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A Low-Cost Multi-Modal Sensor Network for the Monitoring of Honeybee Colonies/Hives

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Abstract. Honeybees, which play an essential role as pollinators, have suffered a significant decline in recent years. Different types of sensors, including acoustic, chemical, vision, mass and temperature, can provide important information to assess their well-being. However, a multi-modal sensor system would need to be economical and affordable in order to be used on a large scale, including by less wealthy farmers or beekeepers. We present details of a low-cost sensor network system to allow the continuous monitoring of honeybee hives in a non-invasive manner, discussing its advantages relative to other existing systems for the same purpose, and initial results from the deployment of such a system in four hives.

Keywords. honeybees; beehives; monitoring; multi-modal sensor network; signal processing

1. Introduction

The honeybee (Apis mellifera) is of very great importance both to the human race and ecology in general, primarily due to its major role as a pollinator of crops and many other flowering plants. However, over recent years, honeybees have been suffering a near catastrophic decline in numbers, including the complete collapse of many colonies. This is due to a variety of factors, including parasites and diseases (e.g. the varroa mite and European and American foulbrood), the use of pesticides such as neonicotinoids, and large scale single crop "monoculture" agriculture, which can restrict bees' sources of food and pollen. Moreover, conventional beekeeping, which has optimising honey yields for sale and human consumption as its principal aim, includes many practices which may not actually be in the best interests of the honeybees. Various aspects of bees' natural behaviour, including breeding and swarming, tend to be suppressed or rigidly controlled, and these factors probably contribute to decline in genetic diversity amongst honeybee populations, making them less resistant to diseases, pesticides and the negative effects of parasites [1]. Furthermore, whilst occasional inspection of hives by beekeepers is essential to check for parasites and diseases, over-frequent inspection is disruptive to the bees, tends to weaken the bees' natural protective materials (notably propolis, used to seal the hive to protect it from outside threats), diverts colony resources to their repair, and can actually increase the transmission of diseases and parasites between colonies via the beekeepers' clothing, etc.

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Although several systems have been developed for the non-invasive monitoring of beehives, most of these are relatively expensive and likely to be beyond the means of most farmers and beekeepers. In this paper, we present details of a low-cost sensor network system, using inexpensive sensors and Raspberry Pi microcomputers, to enable the continuous monitoring of hives whilst allowing the bees to lead their lives with as little disruption as possible.

2. Related Previous Work

2.1. Honeybee Ecology

Much work has been carried out on the biology and ecology of honeybees. Notable amongst this is the work of Seeley (e.g. [2, 3]) who studied the habits and preferences of honeybees over many years. Seeley proposed some principles, backed-up by empirical evidence, regarding what features would make a hive "bee friendly". In a previous paper [4], we described the design and construction of such hives, following Seeley's guidelines, although at that point we had not been able to equip our hives with bespoke sensor networks.

2.2. Monitoring of Honeybee Colonies

There have been several previous attempts to monitor honeybee colonies automatically. However, the majority of such studies have used a single modality to perform this monitoring. Ferrari et al [5], Bencsik et al [6], Howard et al [7] and Qandour et al [8] used acoustic analysis of the sounds made by the bees to infer what was happening within the hive. In [5], the aim was to predict swarming events, whereas in [7] it was to discern whether or not the hive contained a healthy queen, whilst in [8] it was to detect infestations of parasites. Other authors made use of other modalities. Veeraraghavan et al [9], Campbell et al [10] and Salas & Vera [11] used computer vision approaches to monitor bees. Kridi et al [12] and Zacepins et al [13] monitored the temperature within hives, again with the aim of predicting swarms. One of very few previous genuinely multimodal studies is that of Gil-Lebrero et al [14], which employed temperature and humidity sensors, and a weighing scale and monitored 20 hives in Cordoba, Spain over 32 days in the Summer of 2016.

3. Hive Design, Construction and Deployment

As described in our previous paper [4], we have adopted the same philosophy as Neumann & Blacquière [1] – namely allowing the bees to live as naturally as feasible – and the guidelines of Seeley [2, 3] for hive size, design, location and orientation, subject to a constraint of making the hives accessible for maintenance. (Seeley's recommendation for hives to be 5m off the ground is not practical from this perspective.)

Our hives [4] are all of capacity 40 dm^3 with an entrance hole South facing, of area 12.5 cm^2 at the bottom of the hive, and approximately 1.5 m off the ground. With the exception of the latter, all these attributes follow Seeley's recommendations. Details of the hive design and how its constituent parts can be cut and assembled from a template on plywood (or other material with suitable weather-resistant properties) can be found in [4]. Because our new design hives do not allow for honey extraction, we call them "pollenbee" hives, whilst we call the conventional hives "honeybee" hives, see Fig. 1 and Table 1. We had previously deployed 12 pollenbee hives, without sensors, around the South of England. In the current phase of the project, we have equipped two pollenbee hives and two conventional honeybee hives with sensors, all situated close together at an apiary at Kingston University in the South-West suburbs of London.

Figure 1. Left Hand Side image : the hives in the Kingston University apiary. Viewed from the west, the hive entrances face south. From front right to back left: PB01, power "hutch", HB01, HB02 and PB02. The distance from the nearest hive to the furthest is of the order of 30 metres, with the first 3 being within about 15 metres. You can just make out the green camera module on PB01 on the far right of the LHS picture. This camera views the hive entrance, as shown in the Right Hand Side image.

Hive	Hive type	Hive name	Short name
1	Pollenbee	Pollenbee 1	PB01
2	Honeybee	Honeybee 1	HB01
3	Honeybee	Honeybee 2	HB02
4	Pollenbee	Pollenbee 2	PB02

Table 1. Details of the types of our hives and their labelling.

4. Sensor System Design and Implementation

All four of our hives are equipped with commercial sensor systems produced by Arnia Ltd [15]. They are also equipped with a bespoke sensor system of our own design, that specifically allows us to collect raw acoustic data from the hive and video recordings of the hive entrance which the Arnia system cannot provide, as well as weight data on all four hives, which would be prohibitively expensive in the Arnia solution. In this respect, our bespoke sensor system was also designed to provide comprehensive multi-modal monitoring of the bee colonies in the hives at a low cost. Our system's network topology uses a single Raspberry Pi 3 [16] as a WiFi hotspot, to which the other nodes connect using the Raspberry Pi's onboard WiFi (see Fig. 2). We are also shadowing some Arnia sensors, such as hive temperature and humidity, and have added a few more sensor types such as hive gas concentrations and light levels.

4.1 Sensors Used, Sampling Rates and Data Rates

The sensors used in our bespoke network are specified in Table 2 and their respective sampling frequencies given in Table 3. The volume of data produced each day is quite small, (about 200kB per hive day) with the exception of the sound level data and the hive entrance video, which respectively generate about 6GB and 850MB per hive per day.

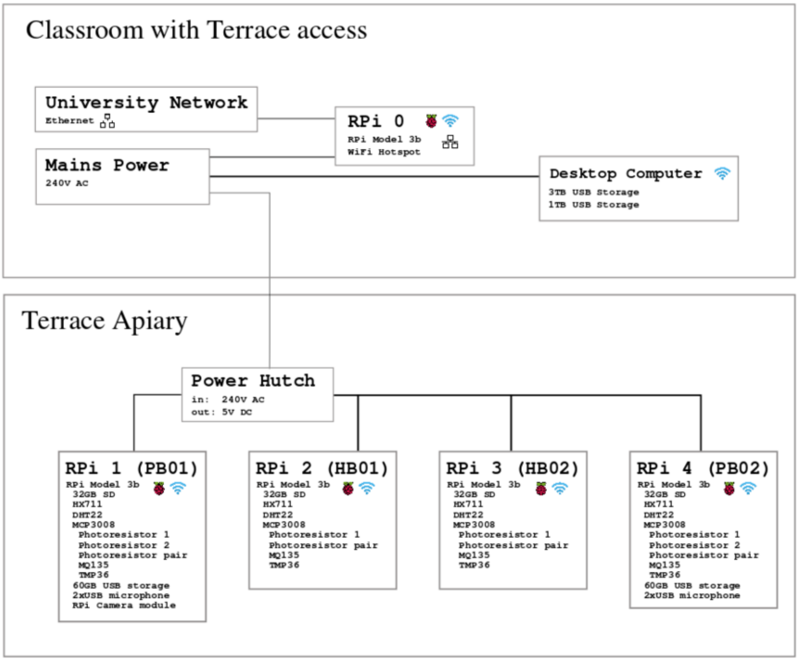

Figure 2. Schematic representation of our sensor network, power supply, etc. The code in parentheses after the number indexing each Raspberry Pi indicates which hive that Pi is deployed in, and the sensors in that hive are then listed below (see also Table 2). The various "slave" Pi computers are connected to the "master" Pi (RPi 0) via the Pi's onboard WiFi, and thence to the University network via the master Pi's Ethernet port. The power is provided from a 240V 50Hz AC mains, converted to 5V DC by a transformer/rectifier in the "Power Hutch".

Each Raspberry Pi is fitted with a 32GB SD card which hosts the Raspbian operating system (a version of Debian Linux) and works as a local hard drive. The low volume data is easily stored on these. The issue of the high volume data generated by the microphones (RPi1 and RPi 4) and camera module (RPi 1) was resolved by adding a 60GB USB hard disk to the Raspberry Pi (RPi). These still need to be backed-up every 3 to 4 days, and that backup cannot be done over the RPi WiFi network because its bandwidth is too small. Although having to back up the data manually, by removing the 60GB hard disks from the hives and manually moving the data to the 3TB drive on the desktop computer, is time consuming and inconvenient, a potentially beneficial side-effect is the fact that the hives then get regularly inspected the hives for a visual confirmation of their progress and well-being. Figure 3 shows one of the hives equipped with the monitoring equipment.

4.2 Power and Data Storage Requirements

The power requirements for each "smart hive" are non-negligible, and initial attempts to power each using a rechargeable battery and/or solar cell proved to be inadequate. A solution was eventually reached, powering the sensor systems and each Raspberry Pi from the AC mains, via a transformer and rectifier in the "Power Hutch". This required both mains power and weatherproof cabling and would not be suitable for deployment of the smart hives in remote locations. Alternative solutions for such situations and optimal sampling rates to reduce the data storage requirements (see Table 3) are being investigated.

Hive Name	**PB01**	**HB01**	**HB02**	**PB02**
Arnia Hive monitoring equipment (The Arnia Gateway measures global temperature in direct sunlight and rainfall)				
Hive internal temperature	yes	yes	yes	yes
Hive internal humidity	yes	yes	yes	yes
Sound level at hive entrance	yes	yes	yes	yes
Weight (mass) sensor	-	yes	-	-
KU bespoke sensor network with Raspberry Pi				
HX711, 4x50kg strain gauges, weight	yes	yes	yes	yes
DHT22, temperature and humidity	yes	yes	yes	yes
MCP3008 ADC	yes	yes	yes	yes
Photoresistor, exterior light level	yes	-	-	yes
Photoresistor, interior light level	yes	yes	yes	yes
Photoresistor pair, exterior light level	yes	yes	yes	yes
MQ135, interior gas sensor	yes	yes	yes	yes
TMP36, interior temperature	yes	yes	yes	yes
Hyundai 60GB USB drive	yes	-	-	yes
RPi camera, hive entrance video	yes	-	-	-
USB microphone, interior sound level	x2	-	-	x2

Table 2. Equipment and Sensors used with the two systems on the four hives.

Sensors used in bespoke KU network with RPi	**Sampling Frequency and size of daily generated data file.**
HX711 with 4x50kg gauges, Weight	Every minute (19 kBytes/day)
DHT22, temperature and humidity	Every minute (45 kBytes/day)
MCP3008 ADC	
- Photoresistor, exterior light level	Every minute (23 kBytes/day)
- Photoresistor, interior light level	Every minute (23 kBytes/day)
- Photoresistor pair, exterior light level	Every minute (23 kBytes/day)
- MQ135, gas sensor	Every minute (23 kBytes/day)
- TMP36, interior temperature	every minute (35 kBytes/day)
RPi camera, hive entrance video	12 seconds of 640x480 pixel MP4 video every minute, while exterior light level is above threshold (850 MBytes/day)
USB microphone, interior acoustics	12 minutes of 44100Hz recording every 20 minutes, recorded 24 hours per day (6 GBytes/day)

Table 3. The various sensors and their sampling rates and daily data volumes.

(a) (b) (c)

Figure 3. (a) Top view of the inside of a “pollenbee” hive with sensors (including an Arnia mass scale) fitted, (b) a side view of the same hive, showing one sensor on the outside of the wire grille which is almost encrusted with propolis and wax, (c) another side view, showing the wax combs and some bees.

5. Data Processing, Analysis and Visualisation

Although we have acquired data through our bespoke system from the hives for several months since March 2017, work on processing, visualising and analysing the data is still at a relatively early stage, and is the focus of the next phase of the project. We are exploring the use of time series, periodicity (e.g. auto- and cross-correlation) and frequency domain (e.g. FFT, Mel Cepstrum) analyses, plus more sophisticated pattern recognition techniques such as decision trees and artificial neural networks, to exploit and explore this data to the full. In contrast, the Arnia system is fully functional and provides a highly detailed web portal that reports the data with features for specifying time periodicity within and cross correlation between data channels.

Some examples of visualisations of our data, as time series, are presented in Figures 4, 5, 6 and 8 . It is clear from these that some signals (e.g., mass and temperature) exhibit fairly smooth variations over time, whereas others, such as relative humidity, are much noisier and may require smoothing before further processing.

6. Results and Discussion

Results obtained from a selection of the calibrated bespoke sensors in one hive over the period 10 – 15 June 2017 are shown in Figures 4-6. This hive is particularly noteworthy over this period since a swarm emerged from it around 9am on 13th June 2017, initially settling in a nearby apple tree before moving on that afternoon (See Figures 5 and 7).
The near periodic daily variation of hive temperature and humidity are not surprising since, during a Summer day, the external temperature will rise from sunrise (around 4:45am in London in mid-June) until late afternoon (perhaps around 17:00), then gradually fall through the evening and overnight. Furthermore, relative humidity will fall as the temperature rises if the absolute humidity is kept constant [17], and hence relative humidity will tend to be low when the temperature is high (and vice versa) even if the absolute humidity remains unchanged. Some authors (e.g. [5, 12, 13]) have reported that the hive temperature will tend to rise in the period immediately prior to a swarm. However, although there is some evidence of this in our data, it is difficult to identify it with certainty, since the daily temperature variation alone would suggest we should expect a substantial temperature rise over the morning subsequent to sunrise.

The hive mass, on the other hand, does show a clear indication of a sudden decrease in mass exactly coinciding with the time of the swarm (see Figure 6). During an ordinary day, the mass of the hive tends to drop a little, by around 500 to 600g, as bees leave the hive during the morning to forage. As they return later in the day, laden with pollen and nectar, the mass of the hive will tend to increase again, and by late evening the mass will tend to be around 300g greater than it was at dawn. However, between 08:40 and 09:30 on 13th June, the mass of HB01 dropped by 1900g, and although almost 700 g were recovered later that day, it was not until around 17:15 on 15 June that the mass returned to its pre-swarm level.

The contrast in the daily mass variation between ordinary (Figure 8), swarm (Figure 5) and hive inspection (Figure 6) days is clear. The regular pattern is for the hive mass to fall by around 0.5 kg as bees leave the hive in the morning, then to rise again in the late afternoon and evening as bees return to the hive laden with pollen and nectar. The mass tends to remain relatively stable overnight, before the pattern gets repeated the following day. For reference, in London sunrise is around 04:45 and sunset around 21:15 in mid June.

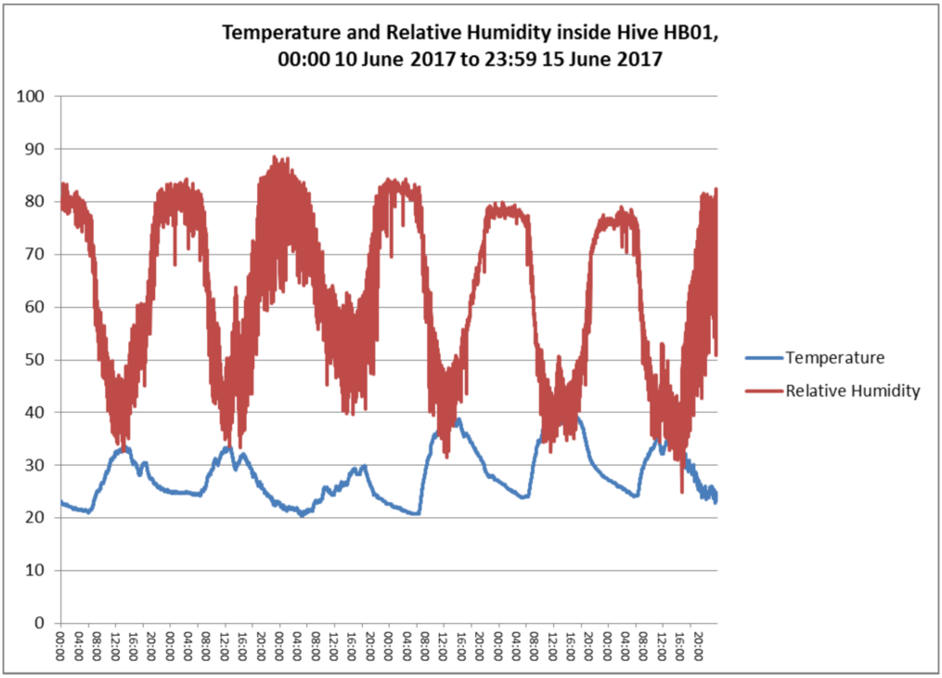

Figure 4. The variation of temperature (in ºC) and relative humidity (% of saturation) inside hive HB01 over the period 10 June to 15 June 2017, measured by our bespoke sensor system. A daily periodic component to both signals is clear.

It should be noted that the change in hive mass noted at the time of the swarm follows a very different temporal profile to the changes occurring over a time interval including a hive inspection. In the latter case (see Figure 6), there is a sudden drop in hive mass by about 15 kg as the roof of the hive is removed, but the mass returns to almost exactly the previous value when the roof is refitted a few minutes later.

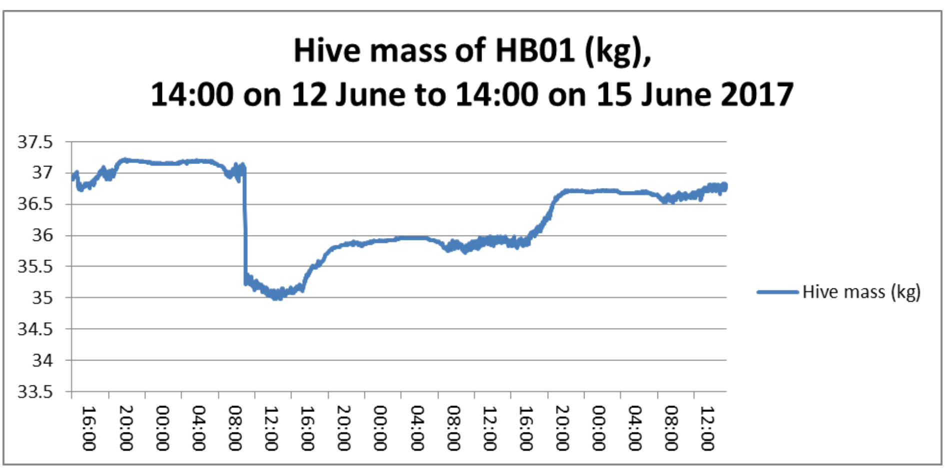

Figure 5. Mass of Hive HB01 over the period 14:00 on 12 June to 14:00 on 15 June 2017, measure by our bespoke sensor system. The swarm occurred around 09:00 on 13 June 2017, accompanied by a rapid drop in hive mass of around 1.8kg – much greater than the decline in mass during the morning of a typical day.

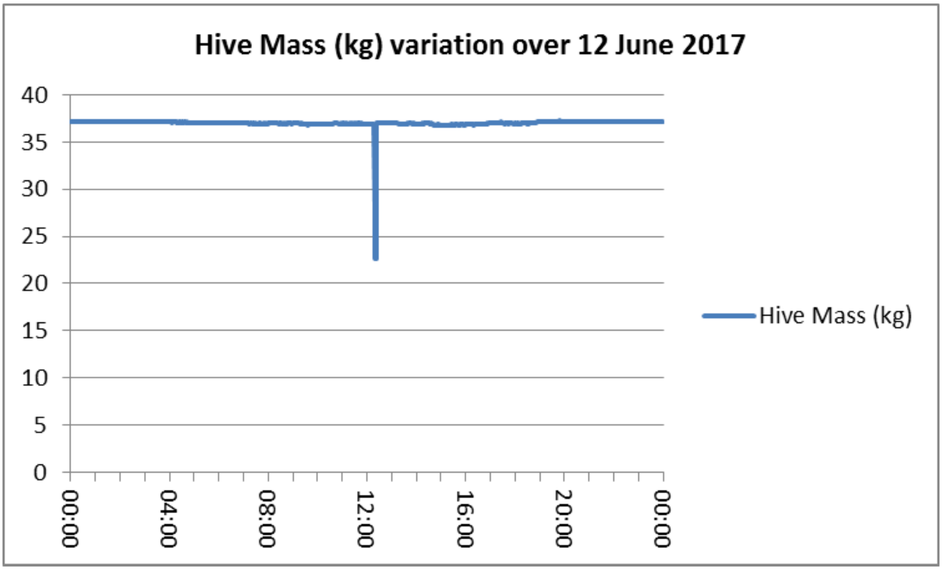

Figure 6. Variation of the mass of Hive HB01 over the course of 12 June 2017. An inspection of the hive (involving removing its roof, causing a temporary drop in mass of about 15 kg) took place between 12:18 and 12:22. Note that, over the course of this day, the mass variation due to bees leaving or entering the hive, consuming resources, and returning with pollen and nectar is negligible compared with the temporary change due to the hive inspection.

(a) (b) (c)

Figure 7. (a) a view of the swarm "beard" of bees around 2pm on 13 June 2017, after it had settled in an apple tree by a wall, around 50 metres from the hive it had come from, (b) and (c) close-ups of the beard, showing individual bees.

7. Conclusions and Future Work

We have successfully designed, implemented and deployed a low-cost network of sensors, controlled by a wireless network of Raspberry Pi microcomputers, to monitor honeybee colonies using a variety of modalities with a view to developing an environment to promote their well-being. Data is being acquired and analysed, using our bespoke sensor systems and Arnia commercial sensor systems, from four hives located in South-West London. Preliminary results of our analyses, including the variations in temperature, humidity and hive mass around the time of a swarm, are presented here.

We hope to identify salient features in the signals monitored which are indicative of important issues for bee colonies, such as swarming, loss of a queen, attacks by predators, infestations by parasites and other factors which may require human intervention. However, in line with the philosophy of Neumann and Blacquière [1] and Seeley [2, 3], we aim to interfere with the bees as little as possible, encouraging them to live in as natural way as feasible, in order to promote their well-being and genetic diversity through the process of natural selection.

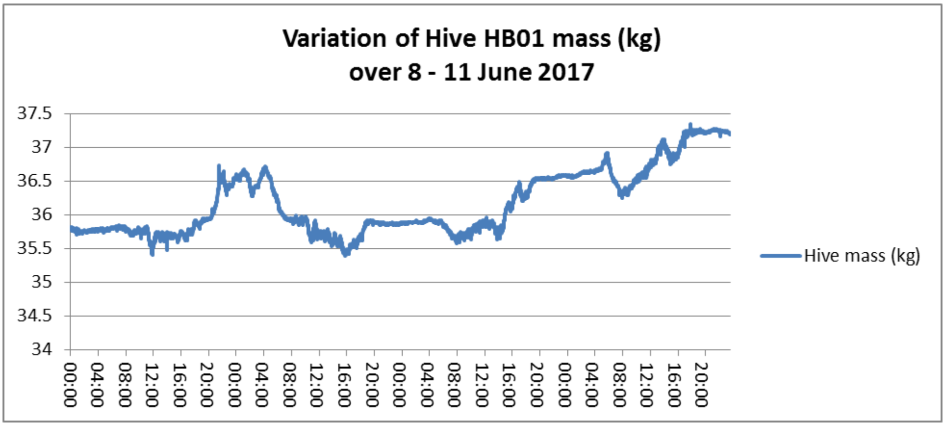

Figure 8. Variation of mass of hive HB01 over the period 9-11 June 2017 inclusive. During this time interval, there were no inspection of the hive, and it was before the swarm. We can see the mass rapidly declines by about 0.3 to 0.5 kg each morning. On 9 June there was also a further decline in mass by approximately 0.5 kg in the early afternoon. However, as the bees return laden with pollen and nectar in the late afternoon and evening, the hive mass rises again. The hive mass tends to be relatively stable overnight. Smaller short term rises and falls in mass could be due to rainfall and evaporation of rainwater respectively.

Regarding the affordability of our sensor system, the most expensive individual component is the USB 2 TByte hard drive, used to back up the data retailing at (GBP) £ 60 in Spring 2017. This might not be essential if (a) a PC with sufficient storage capacity were used as the "master" and/or (b) no storage of audio or video data was required. The Raspberry Pi microcomputers (Model 3 B Quad Core CPU 1.2 GHz 1 GB RAM), which retailed at £ 32 each, were the next most expensive items, followed by the camera module for a RPi which retailed at £ 22 (again, not necessary if video is not required). The HX711 strain gauges for mass (weight) measurement were £ 7 each, as were the DHT22 temperature and humidity sensors. The USB mini microphones each cost £ 3, and each ADC £ 5.50. Each of the 16 GByte SD memory cards for the individual RPi computers cost £ 10.50. Thus, a basic sensor system (with RPi, ADC, power supply, 4 strain gauges, temperature and humidity sensors, 16 GByte SD memory, but no video, audio or mass storage) should be realizable for about £ 100 for a single hive. If audio (via microphones), video (camera) and mass storage were also required, the cost would rise to about £ 190, but the marginal cost per additional hive on the same site (sharing power supply and mass storage) would be lower. For comparison, a commercial system produced by Arnia [15] would cost £ 300 for a central "Gateway" unit, plus £ 150 per hive for a sensor system (including audio, but not including video or mass/weight monitoring). Arnia's hive scales for mass monitoring cost £ 800 per hive. In addition, Arnia charge £ 120 per year subscription to their data storage and visualization service. Our bespoke system is markedly more affordable to small-scale farmers or beekeepers than the commercial one.

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