

# Toward Sustainable Electronic Beehive Monitoring: Algorithms for Omnidirectional Bee Counting from Images and Harmonic Analysis of Buzzing Signals

Vladimir A. Kulyukin and Sai Kiran Reka

**Abstract**—Two algorithms are presented for omnidirectional bee counting from images to estimate forager traffic levels. An audio processing algorithm is also presented for digitizing bee buzzing signals with harmonic intervals into A440 piano note sequences. The three algorithms were tested on samples collected through four beehive monitoring devices deployed at different apiaries in Northern Utah over extended periods of time. On a sample of 378 images from a deployed beehive monitoring device, the first algorithm for omnidirectional bee counting achieved an accuracy of 73 percent. The second algorithm for omnidirectional bee counting achieved an accuracy of 80.5 percent on a sample of 1005 images with green pads and an accuracy of 85.5 percent on a sample of 776 images with white pads. The note range detected by the proposed audio processing algorithm on a sample of 3421.52 MB of wav data contained the first four octaves, with the lowest note being A0 and the highest note being F#4. Experimental results indicate that computer vision and audio analysis will play increasingly more significant roles in sustainable electronic beehive monitoring devices used by professional and amateur apiarists.

**Index Terms**—computer vision; audio analysis, electronic beehive monitoring, sustainable computing

## I. INTRODUCTION

Since 2006 honeybees have been disappearing from many amateur and commercial apiaries. This trend has been called the colony collapse disorder (CCD) [1]. The high rates of colony loss threaten to disrupt the world's food supply. A consensus is emerging among researchers and practitioners that electronic beehive monitoring (EBM) can help extract critical information on colony behavior and phenology without invasive beehive inspections [2]. Continuous advances in electronic sensor and solar harvesting technologies make it possible to transform apiaries into ad hoc sensor networks that collect multi-sensor data to recognize bee behavior patterns.

In this article, two algorithms are presented for omnidirectional bee counting from images to estimate

forager traffic levels. An audio processing algorithm is also presented for digitizing bee buzzing signals with harmonic intervals into A440 piano note sequences. The three algorithms were tested on samples collected through four beehive monitoring devices deployed at different apiaries in Northern Utah over extended periods of time. When viewed as time series, forager traffic estimates and note sequences can be correlated with other timestamped data for pattern recognition. It is probable that other musical instruments can be used for obtaining note sequences so long as their notes have standard frequencies detectable in a numerically stable manner.

The standard modern piano keyboard is called the A440 88-keyboard, because it has eighty-eight keys where the fifth A, called A4, is tuned to a frequency of 440 Hz [3]. The standard list of frequencies for an ideally tuned piano is used for tuning actual instruments. For example, A#4, the 50-th key on the 88-key keyboard has a frequency of 466.14 Hz. In this article, the terms *note* and *key* are used interchangeably.

Buzzing signals and images are captured by a solar-powered, electronic beehive monitoring device (EBMD), called BeePi. BeePi is designed for the Langstroth hive [4] used by many beekeepers worldwide. Four BeePi EBMDs were assembled and deployed at two Northern Utah apiaries to collect 28 gigabytes of audio, temperature, and image data in different weather conditions. Except for drilling narrow holes in inner hive covers for temperature sensor and microphone wires, no structural hive modifications are required for deployment.

The remainder of this article is organized as follows. In Section II, related work is reviewed. In Section III, the hardware and software details of BeePi are presented and collected data are described. In Section IV, the first algorithm is presented for omnidirectional bee counting on Langstroth hive landing pads. In Section V, the second algorithm is presented for omnidirectional bee counting on Langstroth hive landing pads. In Section VI, an audio processing algorithm is proposed for digitizing buzzing signals into A440 piano note sequences by using harmonic intervals. In Section VII, an audio data analysis is presented. In Section VIII, conclusions are drawn.

## II. RELATED WORK

Beehives of all sorts and shapes have been monitored by

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humans for centuries. Gates collected hourly temperature measurements from a Langstroth beehive in 1914 [5]. In the 1950's, Woods placed a microphone in a beehive [6] and identified a warbling noise in the range from 225 to 285 Hz. Woods subsequently built Apidictor, an audio beehive monitoring tool. Bencsik [7] equipped several hives with accelerometers and observed increasing amplitudes a few days before swarming, with a sharp change at the point of swarming. Evans [8] designed Arnia, a beehive monitoring system that uses weight, temperature, humidity, and sound. The system breaks down hive sounds into flight buzzing, fanning, and ventilating and sends SMS or email alerts to beekeepers.

Several EBM projects have focused on swarm detection. S. Ferrari et al. [9] assembled an ad hoc system for monitoring swarm sounds in beehives. The system consisted of a microphone, a temperature sensor, and a humidity sensor placed in a beehive and connected to a computer in a nearby barn via underground cables. The sounds were recorded at a sample rate of 2 kHz and analyzed with MATLAB and Cool Edit Pro. The researchers monitored three beehives for 270 hours and observed that swarming was indicated by an increase of the buzzing frequency at about 110 Hz with a peak at 300 Hz when the swarm left the hive. Another finding was that a swarming period correlated with a rise in temperature from 33° C to 35° C with a temperature drop to 32° C at the actual time of swarming.

Rangel and Seeley [10] investigated signals of honeybee swarms. Five custom designed observation hives were sealed with glass covers. The captured video and audio data were monitored daily by human observers. The researchers found that approximately one hour before swarm exodus, the production of piping signals gradually increased and ultimately peaked at the start of the swarm departure.

Meikle and Holst [11] placed four beehives on precision electronic scales linked to data loggers to record weight for over sixteen months. The researchers investigated the effect of swarming on daily data and reported that empty beehives had detectable daily weight changes due to moisture level changes in the wood.

Bromenshenk et al. [12] designed and deployed bi-directional, IR bee counters in their multi-sensor SmartHive® system. The researchers found their IR counters to be more robust and accurate than capacitance and video-based systems. Since the IR counters required regular cleaning and maintenance, a self-diagnostic program was developed to check whether all of the emitters and detectors were functioning properly and the bee portals were not blocked by debris or bees.

### III. SOLAR-POWERED ELECTRONIC BEEHIVE MONITORING

#### A. Hardware

A fundamental objective of the BeePi design is reproducibility: other researchers and practitioners should be able to replicate our results at minimum cost and time commitments. Each BeePi consists of a raspberry pi computer, a miniature camera, a solar panel, a temperature sensor, a battery, a hardware clock, and a solar charge controller.

The exact BeePi hardware components are shown in Fig. 1. We used the Pi Model B+ 512MB RAM models, Pi T-Cobblers, half-size breadboards, waterproof DS18B20 digital temperature sensors, and Pi cameras (see Fig. 2). For solar harvesting, we used the Renogy 50 watts 12 Volts monocrystalline solar panels, Renogy 10 Amp PWM solar charge controllers, Renogy 10ft 10AWG solar adaptor kits, and the UPG 12V 12Ah F2 sealed lead acid AGM deep-cycle rechargeable batteries. All hardware fits in a shallow super, except for the solar panel that is placed on top of a hive (see Fig. 3) or next to it (see Fig. 4).



Fig. 1. BeePi hardware components.

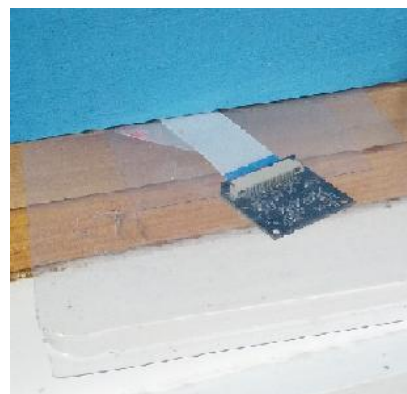


Fig. 2. Covered BeePi camera.



Fig. 3. Solar panels on beehives.

Two holes were drilled in the inner hive cover under a super with the BeePi hardware for a temperature sensor and a microphone. The temperature sensor chord was lowered into the second deep super (the first deep super is the lowest one) with nine frames of live bees to the left of frame 1. The

microphone chord was lowered into the second deep super to the right of frame 9. More holes can be drilled if the placements of the microphone and temperature sensors should be changed.



Fig. 4. BeePi in an overwintering beehive.

The camera is placed outside to take static snapshots of the beehive's entrance, as shown in Fig. 2. A small piece of hard plastic was placed above the camera to protect it from the elements. Fig. 3 displays the solar panels on top of two hives equipped with BeePi devices at the Utah State University Organic Farm. The solar panels were tied to the hive supers with bungee cords. It takes approximately 20 minutes to wire a BeePi monitor for deployment. Fig. 5 shows the first author wiring two such monitors at an apiary in spring 2016.



Fig. 5. Wiring BeePi monitors for deployment .

### B. Software

In each BeePi, all data collection is done on the raspberry pi computer. The collected data is saved on a 25G sdcard inserted into the pi. Data collection software is written in Python 2.7. When the system starts, three data collection threads are spawned. The first thread collects temperature readings every 10 minutes and saves them into a text file. The second thread collects 30-second wav recordings every 15 minutes. The third thread saves PNG pictures of the beehive's landing pad every 15 minutes.

A cronjob monitors the threads and restarts them after hardware failures. For example, during a field deployment the camera of one of the EBMDs stopped functioning due to excessive heat. The cronjob would periodically restart the PNG thread until the temperature went down and the camera started functioning properly again.

### C. Field Deployment

Three field deployments of BeePi devices have been executed so far. The first deployment was on private property in Logan, UT in early fall 2014. A BeePi was placed into an empty hive and ran exclusively on solar power for two weeks.

The second deployment was in Garland, UT in December 2014 – January 2015 in subzero temperatures. A BeePi in a hive with overwintering bees is shown in Fig. 4. Due to strong winter winds typical for Northern Utah, the solar panel was placed next to the hive on an empty super and tied down to a hive stand with bungee cords to ensure its safety. The BeePi successfully operated for nine out of the fourteen days of deployment exclusively on solar power. Over 3 gigabytes of pictures, wav files, and temperature readings were obtained during the nine operational days. These field deployments indicate that electronic beehive monitoring may be sustained by solar power.

### IV. OMNIDIRECTIONAL BEE COUNTING: ALGORITHM 1

Visual estimates of forager traffic are used by professional and amateur beekeepers to evaluate the health of a bee colony. In electronic beehive monitoring, computer vision can be used to estimate the amount of forager traffic from captured images. A sample image is shown in Fig. 6.



Fig. 6. Image captured from the BeePi camera.

The vision-based bee counting algorithms presented in this section and in Section V are omnidirectional, because they do not distinguish incoming and outgoing bee traffic. The reason why no directionality is integrated is two-fold. First, a robust vision-based solution to directionality will likely require video processing. Since the BeePi relies exclusively on solar power, in situ video capture and storage will drain the battery faster, thereby making EBM more disruptive. Second, omnidirectional bee counting can still be used as a valuable estimate of forager traffic so long as it accurately counts bees on landing pads. All algorithms were implemented in Java using the OpenCV 2 image processing library ([www.opencv.org](http://www.opencv.org)).

Since the camera's position is fixed, there is no need to process the entire image. The image processing starts by cropping a rectangular region of interest (ROI) where the landing pad is likely to be. The ROI is made wider and longer than the landing pad, because the camera may occasionally swing up, down and sideways in stronger



winds, which causes the pad to shift up, down, left, or right.

The ROI is brightened when its intensity level is below a threshold. Image brightening provides for more accurate bee identification in darker images (e.g., third image from the top in Fig. 7) captured on rainy or cloudy days. The actual landing pad is detected in the ROI with color histograms, because all landing pads in the hives, where the BeePi devices were deployed, have a distinct green color, as shown in Fig. 7. In Fig. 7, the two color images are the landing pads cropped from the ROIs.

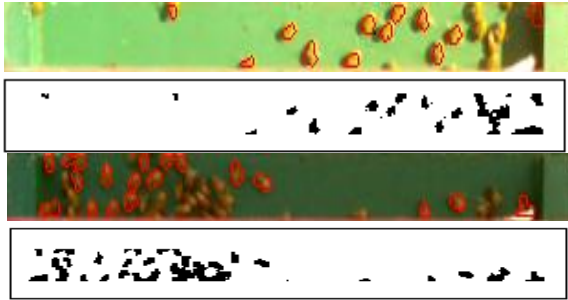


Fig. 7. Bee detection at beehive's entrance.

Two bee identification methods were implemented in Algorithm 1. The first bee identification method is based on a contour detection algorithm in OpenCV 2. An image is binarized and a list of contours, connected components of pixels, is computed. Contours with fewer than 30 or more than 50 pixels are removed. These parameters can be adjusted if necessary. The number of found contours is an estimate of the number of bees on the pad. In the two color images in Fig. 7, the red lines correspond to the contours of detected individual bees.

The second bee identification method is based on binary pixel separation of the cropped landing pad. Each pixel is inspected for the presence of the green color. If the presence of the green color exceeds a threshold, the pixel is labeled as a pad pixel. Otherwise, the pixel is labeled as a bee pixel. The second and fourth images in Fig. 7 show the landing pad's pixels as white pixels and the bees' pixels as black. An estimate of the number of bees on the landing pad is then obtained by dividing the number of detected bee pixels by 30, which is the average number of pixels, experimentally found, in an individual bee.

TABLE I  
Computer vision vs human evaluation.

Images	Bee Counts		Mean		STD		ACC
	CV	HM	CV	HM	CV	HM	
378	1582	2165	4.2	5.7	6.5	6.5	73.07

Both methods were compared in two experiments. In the first experiment, a sample of 135 images of landing pads with bees on them was selected. The number of bees in each image was counted by a human observer. The total number of counted bees was 1204. The methods were evaluated on all images. The contour detection method (method 1) accurately identified 650 bees of 1204 (54%). The background separation method (method 2) found 871 bees out of 1204 (71%).

In the second experiment, the pixel separation method was compared with human evaluation on another sample of 378 images. The images from the first experiments were not

used in the second experiment. The results are tabulated in Table I. The CV columns give the statistics for the pixel separation algorithm. The HM columns give the statistics of the two human evaluators who counted the actual numbers of bees in each of the 378 images. The first human evaluator processed 200 images. The second human evaluator processed the remaining 178 images. The human evaluators counted 2156 bees in 378 images. Human evaluation was used as the ground truth.

Of the 2156 bees found by the human evaluators, the pixel separation algorithm found 1582 bees in the same images. The overall accuracy, given in the ACC column in Table I, was computed as the ratio of the bees found by this method and the bees found by the human evaluators. The accuracy came out to be 73%.

The Mean column in Table I tabulates the mean numbers of bees identified by the pixel separation method and the human evaluators in the images. These numbers indicate that the computer vision algorithm, on average, identifies fewer bees than the human evaluators in each image.

The standard deviation (STD) column shows that standard deviations of the computer vision algorithm and the human evaluation were the same on this sample of images, which indicates that the algorithm is consistent.

The subsequent analysis of individual images on which the pixel separate method underperformed revealed two main causes of error. The first cause was the wrong identification of the landing pad in bright images when the method cropped not only the landing pad with bees but also chunks of grass. Some of the grass blades were erroneously counted as bees. The other cause of error was really dark images where the algorithm found smaller numbers of bees even after the images were brightened. Based on the experiments and observations, the pixel separation method appeared to outperform than the contour detection method on the selected sample of images.

## V. OMNIDIRECTIONAL BEE COUNTING: ALGORITHM 2

In an attempt to improve the performance of Algorithm 1, another algorithm for omnidirectional bee counting was iteratively designed and implemented to address the main causes of failure of Algorithm 1.

Algorithm 2 consists of three stages: pre-processing, landing pad identification, and omnidirectional bee counting. In the pre-processing stage, an approximate image region where the landing pad is likely to be is cropped and the brightness of the cropped region adjusted. The landing pad identification is obtained through iterative reduction of the cropped image to the actual landing pad. Omnidirectional bee counts are computed by dividing the total number of bee pixels by the average number of pixels occupied by individual bees obtained from camera calibration experiments.

The coordinates of the image region with the landing pad is obtained through in situ experiments. The coordinates of the region are set in a configuration file and used in the algorithm to crop the region of interest. The lower image in Fig. 8 shows the output of the cropping step. Note that there may be some grass in the cropped image. The dimensions of the cropped region are intentionally set to be larger than the

actual landing pad to compensate for camera swings in strong winds.

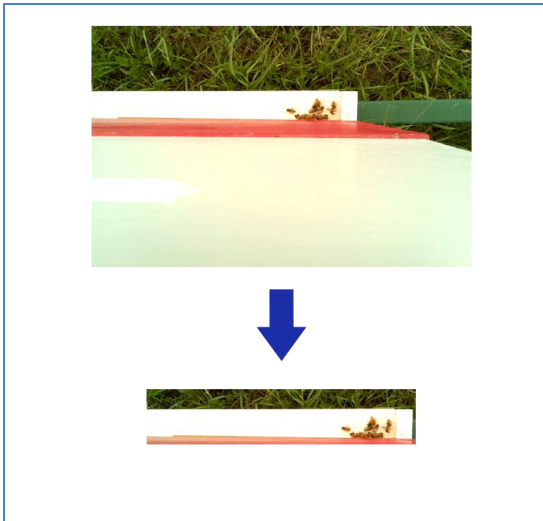


Fig. 8. Cropped landing pad (below) from original image (above).

Image brightness is dependent on the weather. Brightness is maximal when the sun is directly above the beehive. However, when the sun is obscured by clouds, captured images tend to be darker. As experiments with Algorithm 1 described in Section IV showed, both cases had an adverse effect on bee counting. To minimize this effect, image brightness is dynamically adjusted to lie in (45, 95), i.e., the brightness index should be greater than 45 but less than 95. This range was experimentally found to yield optimal results.

Fig. 9 illustrates how brightness adjustment improves omnidirectional bee counts. The upper image on the right in Fig. 9 shows a green landing pad extracted from the cropped image on the left without adjusted brightness. The lower image on the right in Fig. 9 shows a green pad extracted from the same image with adjusted brightness. Only four bees were identified in the upper image on the left whereas in the lower image eight bees were identified, which is closer to the twelve bees found in the original image by human counters.

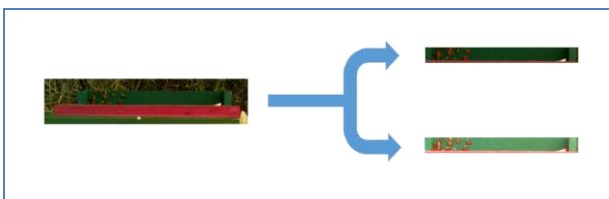


Fig. 9. Extraction of green pad with from image with adjusted brightness.

The three steps of the landing pad identification in the cropped region, i.e., the output of the pre-processing stage, are shown in Fig. 10. The first step in identifying the actual landing pad in the approximate region cropped in the pre-processing stage is to convert the pre-processed RGB image to the Hue Saturation Value (HSV) format, where H and S values are computed with Equation (1).

$$H = \begin{cases} 60^\circ \left( \frac{G' - B'}{\Delta} \bmod 6 \right) & \text{if } C_{\max} = R', \\ 60^\circ \left( \frac{B' - R'}{\Delta} + 2 \right) & \text{if } C_{\max} = G', \\ 60^\circ \left( \frac{R' - G'}{\Delta} + 4 \right) & \text{if } C_{\max} = B'. \end{cases} \quad (1)$$

$$S = \begin{cases} 0 & \text{if } C_{\max} = 0, \\ \frac{\Delta}{C_{\max}} & \text{if } C_{\max} \neq 0. \end{cases}$$

In (1),  $R', G', B'$  are the  $R, G, B$  values normalized by 255,  $C_{\max} = \max\{R', G', B'\}$ , and  $\Delta = C_{\max} - \min\{R', G', B'\}$ . The value of  $V$  is set to  $C_{\max}$ . In the actual implementation, the format conversion is accomplished with the `cvtColor()` method of OpenCV. The `inRange()` method of OpenCV is subsequently applied to identify the areas of green or white pixels, the two colors in which the landing pads of our beehives are painted.

Noise is removed through a series of erosions and dilations. The white pixels in the output image represent green or white color in the actual image and the black pixels represent any color other than green or white.

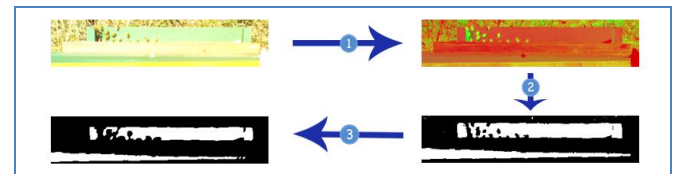


Fig. 10. Landing pad identification steps: 1) HSV conversion; 2) color range identification; 3) noise removal.

To further remove noise from the image and reduce it as closely as possible to the actual landing pad, contours are computed with the `findContours()` method of OpenCV and a bounding rectangle is found for each contour. The bounding contour rectangles are sorted in increasing order by the  $Y$  coordinate, i.e., increasing rows. Thus, the contours in the first row of the image will be at the start of the list. Fig. 11 shows the bounding rectangles for the contours computed for the output image of step 3 in Fig. 10.



Fig. 11. Bounding rectangles of found contours.

Data analysis indicates that if the area of a contour is at least half the estimated area of the landing pad, the contour is likely to be part of the actual landing pad. On the other hand, if the area of a contour is less than 20 pixels, that contour is likely to be noise and should be discarded.

In the current implementation of the algorithm, the estimated area of the green landing pad is set to 9000 pixels and the estimated area of the white landing pad is set to 12000 pixels. These parameters can be adjusted for distance.

Using the above pixel area size filter, the approximate location of the landing pad is computed by scanning through all the contours in the sorted list and finding the area of each

contour. If the area is at least half the estimated size of the landing pad of the appropriate color, the  $Y$  coordinate of the contour rectangle is taken to be the average  $Y$  coordinate and the scanning process terminates.

If the contour's area is between 20 and half the estimated landing pad area, the  $Y$  coordinate of the contour is saved. Otherwise, the current contour is skipped and the next contour is processed. When the first contour scan terminates, the average  $Y$  coordinate,  $\mu(Y)$ , is calculated by dividing the sum of the saved  $Y$  coordinates by the number of the processed contour rectangles.

After  $\mu(Y)$  is computed, a second scan of the sorted contour rectangle list is performed to find all contours whose height lies in  $[\mu(Y)-H, \mu(Y)+H]$ , where  $H$  is half of the estimated height of the landing pad for the appropriate color.

While the parameter  $H$  may differ from one beehive to another, as the alignment of the camera differs from one hive to another, it can be experimentally found for each beehive. For example, if the camera is placed closer to the landing pad, then  $H$  will have a higher value and if the camera is placed far from the landing pad,  $H$  will have a lower value. In our case,  $H$  was set to 20 for green landing pad images and to 25 and for white landing pad images.

Bounding rectangles are computed after the second scan to enclose all points in the found contours, as shown in Fig. 12. To verify whether the correct landing pad area has been identified, the area of the bounding rectangle is computed.

If the area of the bounding rectangle is greater than the estimated area of the landing pad, the bounding rectangle may contain noise, in which case another scan is iteratively performed to remove noise by decreasing  $H$  by a small amount of 2 to 4 units. In most of the cases, this extra scan is not needed, because the landing pad is accurately found. Fig. 12 illustrates the three steps of the contour analysis to identify the actual landing pad.

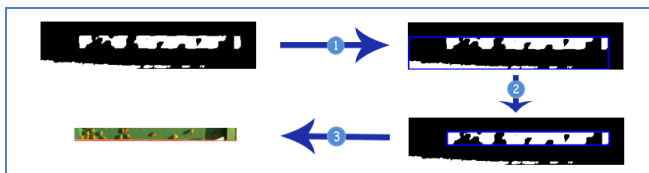


Fig. 12. Contour analysis: 1) 1st contour scan; 2) 2nd contour scan; 3) pad cropping.

Foreground and background pixels are separated on color. Specifically, in the current implementation of the algorithm, for green landing pads, the background is assumed to be green and the foreground, i.e., the bees, is assumed to be yellow; for white landing pads, the background is assumed to be white and the foreground is assumed to be yellow.

All pixels with shades of green or white are set to 255 and the remaining pixels are set to 0. Three rows of border pixels of the landing pad image are arbitrarily set to 255 to facilitate bee identification in the next step. Fig. 13 shows the output of this stage. In Fig. 13, the green background is converted to white and the foreground to black. Since noise may be introduced, the image is de-noised through a series of erosions and dilation with a  $2 \times 2$  structuring element.



Fig. 13. Background and foreground separation.

To identify bees in the image, the image from the previous stage is converted to grayscale and the contours are computed again. Data analysis suggests that the area of an individual bee or a group of bees vary from 20 to 3000 pixels. Therefore, if the area of a contour is less than 20 pixels or greater than 3000 pixels, the contour is removed.

The area of one individual bee is between 35 and 100 pixels, depending on the distance of the pi camera from the landing pad. The green landing pad images were captured by a pi camera placed approximately 1.5m above the landing pad with the average area of the bee being 40 pixels.

On the other hand, the white landing pad images were captured by a pi camera placed approximately 70cm above the landing pad where the average area of an individual bee is 100 pixels. To find the number of bees in green landing pad images, the number of the foreground pixels, i.e., the foreground area, is divided by 40 (i.e., the average bee pixel area on green landing pads), whereas, for the white landing pad images, the foreground area is divided by 100 (i.e., the average bee pixel area on white landing pads). The result is the most probable count of bees in the image. In the upper image in Fig. 14, five bees are counted by the algorithm. The lower image in Fig. 14 shows the found bees in the original image.

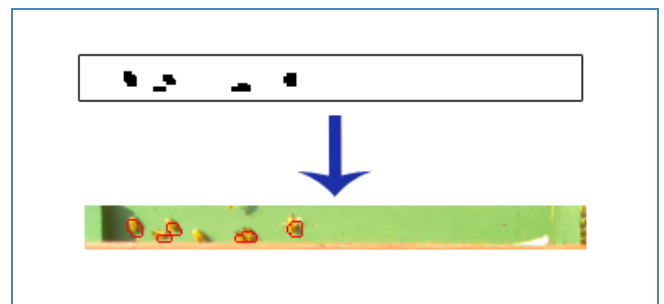


Fig. 14. Omnidirectional bee counting.

A sample of 1005 green pad images and 776 white pad images were taken from the data captured with two BeePi EBMDs deployed at two Northern Utah apiaries. Each image has a resolution of  $720 \times 480$  pixels and takes 550KB of space. To obtain the ground truth, six human evaluators were recruited. Each evaluator was given a set of images and asked to count bees in each image and record their observations in a spread sheet. The six spread sheets were subsequently combined into a single spread sheet.

Table II gives the ground truth statistics. The human evaluators identified a total of 5,770 bees with an average of 5.7 bees per image in images with green landing pads. In images with white landing pads, the evaluators identified a total of 2,178 bees with a mean of 2.8 bees per image.

Table III summarizes the performance of the algorithm ex situ on the same green and white pad images. The algorithm identified 5,263 bees out of 5,770 in the green pad images with an accuracy of 80.5% and a mean of 5.2 bees per image. In the white pad images, the algorithm identified 2,226 bees out of 2,178 with an accuracy of 85.5% and an average of 2.8 bees per image. The standard deviations of the algorithm were slightly larger than those of the human evaluators.



TABLE II  
Ground truth statistics.

Pad Color	Num Images	Total Bees	Mean	STD
Green	1,005	5,770	5.7	6.8
White	776	2,178	2.8	3.4

TABLE III  
Ex situ performance of algorithm 2.

Pad Color	Num Images	Total Bees	Mean	STD	ACC
Green	1,005	5,263	5.2	7.6	80.5
White	776	2,178	2.8	4.1	85.5

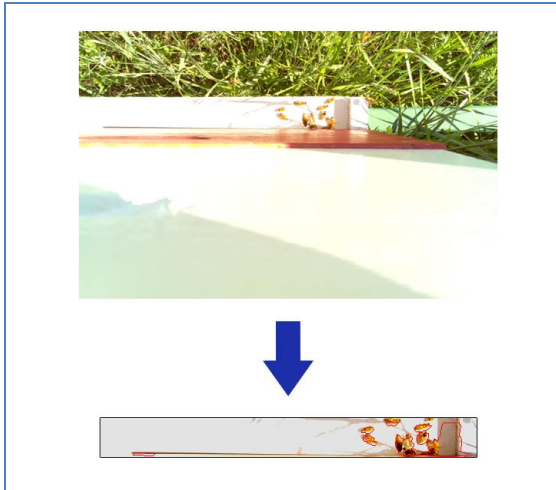


Fig. 15. False positives.

Our analysis of the results identified both true negatives and false positives. There appear to be fewer true negatives than false positives. The main reason for true negatives is the algorithm's conservative landing pad identification, which causes some actual bees to be removed from the image.

The bees on the sides of the landing pad are also typically removed from the image. Another reason for true negatives is image skewness due to wind induced camera swings. If the landing pad is skewed, then a part of the landing pad is typically cropped out during the bounding rectangle computation. In some images, some actual bees were removed from images during image de-noising, which resulted in lower bee counts compared to human counts.

False positives were primarily caused by occasional shades, leaves, or blades of grass wrongly counted as bees. Fig. 15 gives an example of false positives. A human evaluator counted 9 bees in the upper image whereas the algorithm counted 28 bees on the landing pad (lower image in Fig. 15) cropped out of the upper image. The shade pixels on the right end of the cropped landing pad were counted as bees, which resulted in a much higher bee count than the human evaluator's count.

## VI. AUDIO ANALYSIS OF BUZZING SIGNALS WITH HARMONIC INTERVALS

Digitizing buzzing signals into A440 piano note sequences is a method of obtaining a symbolic representation of signals grounded in time. When viewed as a time series, such sequences can be correlated with other timestamped data such as estimates of forager bee traffic levels or temperatures.

Bee buzzing audio signals were first processed with the Fast Fourier Transform (FFT), as implemented in Octave

[11], to compute the FFT frequency spectrograms to identify the A440 piano key notes. The quality of the computed spectrograms was inadequate for reliable note identification due to low volumes.

The second attempt, which also relied on Fourier analysis, did not use the FFT. A more direct, although less efficient, method outlined in Tolstov's monograph [12] was used. Tolstov's method relies on periodic functions  $f(x)$  with a period of  $2\pi$  that have expansions given in (1). Multiplying both sides of (1), separately, by  $\cos(nx)$  and by  $\sin(nx)$ , integrating the products from  $-\pi$  to  $\pi$ , and regrouping, the equations in (2) are obtained for the Fourier coefficients in the Fourier series of  $f(x)$ . The interval of integration can be defined not only on  $[-\pi, \pi]$  but also on  $[a, a+2\pi]$  for some real number  $a$ , as in (3).

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos kx + b_k \sin kx) \quad (1)$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx \, dx, n = 0, 1, 2, \dots \quad (2)$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx \, dx, n = 0, 1, 2, \dots$$

$$a_n = \frac{1}{\pi} \int_a^{a+2\pi} f(x) \cos nx \, dx, n = 0, 1, 2, \dots \quad (3)$$

$$b_n = \frac{1}{\pi} \int_a^{a+2\pi} f(x) \sin nx \, dx, n = 0, 1, 2, \dots$$

In many real world audio processing situations, when  $f(x)$  is represented by a finite audio signal, it is unknown whether the series on the right side of (1) converges and actually equals the sum of  $f(x)$ . Therefore, only the approximate equality in (4) can be used. Tolstov's method defines constituent harmonics in  $f(x)$  by (5).

$$f(x) \approx \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx) \quad (4)$$

$$h_n(x) = a_n \cos nx + b_n \sin nx \quad (5)$$

The proposed algorithm for detecting A440 piano notes in beehive audio samples is based on Tolstov's method and implemented in Java. An A440 key  $K$  is represented as a harmonic defined in (5). Since  $n$  in (5) is a non-negative integer and note frequencies are real numbers,  $K$  is defined in (6) as a set of harmonics where  $f$  is  $K$ 's A440 frequency in Hz and  $b$  is a small positive integer that defines a band of integer frequencies centered around  $K$ 's real frequency. For example, the A440 frequency of A0 is 27.56 Hz. Thus, a set of six integer harmonics, from  $h_{25}(x)$  to  $h_{30}(x)$ , can be defined to identify the presence of A0 in a signal, as in (7).

The presence of a key in a signal is done by thresholding the absolute values of the Fourier coefficients or harmonic magnitudes. Thus, a key is present in a signal if the set in (6) is not empty for a given value of  $b$  and a given threshold.

$$H_f(x) = \{h_n(x) | n \in [\lfloor f-b \rfloor, \lceil f+b \rceil]\}, b \in N^+ \quad (6)$$

$$H_{27.56}(x) = \{h_n(x) | n \in [25, 30]\}, b = 2 \quad (7)$$

A Java class in the current implementation of the algorithm takes wav files and generates LOGO music files for the LOGO Music Player (LMP) ([www.terrapinlogo.com](http://www.terrapinlogo.com)). Fig. 16 shows several lines from an LMP file generated from a wav file. PLAY is a LOGO function. The remainder of each line consists of the arguments to this function in square brackets. A single pair of brackets indicates a one-note chord; double brackets indicate a chord consisting of multiple resulting notes.

```
PLAY [F7]
PLAY [[A0 A0# B0 ]]
PLAY [[A1 A1# B1 C1 C1# D1 F1 F1# G1 ]]
PLAY [C2]
PLAY [F7]
PLAY [[A0 A0# ]]
PLAY [[A0 A0# B0 ]]
PLAY [A0]
PLAY [[A0 A0# B0 ]]
PLAY [[A1 A1# B1 C1 C1# D1 D1# E1 F1 F1# G1 G1# ]]
PLAY [[C2 C2# D2 D2# E2 G2# ]]
PLAY [F7]
PLAY [B0]
PLAY [[C1 C1# ]]
PLAY [A0]
PLAY [A0]
PLAY [A0]
PLAY [[A0 A0# ]]
PLAY [[A0 A0# B0 ]]
```

Fig. 16. LMP instructions with A440 notes detected in wav files.



Fig. 17. Musical score of bee buzzing.

To visualize beehive music, the audio files generated by the LMP can be converted into musical scores. Fig. 17 gives one such score obtained with ScoreCloud Studio (<http://scorecloud.com>) from an LMP file converted to midi.

## VII. AUDIO DATA ANALYSIS

The audio digitization algorithm described in Section VI was applied to the buzzing signals collected by a BeePi device at the USU Organic Farm from 22:00 on July 4<sup>th</sup>, 2015 to 00:00 on July 7<sup>th</sup>, 2015.

Each signal was saved as a 30-second wav file. A total of

152 wav files were collected in this period, which amounted to a total of 3421.52 MB of wav data. The digitization algorithm described in Section VI was applied to these data on a PC running Ubuntu 12.04 LTS.

The A440 piano keys were mapped to integers from 1 to 88 so that A0 was mapped to 1 and C8 to 88, according to the standard A440 piano key frequency table [3]. In Fig. 19, these key numbers correspond to the values on the X axes. Each 24-hour period was split into 6 non-overlapping half-open hour intervals: [0, 5), [5, 9), [9, 13), [13, 17), [17, 20), [21, 0). The frequency counts of all notes detected at a frequency of 44100 Hz were computed for each interval.

The detected spectrum contained only the first four octaves with the lowest detected note being A0 (1) and the highest F#4 (50). The buzzing frequencies appear to have a cyclic pattern during a 24-hour period.

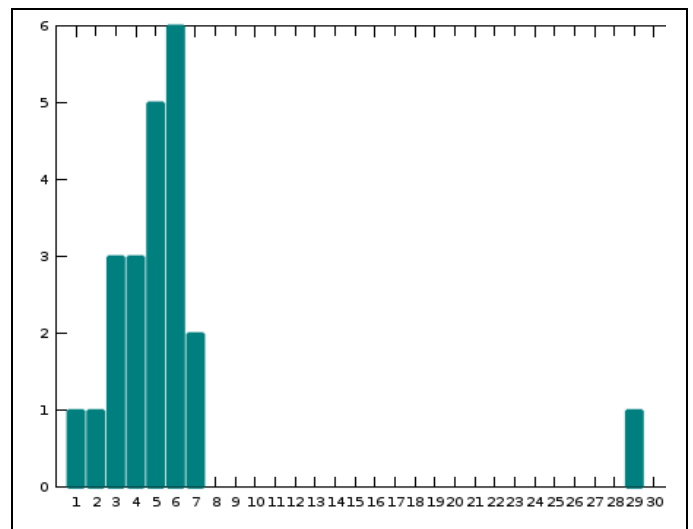


Fig. 18. A440 note frequency histogram for time interval 1 from 0:00 to 4:59; lowest detected note is A0 (1); highest detected note is C#3 (29).

From 0:00 to 4:59 (see Fig. 18), the detected notes mostly ranged from A0 (1) to D#1 (7), with the two most frequent notes being C#1 (5) and D1 (6). Note C#3 (29) was also detected. The frequency counts of detected notes were low and ranged from 1 to 6. The hive was mostly silent.

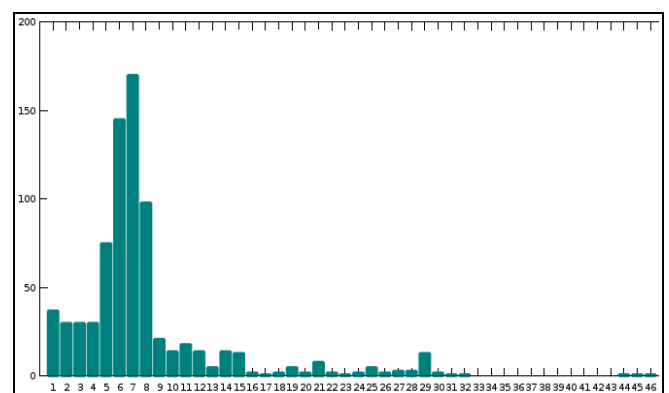


Fig. 19. A440 note histogram for time interval 2 from 5:00 to 8:59; lowest detected note A0 is (1); highest detected note is (46).

From 5:00 to 8:59 (see Fig. 19) the detected note range widened from A0 (1) to F#4 (46). The two most frequent notes were D1 (6) and D#1 (7). The range of frequency counts widened up to 170. The hive was apparently



becoming louder and less monotonous in sound.

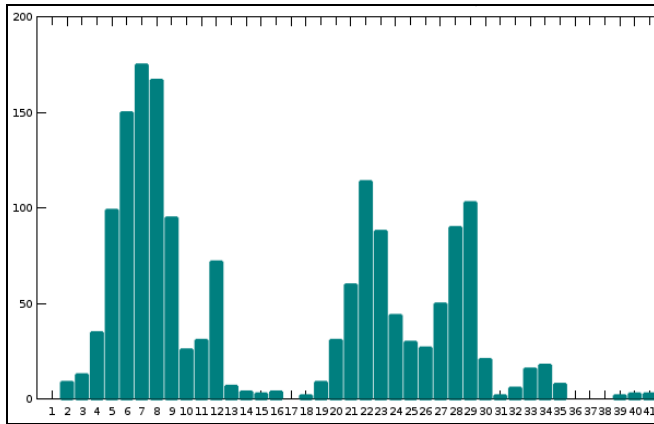


Fig. 20. A440 note histogram for time interval 3 from 9:00 to 12:59; lowest detected note is A#2 (2); highest detected note is C#4 (41).

From 9:00 to 12:59 (see Fig. 20) the note range slightly narrowed from A0# (2) to C#4 (41). However, the note range had three pronounced sub-ranges. The first sub-range ran from A#0 (2) to A1 (13), with the two most frequent notes being D#1 (7) and E1 (8). The second sub-range ran from D#2 (19) to A2 (25), where the two most frequency notes were F#2 (22) and G2 (23). The third sub-range ran from (26) to D3 (30), with the two most frequent notes being C3 (28) and C#3 (29). The frequency count range edged slightly upward to 180. Compared to the preceding time interval from 5:00 to 8:59 the hive appeared to have become louder and the overall audio spectrum shifted higher, as exemplified by the two higher sub-ranges.

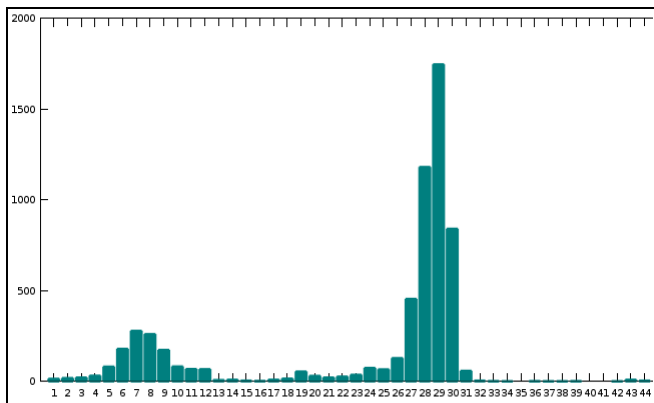


Fig.21. A440 note frequency histogram for time interval 4 from 13:00 to 16:59; lowest detected note is A0 (1); highest detected note is E4 (44).

From 13:00 to 16:59 (see Fig. 21) the detected note range to ran from A0 (1) to E4 (44). The two most frequent notes were C3 (28) and C#3 (29). There were also two pronounced sub-ranges from C1 (4) to G#1 (12) and from G2 (23) to D#3 (31). The lower sub-range carried over from the previous time interval shown in Fig. 21. The most frequent notes in the lower sub-range were D#1 (7) and E1 (8). The most frequent notes in the higher sub-range were C3 (28) and C#3 (29). It is noteworthy that the frequency count range also widened up to 1700.

Both sub-ranges detected in the preceding time interval from 9:00 to 12:59 were still present. However, the lower sub-range with peaks at D#1 (7) and E1 (8) was much less pronounced than then higher sub-range with peaks at C3

(28) and C#3 (29). The audio spectrum appeared to have shifted to the higher sub-range.

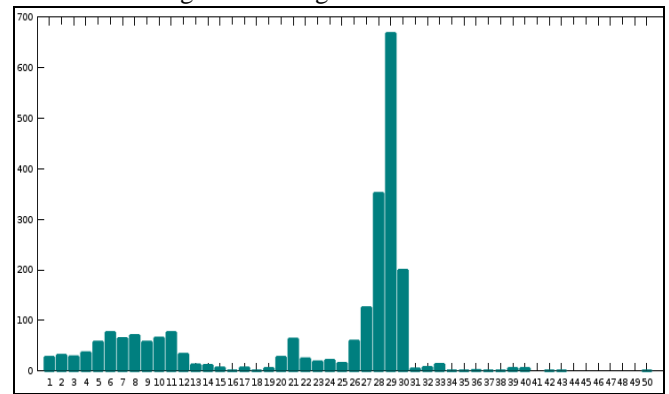


Fig. 22. A440 note frequency histogram for time interval 5 from 17:00 to 20:59; lowest detected note is A0 (1); highest detected note is A#4 (50).

From 17:00 to 20:59 (see Fig. 22) the range ran from A0 (1) to A#4 (50), with the two most frequent notes being C3 (28) and C#3 (29). The frequency count range narrowed down from 1700 in the preceding time interval to 690.

There were three sub-ranges. The first sub-range ran from A0 (1) to B1 (15) with peaks at D1 (6), E1 (8) and G1 (11). The second sub-range ran from D#2 (19) to A2 (25) with a single peak at F2 (21). The third sub-range, the most pronounced one, ran from A#2 (26) to D3 (30) with peaks at C3 (28) and C#3 (29). Compared to the preceding time interval from 13:00 to 16:59, the first sub-range widened whereas the third sub-range remained the most prominent one but its frequency counts were lower.

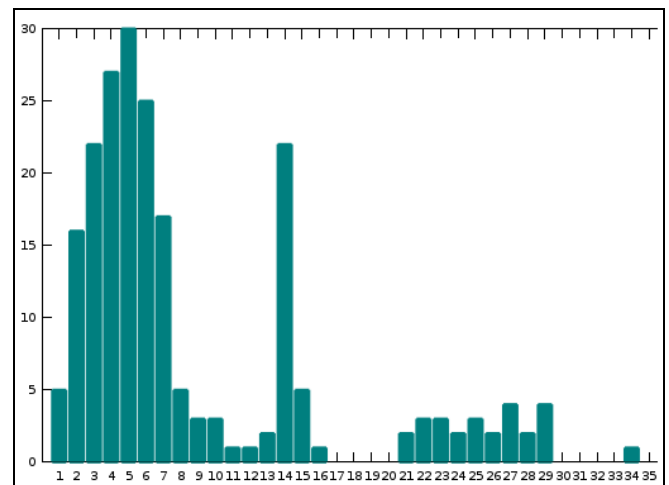


Fig. 23. A440 note frequency histogram for time interval time interval 6 from 21:00 to 23:59; lowest detected note is A0 (1); highest detected note is F#3 (34).

From 21:00 to 23:59 (see Fig. 23), the detected note range narrowed run from A0 (1) to F#3 (34). There were three observable sub-ranges. The first sub-range ran from A0 (1) to F#1 (10) and had peaks at C1 (4) and C#1 (5). The second sub-range ran from A1 (13) to C2 (16) and had a peak at A#1 (14). The third sub-range ran from F2 (21) to C#3 (29) and had peaks at B2 (27) and C#3 (29). Compared to the preceding time interval from 17:00 to 20:59 in Fig. 23 there was a sharp drop in the frequency count range from 690 to 30.

## VIII. CONCLUSIONS

An electronic beehive monitoring device, called BeePi, was presented. Four BeePi devices were assembled and deployed in beehives with live bees over extended periods of time in different weather conditions. The field deployments demonstrate that it is feasible to use solar power in electronic beehive monitoring. The presented algorithms for omnidirectional bee counting and harmonic analysis indicate that computer vision and audio analysis will likely play increasingly more significant roles in sustainable electronic beehive monitoring units used by professional and amateur apiarists.

### A. Computer Vision

Two computer vision algorithms for omnidirectional bee counting on landing pads were implemented and tested. The first algorithm consisted of two methods. The first method, based on a contour detection algorithm, takes a binarized image and estimates the bee counts as the number of detected contours containing between 30 and 50 pixels.

The second method is based on the binary pixel separation of the cropped landing pad into pad pixels and bee pixels. An estimate of the number of bees on the landing pad is obtained by dividing the number of the bee pixels by 30, which is the average number of pixels in an individual bee.

The pixel separation method performed better than the contour detection algorithm on a sample of 135 images. The pixel separation algorithm was compared to the human evaluation on another sample of 378 images with an observed accuracy of 73%. Two main causes of error were individual grass blades detected as bees in bright images and dark images where some bees were not recognized.

The second algorithm for omnidirectional bee counting on landing pads was implemented to address the shortcomings of the first algorithm. The second algorithm consists of three stages: pre-processing, landing pad identification, and omnidirectional bee counting. In the pre-processing stage, an approximate image region where the landing pad is likely to be is cropped and the brightness of the cropped image adjusted. The landing pad identification is obtained through iterative reduction of the cropped image to the actual landing pad. Omnidirectional bee counts are computed by dividing the total number of bee pixels by the average number of pixels occupied by individual bees.

Subsequent analysis of the results identified both true negatives and false positives. The main cause of true negatives is the algorithm's conservative landing pad identification, which causes some actual bees to be removed from the image. Another cause of true negatives is image skewness due to wind induced camera swings. If the landing pad is skewed, then a part of the landing pad is typically cropped out during the bounding rectangle computation. False positives were primarily caused by occasional shades, leaves, or blades of grass wrongly counted as bees.

A weakness of both algorithms for omnidirectional bee counting is landing pad localization. Both algorithms localize landing pads with row and column parameters in configuration files. These parameters are hardcoded for each particular monitoring unit and must be manually modified

when the unit is deployed in a different beehive. To address this weakness, an algorithm is currently being designed to localize landing pads in images automatically. The algorithm has four run time logical steps: brightness adjustment, pad skew detection, cluster classification, and landing pad localization. The third run time step, i.e., cluster classification, requires the offline computation of clusters to improve the performance of histogram back project.

### B. Audio Analysis

The algorithm was presented for digitizing bee buzzing signals into A440 piano note sequences and for estimating forager traffic levels from images. The algorithm for digitizing buzzing signals converts the wav signals into timestamped sequences of A440 piano notes by using harmonic intervals. The detected note spectra contained the first four octaves of the A440 piano.

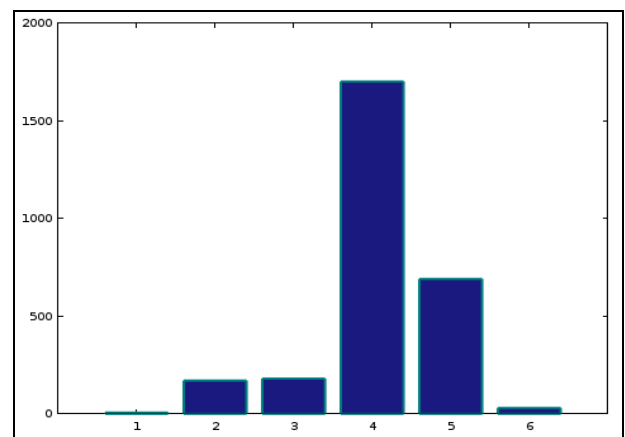


Fig. 24. Upper bounds of frequency note count ranges for six time intervals.

The upper levels of frequency note counts exhibited a cyclic pattern during a 24-hour period. Specifically, as shown in Fig. 24, the upper bounds of the frequency count ranges started at 6 in time interval 1, increased to 170 and 180 in intervals 3 and 4, sharply increased to 1700 in interval 4 and then dropped to 690 and 30 in intervals 5 and 6, respectively.

It was also observed that the peaks in the frequency counts, as the selected 24-hour time period progressed, started in the first octave (D1), shifted higher to C3 and C#3 in the third octave, and returned back to the first octave in time interval 6 at the end of the selected time period. Several notes in the fourth octave, e.g., and F#4 C#4, were also detected but their frequency counts are substantially lower than those of the peaks in the first three octaves.

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