# Beemon: An IoT-based beehive monitoring system

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# Beemon: An IoT-Based Beehive Monitoring System

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**Abstract**

Beekeepers have experienced significant losses to the population of their hives in recent years due to a phenomenon that was once referred to as Colony Collapse Disorder (CCD). In the past couple of decades, there have been some efforts to determine the causes of this disaster and how they can be addressed. Some of the research has relied on the data that the beekeepers collect manually from their hives. Some of the more recent efforts have analyzed audio and video recordings obtained at the hives to better understand the behavior of bees and determine the health status of the hives. Such research requires quality audio, video, and other sensor data captured using a reliable system. To make this practical, the system should be inexpensive and with minimal disruption to the bees' natural behavior at their hives. Moreover, such a system should be capable of providing insights and warnings to facilitate early intervention and help mitigate the dire consequences. This paper provides details on the design and implementation of a data collection and monitoring system that was created in our research lab and is referred to here as *Beemon*. This system automatically captures sensor data (temperature, humidity, weight) and sends them using MQ Telemetry Transport (MQTT) protocol to a ThingsBoard dashboard. The system also sends captured video and audio recordings at the hives' entrance to our remote server for analysis and further research. Beemon operates continuously in an outdoor apiary environment and allows near real-time data collection.

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This paper presents limited results of several years of real-world operations to demonstrate the purpose of the proposed Beemon system.
*Keywords:* Audio Processing, Beehive, Honey Bees, Image Processing, Interent-of-Things (IoT).

## 1. Introduction

Honey bees play a significant role in our life, and the world's economy as they are responsible for the pollination of more than one-third of the global food [1]. Their value to the agricultural industry in the United States is estimated to be around \$21.22 to \$54.75 billion per year [2]. Unfortunately, the number of honey beehives has steadily declined in recent decades, and some beekeepers have reported large numbers of losses due to unknown causes [3, 4, 5]. The causes are collectively referred to as the Colony Collapse Disorder (CCD) [6].

In recent years, there has been some research attempting to determine the causes of the bee population decline [3]. Most beekeepers determine the health status of their hives by visually inspecting the hives and investigating their surroundings for possible problems. This approach has worked well with a reasonable success [7], but as the number of hives grows on a farm, this approach becomes less effective. The challenges of CCD require a new approach that can provide more frequent monitoring of a more significant number of hives efficiently with minimum disturbance of their natural setting. Several recent projects have utilized technology and automation for this purpose. An effective beehive monitoring system can help minimize losses in the honey bee population by enabling beekeepers to assess their hives' status remotely. Also, this approach reduces the stress on the bees as it does not require opening the hive for inspection. With the availability and continuous development of technological resources, there is room for improvement in this approach.

The first step in creating a reliable hive monitoring system is developing a mechanism to capture quality data for analysis. This system must be inexpensive and capable of withstanding the hives' outdoor environment. This system naturally is exposed to rain, sunlight, wind, and other adversities that are detrimental to most electronics. Also, the system's components placed inside the hive must withstand the humidity and temperature inside the hive, as well as the constant disturbance and attack by the bees. The inside components must also be placed in such a way that bees are not able to coat them with propolis. The system should capture high-quality audio and video recordings of the beehive and automatically move the data to a server for analysis. The system should provide capabilities to integrate with temperature or humidity and other sensors.

This paper presents the design and implementation of Beemon. The paper also discusses the development of the original system [8] into a robust monitoring and research platform of beehives over the past few years. In Section 2, we briefly discuss related work. Beemon's hardware and software are discussed in Sections 3 and 4. A brief discussion of the different research components within the Beemon project that rely on the data collected by the system is presented in Section 5. We discuss Beemon networking in Section 6. We dedicate Section 7 to discuss the development of the IoT dashboards and rules engine followed by the future work in the Beemon project in Section 8. Conclusions are discussed in Section 9.

## 2. Related Work

Many approaches have been used throughout the years to leverage technology to assist in collecting data that can be used to study the health and behavior of individual honey bees and their hives. Earlier efforts in the field often relied on electro-mechanical devices or hand-written analog records to obtain their information, although, without the assistance of any technology, the study of bees must often fall back on tedious manual methods. For example, Seeley et al. [9] studied the decision-making behavior of bees by painting tags on the bees and manually counting them as they appeared at feeders. While such studies have provided many valuable data, their ability to scale to multiple hives as well as their ability to monitor beehives in the field is severely limited by the amount of labor required by their methods.

In the past 25 years, computer technology has been applied to the study of honey bees [10]. A large body of work has been done using computerized systems to record and/or analyze audio [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22] and video [23, 24, 25, 26, 27, 28, 29, 30] data to gain valuable information about bees, such as the behaviors of individual bees [31, 32, 33], tracking the number of bees entering and leaving the hive [34, 10, 28, 27], or monitoring the overall health of the hive [24, 13, 14, 15]. Data collection systems may also capture additional information, such as temperature or humidity [28], that helps researchers better understand the context for the audio or video data that is their primary interest. This paper focuses on the data collection component of the Beemon project while showing the potential of using the collected data, including video and audio recordings, for further analysis. It should be noted that, an in-depth review of the literature on the analysis of video and audio collected from beehives is beyond the scope of this paper. We refer interested readers to an excellent recent review by Terenzi et al. [35] on the importance of the sound collected in honey beehives. In the following, we present a summary of the literature efforts in analyzing the audio and video in beehives to show the significance of having cost-effective and reliable data collection systems such as Beemon.

The sounds made by bees are an essential part of their communications mechanism. Analysis of the sounds made by honey bees is an area of research that has seen significant research since it can help identify the various stressors for honeybee colonies. Microphones or accelerometers placed inside or outside a hive can be used to collect the sound generated by the bees.

In 1957, Frings and Little [36] observed that bees react to different sounds. One of which is a signal at a particular frequency and amplitude that causes the whole hive to come to a halt (i.e., freeze). In 1964, Wenner [37] used a spectrograph and a microphone placed inside the colony to perform one of the earliest spectral analyses on the honey bee's sound. Wenner describes his experiment on detecting the sound generated by the "waggle by dancing bee," which later became known as the "waggle dance" as described by Von Frisch in 1967 [38]. The waggle dance is performed when a foraging bee finds a source of food and returns to the hive to convey the information about the distance and direction of the source, which information is embedded in the number of the pulsed sounds generated by the dancing bee [33]. In [31], Nieh used a probe and speaker to emit sounds emulating the stop signal of the waggle dance.

Much of the research related to the sounds of honey bees has focused on attempting to predict the swarming behavior of a hive [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22]. Ferrari et al. [13] developed an audio monitoring system to predict swarming in which audio from the beehive is recorded with 16-bit samples at a 2 kHz sample rate. However, their system was not intended for long-term deployment in the field but was instead explicitly deployed to record a series of swarming events at a research farm by monitoring three beehives for 270 hours. Mezquida et al. [14] performed similar research where they stored hourly recordings from a hive to predict swarming events eventually. However, the audio recordings were short (eight seconds) and relatively low quality (8-bit samples, 6.25 kHz sample rate). One slightly different variation on this topic was done by Bencsik et al. [15]. Rather than recording audible sounds made by the beehive during the swarming process, they embedded accelerometers into the frame of the hive and recorded the vibrations emitted during swarming. Their data was captured in a manner very similar to audio recordings, using 16-bit samples and an 8 kHz sample rate. In [20], Ramsey et al. use vibrational spectra to develop promising non-invasive methods to monitor and predict the swarming activities in a hive. However, the sensor used is not cost-effective, which can hinder the scalability of deployment [35]. Another vibration-based beehive monitoring system has been recently presented by Aumann et al. [22] in which a radar and a vibration sensor have been simultaneously used to distinguish between the swarming and robbing activities in a given beehive.

Despite the evident effectiveness of the vibration sensors and the analysis of the vibrational spectra, studies showed that some of the sounds generated by the bees are not detectable in the vibrational spectra. For example, in [39], Michelsen et al. deployed a laser vibrometer and microphones in a hive and discovered that the waggle dance does not produce vibrations. Instead, the information embedded in the waggle dance is carried by airborne sound. Moreover, the vibration sensor impulse response depends on the resonant characterstics of the wooden hive and its content [22]. This can lead to challenges in the analysis since the content of a hive, and thus the impulse response, continuously changing with the bees traffic and the produced honey.

In [18], Kulyukin et al. developed several convolutional neural networks (CovNets) and compared their performance with Standard Machine Learning (ML) techniques such as logistic regression, k-nearest neighbors, support vector machines, and random forests. The goal is to analyze and distinguish the bee sound, from the background noise and the cricket chirping noise. The analysis shows that raw audio CovNets performed on par, and sometimes better, than the four ML methods and a trained ConvNet.

Previous work has demonstrated that monitoring the activity of bees around the hive's entrance, such as counting the number of bees entering and leaving the hive or watching for signs of swarming behavior, provides valuable data on the hives' health and growth status.

One of the earliest bee-counting experiments was done in 1925 by Lundie [40], who constructed a device that tracked bees entering and exiting a hive by means of sensitive pressure plates connected to electrical circuits activated by the weight of a bee walking across the plate. There were numerous flaws among which was that the device interfered with the hive operation because it significantly restricted the flow of bees into and out of the hive, and it was difficult to gain an accurate count of bee traffic due to multiple bees passing through a channel at the same time.

A more advanced bee counting system constructed by Struye et al. [10] used a system of infrared sensors to accurately count the number of bees entering and leaving a hive. The system uses 32 passages large enough for a single bee to pass through, with two infrared beams used to detect movement within the passage.

The direction of the bee's movement is determined by the order in which the beams are interrupted, indicating whether the bee is entering or leaving the hive. Microprocessors check the status of the infrared beams 2000 times per second, allowing for highly accurate counts. Similar efforts to count or track bees near the hive entrance have been done by Campbell et al. [34], who also forced bees to pass through tunnels, but counted their passage using capacitance bridges. Another common approach to counting or tracking bees is the usage of radio frequency identifier (RFID) systems [32, 41, 27]. However, all of these approaches involve trade-offs that prevent them from being ideal.

Research using video to track and analyze honey bee behavior is mostly limited to the past few decades, as video recording devices and storage tools became available at more accessible prices commercially. Estivill-Castro et al. [23] demonstrated one of the earlier techniques for tracking honey bees using video. Their experimental setup involved inexpensive color charge-coupled device cameras mounted in waterproof boxes along with a battery power source. These cameras were placed in an orchard, positioned to capture video of bees visiting the flowers of trees that were in bloom. Videos were captured at a resolution of 320×240 pixels at 24 frames per second (FPS), with one minute of video captured at ten minute intervals. As they note, their results were limited by the quality of the video, as well as the battery power source, which prevented them from capturing more frequent recordings.

Knauer et al. [24] took advantage of digital video and computer image analysis to perform automated bee tracking. However, their area of interest specifically involved the interior of the beehive, so their recordings were made using an infrared camera, with illumination provided by near-infrared LEDs that emit wavelengths of light invisible to the honey bees. The camera system was limited to low resolution 480×348 video, and the researchers fit each bee in the experiment with individually numbered badges for identification. Video was stored in a long duration digital video recorder.

In the past decade, much research has been done to apply digital image analysis to video of honey bees. Most of the techniques have primarily focused on tracking the movements of bees. Kimura et al. [26] captured recordings using a JVC GR-HD1 digital video camera, at a resolution of 720×480 at 29.97 FPS. Recordings were made of a beehive frame, and a ten second video clip was analyzed using vector quantization methods in order to track the movement of bees walking across the frame, as well as identification of bees performing the waggle dance.

Campbell et al. [25] revisited the concept of counting bees as they enter and exit the hive, using digital video to capture the bees' movement and image analysis to identify bees and track their movements. Video was captured at the hive entrance using a small digital camera board mounted to the hive in a protective housing. Unlike previous bee-counting efforts, this approach had the benefit of avoiding disruption of the hive's normal behavior, and the camera mount was largely ignored by the bees after installation. Video was captured at a resolution of 640×480 at 30 FPS. By using adaptive background subtraction to detect the bees and a maximum weighted bipartite graph matching algorithm to track bee motion, they were able to count the incoming and outgoing bees with high accuracy.

The work that most directly precedes this research is that done by Ghadiri [28], who used wireless surveillance cameras that were either attached to the top of the beehive, or placed in front of it. These cameras recorded digital video at a resolution of 640×480 that was transmitted wirelessly to a digital video recorder for storage. However, the recorder used SD cards as its storage medium, and the 16 GB cards available at the time could only record 72 hours of continuous video before they had to be changed, and the data manually uploaded to a server for storage and analysis.

A similar and successful multi-sensor monitoring system, BeePi [42], has been developed by Kulyukin et al. to collect temperature, audio, and video data which is stored on a 25G SD card inserted into the pi. The system has been undergoing continuous development since its initial deployment. Based on the BeePi system, several techniques have been presented to analyze and count bee motions in video analysis of omnidirectional bee traffic [29] as well as the use of Digital Particle Image Velocimetry for bee motion estimation [30].

Most monitoring systems require significant manual setup or frequent visits for retrieving data from the system at the hives. Only a handful of research platforms have the capability of continuous data collection utilizing a flavor of Internet connection. Also, many of the previous efforts have only captured audio and video recordings of limited quality.

Recently, researchers started to explore the Internet of Things (IoT) potential in the domain of beekeeping. Several conceptual solutions have been presented either to track temperature, humidity, mass, and other sensors data related to the health and safety of the system [43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55]. However, most of the current work focuses on the perception and networking layers of the IoT stack, focusing less on the upper layers such as middleware development and business layer. Therefore, there is a need to make a case for apiary monitoring and management as a viable business vertical in the IoT domain.

This research explores the development of an automated data collection system, Beemon, that reliably captures audio and video recordings of high quality. The system also collects temperature, humidity, and weight data and provides a near real-time monitoring and alerting IoT dashboard to easily help researchers and beekeepers track their beehives. Data transfer from hives to analysis server is automated, continuous, and steady.

## 3. Beemon Design Overview

Figure 1 illustrates the design and deployment of the Raspberry Pi-based Beemon system and summarizes the data flow. Dashed lines in Figure 1 depict several of the in-progress and future research directions. In the Beemon system, a set of hardware sensors and devices captures the desired data from one or more beehives and uploads that data via the internet to our server for research and analysis. The system may also provide a limited on-board analysis for real-time dashboards. Beemon comprises the following seven main components:

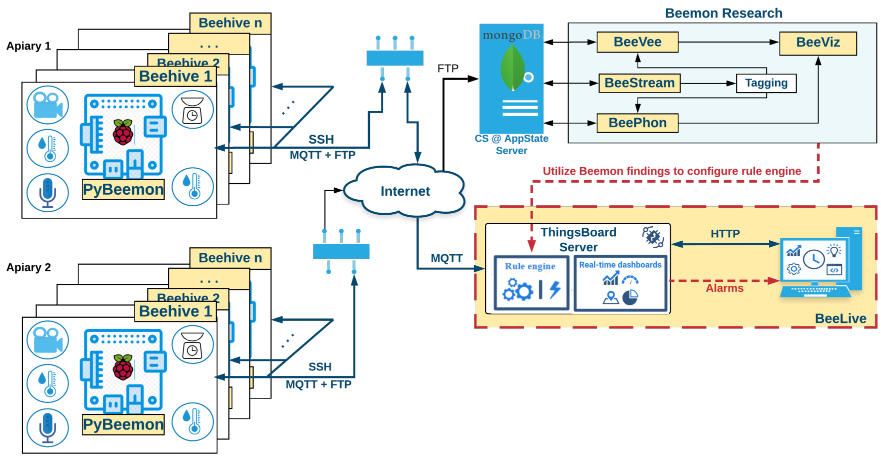



Figure 1: Beemon system to monitor multiple apiaries (two shown). Each apiary consists of multiple hives. The figure shows the seven components of the system as well as the data collection and transfer. Dashed lines depict system components and features that are either in progress or will be added to the system in the near future.

- **Beemon Hardware:** The set of hardware devices and sensors installed inside and outside beehives.

- **PyBeemon:** The software that runs on the Raspberry Pi that is installed on the hive.

- **BeeVee:** A video and image processing research tool used to estimate traffic in and out of a hive and at the hive's entrance indicative of the beehive's health.

- **BeePhon:** Research component mainly for analyzing the audio recordings captured from inside the hives.

- **BeeStream:** A web tool for streaming live and arched videos collected by Beemon. The tool allows viewers (public and other researchers) to select tags and provide annotations on their observations, which will be used for data mining and video/audio analytics.

- **BeeViz:** A web tool for data analytics and visualization. The tool can retrieve data for one or more beehives and generate graphs for significant metrics.

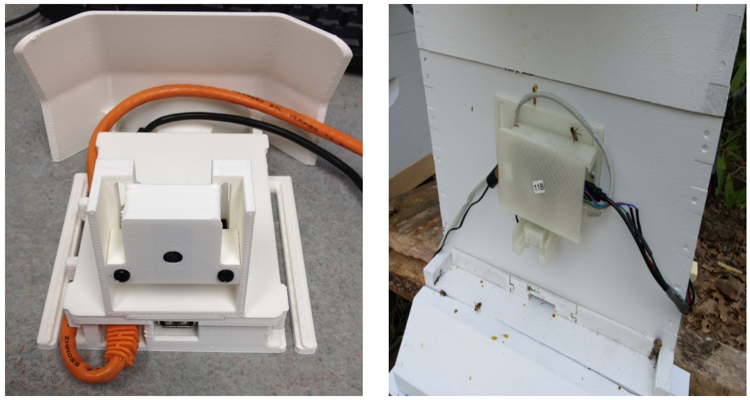
- **BeeLive:** Dashboards used to monitor and inform beekeepers and other stakeholders of the health, trends, and alarms of the beehives using Thingsboard.

In the following sections, we will discuss the components of the Beemon, starting from the hardware deployment in the beehive to the dashboard presented to the user.

### *3.1. Beemon Hardware System Deployment*

The current version of the Beemon system consists of a Raspberry Pi (Rpi) 4. The Rpi system has a 1.5 GHz quad-core ARMv8-A 64-bit processor, 2 GB of RAM, 4 USB ports, 40-pin GPIO, a camera interface, an SD card slot that is utilized for storage space up to the size of the card, and an Ethernet port. The Rpi Camera V3 provides 8 megapixels and can capture still images at 3280 $\times$ 2464 pixels resolution and a video of 1080p. A USB microphone is used for recording audio. The humidity and temperature sensor is connected through the built-in 40-pin GPIO. The Raspberry Pi runs the Beemon application called *pyBeemon* that is developed in our lab. pyBeemon is responsible for recording audio and video, serving as a temporary data storage device until the data is uploaded to the server, and uploading the recorded data to our remote server for archiving and analysis.

Our testing found that it is critically important to use a high-quality SD card with the Raspberry Pi when running Beemon. Most SD cards are very slow [56] compared to mechanical hard drives or solid-state drives. We have found that the most common Class 2 and Class 4 SD cards are too slow to support the needs of the Beemon system. At a minimum, Beemon must perform the recording of HD video and two CD-quality audio streams, as well as the normal, unavoidable disk operations of a Linux operating system. A Class 10 SD card must be used to ensure that disk operations do not cause the system to fail or work inefficiently.



(a) (b)

Figure 2: The Beemon hardware (a) A fully assembled in-house designed and 3D printed Beemon case. (b) A hive with Beemon monitoring system installed.

Deployment of the Beemon system with Raspberry Pis presented several challenges. However, the results proved worth the efforts as the hardware and software solution is cost-effective, efficient, and reliable. The result is a *"plug and play"* system. A custom 3D printed case (an early version is shown in Figure 2-(a)) is produced in our lab and is used to mount the Beemon system outside the hive (Figure 2-(b)).

### *3.2. System's Cost*

One of the primary goals of this project is the development of an inexpensive system allowing it to be deployed on a large scale. Table 1 lists the estimated cost of the components used in the current Beemon system. As it can be seen, the cost is low, considering the system's audio and video recording capabilities.

A significant factor to consider while determining the cost of the Beemon system is the quality of audio and video recordings. In our case, we utilized the Raspberry Pi camera 3 for video recordings which provided sufficiently high quality, but we had several choices for the microphone that would cost from $7 to $70. It is possible to revisit the Beemon system and use lower-cost components that provide data of adequate quality.

Table 1: Beemon Component Cost.

| Component | Cost |
|---|---|
| Raspberry Pi 3 Model B | $45 |
| Power Supply for Raspberry Pi | $7 |
| 16 GB Class 10 SD Card | $9 |
| Raspberry Pi Camera 3 | $29 |
| USB Microphones | $10 |
| Raspberry Pi Case (PLA material cost) | $5 |
| **Total** | **$106** |

## 4. PyBeemon Software

PyBeemon runs on a Raspberry Pi microcomputer that allows recording video, temperature, humidity, weight, and audio. The hardware recommended by PyBeemon is the Raspberry Pi camera, an AM2302 temperature humidity sensor, and USB microphones. Users can set variables, such as start and end time, in a configuration file. The system will then read this file and run it without any further interaction from the user. Figure 3 shows the flow of PyBeemon's data acquisition.

As shown in Figure 3, a Cron job (Linux utility) allows scheduling of commands or scripts at specified times, starts the server process. The server is responsible for starting processes to record data, such as audio. PyBeemon allows usage of the software in two ways. The first is an autonomous mode where the system will run using only the operating parameters from the configuration file "beemon-config.ini" (see Figure 3). A sample PyBeemon configuration file is shown in Figure 4. The second is a manual mode which allows users to override the automated settings. In order to override these settings, a user logs into the system from any command line. Once logged into the system, users are able to run commands, such as start_video, in order to control the system. A client can then be used to relay commands from a terminal connected via a Secure Shell (SSH) connection to the server allowing control over the system.

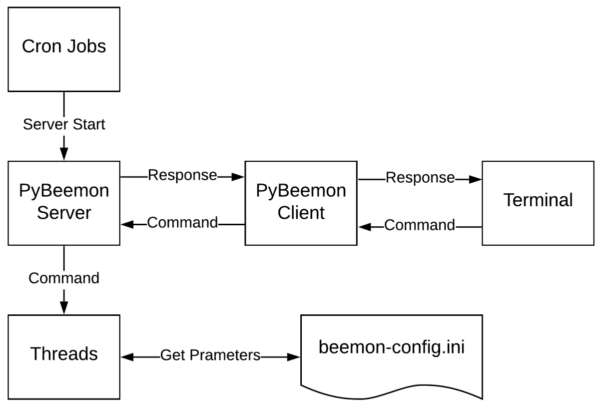



Figure 3: Data acquisition process by PyBeemon.

```
[video]
settings = custom
logging_enabled = True
[video/custom]d = True
# The subdirectory in which to place all of the video data on the server
remote_directoryry in which to p=ace allvideohe video data on the server
# The local directory to put all of the video data before it is uploaded
local_directoryectory to put all=of the /home/bee/bee_tmp it is uploaded
# The amount of time recorded before an upload happenstmp
capture_durationtime recorded be=ore an 60load happens
# Sets video capture interval   =       60
capture_intervalture interval   =       00
# Determines if video is always on      00
always_capturef video is always =n      False
# Determines when to start recording if always_capture is False
capture_start_timeto start recor=ing if 0800ys_capture is False
# Determines when to end recording if always_capture is False
capture_end_timen to end recordi=g if al2000_capture is False
# Whether or not batch uploading is enabled0
batch_upload_enabled    =loadingFalsenabled
# The time to perform the batch upload in 24H HHMM format
batch_upload_timeform the batch =pload i0030H HHMM format
# The target frames per second  =       0030
frames_per_secondes per second  =       30
# The target x-resolution       =       30
resolution_x x-resolution       =       640
# The target y-resolution       =       640
resolution_y y-resolution       =       480
# Determines if the sensor will record while video is being recorded
read_temp = Falsehe sensor will record while video is being recorded
# Determines whether to flip the video or not
flip_video = Falseer to flip the video or not
flip_video = False
```

Figure 4: Configuration file on the the Raspberry Pi.

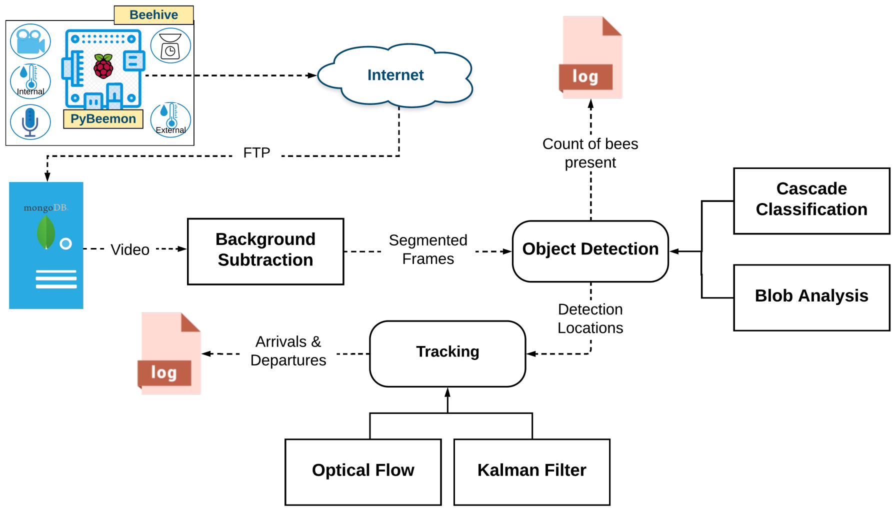


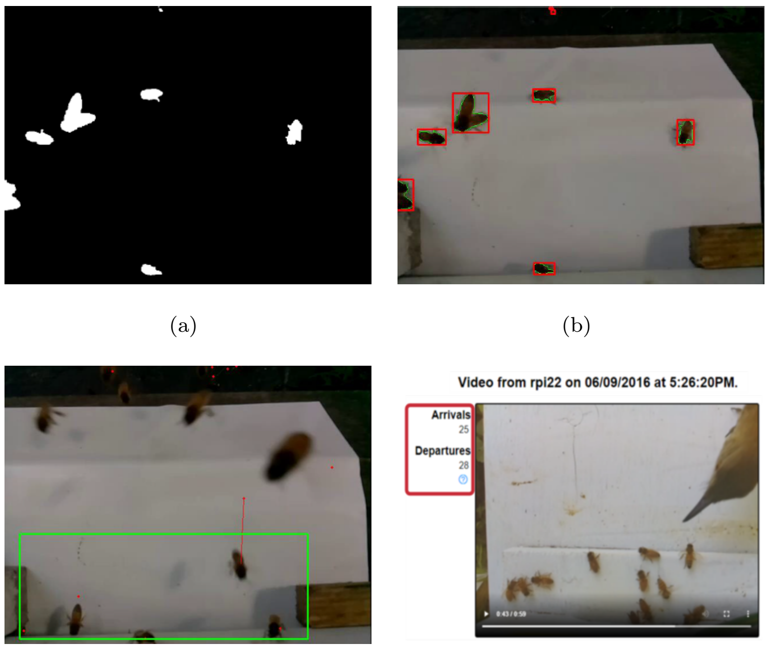

Figure 5: BeeVee's traffic estimation process.

## 5. Beemon Research Tools

Significant analysis of the reliably collected data is still required to identify what beekeepers should be looking for in their beehive's behavior to anticipate and mitigate problems. Beemon research is the core of the Beemon project in which all the data collected from the beehives are analyzed. The results of this analysis and research will help us feed the rule engine in the IoT platform to improve our alerts, data visualization, and control. Despite being the core of our Beemon system, the analysis tools of Beemon are not the focus of this paper. For the sake of completeness, however, we briefly discuss the two core research domains; the image processing (BeeVee) and audio processing (BeePhon) research project components, as well as the streaming (BeeStream) and visualization (BeeViz) tools. Note that the following discussion does not delve into the algorithms' technical details, implementation, and evaluation. Instead, it is included to show that the data collected is viable and reliable for analysis.

### *5.1. BeeVee*

The videos obtained from a hive's entrance can provide a significant repository of valuable data for learning about honey beehive health. Video recordings




(a) (b)

(c) (d)

Figure 6: BeeVee's [57] (a) background subtraction process. (b) segmentation of bees using contours. (c) tracking to obtain the traffic in and out of the hive. (d) traffic estimator displays the number of bees in and out of the the hive on the left-hand side of the video.

can improve our understanding of the hive, for example, by 1) Estimating the traffic in and out of the hives, 2) Determining the diversity of the bees' stripes in a hive, 3) Estimating the number of worker bees and drones, 4) Predicting swarms, 5) Identifying hive robberies, 6) Detecting Varroa Mites, 7) Identifying bee fights, 8) Detecting Intrusions, and 9) Identifying wing deformations. These can provide crucial information about the health of the hives and are of interest to the scientists trying to help the honey bees survive the adversities.

***Traffic estimator***

The traffic estimator provides an estimate of the bee traffic entering and leaving a hive. The number of bees entering and leaving their hive can provide important information about the health status of the hive. Naturally, bees do not die inside their hive; thus, there will be a net difference between the number of arrivals and departures. In cases in which the difference is significant, that can be a bad sign indicating the poor health status of the hive.

The current version of BeeVee uses object detection and tracking techniques on the videos obtained at the hives' entrance to detect the honey bees. Several algorithms, including motion tracking, are then applied to determine the traffic (see Figure 5). Figures 6-(a-c)) depict the algorithm while analyzing one of the recorded videos where background subtraction is performed, followed by segmentation and then tracking the bees. Figure 6-(d) illustrates a screenshot of a one-minute video on June 9, 2016, where the BeeVee's estimate of the traffic in and out of the hive is displayed on the left-hand side of the video.

In order to conduct motion tracking, we use rectangular, triangular, and arc boundaries around the entrance of the hive. This boundary is to determine the bees' motion vector crossing in or out of the boundary frame. Each of the boundaries has its advantages and disadvantages, but the triangular boundary performs better for low to medium traffic. The performance using both boundaries degrades for high traffic mainly because bees walk on top of each other. Also, when they are very close to each other, they may be detected as a single blob, and then they move in opposite directions.

### *5.2. BeePhon*

BeePhon is a web application (see Figure 7) that allows visualization of the honey bee audio files in form of Non-Negative Matrix Factorization [see Figure 8-(a)] and the spectrum [see Figure 8-(b)]. The tool provides options for selecting a range of dates for the audio files, so it is possible to analyze for a period of time, as shown in Figure 8. In addition, the application allows selecting the number of factors of the Non-Negative Matrix Factorization analysis and displays the graphs for each of the components. A great feature of the analysis tool is the possibility to zoom on the $x$ and $y$ axes by using the left mouse button to draw a rectangle to set the limit for the new zoom area [58]. BeePhon is currently under development. The goal is to develop a tool that can help identify the

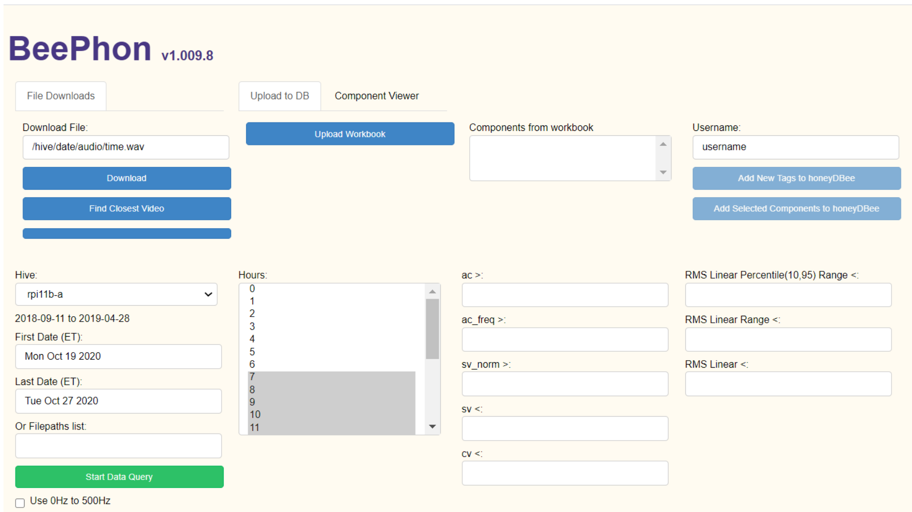
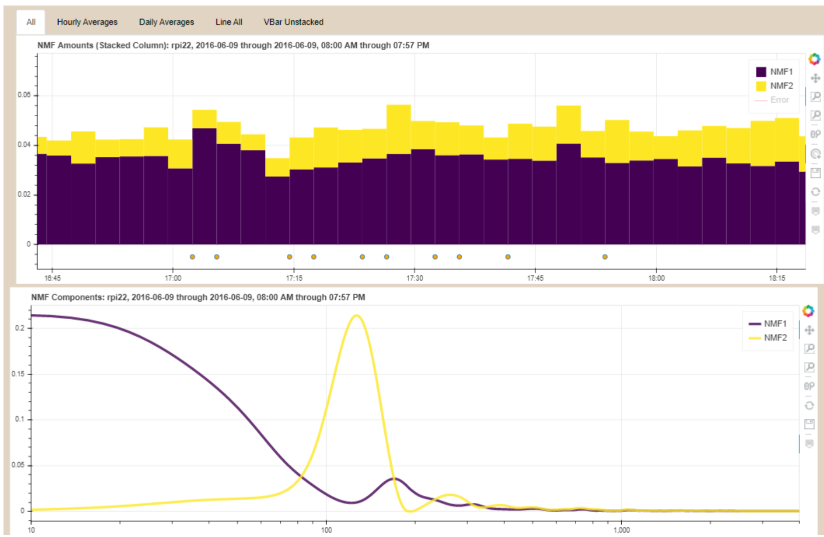


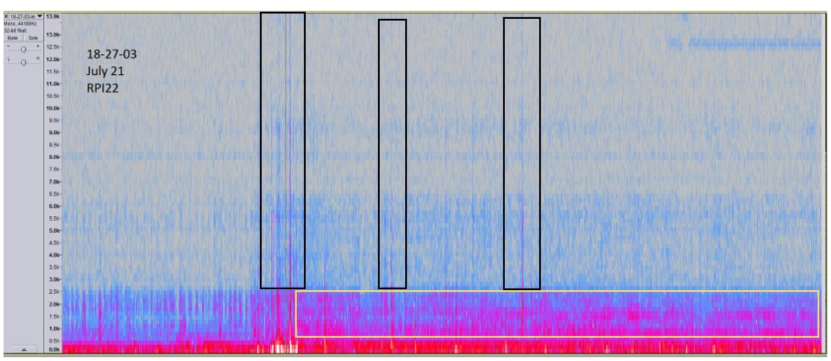

Figure 7: The BeePhon [58] application interface.

different sounds produced within the beehive to assess the health and state of the beehive. For example, we aim to analyze the sound to determine the quality of the sources, identify pre-swarming indicators, and detect if the hive is being robbed. In the example shown in Figure 8, the vertical rectangles show the bee keeper's voice on the side of the hive, and the horizontal rectangle illustrates the bees' intense agitation due to the interference by the beekeeper.

Figure 8 illustrates two powerful analysis tools that are built-in in the BeePhon application. Figure 8-(a) illustrates the results for two components of the Non-negative Matrix factorization. Prior entries made in a MongoDB database during manual observation appear on the graph. For example, on the day of this audio recording on June 9, 2016, at Rpi22, there have been several attempts by birds trying to catch the drones at the entrance. The seven orange circles at the bottom of the bar graph correspond to these attempts, and Figure 8-(b) illustrates the spectrum (frequency vs. intensity) for the audio file on the same day.




(a)




(b)

Figure 8: The BeePhon [58] (a) Non-Negative Matrix Factorization and (b) Spectrogram Tools.

### *5.3. BeeStream and BeeViz*

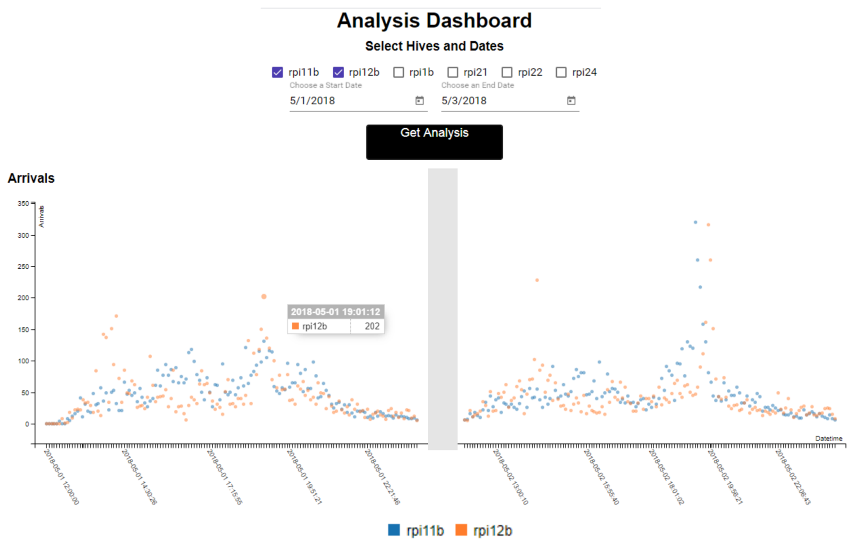
A website has been developed for the Beemon project, and system [59]. The website comprises multiple web pages for each of the sub-systems in Beemon, such as BeeVee, and BeePhon.

The website also provides access to the BeeStream component of the project. In BeeStream, users and researchers can live stream video and audio from beehives or utilize the recorded and archived data from the system on our server to view old video and audio files. While streaming or viewing videos, users and researchers can record their observations in the form of free format text or pre-defined events (i.e., labeling), as shown in Figure 10. BeeStream webpage also provides access to the analytical dashboard through which a user can view the video analysis data related to bee arrivals/departures superimposed on temperature and humidity data.

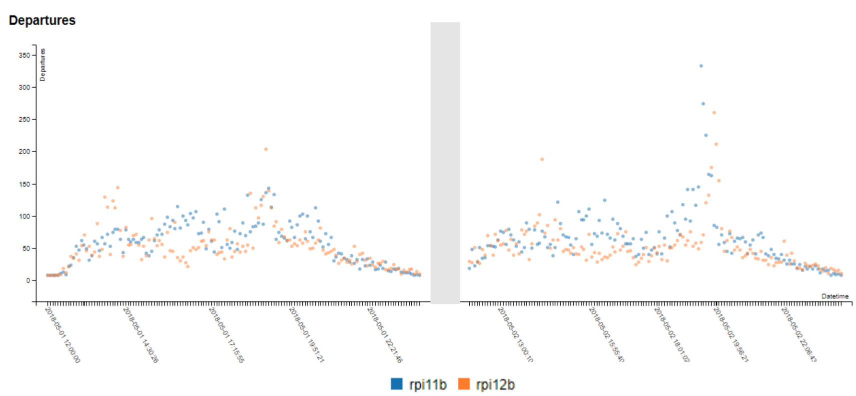
BeeViz tool [60] has been developed to visualize the traffic at the entrance of one or several hives during a specified period. The graphs show data points within which encapsulated data appears as one hoover the mouse over that data point. An example of such an analysis is shown in Figure 9 where the arrival traffic at the hives Rpi11b and Rpi12b are compared. Similarly, Figure 10 illustrates the departure traffic on the same days for these two hives.

## 6. Data Communication and Networking

Beemon is capable of capturing high-quality video at various resolutions and frames per second, high-quality mono audio at 44.1 kHz or higher, and weight, temperature, and humidity data throughout the day. Data communication protocols and technologies selected depend on several factors, such as available connectivity and the size of data to be transmitted. At this phase of the Beemon project, we transmit an abundance of video and audio data collected through Beemon to a remote server for storage, processing, and research analysis. This is essential during the project's current phase since the main goal is to analyze video (BeeVee) and audio (BeePhon) recordings and extract the key indicators




(a)




(b)

Figure 9: A BeeViz sample analysis comparing two hives (Rpi11b and Rpi12b) during May 1 and 2, 2018 [60]. The shaded region represents overnight period during which the Beemon system does not collect data.. (a) Arrival traffic (b) Departure traffic.

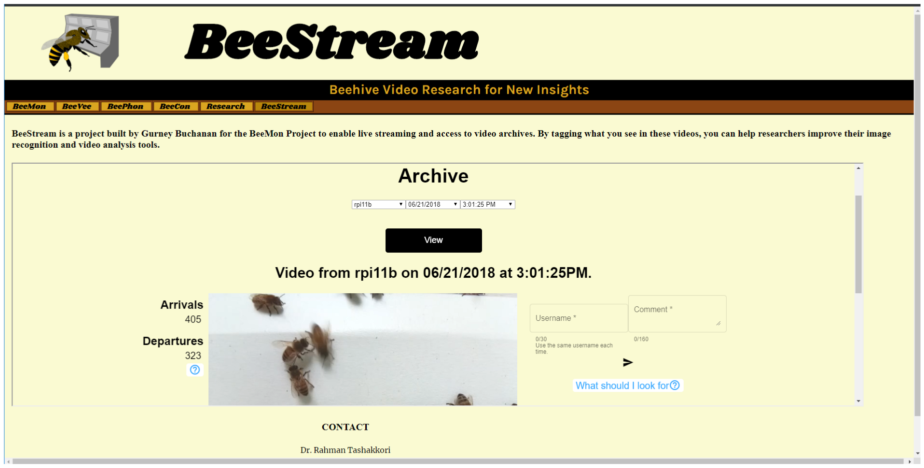



Figure 10: Video viewing and annotation page showing the bee count.

a user should look at to determine the health and performance of a beehive. On the other hand, data requiring basic analysis such as inside/outside temperature and humidity, weight, bee traffic, and physical beehive interruption due to human theft or mammal attack can be directly processed and presented to a user using real-time dashboard.

Currently, there is no efficient approach to wirelessly and reliably transfer a large amount of video and audio data collected by Beemon at the field to our server. Cellular networks are costly and provide limited bandwidth. Also, the local WiFi faced the challenge of the upload capacity imposed by the local ISP. To avoid these complications and transfer costs, we deploy our system only to beehives on the home network grid. The hives were located near a building that could provide power and internet connectivity via extension cords and Ethernet cables. This ensured a reliable transfer of audio and video data to our server using file transfer protocol (FTP). Moreover, Beemon can be configured to optimize performance based on the need/location, e.g., performing bulk uploads during non-active network periods or using less bandwidth by collecting fewer data based on the time of day. We have several preferred configurations depending on the requirements of the location. The data stored on our server was made available for BeeVee, BeePhon, and BeeStream components of the project. In addition, the BeeStream web platform is used to live stream hives video/audio data. The interface developed for BeeStream also allows access to archived video and audio files.

Rural and mountainous areas are suitable locations for apiaries since there are minimal external stressors on the beehives. Costly and challenging transportation is one of the challenges facing beekeepers in such areas. Therefore, internet connection is essential for remote and automated electronic beehive monitoring systems, such as Beemon. However, rural and mountainous areas also experience limitations on the availability and costs of connectivity technologies.

One of the objectives of Beemon is to identify the key indicators of the health of a beehive based on the research in our lab, the goal is to perform processing at the edge of the network (i.e., at the beehive) to collect the required data and develop the indicators required to inform the beehive owners on their monitoring dashboard using low-cost and low-bandwidth local or wide area access networks such as WiFi, Zigbee, BLE, or LoRa and LoRaWAN networks. Existing video-based solutions are either limited in providing short video triggered by motion sensors for detecting human theft or mammal attacks [61] or in providing indicators on the user's dashboard. A more sophisticated system can cost between $380 and $425 per hive [62].

## 7. Beemon IoT Dashboard and Rules Engine

To keep the beekeeper informed and allow easy access to the currently available data, we transfer light-weight data and information such as the inside/outside temperature and humidity, and bee-traffic indicator data using MQ Telemetry Transport (MQTT) protocol over the same link to the ThingsBoard server. ThingsBoard is the IoT platform we currently use for the Beemon project [63]. Data is collected and then presented on a real-time dashboard accessible to the beekeeper using a desktop or phone.

A ThingsBoard dashboard has been developed to collect data from moni-

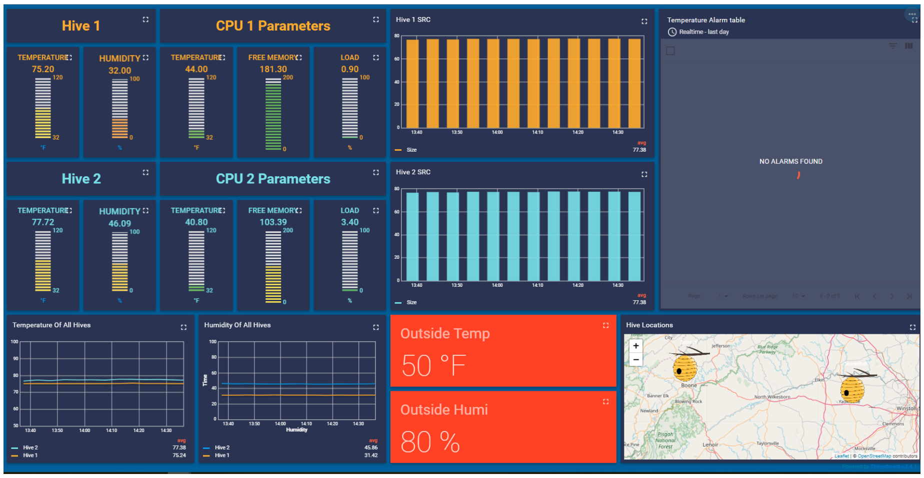



Figure 11: Example of a ThingsBoard Dashboard developed to monitor two Beemon-powered hives.

tored beehives and present it near real-time to users allowing quick access to important data. Figure 11 depicts the dashboard developed. The dashboard displays outside temperature and humidity, internal temperature and humidity, as well as high-level traffic indicators, locations, and RPi parameters for each beehive.

## 8. Future Work

This paper aims to illustrate that it is possible to collect reliable data at a low cost using the proposed Beemon system. It is now possible to focus our attention on the other components of the Beemon project, such as the research and the IoT rules engine and dashboard. In this section, we briefly discuss the current progress and the plans for the different components of the Beemon project.

Beemon's hardware and data collection component of the project will continue to undergo continuous updates and development. This development will be driven by the emergence of newer, more powerful, and cost-effective technologies (i.e., Pi, camera, and sensors) and feedback from the project's research component.

The BeeVee research focuses on performing bee count, fight detection, and fanning detection. We are currently tackling the three problems simultaneously by exploring Machine Learning (ML) and Deep Learning (DL) techniques.

The bee count includes the traffic in and out of the hive and the number of worker and drone bees. These parameters can help the beekeeper and researchers to understand the health status of the hive.

Bee fights at the hive entrance can provide an insight into the strength of the hive as weaker hives often get robbed by the bees from the neighboring hives. In an attempt to prevent complete demolition of a hive that is being robbed, it is essential first to identify the fights between the guards in the hive target of a robbery and the intruder bees. We are developing algorithms to identify fights at the beehive entrance automatically.

Fanning is mainly one or more bees lining up at the hive entrance flapping their wings perpendicular to their bodies to cool down the hive or circulate air in the hive to remove the moisture from the stored nectar. This is a crucial task as it can indicate that the hive's temperature is extremely high when fanning goes on for too long by many bees. Also, this can indicate that the humidity inside the hive is high and/or there is fresh honey in the cells ready to be capped by removing the excess moisture from it. The level of fanning, temperature, and humidity combined can provide a good indicator of the overall health of the hives.

Similarly, we are developing a number of algorithms using machine and deep learning to analyze the audio recorded from the beehives and help monitor the status of the hive. Ideally, we would like to detect the status of the food sources around the hive, the existence of intruders, probability of robbery or swarming.

We have not fully utilized the IoT platform (ThingsBoard) and its capabilities yet. By working on developing rule chains and a sophisticated rule engine that the BeeVee and BeePhon continuously update, we will improve the dashboard quality and equip it with alarms and better insights for the beekeepers. The ultimate goal is to elevate the quality of the dashboard from merely reporting measured data to provide the beekeeper with a complete picture. For example, the counts of the bees, measured temperature, and humidity, along with the fanning activity, can be all infused together to give a simple one-metric indication about the overall status of the hive in terms of climate control. A better rule engine can also help us improve the configuration parameters of our Beemon system.

## 9. Conclusion

The Beemon Raspberry Pi system we have built is inexpensive, can be easily deployed, and provides many different options for data acquisition. Also, it delivers high-quality data to our server for analysis. The system is extensible and easy to update and provides several levels of calibration at the hardware and software levels. The system does not disturb the natural life of the bees, is mostly in the realm of consumer products, and has succeeded in dealing with most of the conditions that pose a risk to our electrical systems. Beekeepers can remotely view video and audio streams of their hives and address any concerning behavior. Moreover, we developed a dashboard that allows the beekeeper to have quick access to the beehive vitals. The dashboard will be improved to provide proper alarms and warnings that keep the beekeeper informed.

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