



Development of a digital spring-based weight sensor for monitoring beehive weight

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Abstract

The major problem facing apiculture due to climate change and unpredictable honey harvesting seasons is low honey yield. The main cause of low honey harvests is uncertain harvesting, particularly when beekeepers delay harvesting honey or disturb the hive to determine when it is ripe to harvest. Beehive weight is monitored in modern apiculture to evaluate the bee colony's health and the honey's status, helping beekeepers harvest at the optimum time. However, in low-income communities where many beekeepers reside, strain gauge load cell-equipped smart beehives performing this purpose are out of reach due to their high cost which is 85,000 Tanzanian shillings (TZS) per unit. This study developed and evaluated a cost-effective (50,000 TZS per unit) and dependable solution, the Digital Spring-Based (DSB) weight sensor which can serve remote hive weight monitoring at a minimal cost compared to a strain gauge weight sensor. DSB weight sensor was devised with a spring weight scale, a microcontroller, fixed resistors, and a sliding potentiometer (variable resistor). They underwent rigorous evaluation and demonstrated a quantitation range from 4 to 24 kg in the calibration graph with a linearity having adjusted R-square of 0.997 then tested to beehives and capable of monitoring the beehive weights. In the beginning, the hive weight was 7 kg and reached 21 kg when filled with ripe honey which is ready for harvest. These evaluated metrics are useful in validating the performance of DSB weight sensors in beehive weight monitoring as a key parameter to gauge honey harvesting time. Moreover, the developed DSB weight sensor seamlessly connects with communication modules, facilitating effortless remote weight monitoring.

Keywords: *Spring-based weight sensor, Digital weight sensor, Apiculture technology, Hive management, and Beehive's weight monitoring*

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Introduction

Beekeeping (apiculture) is a globally practiced activity that aims to produce honey, and support crop pollination, vital for food production and biodiversity (Haldhar et al., 2021; Khan & Khan, 2018). Despite having many valuable products like bee pollens, wax, and venom from

apiculture, honey is the primary product of interest to which most beekeepers depend (Kamala & Devanand, 2021). However, due to uncertain harvesting times, most beekeepers face a significant challenge in achieving satisfactory honey yields, thus they get less honey than their expected harvests or unripe honey having lower quality invaluable to the market (Landaverde et

al., 2023). Delay honey harvesting time reduces honey yields as bees consume the stored honey, especially during drought (Vercelli et al., 2021). Also, premature harvesting yields unripe and lower-quality honey with reduced market value (Mohammed & Hassen, 2021). Several beekeepers inspect the honeycomb inside the beehives to check if the honey made inside is ready to harvest (Kasangaki et al., 2014). This leads to bee disturbance and eventually, they start to consume the stored honey if not harvested by the time when the disturbance occurs (Kamala & Devanand, 2021; Mucsi, 2020). This challenge pressed the need for a hive weight monitoring platform that can aid a beekeeper in identifying the bee colony health, and the estimated honey amount made in the hive despite variations in harvest times, influenced by climate and bee foraging behaviors, making predicting the optimal harvest time difficult (Robinson et al., 2022).

Monitoring the beehive's weight is a recent dependable practice in modern beekeeping used to identify bee colony health and stands as the key parameter in judging honey harvesting time (Biswas, 2020). The use of beehive weight monitoring technology has been adopted by beekeepers who produce bee products on a large scale, mostly in developing countries where this technology is accessible (Hadjur et al., 2022). These beekeepers rely on hive weight monitoring to assess colony health and predict the best time for honey collection rather than using a beekeeping calendar (Degenfellner & Templ, 2024; McMinn-Sauder et al., 2024). Equipping the beehive with recently available weight sensors to facilitate hive weight monitoring has failed to be adopted in developing countries due to high costs (Bwalya, 2020; Zacepins et al., 2015). Tanzania is among the African developing countries in which apiculture is highly performed however, actual honey production is lower than the available potential (Forestry and Beekeeping Division, 2021; Namwata et al., 2013; Tutuba & Vanhaverbeke, 2018). This is also because of the conventional technologies used in honey production (Kimaro et al., 2013). Considering the recent approach of applying weight sensors to monitor beehive weights as a key parameter to identify optimal honey harvesting time, the cost of the weight sensors

that can measure a load of at least 20kg costs 85,000 TZS in Tanzania (BAFREDO Electronics Limited, 2024). Hence, became a barrier to the adoption of developing smart beehives equipped with weight sensors.

Therefore, there's a pressing need for affordable alternatives in beehive weight sensing technology to make monitoring economically feasible in such areas. This paper introduces evaluation and performance results for the novel and cost-effective weight sensor tailored for seamless integration into beehive weight monitoring systems, addressing economic constraints in low-income communities and aiming to enhance honey harvests.

Materials and Method

Materials and instruments used

Weight scale springs (25 kg capacity), slide potentiometer/variable resistor (B103), fixed resistors (10 kΩ and 20 kΩ), and microcontroller were purchased from Bafredo Electronic Limited and utilized in DSB weight sensor fabrication. GSM modem SIM 800C, hanging rope, 5V solar panel, 3.6 V Li-ion battery, and beehives were purchased from the local market in Dodoma, and used in testing the DSB weight sensor in the beehive. A desktop and multimeter (MAS830L), and an electronic balance were used as the tools to develop a DSB weight sensor.

DSB Weight sensor circuit design.

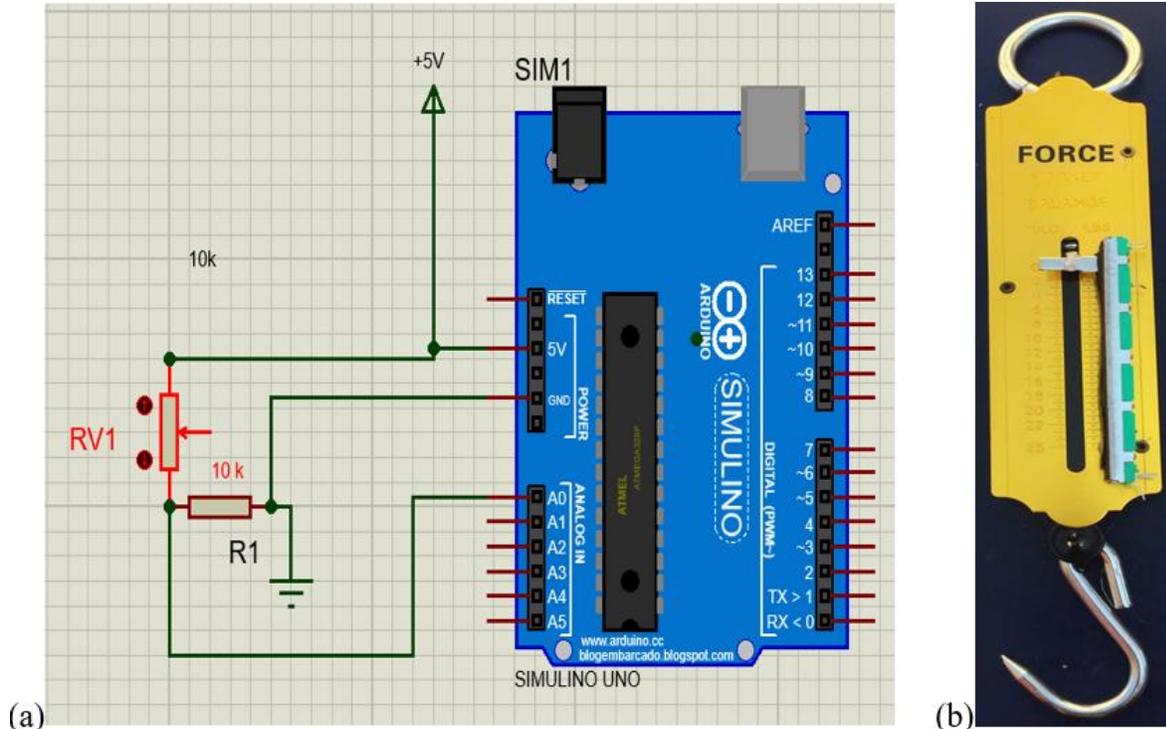
The circuit to construct the DSB weight sensor was drawn in Proteus software (Figure 1a). The program for the DSB weight sensor was written in Arduino Integrated Development Environment (IDE) software and uploaded into the developed circuit. The voltage reading at the analog pin (A0) from the junction between RV1 and R1, was calculated using equation 1 which was used in the program uploaded to the microcontroller. The drawn circuit was simulated in the proteus program to verify its functionality.

$$V_{out} = V_{in} \times \left(1 - \frac{RV1}{(RV1+R1)}\right) \quad (1)$$

Where; V_{out} represents the voltage across the fixed resistor (R1), and V_{in} represents the voltage input that is applied to the end of the variable resistor (RV1).

Figure 1

(a) A circuit diagram in which, RV1 stands for sliding variable resistor, R1 stands for a fixed resistor, and SIMULINO UNO stands for a microcontroller (Arduino UNO), (b) Sliding potentiometer attached on the weight scale equivalent to RV1



Construction of DSB Weight Sensor

Initially, the calibration process was carried out in both a slide variable resistors' resistance against knobs moving (sliding) distance and a weight scale pointer moving distance against suspended object weight. The relationship between knob's movement and resistance change was evaluated using the digital multimeter. After knowing their response from the calibration results, a variable resistor was connected with a weight scale spring. To ensure synchronized movement between the spring weight scale pointer and the sliding variable resistor's knob, they were affixed together using hot glue. This arrangement allowed the direct manipulation of the sliding potentiometer's knob by the weight scale pointer. The movement of this knob modulates the resistance of the potentiometer and facilitates a precise suspended object weight measurement. This configuration is depicted in Figure 1(b). The potentiometer integrated with a 10K fixed resistor to form a potential divider setup altered the voltage output concerning the

resistance change caused by the knob's movement attached to the weight scale pointer. This voltage is measured across the fixed resistor which changes as the potentiometer resistance change is transmitted to a microcontroller for further processing and weight determination (Figure 1a)

Finally, a USB cable was connected between the desktop computer and the microcontroller. The Arduino IDE program was subsequently launched then a program code was written and uploaded to the microcontroller. The serial monitor was opened to observe the voltage detected in the potential divider. The standard weights made up of cast iron ranging from 0 to 30 kg were suspended on the DSB weight sensor for calibration purposes. The voltage readings displayed in the serial monitor were systematically recorded during each weight suspension. The recorded voltages were used in developing a calibration graph which used to develop models used to calculate the suspended object weight.

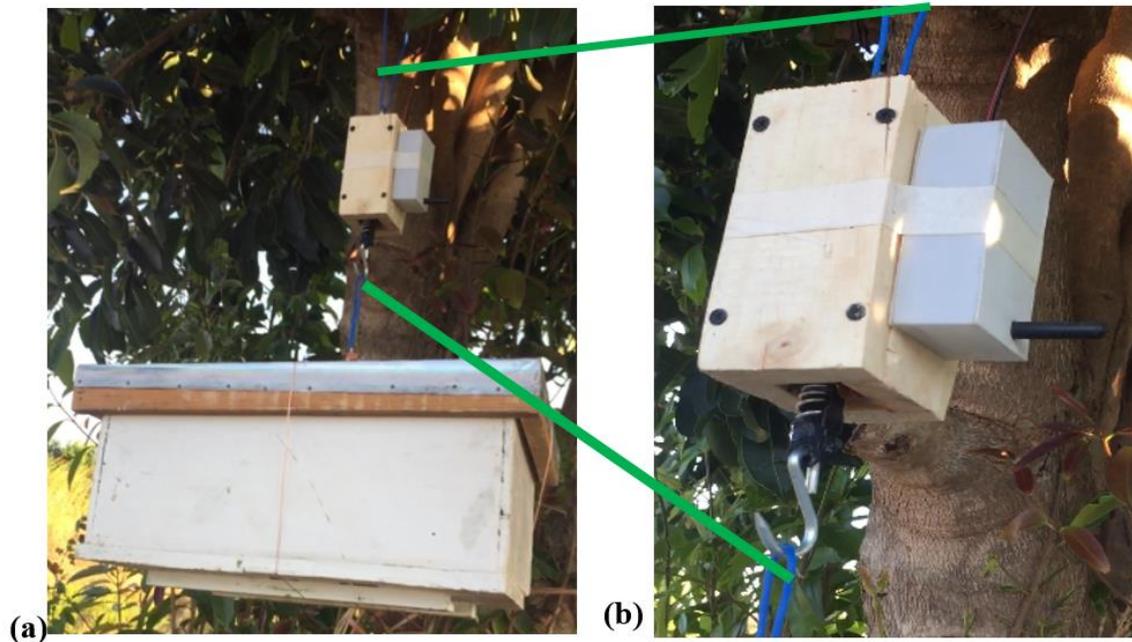
Installation of DSB weight sensor to the beehive.

The DSB weight sensor was integrated with a GSM modem to enable remote data transmission via Short Message Services (SMS). The SMS containing daily average hive weight data was sent from DSB to the mobile phone daily and recorded to aid weight trend monitoring. Initially, one end of a string was connected to the tree branch and held the DSB sensor. Another piece of

the string was connected to suspend the beehive and attached to the held DSB weight sensor. This configuration allowed the continuous beehive weight sensing and sent the weight data to the mobile phone daily (Figure 2). Two DSB weight sensors were installed in separate identically designed beehives and their weights were recorded from January 15th, 2023, to May 18th, 2024. The average beehive's weight data were recorded daily.

Figure 2

(a) DSB weight sensor configured with a beehive in the apiary farm for remote hive weight data transfer, (b) A DSB weight sensor attached to the communication module



Results

Calibration results for sliding potentiometer and weight scale spring

The calibration of the slide potentiometer and weight scale spring revealed that resistance decreased with increasing knob position, as depicted in Figure 3a. Notably, the resistance versus position relationship exhibited non-linearity at both extremes of the knob's range. For accurate position detection, the linear segment of the resistance-position graph, covering the range from 1 to 5 cm (Figure 3b), was identified as the valid range.

Introducing a fixed resistor in series with the sliding variable resistor created a potential divider circuit, enabling the variation of the output voltage in response to changes in the variable resistor's resistance due to slider position adjustments under the weight of the suspended object. The relationship between the suspended object's weight and the output voltage was quantified using Equation 4, which was derived by integrating equations 1, 2, and 3. Equation 2 was based on the linear segment analysis from Figure 3b, while Equation 3 was derived from the data in Figure 3c.

In this context, Equation 4 utilized an applied voltage (V_{in}) of 5 volts and a fixed resistor (R_1) of

10 kilohms. This derived equation effectively allows for calculating the suspended object's

weight from the voltage signals detected by the microcontroller.

$$RV1 = -2.51667d + 12.54556 \quad (2)$$

RV1 = resistance for variable resistor, d = knobs moving distance

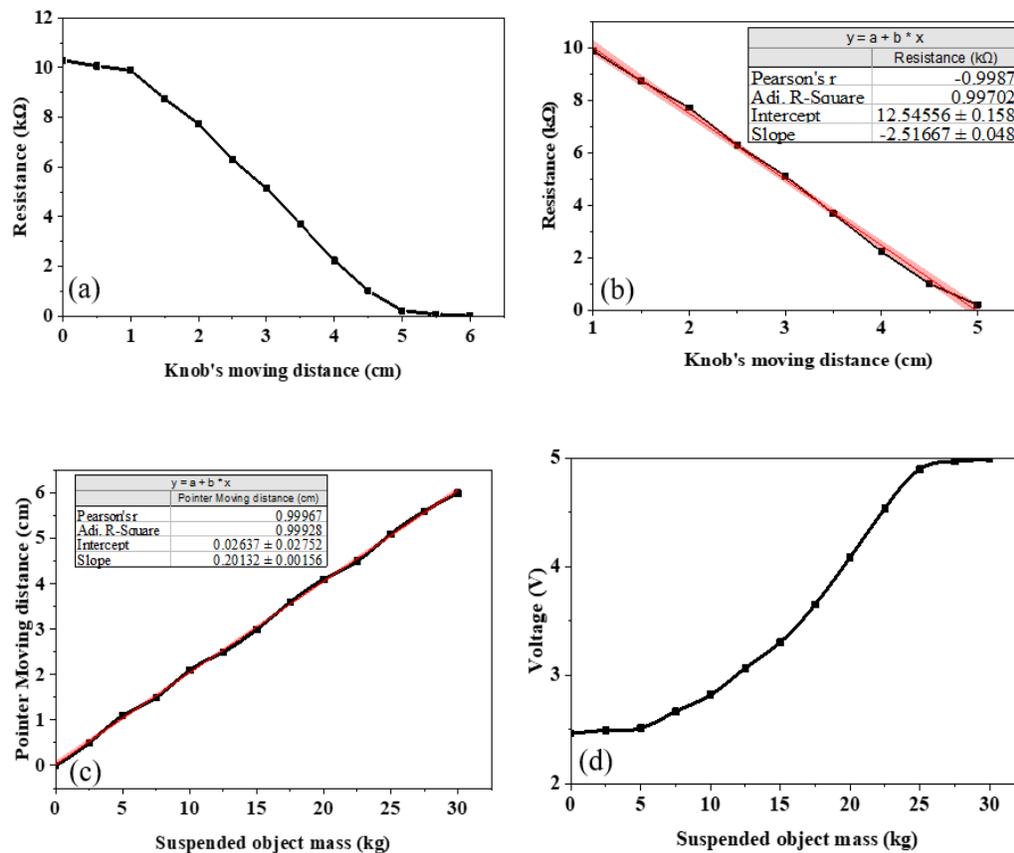
$$d = 0.20132x + 0.02637 \quad (3)$$

d = weight scale pointer moving distance, x = suspended object mass

$$V_{out} = 5 - \frac{(-2.5333x + 62.396)}{(-0.50666x + 22.4792)} \quad (4)$$

Figure 3

Experimental calibration graphs: (a) The graph of a sliding variable resistors resistance against the knob moving distance, (b) the Selected linear part of the graph showing variables' resistance against the knob's moving distance, (c) Weight scale pointer moving distance against the suspended object mass, and (d) Voltage displayed on the serial monitor against suspended object mass



Voltage Trend of the DSB Sensor Versus Suspended Object Weight

The calibration metrics for the sliding potentiometer and weight scale spring facilitated the development of an equation to

determine the weight of a suspended object from voltage signals read by the microcontroller.

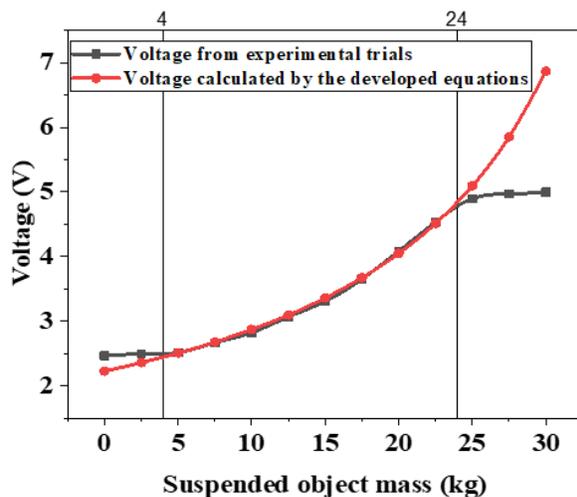
Figure 4 displays the voltage trend for the suspended object's weight, comparing the predicted values from the developed equation (red line) with the actual voltage readings from the sensor for standard weights (black line).

The results indicate that the predicted and measured voltages align closely within the 4 to 24

kg weight range. This range demonstrates the equation's effectiveness in accurately calculating the suspended object's weight. Validation through mathematical analysis and experimental data further supports that the equation provides reliable weight quantification within this range. Therefore, the equation has been integrated into the microcontroller programming for precise weight measurements.

Figure 4

Voltage trend against suspended object weight comparison between experimental trials and developed equations



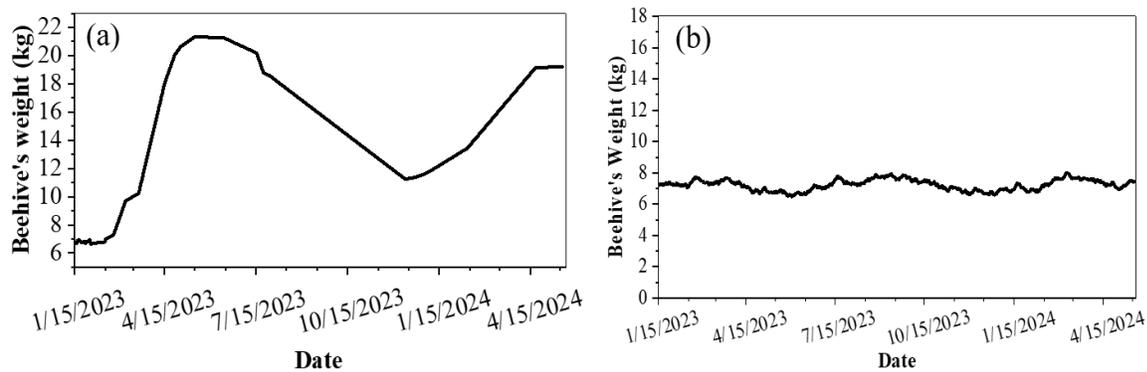
DSB weight sensor performance in monitoring beehive weight

One of the beehives was successfully inhabited by bees in which honey production also occurred within it. The weight of that beehive inhabited by bees appeared to increase from January to May 2023 when it reached its peak weight. From late May to June 2023, the weight was maintained constant, then slightly decreased until July 2023. The gradual decrease in the hive weight was

observed from July to December 2023. Subsequently, the hive weight started to increase slightly from December 2023 to late February 2024, then steeply increased from February to late April 2024. The hive's weight was almost constant from late April to May 18th, 2024. The beehive that didn't get bees had almost the constant weight from the installation date in the apiary farm until the last date of data collection.

Figure 5

Beehive weight trend: (a) Beehive having bees, (b) Beehive without bees



Discussion

A digital spring-based weight sensor was developed, and its features were studied accordingly. This study unveiled the procedures for making the DSB weight sensor its validation result per each essential component, and its performance in beehive weight monitoring. The DSB weight sensor was employed to monitor the weights of tree-suspended beehives located in Dodoma. Its performance is considerably good in showing beehive weight trends as it aligns closely with natural activities taking place inside the beehives. Also, it depicted the right time for honey harvesting which is nearly the same as the beekeeping calendar which shows that May is the optimal honey harvesting month (Echazarreta et al., 1997). This essence helps identify the hive occupied by bees, honey production, and honey harvesting time when linked to communication modules like the GSM modem.

DSB sensor calibration results discussion.

The resistance of the sliding potentiometer exhibited a progressive decline in slope as the knob moved from 0 to 1 cm. As the knob's position increased from 1 to 5 cm, the slope became steeper. Finally, once the knob's position reached 5 to 6 cm, the slope decreased again (Figure 3a). Generally, the slide potentiometer demonstrated a reasonable linear relationship to its knob's position although the graph failed at the endpoints. Therefore, the optimal region to be used in gauging the position of the knob using its resistance is between 1 to 5 cm. Other studies show that the linearity of the slide potentiometer might be lost at the end position of the slider

(knob). This loss of linearity can occur due to the end resistance, which is also known as the physical termination of the resistive track, or the design of the wiper mechanism (Sinclair, 2000). The knob's position between 1 to 5 cm and the corresponding measured resistance demonstrated a linear correlation with an adjusted R-square of 0.99702. This correlation indicated a very close linear fit which highlighted its effectiveness in sensor devising applications as it is estimated to offer high accuracy in detecting the knob's position within the range of 1 to 5 cm.

The weight scale pointer also underwent a rigorous evaluation to assess its pointer movement which aligns with its spring length change caused by the weight of the suspended object. The movement of the weight scale pointer position showed a linear correlation with the suspended weight object ranging from 0 to 30 kg. The obtained pointers position results against the suspended object weight were plotted and shown to fit into the linear model, which achieved an adjusted R-square of 0.99928, supporting Hooke's Law (Moyer, 1977). A little discrepancy was observed to lower the linearity of the adjusted R-square below 1.0, which might be because of wind disturbance, spring discrepancies, or errors caused by standard weight preparation (MILLS et al., 2003).

The linked potentiometer knob and the pointer of the spring weight scale facilitated the conversion of suspended object weight into resistance. The whole performance of such a configuration was mostly limited to the quantitation range to which

the knob's position had a proper linearity. Therefore, the knob's position is between 1 to 5 cm, showing a linear correlation of the resistance attained corresponding to the suspended object weight. Such a region was optimal for accurate weight measurement.

Regarding the experimental trial results obtained through rigorous evaluation, as shown in Figure 3, the sensor fails to accurately quantify the mass of suspended objects below 4 kg and above 24 kg.

Figure 4. Nevertheless, the change in weight scale spring length (represented by the pointer moving distance) corresponding to the suspended object weight was reproducible and largely adhered to Hooke's Law, as illustrated in Figure 3c. Thus provided a constructive way of quantifying the suspended object weight.

Figure 5a which demonstrates the hive that was inhabited by bees, there was a consistent increase in the beehive weight from January to May 2023 which was followed by a similar trend from February to late April 2024. These periods were covered with intense flower shedding which indicated the active nectar collection by bees from the plants surrounding the apiary (Lucas et al., 2023). From May to July 2023 there was a slight decrease in the beehive's weight which indicated that the beehive was probably filled with honey and the swarming event temporarily occurred and halted the gathering of additional food Figure 5b. Such a phenomenon is likely to be caused by the influence of environmental factors such as wind and rainfall.

Generally, the ability of the DSB weight sensor to monitor the beehive's weight provided critical information for making decisions regarding honey harvesting time and became a tool for effective beehive management.

Cost evaluation for DSB weight sensor

The DSB weight sensor configuration was equipped with a spring weight sensor (25 kg capacity), sliding variable resistor (B103), fixed resistor (10k Ω), and a microcontroller (Arduino UNO), Their cost as supplied by BAFREDO Electronics Limited (2024) is 10,000, 4,500, 500, 35,000 TZS which marks the summation of cost

Below 4 kg, the weight scale pointer position is less than 1 cm from its origin, where the resistance of the variable resistors loses linearity, as depicted in Figure 3a. Similarly, this issue applies to masses above 24 kg, where the variable resistor's knob position exceeds 5 cm.

There may be slight deviations caused by air disturbances in the experimental region, which could have contributed to the reduced accuracy of the results observed in

DSB weight sensor performance in monitoring beehives

The DSB weight sensor showed good performance in monitoring the beehive weight, in which its trend provided valuable insights to identify events going on in the hive, bee behavior, and hive dynamics essential for notifying the appropriate honey harvesting time. Considering

(Painkra, 2023). From July to December 2023 there was a continuous decrease in the beehive's weight which reflects drought conditions in the Dodoma region where the experiment was conducted that led to food scarcity and prompted bees to consume stored honey (Yohana, 2021).

The beehive that wasn't inhabited by bees had maintained its weight from the date of installation to the end of data collection. The remarkable weight fluctuation despite the absence of bees was observed as depicted in

equals to 50,000 TZS. The configuration seamlessly integrates with communication modules like GSM modems without needing an additional microcontroller. In contrast, the strain gauge sensors (load cells of 20kg capacity) cost 85,000 TZS and need a microcontroller to be integrated with the communication modules to facilitate remote hive weight monitoring. Therefore, this study has potentially unlocked the affordable solution for hive weight monitoring.

Conclusion

The design, implementation, and evaluation of the digital spring-based (DSB) weight sensor

have been made and investigated greatly for several applications, mainly in precise controlled suspended load monitoring and beehive weight monitoring systems. The ability of the sensor to quantify weights well within these ranges with high correlation coefficients and alignment with theoretical models substantiates its reliability within real-world scenarios. Interchanging resistors within voltage dividers, which is essentially how the sensor converts weight to applicable electrical signals, makes it ideal for producing correct weight-measuring results of suspended items. Alternatively, the conditions were more challenging as the sensor operated non-linearly nearing the tails of the measurement spectrum, due to nature, nonetheless even at all ranges the sensor implemented repetition of Hooke's Law - proving its inherent robustness to accurately examine the entire health of the hive. For beehive monitoring, the DSB weight sensor has helped in keeping a record of hive weight trends based on bee behavioral patterns and the external environment. With this, beekeepers can know the perfect time for honey harvesting, and they can also keep track of the health of hives remotely without the need to attend the apiary farm.

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Recommendation

This study recommends integrating DSB weight sensors with communication modules to identify the optimal time for bee harvesting in apiculture. This can help beekeepers to avoid unripe honey or delayed harvests. A longer sliding potentiometer or two spring weight scales can increase the sensor's current quantitation range of 4-24 kg. Future studies may develop sophisticated algorithms to detect natural changes and address environmental disturbances.

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