Design and Development of a Smart Weighing Scale for Beehive Monitoring

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***Abstract* — In recent years monitoring of beehives through technology has become increasingly frequent in research and industry. This is due to a decline in beekeeping, and stagnant honey bee populations across the globe, due to, among other factors, pests and disease. Recent advances in the area of low power wireless sensor network technology can be applied to the beehive for a better understanding of the colony's condition. This combination of engineering and beekeeping has led to the emergence of Precision Beekeeping. One of the key metrics of the strength of a beehive is the weight of the colony. Changes in weight can accurately reflect the productivity of the colony, as well as its health and condition. This paper describes the development of a wireless platform weighing scales, for implementation as part of a smart beehive. A single point impact load cell was selected as the most appropriate load sensor and was integrated into the design of the scales. The final weighing system was interfaced via a high precision analogue to digital converter to an off-the-shelf processing platform enabled with a low power Zigbee radio, to allow for data transfer to the base station. An initial simulation of the scale's ability was carried out, using standard weights to simulate the brood chamber of a beehive and varying weight to mimic the production and consumption of honey. The results showed that the initial platform scale has a linear output characteristic. The analogue to digital converter was evaluated and the system was found to be able to detect changes in weight in the order of tens of grams. A power analysis of the system was also undertaken to confirm that the solution was suitable for remote, battery powered, deployments.**

Keywords—Precision weighing; Wireless Sensor Networks (WSN); Environmental monitoring; Internet of Things (IoT); Precision apiary; Biological and physical sensors

I. INTRODUCTION

Beekeeping (Apiculture) can be dated as far back as primitive human culture. Prehistoric wall paintings show humans procuring honey from bee colonies. At the dawn of apiculture most of the hive's raw products i.e. honey and wax, were utilised. [1] However, in modern times honey production is considered a by-product of the western honey bee (*Apis mellifera*), as the pollination of plants is by far their most important activity. [2] Up to 79% of the human food supply today is dependent on pollination, and the honey bee is the most widespread and active pollinator animal worldwide.

Beehive weight is a key indicator of the productivity and condition of the honey bee colony; studies on how to effectively determine beehive weight have been carried out since the birth of apiculture. The USA Department of Agriculture released a document in 1925 outlining the effects of the weather on apiaries. It concluded that factors like ambient temperature, hours of sunshine, variation in temperature, and humidity can affect the weight of the beehive. The most commonly utilized method of weighing is to place a mechanical balance under the beehive, then adjust the scale as the weight changes [3].

A simple rule of thumb developed by beekeepers, is to use a basic tension scale e.g. a luggage weight scale, tilt the beehive on one side and double the value determined. The objective of weighing the colony during the honey production season is to determine when the hive's honey stores have reached maximum capacity, and then harvest them. This is difficult to achieve with the traditional, inaccurate weighing methods. The main difficulty surrounding hive weight measurement is that to gain an accurate picture of the hive status it is necessary to weigh several tens of kilograms but to an accuracy of tens of grams.

Recent advances in the areas of embedded sensing, miniaturization, wireless communications, low power operation, and energy harvesting contribute to form the technology known as "Wireless Sensor Networks" (WSN). WSN are an integral part of the emerging concept of the Internet of Things (IoT). WSN are fast becoming an integral part of everyday life in many areas including healthcare [4], smart homes [5], and security [6]. They have become a key research area in academia and industry, with many off-the-shelf solutions available.

In this paper a solution for remotely determining the weight of a beehive is presented. This solution utilised a load cell platform weighing scale system, enabled with WSN technology and an ultra-accurate analogue to digital converter, for remote collection of precision weight data. A temperature and humidity sensing node from an existing beehive monitoring system was utilised to provide error compensation for the load cells, which are susceptible to drift error as a result of these parameters [7]. These nodes were designed to integrate into a larger sensor network for monitoring the health of a beehive [8]. The final demonstration node can measure weight changes in the range of just tens of grams, making it well suited for determining when the hive has produced its maximum amount of honey as described above. This paper is organized as follows: section II outlines the current state of the art in beehive weighing technology; section III outlines the methodology of the project; section IV describes the hardware and system design utilized in the development of this work; section V describes the experiment used to validate the final system; section VI presents some results from testing; and section VII concludes.

II. Related Work

An example of an early scientific study into beehive weight was carried out in 1977 [9]. A high precision mechanical scale was used and modified for use, including protecting the mechanical components from rust and creating a jig to translate the weight of the beehive onto the balance. An elaborate vision system was used to view the changing values. This was one of the earlier implementations of non-invasive weight measurement i.e. the scale was integrated into the system, rather than attached at selected time periods. The scale became part of the beehive. The scale had an accuracy of about 0.5 kg and provided reliable data for the research groups study. Researchers travelled to the beehive and recorded the weight on an hourly basis, over a period of 3 years.

Advances in the development of load cells, pressure sensors and strain gauges have made these technologies more attractive for use in weight measuring applications. Load cells have become a standard in beehive weighing systems. In the application of a single, robust load cell used to weigh an entire beehive [10], the maximum weight the load cell can accommodate is 200 kg, which satisfies the requirements of an average sized beehive. The jig used to translate the weight of the beehive to the load cell allows for uniform weight distribution and can cope should an imbalance of weight occur in the beehive.

Another application of load cells can be seen in the Arnia Scale [11]. The concept of the scale is similar to the previous model, but utilizes a more minimal design. The system uses 4 load cells, one in each corner, to balance the weight load. The design has taken into account greater ventilation of the beehive and allows any hive debris to fall directly to the ground and prevent a build up at the base of the beehive. The overall height adds 35 mm to the overall height of the beehive. The scale has a working capacity of 150 kg, measuring weight in increments of 10 g. The system of strain gauges adds a layer of complexity to the design of the scale.

Previously, beehive weight measurement depended greatly on researchers traveling to the site of an apiary and manually recording the value displayed on the mechanical balance [9]. Recordings were often required on an hourly basis, which was cumbersome and required additional attention. Recent development in technology has significantly reduced the need for site visits. The advent of data logger technology has removed the necessity to manually monitor the weight of hives as it can automatically record the changes over time. The accumulated data can then be collected at less frequent intervals.

For completely remote observation, significant strides have been made to allow beekeepers to check on the condition of their beehive. Some systems, such as Arnia, have incorporated wireless components that are able to send data to a singular hub. These data are then accessible from various devices such as PC's, tablets, or smart phones [12]. Such applications provide the necessary information to prevent any sudden loss of bees in the beehive, for example through theft or disease.

III. Methodology

One of the most utilized sensors used in weighing applications these days are load cells. The combination of both mechanics of materials and resistive theory has produced a sensor design that can be used to measure changes in weight reliably. The load cell utilised in this work operates by measuring the deflection of a beam upon which the load to be measured has been placed. The beam is designed from material with a suitable elastic deformation characteristic, i.e. a material that can be deformed with force, returning to its original shape when the load is removed, while causing no permanent, plastic deformation. The beam is designed with a weak point usually in the centre to allow the deflection to be concentrated on a specific point for accurate measurement. The bottom face of the load cell beam is fixed to a base, while the opposite side is used for applying force.

The beam also adheres to Poisson's ratio, where a beam, when in tensile straining will extend in length in the direction of the force, but it's cross sectional area (CSA) will contract. When a beam experiences bending, its top surface experiences a tensile strain and its bottom surface experiences a compressive strain (depending on the direction of bending). If the beam is behaving elastically, then the strain is directly proportional to stress, and hence to the applied force. These changes in the beam can be used to measure the force applied precisely, by means of strain gauges.

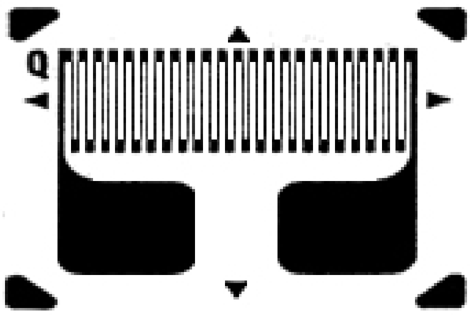

Fig. 1. Resistive Gauge [13]

There are many varieties of strain gauges including semiconductor and piezoelectric gauges, but one of the most practical is the resistive strain gauge, as shown in Figure-1. The size of strain gauge can range significantly from only a few millimetres to several centimetres, depending on the application. A resistive strain gauge usually comprises a single wire in a meandering pattern as shown in Fig 1, so that it has more sections and hence most of its length aligned in the direction of the desired strain measurement. This increases its sensitivity in that direction. The gauge in Fig 1 is sensitive to vertical strain, as shown. This change in length varies the resistive properties of the gauge, and can be measured using a small signal amplifier. The beam and the strain gauge must be bonded together, with adhesive, to change proportionally and measure minute deflections in the beam through the response of the strain gauge.

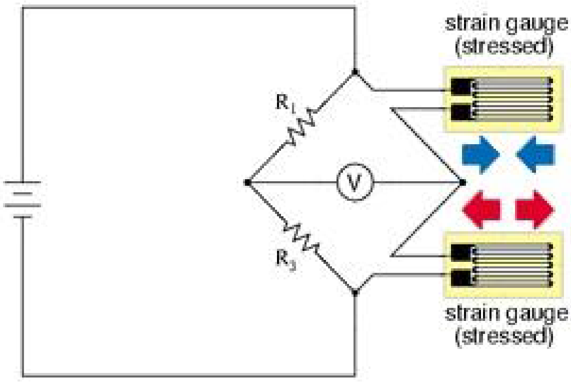

Fig. 2. Half Wheatstone-Bridge [14]

The circuit that is traditionally used with load cells is the Wheatstone-Bridge. The circuit design of the bridge can vary, depending on the number of strain gauges used. A greater quantity of cells provides greater precision. Fig. 2 describes a Half Wheatstone Bridge circuit, utilizing two strain gauges, similar to the scenario described above, where one is fixed to the top surface, while the other is bonded to the lower surface. The two measured strains are usually equal and opposite, doubling the output of the bridge circuit. This arrangement can be considered a single load cell.

The circuit is comprised of four resisters, two fixed resistors, R1 and R3 and two variable resistors; in this case the variable resistors are strain gauges. Usually, one of the fixed resistors is also a variable resistor so that the bridge can be balanced, i.e. to give zero output at zero load. When force is applied to the load cells, the resistance of the strain gauges vary and the output voltage of the system changes. The difference in current drawn between the positive strain gauge and the negative strain gauge can describe an applied force with great accuracy, in terms of a voltage output difference. This value can then be used to describe the varying weight.

IV. Hardware and System Design

A. Load Sensor

For the prototype described in this paper, an AMS-750 Load Cell was used. Developed by Hanyu, the AMS was a Single Point Impact Cell (SPI). The design of a SPI differs greatly from other configurations, to allow greater deflection of the beam. This not only increased the range of loads it can withstand but can also be used to introduce a safety stop to protect the strain gauges from overloading.

The AMS was a four wire load sensor, with two excitation wires (power and ground) and two signal wires (positive and negative signal). The Wheatstone-Bridge circuit is integrated into the sensor. It had a rated loading of 750 kg and an accuracy grade of 0.02% full scale. For outdoor applications, such as the one described in this paper, the load cell was also rated IP65, which guaranteed protection from dust and water jets. [15]

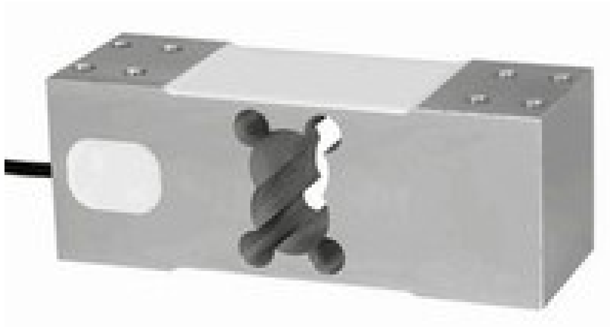

Fig. 3. AMS- Load Sensor [15]

B. Analogue to Digital Converter

To create a weight sensing node which was extremely accurate over a large input range (up to 200 kg) an ultra-accurate analogue to digital converter (ADC) was vital. For this system the Analog Devices AD7190 was selected, which is an ultra-low noise, 24-bit ADC with 2 differential inputs, designed for accurate weighing scales applications. It also had an SPI interface which made it ideal for use in an embedded system such as the one described in this paper. At the desired gain (G = 128) the AD7190 had 16 bits of noise free output. The maximum output of the AMS-750 load cell was 750 kg; therefore the minimum theoretical detectable weight change was calculated to be 11.4g.

C. Humidity and Temperature Sensors

Humidity and temperature are two properties which can lead to error in load cells. [7] The existing beehive monitoring sensor network [8] had a node with a humidity and temperature sensors, 808H5V5 and MCP9700A. This node could be utilised in conjunction with the weighing scale node to provide compensation for a more accurate weight measurement. It was important in this application to perform such adjustments as outdoor applications are subject to a wider range of temperatures and moisture levels than indoors.

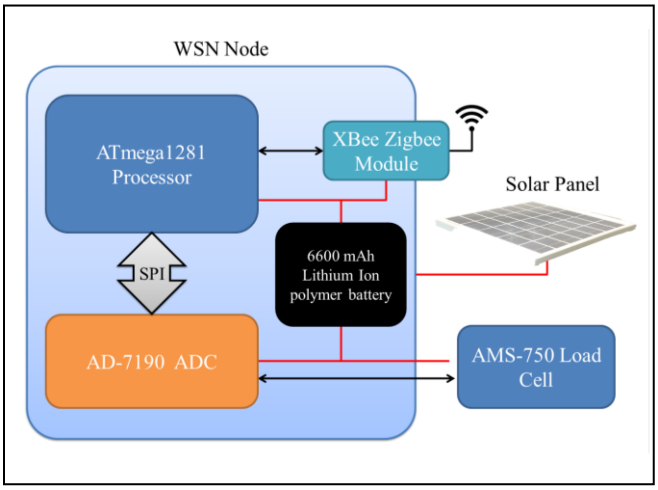

Fig. 4. Node Architecture

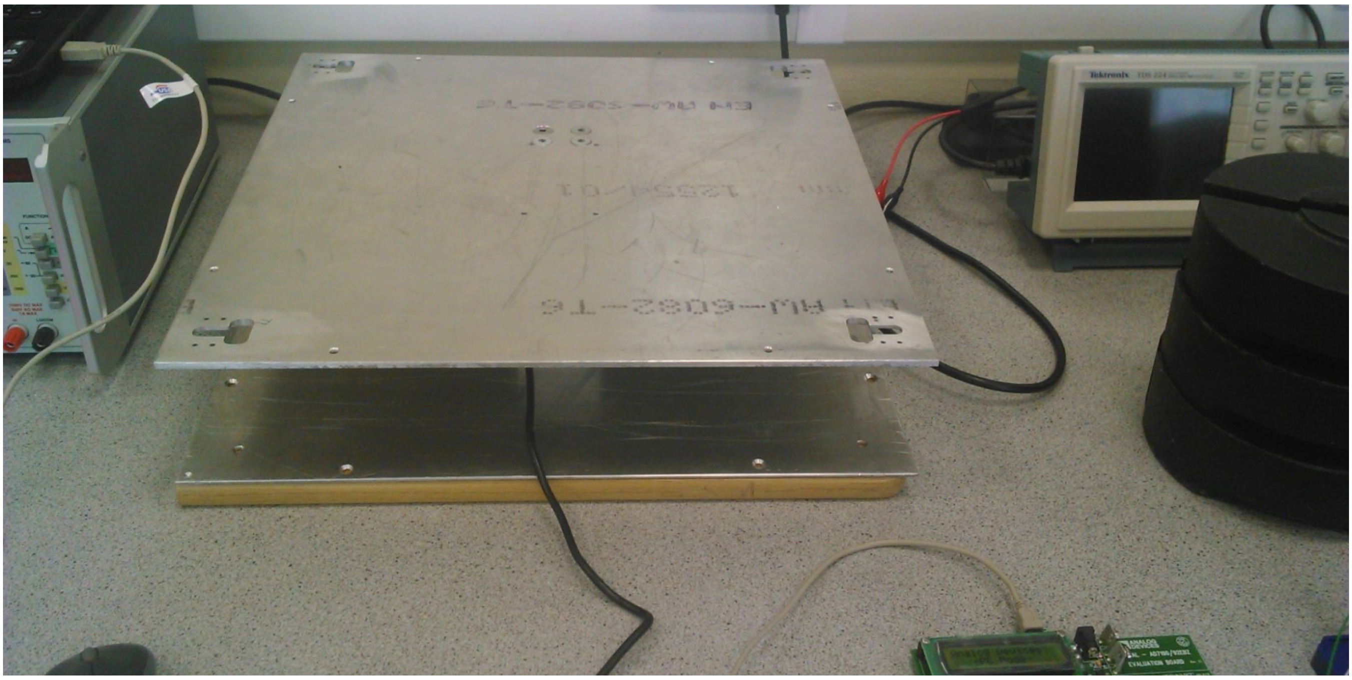

Fig. 5. Platform Weighing Scale

D. Wireless Platform and Node Architecture

Fig. 4 shows the architecture of the developed weight measurement wireless sensor node. The node was developed using an off-the-shelf ATmega 1281 based platform. This platform was designed for developing low power WSN prototypes. It incorporated a real time clock, sensor interfaces, an energy harvester adapter, low power sleep modes (55 µA at 3.7 V), an SPI interface, and an XBee compatible radio slot. To join the same network as in the existing system described in [8] a Zigbee radio was selected. A solar panel (234 x 160 mm, maximum output 7 V at 500 mA) was connected to the energy harvesting input to achieve energy neutral operation by charging a 2600 mAh battery allowing for continuous operation even in the case of several days with no direct sunshine. The platform was interfaced with the ADC and load sensor via SPI, and firmware was written to wake up, sample the weighing scales, transmit the reading to the base station, and return to sleep mode four times in a 24 hour cycle. These readings correspond to the four weight levels of interest every day: night-time when all bees are in the beehive, the morning before foraging for pollen and nectar has begun, midday when the maximum number of bees are out foraging, and the evening when all of the pollen and nectar for the day have been collected and the bees are returning to the beehive.

V. EXPERIMENTAL DESIGN & IMPLEMENTATION

The load cell was designed to operate as a platform weighing scale that would be fitted to the base of the brood chamber of the beehive, as shown in Fig. 5. This was achieved by fixing the load cell to two spacer blocks and two aluminium plates (base and platform). The recommended power supply to the load cell was 10 V. An Analogue-to-Digital Converter (ADC) was used to acquire the data from the Platform Scale. The ADC used was the AD-7190, which was available as an evaluation board from Analog Devices. The advantage of using the evaluation board was that during test it could display its 24-bit (16-bit noise-free) bit output in decimal format on its built-in LCD. The evaluation board also had PC based software that recorded data from the scales. The software was LabVIEW based and plotted real time graphs of the ADC output. The PC software was used for initial testing of the load cell performance and was not used in the final prototype.

The next task in the experiment was to evaluate the ADC's ability to output a reliable weight value, without the software. Once this was completed, the ADC was calibrated. This was best achieved by zeroing the platform scales, to allow the platform plates weight to be removed from the data output. An initial weight of 10 kg was applied to the scales which were then calibrated. The final system comprised the platform scales linked to an ADC, which were read by the off-the shelf platform, for transmission via Zigbee to the base station of the network. To test the functionality, various weights were applied to the scale.

VI. RESULTS

From the initial experiment, using the LabView software, Fig.6, was generated. The output voltage of the load cell system varied in response to the loads of 0 to 50 kg. Using standard weights, weight was incrementally applied to the platform. The output voltage for the bridge was recorded, by reading the value from the software. The data points plotted confirmed the load cell was linear. From the graph plotter on the PC, the noise at kg level increments was significantly low, with little or no effect on the output value.

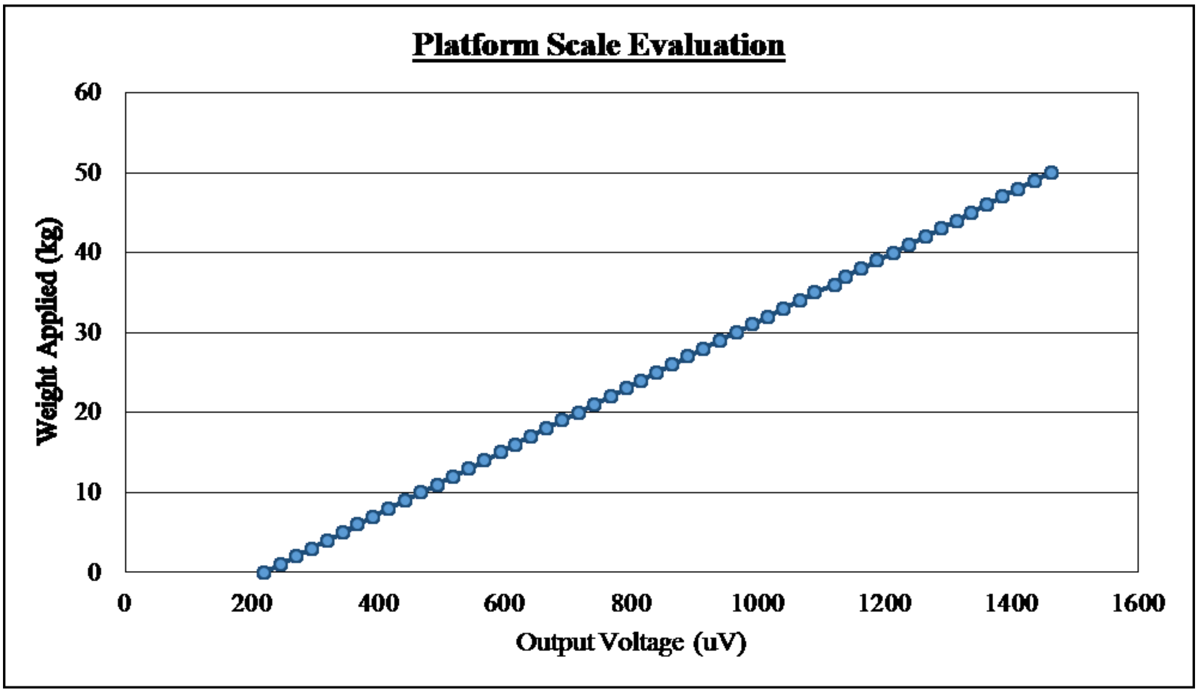

Fig. 6. Output Voltage of Scales

The system was then disconnected from the PC and used as a standalone system. Known weights were applied to the load cell, and the output of the system was recorded. Table 1 was produced and the error of the ADC readout was calculated. This method of weighing proved to have low variation between the actual weight and the ADC's weight, with slight variation with the 5 kg weights.

TABLE I. INITIAL LOAD CELL EXPERIMENT

Weight (Kg)	Average ADC Reading (kg)	Error (%)
0	0.0024	-
1	0.9967	0.33%
2	1.9975	0.12%
3	3.0153	0.51%
4	4.0155	0.39%
5	4.9418	1.16%
10	10.0184	0.18%
15	14.9397	0.40%
20	20.0186	0.09%
25	24.936	0.26%
30	29.98	0.07%
35	34.93	0.20%
40	39.98	0.05%
45	44.91	0.20%
50	49.97	0.06%

The minimum detectable weight calculated was estimated as 11.4 g. To confirm that the system could detect weight changes in this range the lowest available standard weights, in steps of 10 g were applied. Fig. 7 shows the output of the LabView software on the PC to a series of 10 g weights being applied. The changes of 10 g were identified by the system, with a small amount of noise. It is possible, with some signal processing to remove noise and averaging of the ADC output, that changes of the beehive weight in the range of tens of grams could be detected.

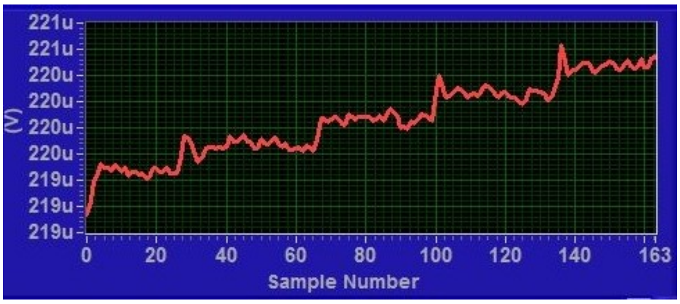

Fig. 7. Output Volatge of 0 to 40g, in steps of 10g

The initial validation of the load cell described greater error, when incremental weights of 5 kg were applied. This was later proven to be caused by the slight variation between two pre-fabricated sets of weights. As the system was calibrated with a standard 10 kg weight, Table 1 shows increments of 10 kg were more accurate than those of the other brand of standard weights. To prove this hypothesis, the ADC was calibrated to use the 5 kg weight as its reference value and the accuracy of said weights applied then increased significantly. This test was also carried out with the 1 kg weights, which confirmed the hypothesis.

A power analysis of the system was performed to confirm that the final prototype had suitable low power performance; the results of this analysis are shown in Table 2. The load cell was found to be the most power hungry component, as expected. To prevent this sensor from dramatically affecting the energy performance of the system the design of the prototype was revised to instruct the microcontroller to disconnect the load cell from the power supply when it was not actively being read. All other components in the system are low power, or heavily duty cycled to maximise energy performance. A solar panel (234 x 160 mm, maximum output 7 V at 500 mA) was included in the final design of the system to allow a long term, energy neutral deployment of the system in remote locations with little or no access to power lines.

TABLE II. POWER ANALYSIS

System Block	**Power Results**			
	Task	***Current***	***Voltage***	***Power***
Load Cell	On	20 mA	10 V	200 mW
ADC	On	10 mA	5 V	50 mW
Xbee Radio	Send	220 mA	3.3 V	726 mW
Master µC	Awake	15 mA	3.7 V	55.5 mW
	Asleep	0.55 mA	3.7 V	2.05 mW

VII. CONCLUSION

The weight of a beehive is one of many metrics that give a clear indication to the status of the colony and the health of the honey bees. In recent years, protecting honey bee populations has become an important topic due to increases in colony losses, and there has been an increased interest in developing monitoring systems for apiaries. Precision Apiary projects have become a key area of research in the field of biology and environmental science, but also engineering, with the development of more sophisticated sensors and data collectors. This paper outlines the design and development of a platform weighing scale, for deployment as part of a smart beehive. The scale was validated with an ADC evaluation board and PC software initially, providing the characteristics of the platform scale. The system was then separated from the PC and used in a standalone mode. The results of the tests led to the conclusion that this design of platform scale, along with the infrastructure of data collection and distribution was a viable solution to accurately measure weight levels of the beehive. A significant aspect of the experiment was the ability to characterise and read small weight change, in the order of 10 g. The system was integrated into to a WSN node to provide a flow of information between the smart weighing scale and the base station. To provide an environmentally neutral power supply solution, a solar cell, along with a lithium ion polymer battery was used to deliver power to the system. The solution developed mirrored similar projects in the emerging field of Precision Agriculture, i.e. vineyard monitoring, cheese production and other remote processes that may not be feasible to constantly attend. Before the system can be integrated into a busy hive, the scale must be completely weather protected. Future work will include stabilisation of the platform against wind, and improvement of the noise performance of the system.

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