An Automatic, Wireless Audio Recording Node for Analysis of Beehives

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Abstract— **Monitoring the sounds emitted by honey bees in a beehive is an important activity for beekeepers to ensure that their bee colonies remain healthy and to maximise productivity. A particular reproductive event called "swarming", involves the departure of a queen bee with a large portion of the hive population. Swarming can be identified through sound, and if allowed to occur unchecked can lead to a drop in hive productivity or, in extreme cases, colony death. A method of effectively alerting the keeper that such an event is imminent would aid in protecting the honey bee population and reducing beekeeping costs. In this paper, a solution using off the shelf Wireless Sensor Network (WSN) technologies with low power signal processing to monitor colony sound, as well as the temperature and humidity of the hive interior is presented. The system provides alerts to the beekeeper when an event is detected. The node was designed to work with a larger sensor network designed for monitoring health and conditions of the beehive, and uses the network from this system to send alerts. An interrupt circuit provided a wake up signal to the node when the sound associated with an important event was detected. This made the solution ultra-low power, by turning on the recording circuits only when they were explicitly required. In this paper the design and development of the prototype system is described, with the results of preliminary tests and analysis. A power analysis and energy budget confirmed that the final solution was energy neutral, providing additional energy for recharging, even in the case of several recording alerts in a single day.**

Keywords—Precision honey bee monitoring; Wireless Sensor Networks (WSN); Embedded digital signal processing; Environmental monitoring; Intenet of Things (IoT)

I. INTRODUCTION

Wireless sensor networks (WSN) are an emerging technology, and an important component of the "Internet of Things" (IoT). This technology utilises a combination of embedded computing [1]-[4], energy harvesting [5], sensing [6], and radio communications [7][8], to monitor conditions over a wide area without disturbing or changing the processes being monitored. They have found applications in a wide range of areas including education [9], structural monitoring [10], and personal healthcare [11]. The versatility and ubiquitous nature of WSN has made them widely popular in both industry and research applications. A wide range of off-the-shelf solutions for WSN development are now available.

Honey bees and humans have had an important relationship from the dawn of civilisation, with records of humans keeping bees for honey and wax dating as far back as ancient Egypt (2500 BC) [12]. In modern times the most important role of the honey bee is pollination. Pollination is vital to many of the most nutritionally important foods for humans globally, 79% of the world's food supply is dependent on honey bees [13]. Along with this, honey bees produce several important by-products including honey, wax, venom, and propolis which are important for nutrition, medicine, and industry. As the human population continues to grow, and the pressure on food supply increases proportionally, it is vital that bee populations are protected, and provided opportunities to grow.

An important part of a beekeeper's activities during the reproductive season is to monitor for "swarming", which is the method by which a natural colony of *Apis mellifera* (the western honey bee) reproduces. New queens are produced by the colony and, as they develop, the old queen leaves the hive with a substantial proportion of the bees (e.g. 50%) as a prime swarm, to form a new colony. Sequential hatching of new queens can lead to secondary or further swarming events with progressively fewer numbers of bees in each swarm and the original colony which are unlikely to survive winters. All such swarming events, if not managed, represent considerable losses to beekeepers in terms of lost colonies, reduced numbers of bees in remaining colonies and reduced honey production. Newly formed queens produce specific sounds known as "piping" at or just prior to their hatching. Traditional beekeeping methods involve managing swarming (prime or secondary swarms) to avoid losses of bees from an apiary. Such management requires close monitoring of the formation of virgin queens by the colony with frequent (even weekly) visits by the beekeeper. Emerging virgin queens can also kill other emerged as well as developing (unhatched) queens which are sometimes used to form new colonies. This makes swarm management a labour intensive and time critical activity for the beekeeper.

In this paper the design and development of a WSN node for detecting the signs of an imminent swarming event by observing the sounds coming from the honey bee colony are described. This node detects both the specific "piping" noise emitted by queens, as well as the louder sounds produced by the rest of the colony prior to swarming. When an imminent swarming event is suspected the node made a short, high quality recording of the hive sound as well as sending an alert to the beekeeper through the network. This node was designed to work together with a larger sensor network designed for monitoring the health and conditions of the beehive [14].

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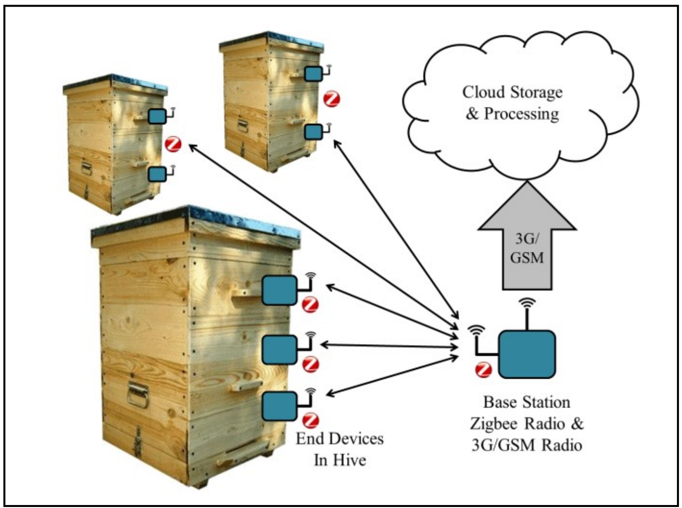

Fig. 1. Beehive sensor network

The existing network, however, had a low-power, low data rate Zigbee network for inter-hive communications. A key step of the work outlined in the paper was finding a solution for collecting audio data and alerting the keeper without dramatically increasing the power or communication requirements of the network. The network outlined in [14] monitors a range of other parameters including temperature, humidity, and gas levels (CO_2, O_2, NO_2, etc.). Some of these parameters could be used together with the node presented in this paper to improve the accuracy of the swarming prediction.

The contributions of the paper are: a novel Internet of Things application for live beehive sound monitoring; a low power wake up circuit for alerting an embedded system to the presence of a noise within a specific frequency band; unobtrusive, continuous, and energy neutral monitoring of a beehive; and a system design suitable for remote deployment locations with little access.

This paper is organized as follows: section II describes existing work on using sound to monitor beehives; section III describes the research methods employed in the demonstration; section IV outlines the sensor selection for the system; section V shows the design and implementation of the demonstration system; section VI presents some results from prototype testing; and section VII concludes the paper.

II. Related Work

The sounds emitted by a beehive have been used to assess the condition of the in-hive colony from the dawn of apiculture. Records are identified in [12] of beekeepers in Egypt (404 – 343 BC) playing reed pipes to "call" young queens from their hive and using them to create new colonies. In 1609 Charles Butler wrote a treatise on bees and beekeeping titled "*The Feminine Monarchie*" [15]. In this document he observed the piping, quacking and tooting sounds of the queen bee, and described the calls of two rival queens in terms of musical notes. He also noted that many writers throughout history have observed both piping and swarming in beehives and written on the activity, including Aristotle and Virgil. With the advent of modern signal processing and audio recording techniques many articles have been published in which the sounds produced by honey bees, and particularly queen bees were investigated [16]. There are also several experiments described in which artificial piping noises were applied to the hive to observe the response of the colony [17].

In Eren et al. [18] an experiment was described where a frequency analysis of both worker honey bees and a large group of queen bees was performed. The results were then used to generate audio files, which could be played to the hive during honey harvesting. The files caused the bees to expect a swarming event, many of them then left the hive, allowing the keeper reduce bee loss during harvest.

In Ferrari et al. [19] a long term, multi sensor beehive monitoring system was described. The sound, humidity, and temperature of a swarming beehive were recorded. This system provided an insight into the changes in humidity and temperature preceding a swarm, as well as high quality sound recordings of swarm events. The system described by Ferrari et al. was not low power, wireless, or battery powered and did not provide swarming alerts. These features are present in the system described in this paper, making it more useful for a beekeeper and suitable for remote deployments.

III. Methodology

The objective of the work described in this paper was to design and develop a sensor node which could detect important sounds emitted by a beehive, and record a sample of the sound for the beekeeper to use for hive analysis. Wireless connectivity was included to allow the node to interface with an existing sensor network (shown in Fig. 1). The sound data could be correlated with the other sensor data including gas levels, temperature and humidity. The network also allowed alerts on important audio events to be passed to the keeper.

The prototype was developed using off-the-shelf solutions for processing, energy harvesting, and networking. Separate processing units were used - one to achieve the frequency requirements of the more intense activities (sampling and storage of audio data), and one low power unit to preserve battery life during less demanding activities (energy harvesting, networking, and controlling sleep cycles).

Eren et al. [18] showed that the vast majority of sounds produced by honey bees (workers and queen) lie in the <3 kHz range. Based on these findings a high sampling was required to get a high quality representation of the in-hive activity (the final sampling frequency of the node was 6.3 kHz). Due to this sampling rate, the files generated are relatively large and not suitable for transmission though the low-power, low data rate Zigbee network utilised by the current deployment [14]. Local storage of the sound data on an SD card (secure digital non-volatile memory card) was selected instead, an alarm message was also sent though the network to the beekeeper, notifying him that an event was detected. When the beekeeper receives this alarm he/she can go to the hive to inspect the condition of the colony. If no source of the alert can be identified, the SD card can be extracted from the hive. The file, containing the sounds which triggered the alarm, can be analysed for an explanation of the alarm.

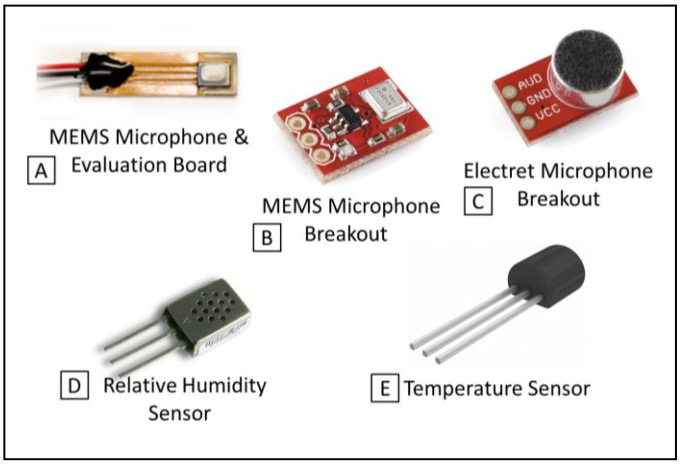

Fig. 2. Sensors

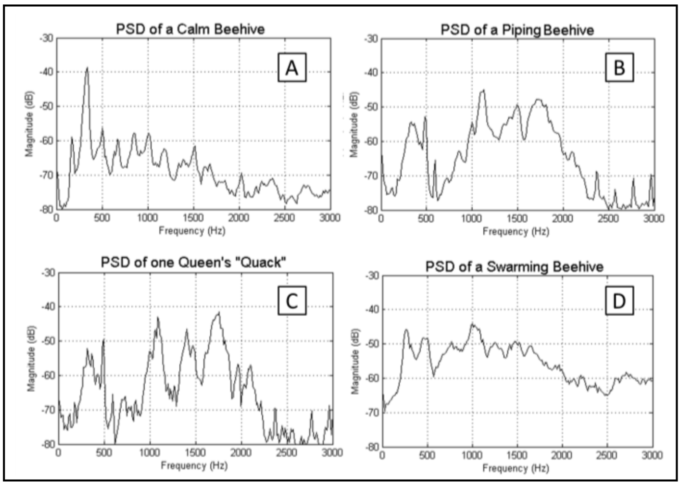

Fig. 3. Power-spectral density of beehive sounds

For testing the prototype developed in this paper, the sounds of different hives in various stages of the swarming process were required. A mature beehive typically only produces between one and three swarms per year, so, to get a clear indication of the prototype performance, a series of high quality recordings of swarming hives and piping hives were used in a controlled laboratory environment to simulate the sounds and volume levels (described in [18]) of a live beehive.

IV. Sensors

A. Microphones

Two microphones were selected for use in the node, for separate audio applications, (Fig. 2). The first was a low power (17 µA at 0.9 V) analogue MEMS microphone INMP801 (Fig. 2A) for use in the interrupt circuit. It allowed for continuous (24/7) monitoring of the sound levels in the hive with a low energy consumption rate. This microphone was combined with an interrupt circuit designed to detect sound levels and frequencies of interest in the hive. In laboratory tests an alternative MEMS microphone was used (ADMP401) (Fig. 2B) but which is now obsolete. The second microphone selected for use in the prototype was a high quality omni-directional foil electret microphone (CEM-C9745JAD462P2.54R) (Fig. 2C), it had a higher power consumption (max 0.5 mA at 1.5 V). The output was amplified to give a high quality output for sampling. This microphone was used in the high frequency, high energy consumption sound recording circuit, which was duty cycled to maximise energy performance. Energy harvesting from a solar panel was also included to extend the lifetime of the node.

B. Temperature and humidity sensors

In the existing system described in [14] a temperature and humidity sensing node was developed. The sensors used to measure these parameters were a humidity sensor (808H5V5) and temperature sensor (MCP9700A) shown in Fig. 2D and E respectively. These sensors were moved to the sound node described in this paper. This reduced the number of nodes, and amount of traffic in the Zigbee network. This also allowed temperature and humidity data to be collected in conjunction with the audio data to provide an extra dimension for analysis.

V. System Design & Implementation

A. Interrupt circuit

To design the interrupt circuit for detecting in-hive events a power spectral density analysis of several high quality recordings was performed. These recordings were sampled at 6.3 kHz, which was also the frequency of the WSN node. The results of this analysis are shown in Fig. 3. A calm, healthy beehive (Fig. 3A) where swarming is not happening has one very distinct peak in the 200-300 HZ range, this was expected, as the vast majority of bees, excepting the queen bees, produce sounds in this frequency range when they move their wings during their typical hive activities.

In Fig. 3B the frequency spectrum of a hive with a cell containing a new "virgin" queen is presented. The feature of most interest is the peak at approximately 500 Hz. This is the frequency range of the "piping" action, which takes place when the new queen is preparing to hatch. In Fig. 3C a single "toot" produced by the queen was analysed and the peak around 480 Hz was clear. There are also various sounds detected in the analysis at higher (>1 kHz) frequencies, these are produced by the bees present in the hive as it prepared for the swarming event to begin.

The piping sound usually starts 6-8 hours before the swarming action begins and is an important indicator for the beekeeper. This sound was selected as important to identify immediately. A band pass filter on the output of the MEMS microphone in the range 300-700 Hz selected the relevant frequencies for piping sounds, and a comparator provided a wake up signal for the microcontroller when the sounds reach the desired threshold.

The frequency spectrum of an actively swarming hive is shown in Fig. 3D, the frequency components are in the same range as in the earlier piping hive, but the power levels have increasedfor most frequencies. This shows that the volume of the sound during a swarm is much higher than for a calm beehive. There are other important events which cause the bees to increase the power level of their sound, including interference from intruders (humans or animals).

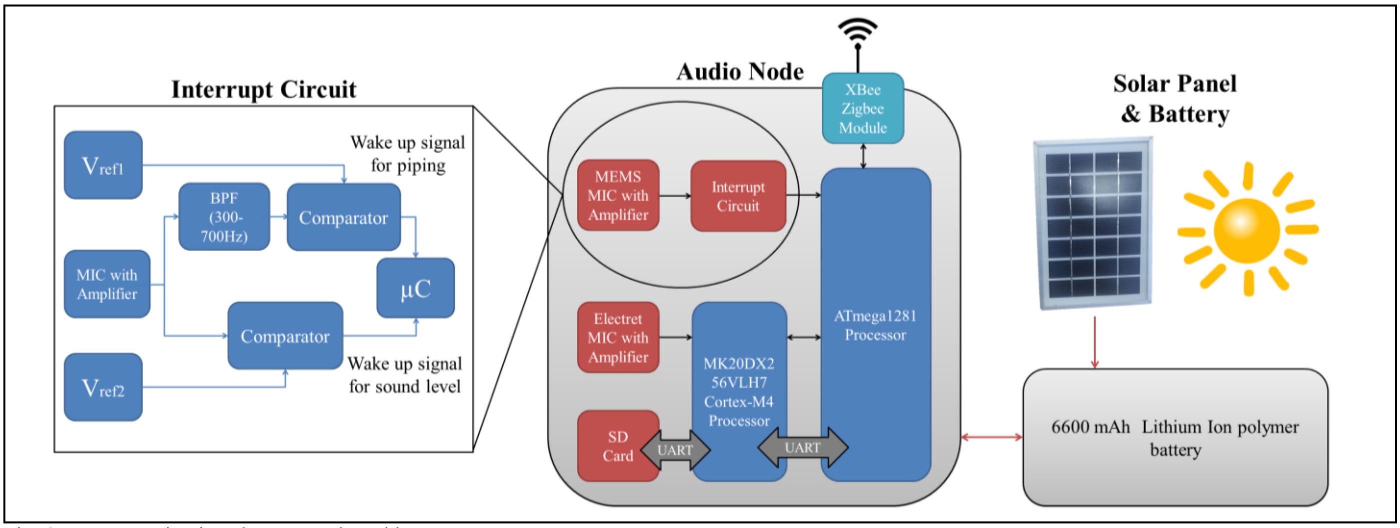

Fig. 4. Interrupt circuit and sensor node architecture

These events are important for the beekeeper to address as quickly as possible. For these reasons it was decided that a second wake up signal to the microcontroller was required, based solely on the amplitude of the sound detected by the MEMS microphone. This was developed using another comparator with a set threshold. A block diagram of the interrupt circuit is shown in Fig. 4, along with the wake up signal's response to a recording of a swarming hive in Fig. 5.

B. *Node architecture*

Fig. 4 shows the architecture of the node presented in this paper. The interrupt circuit generated a wake up signal as described in the section above. This signal was passed to an off-the-shelf ATmega based platform as an interrupt. This platform features a Real Time Clock (RTC), ultra-low power sleep modes (0.7 µA), energy harvesting compatibility, a socket for an XBee radio, and the interface for both the temperature and humidity sensors used, but it could not operate at a high enough frequency to sample the microphone output at the desired rate of at least 6 kHz while storing the data on an SD. This platform acts as the "master" processor in the system. The networking in the node was controlled by an XBee Series 2 Zigbee radio module connected to this platform.

The processing unit used for recording and storing the in-hive sounds was another off-the-shelf platform. This system was based on a Freescale Semiconductor MK20DX256VLH7 which had an ARM Cortex-M4 architecture, and featured a 72 MHz clock speed, 64 KB of RAM, and a 16 bit analogue to digital converter. These features made it ideal for sampling high quality audio, and storing these data in an SD card adaptor (microSD Card PROTO Board). This system was far more power hungry than the master processor (up to 185 mA vs. 15 mA) and did not have a built in RTC.

C. *Energy harvesting and power preformance*

The interrupt circuit was the only part of the system designed for continuous use and was therefore designed to operate at a minimum power level. The "master" processor utilised its ultra-low power sleep mode to minimise consumption until an interrupt. The radio, sensors, and sound recording circuit were all duty cycled as they were power hungry. A solar panel (111X91 mm, Max output 6.5V at 205 mA) was utilised to harvest energy in a remote deployment. The goal was to achieve energy neutral operation. The results of a power analysis can be found in Section 6.

D. *System software*

The node sampled the sound within the beehive four times per day, as well as any time an interrupt was generated by the circuit. The "Master" processor handled the interrupts, communication, RTC and duty cycling. Firmware for the operation of the master processor was written as follows:

- Wait for sound interrupt or RTC interrupt
- Turn on the sound recording circuit and processor
- Turn on XBee module and connect to network
- Send RTC time and date to recording processor via UART.
- Sample temperature sensor (average over 10 samples)
- Sample humidity sensor (average over 10 samples)
- Send temperature, humidity, and RTC data to base station
- Delay 40 seconds, turn off all peripherals and sleep

Separate software was required for the audio recording processor, which was completely shut down in between sampling events to preserve energy. The time and date were passed to the recording processor over the UART connection to effectively name SD files. Firmware was written for the audio recording processor as follows:

- When turned on, set ADC resolution to 12 bits, and averaging to 4 samples
- Initialise SD card
- Receive time and date over UART and create new file on SD card with these data.
- Sampling loop for 30 seconds:
  - Read ADC and write value to SD file
  - Delay 70 µs
- Check average sample time = 158 µs
- Close SD file and wait to be shut down

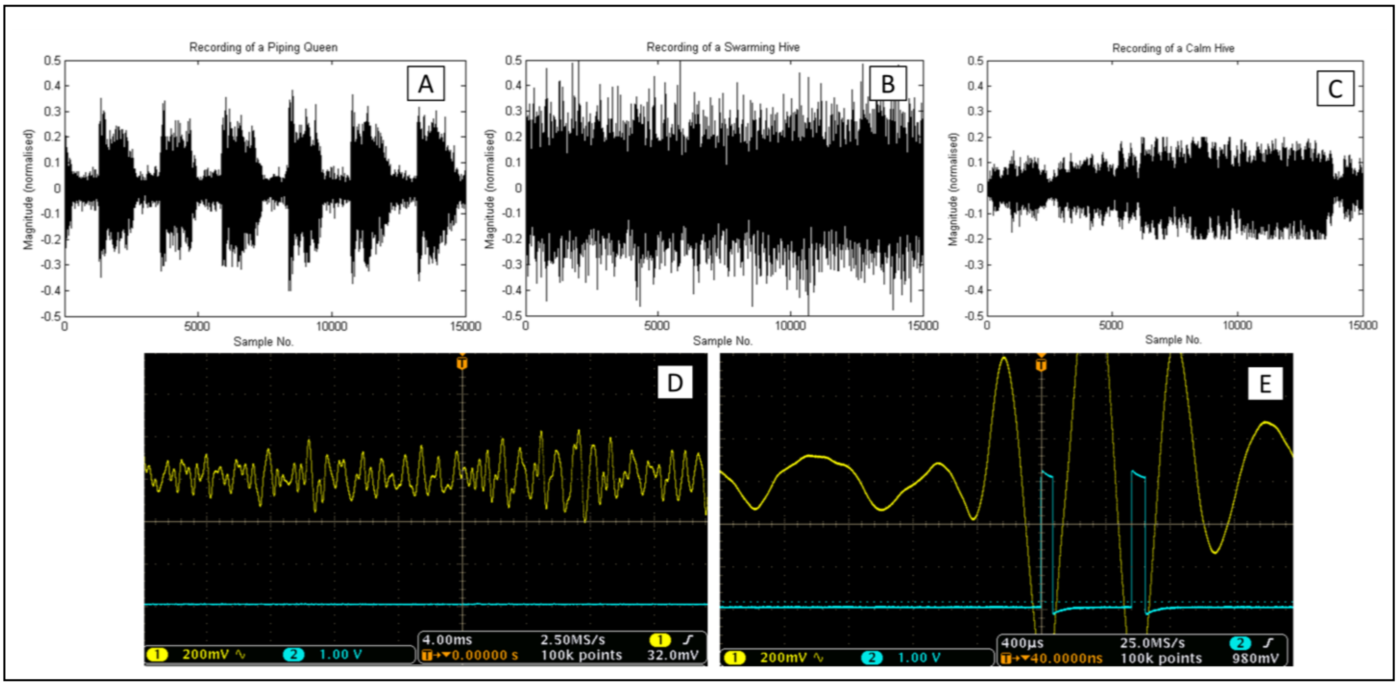

Fig. 5. Results: A, B, and C are plots of recorded beehive noises; D and E are plots of the interrupt circuit response.

VI. Results

A. Recorded audio

Some examples of the audio files recorded by the demonstration system in experiments are plotted in Fig. 5. Plot A shows the output from a piping queen, B shows the result from a swarming hive, and C shows a calm beehive with no piping. It can be seen that the audio recording block of the demonstration was operating at a high enough frequency and the microphone input was correctly set up to capture all of these events successfully.

B. Response of interrupt

Fig. 5 also shows the response of the interrupt circuit to two different hive sounds. In Fig. 5D the volume and frequency of the bees were both insufficient to require a recording. In Fig. 5E the volume of the in hive noise was sufficient to trigger a recording, and the wake up line triggered twice. This would lead to one recording as the two wake up signals were < 30 seconds apart.

C. Power and energy analysis

To confirm that the system was low power and energy neutral, a power analysis and energy budget calculation were performed. For the power analysis (seen in Table 1) a worst case scenario (highest current draw) for each of the systems operations was taken. It is clear that design of the interrupt circuit was quite low power, as desired. It was also confirmed that the recording block consumed a large amount of power, as predicted.

The aim of the energy budget (Table 2) was to confirm that the system was energy neutral when used in conjunction with the solar panel described above (maximum output 6.5 V at 205 mA). To achieve this, the energy consumed by the system in a typical day (5 scheduled recordings) was calculated based on the power analysis results. The energy of each additional recording (e.g. triggered by the interrupt circuit) was calculated.

The energy provided by the solar panel with an average Irish day's amount of direct sunshine (2 hours) at an efficiency of η=0.44 (this figure is from previous work with this solar panel [14]) was also calculated. It was found that the solar energy provided in one day exceeded the energy consumed, and the system is therefore energy neutral.

TABLE I. Power Analysis

Unit	Power Results			
	Task	***Current (mA)***	***Voltage (V)***	***Power (mW)***
Interrupt	On	0.85	3	2.55
Master µC	Awake	15	3.7	55.5
	Asleep	0.55	3.7	2.05
Recording µC	Processor & Microphone	115	5	773
	SD	60	3.3	
Radio	On	220	3.3	726

TABLE II. Energy Budget Calculations

Unit	Energy Budget for one 24 hour cycle			
	Task	***Power (mW)***	***Om Time (mins)***	***Energy (J)***
Interrupt	On	2.55	1440	220.32
Master µC	Awake	55.5	15	49.95

Unit	Energy Budget for one 24 hour cycle			
	Task	***Power (mW)***	***Om Time (mins)***	***Energy (J)***
	Asleep	2.05	1435	177.12
Recording µC	Processor & Microphone	773	5	231.9
Radio	On	726	15	653.4
Total Expenditure:				1,272
Each additional Recording:		773	1	186.96
		781.5	3	
Income from Solar Panel @ η=0.44		586.3 W	120	4,220

VII. Conclusions and Future Work

In this paper the design, development, and test of a wireless senor network node for continuously monitoring the audio events within a live beehive is described. To achieve this, the range of frequencies related to important in-hive events (specifically swarming) was identified through analysis of high quality recordings of beehives in various stages of the swarming process.

An interrupt circuit was designed to provide a wake up signal to the node when an event within the defined frequency range occurred, or when the overall volume of the colony's activity rose above a specified threshold. This wake up circuit allowed the solution to be ultra-low power, by turning on the power hungry recording circuits only when they were explicitly required.

Additionally, there were five scheduled recording events per day to build up a history of the sound activity in the hive. The final solution was powered by a 6600 mAH rechargeable battery with a solar panel for energy harvesting. A power analysis and energy budget confirmed that the final solution was energy neutral, providing additional energy to the battery for recharging, even in the case of several recording alerts in a single day.

Future work will include miniaturisation of the node, and introducing other energy harvesting sources. A demonstration deployment of the node in at the same site of the existing bee sensor network will also be put in place to show the system's response to a live beehive.

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References

[1] M. Magno, D. Brunelli, L.Thiele, and L. Benini, "Adaptive power control for solar harvesting multimodal wireless smart camera," *Distributed Smart Cameras, 2009. ICDSC 2009. Third ACM/IEEE International Conference on*, pp. 1-7, 2009.

[2] A. E. Şuşu, M. Magno, A. Acquaviva, D. Atienza, and G. De Micheli "Reconfiguration strategies for environmentally powered devices: theoretical analysis and experimental validation." *Transactions on High-Performance Embedded Architectures and Compilers I*. Springer Berlin Heidelberg, pp. 341-360, 2007.

[3] V. Jelicic, M. Magno, D. Brunelli, V. Bilas, and L. Benini. "An energy efficient multimodal Wireless Video Sensor Network with eZ430–RF2500 modules," *Pervasive Computing and Applications (ICPCA), 2010 5th International Conference on* , pp. 161-166, 2010

[4] V. Jelicic, M. Magno, G. Paci, D. Brunelli, and L. Benini. "Design, characterization and management of a wireless sensor network for smart gas monitoring," *Advances in Sensors and Interfaces (IWASI), 2011 4th IEEE International Workshop on* , pp. 115-120, 2011

[5] E. Popovici, M. Magno, and S. Marinkovic. "Power management techniques for wireless sensor networks: a review." *Advances in Sensors and Interfaces (IWASI), 2013 5th IEEE International Workshop on.*, pp. 194-198, 2013.

[6] M. Magno, F. Tombari, D. Brunelli, L. Di Stefano, and L. Benini. "Multi-modal video surveillance aided by pyroelectric infrared sensors." *Workshop on Multi-camera and Multi-modal Sensor Fusion Algorithms and Applications-M2SFA2 2008*. 2008.

[7] M. Magno, S. Marinkovic, B. Srbinovski, and E. M. Popovici. "Wake-up radio receiver based power minimization techniques for wireless sensor networks: A review." *Microelectronics Journal,* vol. 45, no. 12, pp. 1627-1633, 2014.

[8] M. Magno, D. Boyle, D. Brunelli, E. Popovici, L. Benini, "Ensuring Survivability of Resource-Intensive Sensor Networks Through Ultra-Low Power Overlays," *Industrial Informatics, IEEE Transactions on* , vol.10, no.2, pp.946-956, 2014

[9] R. Srivastava, R. Muntz, and M. Potkonjak. "Smart kindergarten: sensor-based wireless networks for smart developmental problem-solving environments." *Proceedings of the 7th annual international conference on Mobile computing and networking*, pp. 132-138, 2001.

[10] D. Boyle, M. Magno, B. O'Flynn, D. Brunelli, E. Popovici, and L. Benini. "Towards persistent structural health monitoring through sustainable wireless sensor networks." *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2011 Seventh International Conference on.*, pp.323-328 , 2011.

[11] P. Kulkarni, and Y. Ozturk, "mphasis: Mobile patient healthcare and sensor information system." *Journal of Network and Computer Applications,* Vol. 34, No. 1, pp. 402-417, 2011.

[12] E. Crane, *The world history of beekeeping and honey hunting*. New York: Routledge, pp. 169-171, 1999.

[13] M. Aizen, and L. Harder. "The global stock of domesticated honey bees is growing slower than agricultural demand for pollination." *Current biology* vol. 19, no. 11, pp. 915-918, 2009.

[14] F. Edwards Murphy, E. Popovici, P. Whelan, and M. Magno, "Development of an heterogeneous wireless sensor network for instrumentation and analysis of beehives," *2015 IEEE International Instrumentation and Measurement Technology Conf.*, Pisa, Italy, 2015.

[15] C. Butler, *The feminine monarchie: or the historie of bees*. London: Printed by Iohn Hauiland for Roger Iackson, and are to be sold at his shop in Fleetstreet, 1623.

[16] J. Simpson, "The mechanism of honey-bee queen piping." *Zeitschrift für vergleichende Physiologie,* Vol.48, No. 3, pp. 277-282, 1964.

[17] H. G. Spangler, "Effects of recorded queen pipings and of continuous vibration on the emergence of queen honey bees." *Annals of the Entomological Society of America,* Vol. 64, No. 1, pp. 50-51, 1971.

[18] H. Eren, L. Whiffler, and R. Manning. "Electronic sensing and identification of queen bees in honeybee colonies." *Instrumentation and Measurement Technology Conference, 1997. IMTC/97. Proceedings. Sensing, Processing, Networking.,* Vol. 2, pp. 1052-1055, 1997.

[19] S. Ferrari, M. Silva, M. Guarino, and D. Berckmans. "Monitoring of swarming sounds in bee hives for early detection of the swarming period." *Computers and Electronics in Agriculture* Vol. 64, No. 1, pp. 72-77, 2008.