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Sensor phenomena

Janus: A Combined Radar and Vibration Sensor for Beehive Monitoring

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Abstract—A novel beehive monitoring sensor with two faces is described. This sensor is attached to the outside of a hive, near the hive entrance. The outward-looking sensor is a 24-GHz continuous-wave Doppler radar for monitoring bee flying activity. The inward-looking sensor is a piezoelectric transducer. Unlike a conventional microphone that would pick up the sounds bees make, the piezoelectric transducer picks up the incidental vibrations transmitted by bee activity to the hive structure. The root-mean-square powers in concurrent radar and vibration measurements are shown to be highly correlated during honeybee swarming and robbing events. Principal component analysis was applied to radar, vibration, and environmental measurements to further reduce false alarms.

Index Terms—Sensor phenomena, beehive monitoring, Doppler radar, piezoelectric vibration transducer.

I. INTRODUCTION

There are two unusual events in an apiary that require immediate intervention by the beekeeper: swarming and robbing.

Swarming is a natural event during which about half the bee population leaves the hive to establish a new colony. In as much as possible, beekeepers like to avoid swarming, and its associated loss of honey production, using proper management techniques [1]. When swarming happens unexpectedly, however, the beekeeper would like to be alerted as soon as possible. Swarming may take place in a matter of minutes. It usually starts with a great uproar from the beehive, followed by a rapid disgorgement and flight of thousands of bees in a cloud. The swarm initially lands and forms a tight cluster close to the original hive before flying off to its final destination. This bivouac may last for as little as an hour, or depending on the weather, it may last for days [2]. Quick action during the bivouac phase is the beekeeper's best chance of capturing a swarm and thereby increasing his apiary stock [3].

At times of poor honey flow, bees from a stronger hive may attack a weaker hive and steal its honey [4]. If successful, robbers can clean all the honey out of a hive in a few days. Robbing tends to be a persistent, all-day event that is usually accompanied by a high level of noise and continuous frenzied flying activity in front of the hive [3]. One way of dealing with that situation is either to reduce temporarily the size of the hive entrance or to close it altogether [3].

A commonly occurring and harmless activity is the "mass orientation flight," a bee activity that has so far eluded a concise biological explanation [5]. In this scenario, a substantial cloud of bees flies back and forth in front of the hive entrance. Mass orientation flights have often been mistaken for swarming, except that the bees do not fly far away from the hive, and they return to the hive after a few minutes. The level of flying activity of orientation flights and swarming can be very similar; however, the level of acoustic noise associated with orientation flights is considerably lower. Although orientation flights are also detected by our sensor, they usually do not require intervention by the beekeeper.

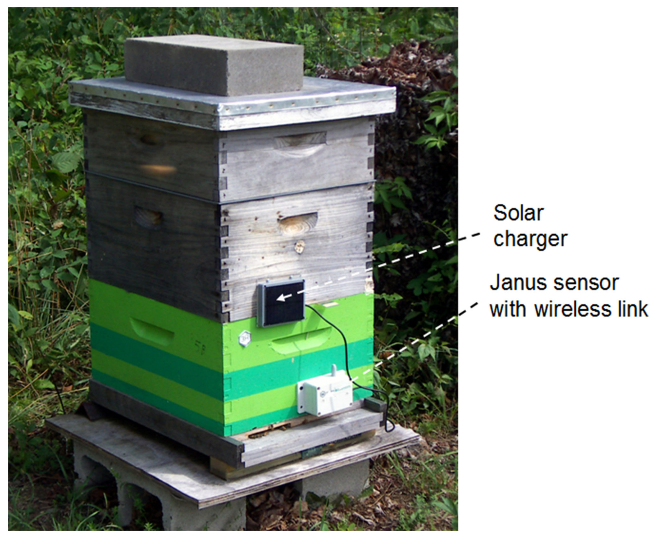

Fig. 1. Radar/vibration sensor installed on beehive 8B.

By carefully noting flight activity near the beehive entrance and acoustic noise from the hive, an experienced beekeeper can tell very quickly if the bees are happy, sad, or mad [6]. However, it is often not practical for the beekeeper to check on hives in a remote apiary every day. An inexpensive beehive monitoring system is of interest to that would warn the beekeeper that a swarm is about to take place, or has just occurred, or that a robbery is in progress.

An external sensor, as shown in Fig. 1, can meet the aforementioned requirement. We will show that the observations of swarming events, done both with a Doppler radar and with a vibration sensor, are highly correlated, even though they are based on entirely different phenomenology. When a major hive perturbation occurs, and the Doppler and vibration levels are both high, then it is likely to be a

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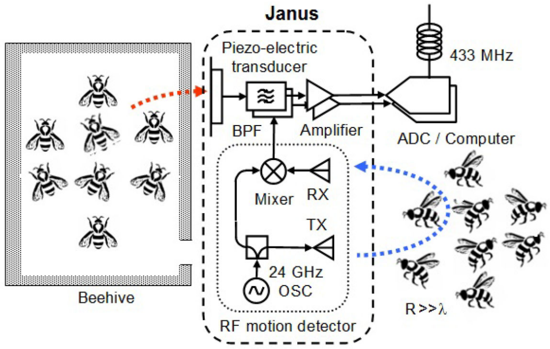

Fig. 2. Radar/vibration sensor block diagram.

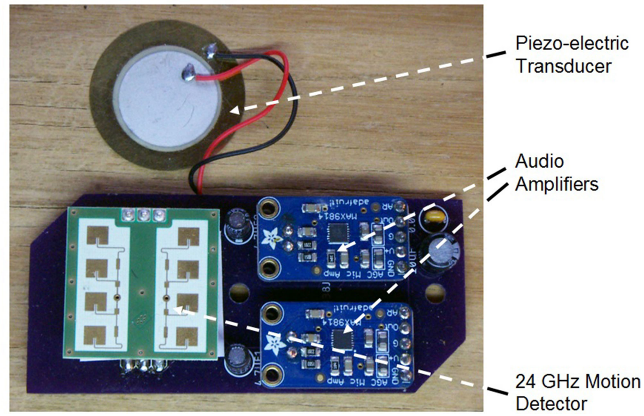

Fig. 3. Janus front end.

swarm. When the levels differ significantly, then the event is most likely due either to robbing or to an "orientation flight."

We review prior related work in Section II. The sensor hardware is described in Section III. In Section IV, we verify the operation of the two-faced sensor, and in Section V, we show some experimental results.

II. PRIOR WORK

The unique sounds that bees make have been described since antiquity [3]. We are all familiar with the buzz of bee wings, which is typically at 270 Hz. At other times, one can hear intermittent sounds, such as queen bees tooting (550 Hz) or quacking (300 Hz), or workers piping (400 Hz) [7]–[9]. Most bee sounds are well below 600 Hz.

Numerous sensors have been developed for collecting, remotely and in real-time, acoustic signals from bees within a beehive [10]–[17]. A review of such sensors can be found in [17]. The installation requires opening the hive and inserting a microphone between the frames. Eventually, the microphone becomes covered with propolis and thereby rendered less effective. Interpretation of the bee sounds is left to the beekeeper or else requires expensive offline equipment for the needed feature extraction. Sounds captured with an acoustic microphone outside the hive [17] while easier to achieve have often been found to be corrupted by environmental interference.

Bee behavior has also been studied by measuring localized vibrations with an accelerometer. In such studies, the accelerometer was installed either inside the hive [4], [18] or in the hive wall [19].

In an entirely different approach, we demonstrated the use of a low-power continuous-wave (CW) Doppler radar to listen to bee sounds [20] or to monitor flying activity outside the beehive [21]–[23]. In this letter, we combine this radar sensor with a vibration sensor in a two-faced apparatus to improve swarm detection.

III. JANUS SENSOR

We have named our sensor "Janus" after the god of Roman mythology. Janus is usually pictured with two, sometimes dissimilar faces, one looking forward and one looking backward. Similarly, our system contains two sensors, looking in opposite directions. A block diagram of the system is shown in Fig. 2. One sensor monitors bee activity inside the beehive (red), and one sensor monitors activity outside the beehive (blue). A Janus sensor implementation is depicted in Fig. 3.

A. Vibration Sensor

The vibration sensor is based on a very inexpensive 26-m-diameter piezoelectric transducer commonly used in acoustic guitar pickups. It is firmly attached to the outside wall of a wooden Langstroth hive above the hive entrance. The transducer is connected to an audio amplifier with about 70-dB gain and a 300–2000 Hz frequency response, as shown in Fig. 5 in red.

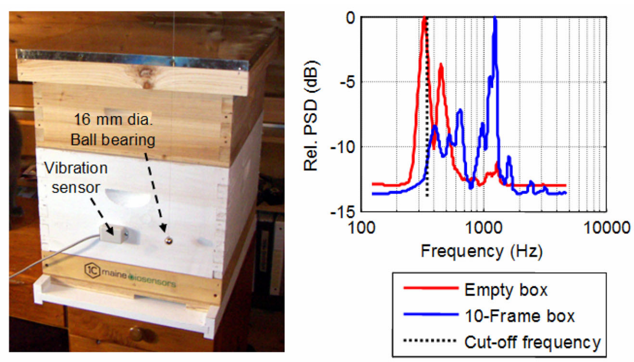

Fig. 4. Vibration sensor impulse response.

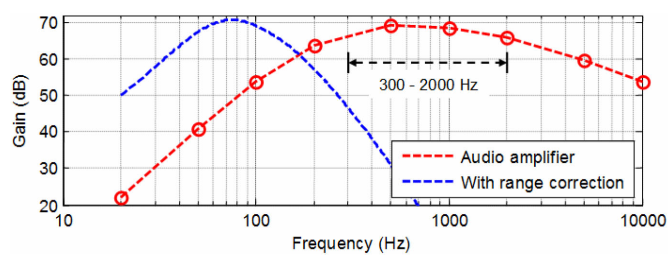

Fig. 5. Relative signal strength of vibration (red) and radar (blue) sensors after amplification.

Careful observations reveal that the frequency of the signal measured by such a sensor installation is primarily determined by the resonant characteristics of the wooden hive and its content. It has very little to do with the classic "bee sounds" described in Section II. It is a by-product of thousands of bee feet "strumming the guitar," as it were. We verified the response of an empty hive by striking it with a suspended ball bearing. The data processing is described in Section IV. Consistent with the theoretical acoustic cutoff frequency, a completely empty hive has a resonance at about 360 Hz. We then repeated the test with a hive filled with ten empty frames. As illustrated in Fig. 4, the resonant frequency of the full hive has shifted to about 1100 Hz.

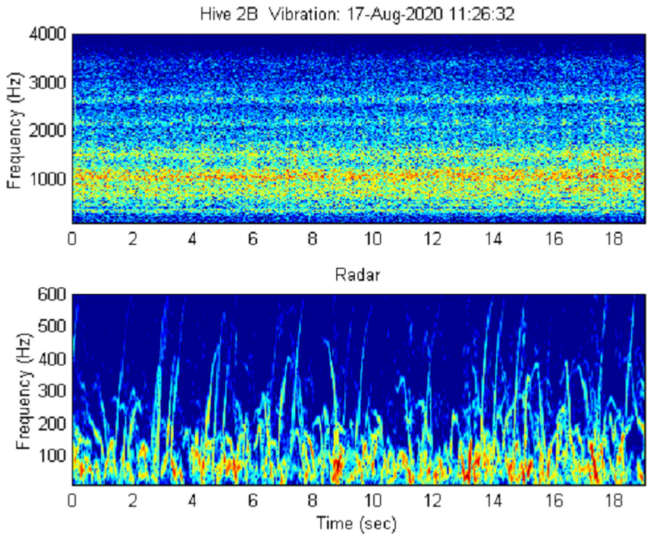

Fig. 6. Vibration and radar FTI plots.

B. Doppler Radar

The motion detector, shown in Fig. 3, is a 24-GHz CW Doppler radar found in automobile collision avoidance systems. This sensor has been used successfully to observe bee flying activity [23]. No adverse radiation effects on bees were observed from an active cell phone inserted into a bee hive [24]. The present radar is outside the hive and transmits 1/100 power of a cell phone. A similar 10.5-GHz sensor was described in [22]. However, due to the much higher radar cross section of bees at 24 GHz, such a radar has significantly better sensitivity [22].

The departure of foraging bees from the hive entrance causes the Doppler frequency of the 24-GHz CW radar to shift from 0 Hz to about 800 Hz over a distance of about 2 m [23]. When using the same audio amplifier as above, the corresponding $1/R^4$ losses distort the effective signal amplification, as shown in Fig. 5 in blue.

IV. DATA COLLECTION AND PROCESSING

Two different data collection and processing systems were used with the same Janus front end.

A. Hard-Wired Sensor

In the initial system, the Janus front end was directly connected from a beehive to the stereo microphone input of a laptop computer. Raw 12-b Analog-to-digital converter (ADC) samples at 8 ksamples/s were collected from both, the radar and vibration sensor. These samples were recorded for 20 s every 2 min from sunrise to sunset. Frequency-time-intensity (FTI) plots were generated with MATLAB for each 20-s data collection. An example is given in Fig. 6.

While the radar FTI shows the Doppler of individual bees coming and going, the vibration FTI from thousands of bees is considerably more uniform. In Fig. 7, we averaged the FTI's of both channels over the 20-s data collection. The plot shows remarkable similarity to the expected frequency response shown in Fig. 5.

It was shown in [21] that the root-mean-squared (rms) value of the raw Doppler signal is equivalent to the total power in the Doppler spectrum and is a good indicator of the level of bee activity. We similarly calculated the rms value of the vibrational signal. The rms

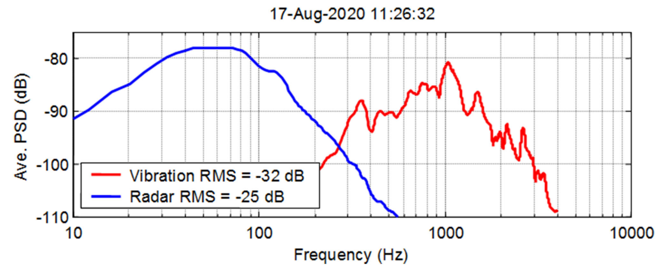

Fig. 7. Average frequency response of Fig. 6.

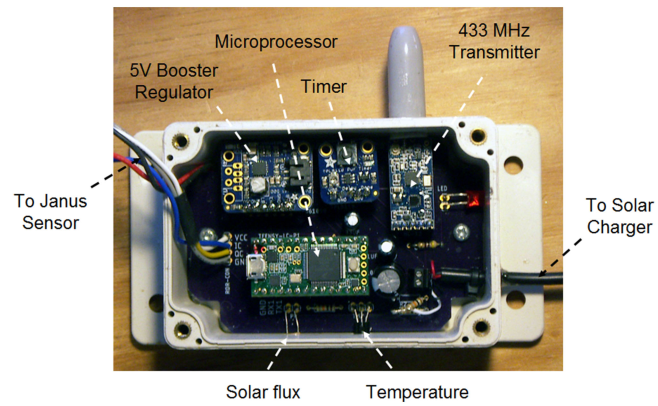

Fig. 8. Remote bee activity sensor.

values in Fig. 7 were calculated directly from raw ADC samples without spectral analysis.

B. Remote Sensor

The second sensor version, for remote data collection from multiple hives, was built with commercial break-out boards, as shown in Fig. 8. Here, a solid-state timer actuated a microprocessor approximately every 2 min. The microprocessor then collected 2 s of 12-b radar and vibration samples and calculated their rms values. These data were time tagged and transmitted over a 433-MHz wireless link to a base station for recording on a laptop computer. Up to nine sensors could be monitored from a distance of almost 200 m. Since the transmission duty factor is only 0.02%, message collisions occurred only very rarely and were easily identified by checksum error.

V. EXPERIMENTAL RESULTS

Radar and vibration measurements with identical wireless sensors were made on three beehives, identified as 6B, 7B, and 8B, located in Dover-Foxcroft, ME, USA. The hives were continuously monitored from July 2020 to October 2020.

A. Daily Measurements

Representative examples of days with unusual events are shown in Fig. 9. All events were visually confirmed. Radar and vibration rms levels for a swarming event [see Fig. 9(a)] were very high and highly correlated ($\rho > 0.5$). No significant lag between vibration and radar data could be observed. As expected, the vibrational level was higher during a robbing situation [see Fig. 9(b)] and lasts for most of the day. Although the radar signals in Fig. 9(a) and (c) are similar, correlation between radar and vibrational signals for "orientation flights" was very low.

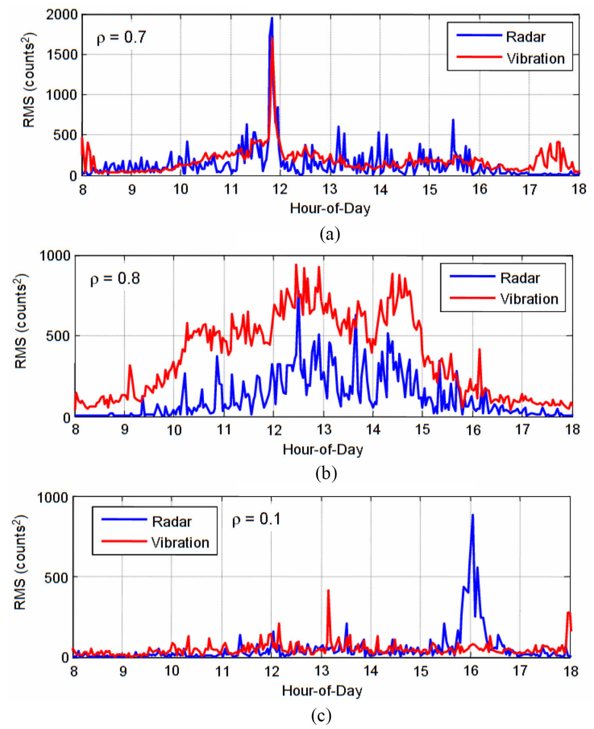

Fig. 9. Examples of (a) swarming, (b) robbing, and (c) orientation flights.

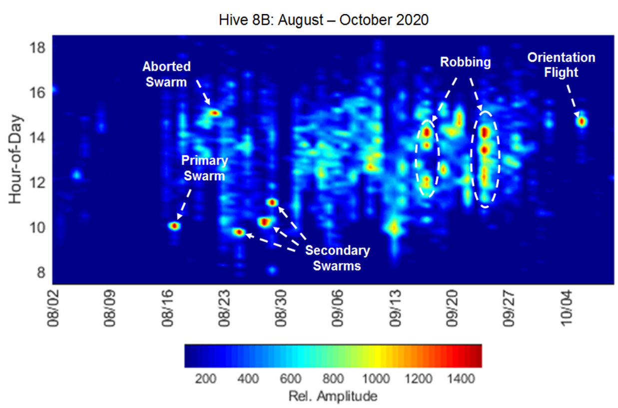

Fig. 10. PCA analysis of hive radar and vibration data.

B. Seasonal Measurements

Observations over the course of the season indicated that unusual activities did not always match the ideal cases illustrated in Fig. 9, leading to false alarms. Other factors, such as ambient temperature and solar radiation [22], also influence the level of activity. We explored the correlation between radar, vibration, temperature, and solar flux by principal component analysis (PCA). The PCA analysis was carried out in MATLAB on a laptop attached to the base station. Each vertical line in Fig. 10 represents the magnitude of the most significant principal component derived from daily data, as exemplified in Fig. 9.

As an experiment, for one hive (8B), the space available for bee population expansion was limited on purpose to induce swarming. Indeed, the hive swarmed five times. PCA analysis clearly and unambiguously identified these events, allowing the swarms to be captured. We noticed a reduced level of activity about ten days before the primary swarm. This reduced activity level has been reported elsewhere [25], but it is difficult to detect automatically or in advance.

VI. CONCLUSION

Both the radar and vibration sensor, when mounted on the outside wall of a beehive, are capable of detecting swarming and robbing activity. While the vibration sensor by itself is considerably less expensive, the detection performance can be improved (i.e., false alarms reduced) by combining measurements from both sensors and subjecting them to a PCA.

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