

Efficient Monitoring of Livestock Feed Inventories

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Abstract—Understanding the current inventory of livestock feed is crucial to modern farm operations. While typically accomplished via monitoring the weight of feed bins, commercially available calibrated load cells suitable for this purpose can be prohibitive in cost. Here, we describe an approach to using uncalibrated load cells, which are inexpensive to produce, that then undergo a persistent, non-linear calibration process during manufacturing. By comparing the output signal from multiple load cells on an individual feed bin, we also diagnose failures in the field, continuing functional operation prior to repair.

Index Terms—livestock feed, grain bins, bi-directional communications, load cells, calibration

I. INTRODUCTION

Knowledge of the weight of a feed bin and its contents is a common method for assessing the amount of grain that is stored in the bin [1]. This is typically accomplished by instrumenting each of the support legs of the feed bin with a load cell and aggregating the total weight via the summation of the load experienced at each support leg. This illustrated in Fig. 1, in which a load cell would be installed at the base of each leg.

One of the challenges inherent in instrumenting a system like this is that one requires calibrated load cells to be able to accurately determine the total weight, and the cost of calibrated load cells has historically been prohibitively high, such that instrumenting the feed bin could cost as much as constructing the feed bin itself.

In this paper, we make the following contributions:

- We describe an approach to efficiently calibrating an inexpensive, uncalibrated load cell post-manufacture. The



Fig. 1. Feed bins.

calibration supports non-linearity in the response function.

- We describe an approach to achieve bi-directional communication over a traditional 4-20 mA current loop, which is then used to support the calibration process without requiring an additional communication path.
- We describe an approach to detect load cell failure.
- We describe an approach to enable graceful degradation of the system's operation in the event of load cell failure.

The feed bin weighing system comprises load cells at the base of each support leg (typically 4 to 12) and an aggregation unit that combines the results into a single weight value that is both displayed locally and securely communicated to a remote location [2].

II. BACKGROUND AND RELATED WORK

Modern farms are effective users of IoT technology [1], including the automated feeding of livestock, monitoring of feed inventories, environmental control, monitoring of equipment health, etc. Remote communications are crucial, given the distances involved (e.g., farm managers are often at separate locations from the farm itself). We have previously described approaches for secure communication with IoT equipment, even legacy devices [2], both on the farm and in other contexts [3]. The benefits of knowing feed inventories include not only the management of feed deliveries, but also include monitoring the health of both the livestock [4] and the equipment (e.g., automated feeders).

Given the substantial cost differences between uncalibrated and calibrated load cells, others have previously developed approaches for use of uncalibrated load cells. Livingston [5] described a technique whereby uncalibrated load cells can be dynamically calibrated in the field by noting the readings from individual local cells twice, when the feed bin is empty and when it has just been loaded.

The approach above, however, assumes that the response of the load cell is linear. This is often not the case. Dontu [6] performed extensive characterization on an aluminum bar load cell quantifying nonlinearity and other properties. Yi [7] modeled nonlinearity due to elasticity in load cells. Xianyi [8] gives a method for improving the linearity of a load cell's response through improved manufacturing techniques. Huang et al. [9] study load cells with a focus on dynamic behaviour, and Joung et al. [10] explore an alternative material technology

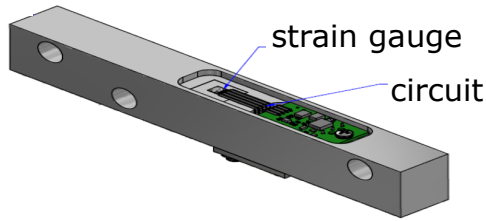


Fig. 2. Load cell (inverted to show assembly).



Fig. 3. Load cell installation.

that can be 3-D printed, potentially lowering the manufacturing costs. Our approach relies on traditional, inexpensive load cells that are calibrated post-manufacture to keep manufacturing costs as low as possible.

III. SYSTEM DESCRIPTION

Fig. 2 shows the bottom view of the load cell (with the strain gauge and circuit visible). After the strain gauge and circuit board are installed, the entire cavity that includes the two is potted. This provides environmental protection and security from electronic tampering. As an additional security feature, the program stored in the microcontroller on the circuit board is inaccessible after the potting material has cured.

When the load cell is installed at the farm, the weight of one leg of the feed bin is applied to the surface opposite the strain gauge. An image of an installation is shown in Fig. 3. In operation, the circuit board contains electronics that translate the strain information from the strain gauge into a calibrated current signal that represents the load on the leg in which the load cell is installed. Electrical connections to the load cell comprise three wires: power (Vdd), ground, and signal (a 4-20 mA current loop).

The schematic diagram of the load cell circuit is shown in Fig. 4 (to the left of the 4-20 mA signal wire). Post manufacture, but prior to shipping to customers, the finished load cell is placed in a fixture and calibrated. The calibration

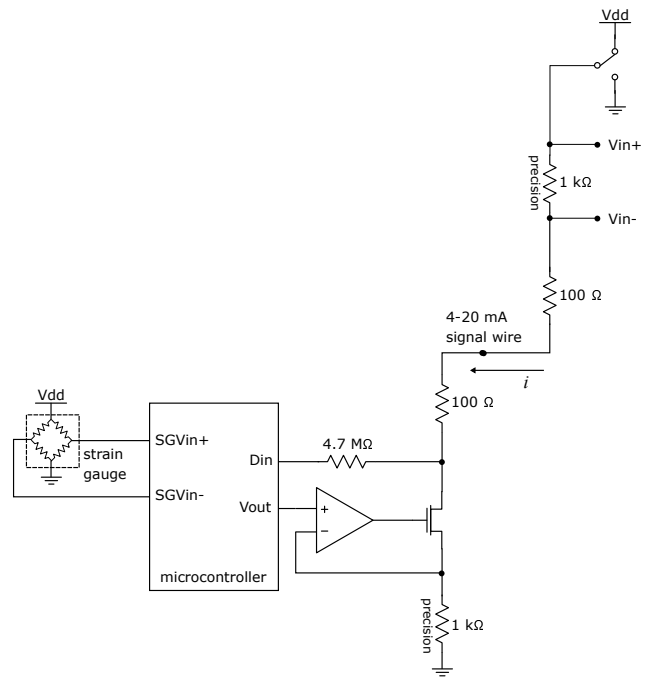


Fig. 4. Schematic diagram of load cell circuit (left of signal wire) and test fixture circuit (right of signal wire).

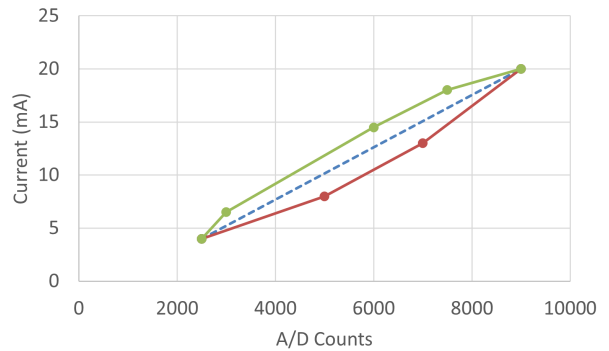


Fig. 5. Example nonlinear response curves.

parameters are stored in non-volatile memory (within the microcontroller) so that they are retained when power is not present. During operation, the calibrating transformation (from strain gauge to load cell output reading) is performed within the load cell itself.

To support nonlinearity in the response of the strain gauge, the calibration process utilizes an arbitrary (fixed) number of calibration points, and the output current signal is computed as the piece-wise linear concatenation of these calibration points. This is illustrated in Fig. 5, which shows two candidate calibrations.

The graph shows the output current (delivered on the 4-20 mA signal wire) as a function of the input analog-to-digital signal from the strain gauge (the difference between

SGVin+ and SGVin-). Here, we assume the use of a 14-bit A/D converter. The dashed line represents a linear response, while the piecewise-linear curves above and below the dashed line illustrate two possible nonlinear responses.

IV. CALIBRATION PROCEDURE

As mentioned earlier, one of the security features is that once the load cell is potted and the circuit board is no longer accessible, the programming pins for the microcontroller are no longer available. The only external wires, post-cure of the potting material, are power, ground, and signal. This poses a challenge, however, for calibration, because the calibration must happen after the potting material has cured, as it can impact the physical response of the strain gauge.

To address this issue, the calibration is performed by communicating with the microcontroller bi-directionally using the same signal wire that is used for the 4-20 mA current signal in normal operation. In effect, the signal wire's functionality is expanded to support bidirectional communication. While existing technology (e.g., the HART protocol [11]) is one approach to addressing this issue, our approach requires less circuitry than the frequency shift keying techniques of HART.

Our approach will be explained in the context of communicating between the load cell and a calibration/test fixture used at the end of the manufacturing process. This calibration takes place once the potting material has cured and prior to shipping the load cell to the customer. For signaling from the load cell to the test fixture, the communication is a current signal. Under normal operation, this current signal indicates weight. However, under software control of the microcontroller, it is possible to send digital information via this current signal. Current less than a specified threshold (e.g., half-scale or 12 mA) is received as a logical low (0 bit) and current above the threshold is received as a logical high (1 bit). Alternatively, individual fixed current levels can be defined to have specific meaning. For example, a fixed output of top of scale might indicate "invalid calibration parameters." In the current design, the load cell outputs a low current (under 4 mA) to indicate "waiting for calibration data."

For signaling from the test fixture to the load cell, the communication is a voltage signal. This can be best understood by first exploring the load cell interface circuit shown in Fig. 4 (to the left of the 4-20 mA signal wire, i). In this circuit, the desired output current is established (by the microcontroller) at V_{out} , with the current i effectively $V_{out}/1\text{ k}\Omega$. This current can be read at the calibration fixture with the circuit shown to the right of the signal wire (by measuring the voltage between Vin+ and Vin-). With the switch in the calibration fixture connected to Vdd, the current signal i from the load cell establishes a voltage $V_{in} = i \cdot 1\text{ k}\Omega$ across the precision resistor in the fixture, enabling the fixture to read the current signal from the load cell. (Note that while drawn schematically as a physical switch, in the actual implementation, the switch is constructed using transistors.)

We are now in a position to understand how a voltage signal can be communicated from the calibration fixture to the load

cell. First, to send a logical 0 (low level) to the load cell, the calibration fixture sets the switch to GND (0 V). Under this circumstance, independent of the value of V_{out} in the load cell, the voltage at Din within the load cell is a logical low (0 V). Din is connected to a digital input pin of the microcontroller. To send a logical 1 (high level) to the load cell, the calibration fixture sets the switch to Vdd. In this case, the voltage at Din will depend upon the output current i , which can be controlled by the microcontroller to ensure that the voltage at Din will be received as a logical 1 (high level). In this way, the calibration fixture can communicate digital information to the load cell. If the switch is controlled by the TX line of an asynchronous UART on the calibration fixture, and the Din is connected to the RX line of an asynchronous UART on the load cell, serial communication is straightforward.

An additional feature that reduces the chances of an accidental (or malicious) recalibration is the timing requirements of recalibration. On power-up, the load cell sends an analog output signal to indicate it is "waiting for calibration data." It maintains this output for only 5 seconds (a fixed time that could be set to any desired amount). During this time window, it is receptive to a calibration message (i.e., a message from the calibration fixture that the fixture wishes to perform a calibration). After this time elapses, if a calibration has not been initiated, the output signal reverts to signaling the weight incident on the load cell, and no calibration messages are acknowledged.

There are multiple methods by which one can determine the calibration points illustrated in Fig. 5. Several are described below. As shown in the figure, the calibration points themselves can be represented by a set of ordered pairs, $(count_k, current_k)$, where k ranges from 1 to the number of calibration points. One approach to determining these points is for the microcontroller software to provide information to the calibration fixture as to the actual value of the A/D counts at a discrete set of imposed weights. In this method, the calibration fixture imposes a known weight on the load cell, the load cell informs the calibration fixture of the A/D counts at that weight, and the process is repeated for several different weights. The communication of the A/D counts can happen in a pair of ways: (1) using the digital communication techniques described above, or (2) adopting the linear transduction curve of Fig. 5 (the dashed line) and communicating the A/D counts as an analog signal (which is then read at the Vin+ and Vin- terminals on the calibration fixture).

A second approach is for the calibration fixture to impose a set of weights on the load cell, and for each distinct value of weight, the calibration fixture communicates to the load cell the desired output current, the load cell samples the A/D counts and stores the $(count_k, current_k)$ pair as one of its calibration points.

Each of the above approaches has merit, but they both make the simplifying assumption that the digital-to-analog converter for the microcontroller on the load cell and the voltage-to-current circuitry illustrated in Fig. 4 both give a linear response. This third, iterative approach does not make

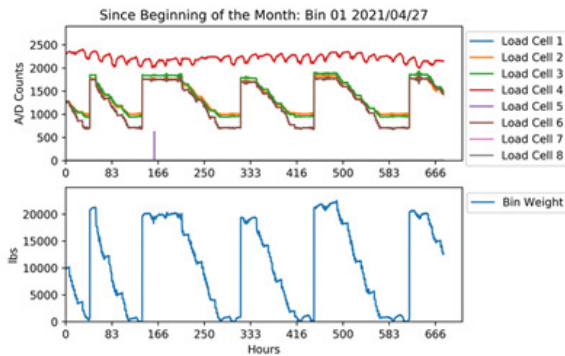


Fig. 6. Malfunctioning load cell measuring bin weight (top) and computed weight of grain in the feed bin (bottom) [1].

this assumption, and will correct for non-linearities throughout the load cell signal path (from mechanical stress all the way to output current signal).

The iterative approach can be expressed in terms of the following greedy algorithm:

- 1) Start with an initial set of calibration parameters (e.g., a set from Fig. 5).
- 2) Loop over a set of fixed, known weights applied by the calibration figure, measuring the current output at each position. Compute the error between the known weight and the desired output for each point.
- 3) For one of the points that has a non-zero error (e.g., the point with the maximum error), adjust the calibration parameter at that point to diminish the error at that point.
- 4) Repeat from step 2 until the maximum error is below a given desired amount.

The iterative approach described above is in the form of a greedy algorithm. However, any iterative meta-heuristic would be reasonable (e.g., simulated annealing [12], genetic algorithms [13], threshold acceptance [14], etc.).

V. GRACEFUL DEGRADATION WITH FAILURES

The aggregation unit that sums the signals from each of the load cells is also in a position to detect failures. Consider the top graph in Fig. 6, which shows the input signal from each load cell separately (where the input current signal has been converted to a digital signal via a 12-bit ADC). The response of all but one of the load cells is typical, comprising the following elements: (1) sharp increase associated with filling the bin with grain, this happens five times during the time period displayed, (2) gradual decrease as feed is consumed, and (3) stable periods where an alternate feed bin is supplying feed (it is common for barns to have multiple feed bins and their usage alternates).

One load cell, however, is clearly not following the pattern. Whenever an individual load cell does not respond in tandem with the remaining load cells, the base unit that aggregates

signals from the various load cells marks that load cell as failed.

In the presence of a load cell failure, the base unit then takes two actions. First, it communicates the failure to the operators (either through the local display or via remote communication) so that it can be repaired or replaced. Second, it uses the information from the remaining load cells to estimate the weight of the feed bin (resulting in the bottom graph of Figure 6). It does this by making the assumption that the load cell that has failed would be providing a reading that is equal to the average of the remaining load cells.

In an ideal system, this approach of averaging the values from the remaining load cells would actually provide the correct weight. In fact, in such an ideal environment, one would not need to instrument all of the legs of the feed bin at all, one would be sufficient. However, there are a number of non-idealities in the practical system on the farm. The two most significant are: (1) asymmetry in the loading due to positioning of the feed in the bin and/or variation in the physical properties of the feed bin itself, and (2) variation in loading due to dynamic factors such as wind. Note again the load cell signal curves in the top graph of Fig. 6. While they all exhibit the same patterns described above, they do not give identical values. There is clearly variation between load cells.

Given the different responses of the load cells on each support of a feed bin, each individual load cell does provide additional information not fully predictable by the other load cell readings. This is why each support is individually instrumented. However, in the case of a failure of a load cell, using the remaining functional load cells to approximate the weight gives a reasonable estimate. The knowledge of the grain inventory stored in the feed bin is not as precise as it would have been if all the load cells were operational, but the most important information (e.g., when will the bin be empty) is still available to the farm operators.

VI. CONCLUSIONS AND FUTURE WORK

We have presented an approach to instrument feed bins that is substantially more cost efficient than previous options, taking advantage of the lower manufacturing costs of uncalibrated load cells and enabling them to be calibrated post-manufacture. The calibration supports the linearization of a nonlinear strain gauge response and is accomplished through bidirectional communication with a test/calibration fixture utilizing the existing 4-20 mA current signal wire.

The result is that farmers can be well informed of the inventory of grain in their feed bins, including in the presence of equipment failure, enabling more timely deliveries of grain to the farm.

Beyond simple inventory control, real-time recording of feed usage can also be used for a number of additional purposes, including monitoring the operation of automated feeders and keeping track of the health of the livestock.

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