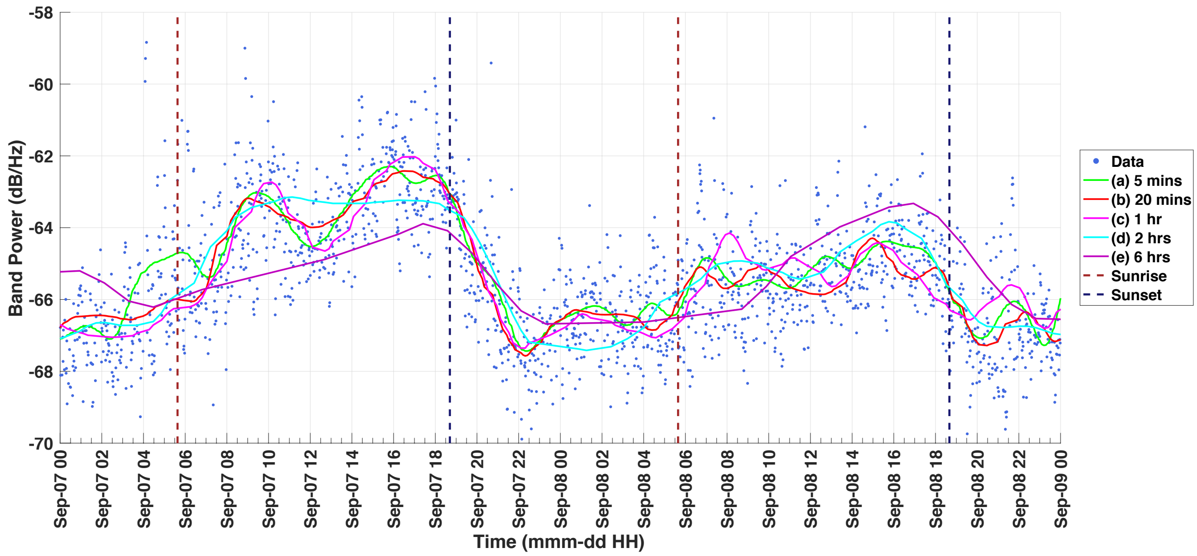

Figure 4-6 - GPR model for sound power level profile (200-300 Hz) using various time interval.

By comparing models presented in Figure 4-6, the optimal frequency of samples taken can be determined. Empirical analysis of these plots shows that, as the period between the samples is increased from 5 minutes to 6 hours, the GPR models vary in profile details. Each model exhibits the same general pattern of increase and decrease during the daily activity of the hive. Lower time frames between samples show fine scale variation of the sound profile during the day. As the time frames increase the profile is coarser and details are missing. Longer observation of the colony is required to determine which details are relevant. Nevertheless, it is depicted that taking samples every hour can also show the majority of the sound profile without missing details. Depending on the study and the power requirements the time frame can be chosen accordingly. It is evident that a larger dataset is required for generating a suitable decision support system.

4.5. Chapter Conclusion

In this chapter, the observations presented in Chapter 3 are examined in more detail. The data are studied collectively to investigate the colony's state for designing the support system. Our main findings are as follows:

- The relative changes in temperature and RH measurements inside the hive compared to the ambient variations can show the daily activity of the hive.

- Seasonal changes are also present in the temperature and RH data. There is a faster drop in the moving average of the measurements inside the hive compared to ambient values, which represents the start of the colony resizing the brood for winter.
- Higher temperature and, comparatively, lower RH inside the hive in winter indicates the presence of the colony.
- The comparison in the variations of the sound power level for daily activity of the colony led to observation of known colony responses to events such as intrusion.
- It is observed that the combined information contained in temperature, RH, and sound measurements is crucial in assessing the colony's condition and responses.
- Statistical analysis of the sound data using a GPR model allows us to extract dominant patterns in data and optimize data collection frequencies.

Chapter 5.

Conclusion

In this thesis, a honey bee hive monitoring system was developed, and implemented. The system was then deployed on a honey bee colony in the field where data was collected and analysed. The aim of the analysis was to obtain fundamental information regarding the relationship between the state of the honey bee colony and the monitoring variables. The research's summary is described in this chapter, followed by a discussion on future directions of research.

5.1. Summary and Contributions

The aim of the work carried out in this thesis project was to develop and implement a monitoring system to continuously observe the colony's state. The monitoring system was designed in various iterations of design and hardware assembly. Software for on-site measurement and data transfer, and software for data analysis and visualization were studied. Below we present a more detailed summary of these design steps.

➢ **Colony observation parameters**

- To monitor honey bee colonies, the measurable physiological activities of the colony were identified by a thorough review of literature.
- Existing commercial or research monitoring systems and their measurement variables were also considered.
- The measurement parameters were examined closely to identify their usefulness in the analysis of colony's condition and health versus their memory, cost and power requirement.
- It was concluded that, within the constraints of the system, sound, temperature, and relative humidity are most effective in colony monitoring.

- **Hardware design and implementation**
  - Sensor requirements were identified based on literature, such as temperature range, frequency range, and respective variations in the colony's response to events.
  - Various iterations of sensor placement methods were tested to finalize an effective prototype and minimising modifications to the hive.
  - A sensor box was designed and implemented using 3D printing to encase the sensors. The sensors were wired to a central RPI unit for data collection.
  - The system was equipped with a 3G-network connection for remote control, data collection and data transfer.
- **Data collection**
  - Continuous data collection was performed on a bee hive in the field for the duration of September to November 2017.
  - The temperature and RH data were observed at the center of the brood, where most of the thermoregulation and activity of colony was expected.
  - An algorithm was developed for sound data collection and processing. The algorithm was used to extract useful information regarding the state of the colony.
  - The sampling rate was optimized using the collected data to reduce the data consumption and transfer requirement.
- **Data analysis and colony state observations:**
  - The temperature and RH measurement data along with the processed sound data were studied for various days and durations.
  - The colony's temperature and RH circadian changes were observed in relation to the daily ambient variations. From these data, it was observed that these measurements could be used to indicate the presence of the colony and changes in brood from summer size to winter size.

- The single bee signal was observed in the audio data. The single bee's signal matches closely with what literature presents as the piping signal. This confirms the accuracy and consistency of the monitoring system.

- The detection of the single bee's signal presents a clear observation of the honey bee signal frequency range. It was also observed that each signal consists of a frequency bandwidth in each pipe.

- Processed audio data revealed daily patterns in various frequency ranges. The sound levels changed as the colony's activities heightened during the day and the colony stopped most of its communication signals at night.

- The audio data further showed variations in sound level during various events. Daily variation in the sound data was an indication of the colony's condition. For instance, when the colony was disturbed there was a sudden increase in the sound level which continued to the next day. This increase, depends on the size of the colony and time of year as is evident in the difference between October (Figure 4-3) and September (Figure 4-4) measurements.

- It was observed that certain events related to the state of the colony could only be detected by considering the combined information in the three monitoring variables. For instance, certain variations in the sound data were attributed to rainy or sunny days as indicated by the temperature and RH measurements (see Figure 4-5).

The following is the summary of the primary findings associated with the condition, state and health of the honey bee colony on which the monitoring system was installed.

- The drop in moving average of the temperature and increase of RH level from September to November shows the change in the size of the brood as the brood entered the winter brooding period. During this time the colony resized to a smaller cluster as shown in Figure 2-5.

- There was a clear relationship between the daily changes in temperature and RH inside the hive compared to ambient values. However, when the ambient temperatures were low, the colony regulated the brood's temperature at higher values. This indicates that a healthy colony performs climate regulation inside the hive.

- The band-power computed for lower frequency ranges of the sound data (i.e., 10-500 Hz) shows a daily pattern in the sound of the hive. The sound level increased at sunrise, peaked at noon, and decreased at sunset. This profile of the sound level depicts the communication signals of the colony and the activity level of the bees, which is in-line with prior knowledge of honey bee biology.

- The sound level variation between consecutive days indicated changes in the state of the colony. For instance, on October 23rd after a feeding event sound level of the hive increased consequently, indicating a reaction to introduced food or disturbing effect of opening the hive. Continuous comparison of the sound level variations and total sound power is key in analysing and detecting events in the colony's audio signal.

- The combined observation of sound, temperature and RH offers rich information that enables the continuous monitoring of the health and activity of honey bee colonies.

5.2. Future Work

The next stage of the research focuses on enriching the data collected from various colonies, and the design of the decision support system. The future directions of research are categorized in the following three sections:

➢ **Hardware**:

Using the data analysis provided in this work, data collection rates have been established for audio, temperature, and RH. Instead of wiring the sensors, Bluetooth Low-Energy (BLE) modules can be used for faster and more convenient installation. The sensors and the BLE modules can be developed into a customized PCB. The system can be powered using solar energy, which allows for portable, stand-alone monitoring systems.

- **Software**:

  The developed algorithm can be used to perform onsite analysis of the data. This will lower memory consumption and allow easier transfer of data via wireless network connection. Sampling rate, period, and time frame between samples can also be optimized to improve power consumption and overall efficiency of the monitoring system.

- **Field Studies**:

  A large-scale data collection study is needed in order to confirm the correlations between the measurements and state of the hive. Such a study should involve a larger number of hives that are constantly observed by experts. Important events should be recorded so that clear patterns in the data can be linked to different events. Since colonies are complicated super organisms with complex behaviour, such a field study must be performed over a longer period (1-3 years) in order to obtain a clear understanding of the various states of the colony that are identifiable by the data.

- **Decision Support System**:

  With the software and hardware improvements, the system can be produced and installed on a larger number of hives. Afterwards, a comprehensive field study can be performed to obtain a dataset that can be used alongside machine learning algorithms in order to design a platform for automatic detection of events and monitoring of hives. Such a platform will be capable of identifying important behavioural changes such as sudden reduction in population, death of a queen or swarming. In addition, using better interfaces to visualize data will allow experts to closely examine the measured data and gain further insight into the state of the colony. This step is especially useful for bee researchers and biologists as it enables the discovery of new behaviour and mechanism in bee colonies.

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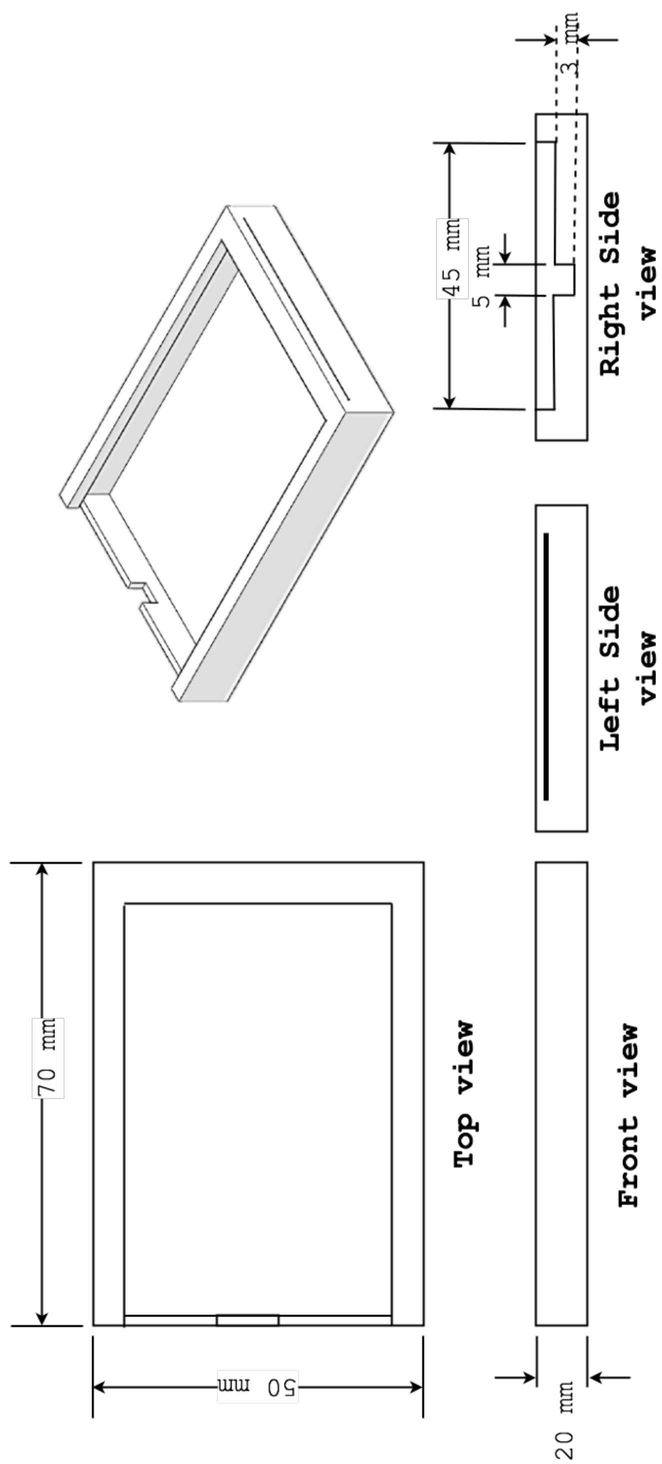
Appendix A

Section view of the 3D printed sensor box.



Appendix B

In Figure B-1, another instance of a single bee piping is presented. However, this signals lasts for a very long time. Although, the fundamental frequency of this signal is in the bandwidth known to honey bees, the message encrypted in this signal is unclear. It only serves as a "proof of concept" for the frequency range of a signal produced by a single bee.

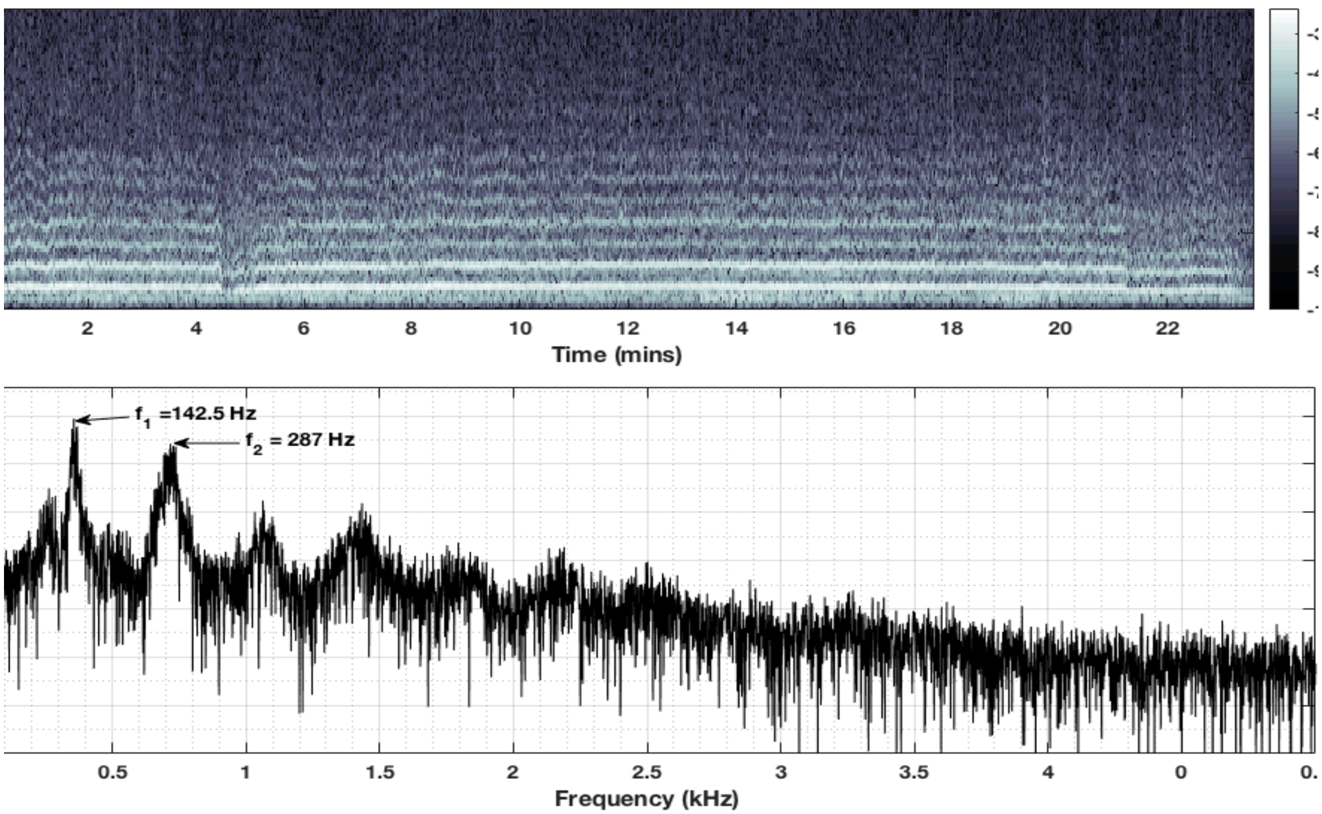


Figure B-1. A single bee producing a piping signal.