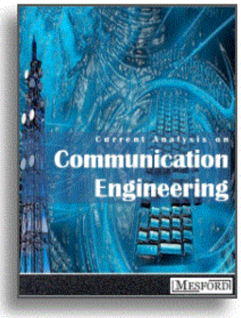

Knowledge Discovery in Agriculture: An IoT Network of Cattle Monitoring Devices

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Background

As newer technologies come along, greater opportunities for in-depth knowledge present themselves to the modern farmer. In agriculture and agricultural research, the use of sophisticated technology to help improve crop and animal production is growing rapidly. This paper investigates one such application in which beef cattle are monitored for feed efficiency using a network of Radio Frequency Identification (RFID) detectors, feed and animal scales, and other programmed equipment.

Objective

The system discussed in this study is intended to assist in the discovery of new knowledge that can be used to improve efficiency in the food supply chain. We discuss how the collection, processing and analysis of the data obtained through an Internet of Things (IoT) network is able to monitor cattle, determine feed efficiency, control the equipment used, how the network and its operation will help to improve beef production while maintaining good animal health, and how this is leading to discoveries in what can be considered an autocatalytic process.

Method

We created a prototype system consisting of a set of smart devices arranged as an Internet of things that was designed to fully automate the feeding process of beef cattle and collect and analyze feed consumption data on a per animal basis. Combined with periodic growth measurements, these data are used to calculate feed efficiency in order to assist in making better decisions of animal husbandry.

Results

The process of building and analyzing data from the prototypical system has highlighted problems encountered and offered solutions to provide a much more efficient monitoring system that can lower the costs of raising production animals.

Conclusion

This study helps to point the way towards improved animal health and improved efficiency in farming operations, which can lead to greater production levels. As food stocks decline or remain steady, more efficient operations such as this may help feed a world whose human population continues to grow.

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1. INTRODUCTION

The current state of animal husbandry is being increasingly enhanced by information technology (IT) in the areas of production management, animal health surveillance and welfare, sustainability and environmental effects [1]. Some examples of newer techniques include genomic-enabled prediction of phenotypes, mastitis prediction (a significant disease among dairy cattle), investigating complex traits in animals known as microbiome and image analysis [1]. Image analysis is used to calculate and track animal body weight [1] and in the identification of specific animals [2], an important consideration in epidemiology. The Internet of Things (IoT) paradigm has added additional enhancements, such as health monitoring and diagnosis [3], understanding cattle behavior,

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prevention of cattle rustling [4] and, as will be discussed here, monitoring feed consumption to calculate feed efficiency.

In the United States alone, the beef cattle industry generates $78.2 billion in revenue from nearly 100 million head each year [5]. Cattle feed efficiency is described as units of feed/forage consumed divided by the units of animal weight gain over a specific time period [6]. Animals with better efficiency may grow at the same rate as animals with lower efficiency but will use less energy in feed to do so [7]. More efficient production livestock incur lower costs and are generally more profitable in an inelastic commodities market [8]. More efficient seedstock pass on their efficiency to future generations and are therefore more valuable at auction. This economic leverage makes it imperative that cattle producers know the efficiency of each animal in their herds. This paper introduces a network of smart sensors and programmed equipment used in a beef cattle production operation that is designed to measure and report feed efficiency to the farmer. The sensors provide data that is used to monitor and control feed rations to the animals and help the farmer make informed decisions regarding animal grouping, control and genetic selection to help improve beef stock quality over time. Programmed equipment is used to stock and deliver feed to the animals according to a predetermined schedule, and if necessary, upon remote command. While cattle feed control and monitoring are not new concepts, the system described here improves and enhances the data collection and analysis processes, and it adds automated components that can monitor and control existing operations and have not yet been done. Such data analysis leads to more knowledge regarding animal husbandry, which in turn results in new theories and techniques. As new discoveries are implemented, this leads to more opportunities in research. This process will also lead to new applications and improved technology in a process that can be described as autocatalytic—that is, each new discovery can lead to new technology, which can help us solve even bigger problems.

The Internet of Things (IoT) is considered to be sets of intelligent devices that are able to collect data and communicate with one another. While connecting devices to share data is not new, its impact has recently grown to such proportions that businesses are now able to gain insight that was previously unattainable [9]. It seems that we are empowering computers to collect data on their own, "…so they can see, hear and smell the world for themselves, in all its random glory" [10, p. 1]. This paradigm is expected to bring "massive gains in efficiency, business growth, and quality of life" [11, p.3].

Location sensors used in a dense environment are one application of IoT and have been used in such areas as environmental and ecosystems science [cf., e.g., 12], in chemical and biological defense [13], in manufacturing to monitor equipment status and energy consumption [14], in supply chain and distribution systems [15] and a host of others. There appears to be no end to new uses and applications on the horizon. Placing location and motion detection sensors and receivers in a dense environment allows us to better see and interpret what has happened and use that interpretation to predict what might happen. As an example, location sensors are now being employed in the National Football League (NFL) to track players as they run down the field. This technology will improve instant replay graphics and may even be used in training regimens, strategy and injury analysis in the future [16].

Animals can be monitored using these same devices as they wander around, and since they can't tell us how they are feeling, we may be able to infer things about their health if we are given enough data. Wireless sensors on animals have been studied for pastoral tracking and control applications of domestic animals [17], monitoring of wildlife [18, 19], very large-scale cattle monitoring [20] and for health monitoring [21]. Most sensors currently used on animals are unable to report health status, either from a direct reading or by interpretation of the data. It is possible however, to infer health and feed efficiency of an animal by observing its behavior and monitoring its feed intake. For cattle, there are several methods that can be used to do so [22]. These methods can be manually employed through direct observation by trained personnel or automated using various electronic devices attached to or worn by each animal. Electronic surveillance techniques include accelerometers, pedometers, active ear tags, Global Positioning Systems (GPS), and temperature sensors [22]. Data collected using electronic devices is transferred to an electronic file system where it is analyzed. In some cases, the devices are recovered from the animal and manually uploaded, but in others, the data is transmitted to receivers and processed as it is received. These records essentially hold animal movement and behavior in digital format. By capturing and creating historical data from healthy animals, algorithms can be used to compare real-time data streams with the historical data and assess the health status of each animal with remarkable accuracy and speed [3, 23].

The net result of this flood of data is a wealth of information that can be used to make decisions that could directly impact animal health and improve the efficiency of production. In the beef cattle industry these decisions affect the cost of production and the quality of meat to the consumer.

2. BACKGROUND

The profitability of livestock production is affected by the cost of feed and the feed efficiency of the animals, especially in an inelastic commodities market, where individual farmers have almost no control over market prices [24]. The cost of feed for the typical beef producer represents 55 to 75% of the total costs [25] and as the price of corn and other grains fluctuate in the market, these costs can reach as high as 80% [6]. Weaber [26] estimated that a 10% reduction in feed will save farmers approximately $1.19 billion each year. Lamb and Maddock [25] estimate that a 5% change in feed efficiency would have an impact four times that of a 5% improvement in daily weight gain. While these estimates represent a sizeable savings, the question is whether or not reducing the feed intake to an animal is possible without adversely affecting its health. The answer to this question is contained in an animal trait known in animal science as feed efficiency. Feed efficiency is a measure describing the number of units of feed consumed by an animal compared to the animal's weight gain over a specified period [25]. Economically, it represents the amount of commercially valuable product produced for each unit of input (measured as feed consumed) [25]. Two animals may have the same weight gain over a period of time, but the one with the better efficiency will have eaten less during the period. The trait is moderately heritable [8] with a significant amount of genetic variance in beef cattle [27]. This means that we can selectively breed animals to improve the efficiency of future generations. There are several metrics for feed efficiency, including animal gross feed efficiency, which is defined as the ratio of live weight gain to dry matter intake (DMI); residual average daily gain (RADG), which is the difference between actual weight gain and a predicted value based on DMI, body weight maintenance and fat cover; or residual feed intake (RFI), which is the difference between actual and predicted weight gain based on body weight maintenance [28]. Because efficiency is an individual animal parameter, calculation of these metrics requires that we determine the daily feed consumption of each animal and that we record periodic measurements of the animal's weight.

In this paper, we present an animal feed system that utilizes an intelligent network of collaborating devices that can be used to monitor and improve animal health and thereby achieve the business goals of the cattle industry—to reduce the costs of production and improve the quality of beef products. While we focus on the cattle industry here, similar networks could be developed for other types of animals in the human food chain, such as porcine, ovine, caprine and poultry; however, of these groups of animals, the bovine is the least efficient and the largest consumer of feed [6].

Our discussion proceeds as follows. First, we describe the components of the system and its architecture. Next, we discuss normal system operation and how the data is collected, analyzed, and presented to the users. We also present some of the effects that this information can have on animal husbandry decisions. We conclude with some suggestions for future research.

3. SYSTEM COMPONENTS & ARCHITECTURE

On a small ranch or in a feed lot, where animals are confined and unable to graze on naturally growing plants, animals are fed using a feed bunk system. This is generally a metal or concrete trough that lays on the ground just outside the cattle pen. The cattle line up next to each other, stick their heads through the fence to access the feed laying in the trough. To fill the trough, the rancher can place the feed in a specialized trailer attached to a tractor. The trailer has a spout to allow the feed to be deposited evenly in the feed bunk as he drives past. It also has a scale so that he can tell how much feed is dispensed. The rancher then knows the daily amount of feed he provides to all animals and can therefore determine the average amount consumed by each animal; however, he does not know the amount that each animal consumes. Lacking this data, he is unable to determine individual feed efficiency.

In order to accurately measure individual feed consumption, feed troughs need to be outfitted with load cells and they need to be separated to permit access by only one animal at a time. The load cells need to report continuously so that the weight of feed consumed can be calculated from the difference in weights of the feed bin when an animal starts eating and when it stops. To meet these restrictions the farmer can install one or more feed bins outfitted with both load cells and an RFID antenna. This antenna will detect reflections from a passive ear tag worn by each animal for positive identification. The RFID components identify the animal at the feed bin for as long as it remains at the bin, because the RFID antenna is transmitting continuously. The signals from the scale and from the RFID antenna are received by a set of signal conditioners and can be forwarded in one of a number of different protocols, such as RS-232 or RS-485 serial data streams and can be wrapped in Ethernet packets. Because a feed bunk may be located out in the middle of a pasture at some distance from an office that would have devices capable of processing the data, the signals can be transmitted by radio to a receiving station, which may be located up to three or more miles from the animal herd. Using Ethernet, each measurement device (scale and location detection antenna) is assigned a distinct IP address so that signals at the receiving station can be distinguished. All data are logged into electronic files at the receiving station, which may be the farmer's office, and later forwarded to servers programmed to store and analyze the received data. These servers are placed in a separate location and they receive and process data from multiple groups of cattle on separate farms and provide the results of the analysis to the ranchers on a near real-time basis, who can then make informed decisions regarding their livestock, including amounts and content of feed, selective breeding, day-to-day care and animal groupings.

Two optional components can also be included in the system. The first is a video camera, which can be located at the feed bins to validate the data streams provided by the animal location sensors and to provide a visual indication of animal health. The second is an automated feed loader. Ranchers usually use a manual feed loader to supply feed to each bin, but in this system, the feed loader is automated so that the amount of feed it places in each bin (and when it does so) is determined by the data analysis.

System architecture can be classified using three categories: the degree of automation, the extent of animal location information, and the required response time of data analysis. We now discuss these categories and provide a description of each. We also include a visual representation of the architecture, which shows how they are related in fig. (**1**).

3.1. Degree of Automation

The extent to which this system is automated can vary. The relationship between the degree of automation and the amount of labor needed to tend to animals is inverse, such that as automation increases, the amount of manual labor required to feed animals decreases. This is shown in the top part of fig. (**1**). In a minimal configuration, only data collection is automated, and the farmer continues to manually feed the animals. Feeding includes maintaining an adequate stock of feed and dispensing it to each bin as the bins are emptied. Usually feed bins need to be refilled twice a day. Thus, a system that could automate this process would relieve the farmer of a considerable workload. Such automation can be achieved in a number of ways, including using conveyor systems or a remotely controlled robotic tractor/trailer combination. Because storage silos are generally at a large distance from the feed bins and because there may be several non-collocated sets of bins, conveyors are not usually economically feasible. On the other hand, a programmable tractor/trailer combination can economically service several sets of feed bins that are geographically dispersed. In this scenario the feed loader navigates back and forth between the feed silo, where it receives feed, and the feed bins, where it dispenses the feed for the animals. The vehicle is sent navigation commands to move it from the silo to the bins and back again, and commands that regulate the amount of feed received from the silo and dispensed to each feed bin. This operation requires that the silo never run empty; however, if it does, the vehicle can sense this since it has a built-in scale, which can trigger an alert to the farmer.

3.2. Extent of Location Information

Animal location information can be obtained continuously as the animals wander around in the pasture or pen using active ear tags that transmit to receiving antennas located on the periphery of the enclosure. These data are useful for pasture raised animals as well as those enclosed in pens. For animals free to graze in large pastures, the farmer is more interested in precise location, while for animals enclosed in pens, location data can be combined with behavioral data that can be used to help determine animal health [cf. e.g., 3]. In the middle portion of fig. (**1**), the location dispersion is shown and its effect on transmission range. Transmission distance is considerably shorter for penned animals than those allowed to graze in a pasture. Active RFID devices are used when the range is large and/or when the primary purpose of collecting location data is to infer animal health. Passive RFID devices are used when the primary purpose of the location data is to determine feed consumption.

3.3. Required Response Time

Required response time is determined by the purpose for the data. Faster response is needed for location information than for assessing an animal's health or for determining feed efficiency based on consumption. This is shown in the bottom portion of fig. (**1**). When animal location is tracked in a large pasture, a faster response time is needed to prevent the farmer from having to manually search for all animals in the herd. Health assessments usually require a minimum observation period of 3 days in order to collect enough data before a diagnosis can be made [23], and feed consumption can only be computed once the animals have been weighed. Animal weight data is obtained once every two weeks.

While the required response time is shorter for location information than it is for health assessment or feed consumption analysis, processing location and health assessment data is more difficult because errors can be induced from three naturally occurring factors. First, the transmission distance is much larger for pastured animals, which may result in losing some signals due to attenuation. Secondly, active transmitters, which are usually attached to the animal's ear, can be blocked by other animals, obstructions in the pasture or by the animal itself who may lay down and block the signal with its head. A third reason that this occurs is due to the interference of signals at the receiving antenna. This is thought to be caused by the superposition and elastic recoil of the transmitted waves, which can create both constructive and destructive interference [29].

Fig. (**1**) depicts the choices to be made in planning the system architecture and their dependencies. Starting in the middle of the diagram, we locate the type of environment that we are working with. There are three choices for location dispersion: pasture raised animals, which are free to roam over a large area, feed lots where thousands of animals in the finishing stage just prior to harvest are confined in pens and unable to roam far, and small ranches where animals are also confined in pens but are in a growth stage during which feed consumption is the more important parameter to the farmer.

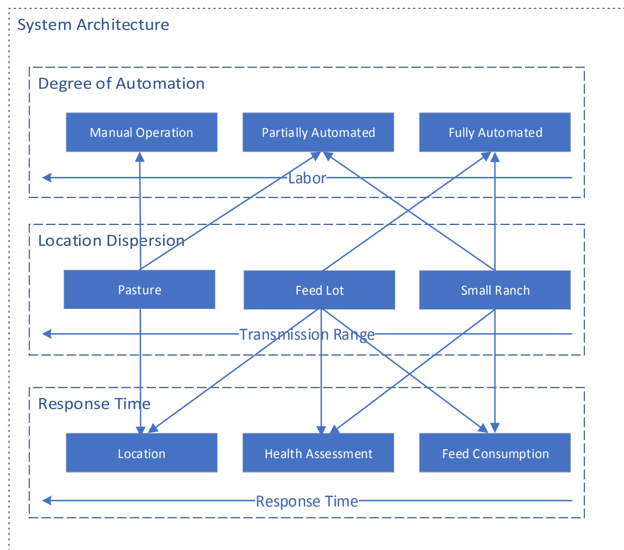

Fig. (1). System Architecture Dependencies.

Having determined the environment, fig. (**1**) displays the choices in degree of automation and required response time for each environment that would provide the most benefit. Pastural animals would be assessed solely for location, which can be determined either manually or by using active transmitting systems of some sort (partial automation). Fully automated health assessment of pastural animals is not fully developed and feed consumption is not applicable since animals can graze on naturally occurring plants. Conversely, feed lots, which may have thousands of animals in pens, can benefit greatly from a fully automated system, because this will reduce the amount of labor required to manage the animals. They would use this data to provide location information, health assessments, and feed consumption. Small ranches can also benefit from a fully automated system, but due to the investment, may need to start in a partially automated mode. In this application farmers would use the data primarily for determination of feed consumption and feed efficiency.

For the current study, we focus on feed consumption and efficiency determination and limit the discussion to a fully automated system in which the feed is dispensed using robotic tractors and trailers, animal location data is limited to feed bin appearance captured by a single RFID antenna and a passive ear tag, and data is immediately forwarded to a remotely located system for analysis. Processed data is then sent back to the individual farms for immediate viewing as a set of selectable dashboards.

4. FULLY AUTOMATED SYSTEM OPERATION

Feed bunks are generally refilled twice a day—once in the morning at daylight and once again in late afternoon; however, animals eat *ad libitum*, and this may require additional replenishment. Refilling the feed bunks proceeds either at a time prescribed by the rancher or on demand from the system if the feed bunks are low. The process is described below and is depicted as a process diagram in fig. (**2**).

1) The approaching tractor signals the access window for the first bin to close, thus preventing animals from feeding during the refilling operation.
2) The tractor positions the trailer next to the bin, and the trailer begins to refill the bin. Refilling is stopped when the scale in the trailer reaches a predetermined value.
3) The scale for the bin will also sense when it has received enough feed and signals the window barriers to be removed so that the animals can begin to feed.
4) The tractor positions the trailer next to the next bin and the process is repeated.
5) When all bins have been filled, the tractor either:
    a. Proceeds to another set of bins and repeats steps 1 through 4 or
    b. Returns to the silo and continues with step 6.
6) When the tractor returns to the silo, it positions the trailer below the silo to take on additional feed for the next bin filling operation.
7) The tractor signals the silo that the trailer is present, and the silo refills the trailer. Refilling stops at a predetermined weight.
8) The tractor and trailer will then remain idle until it is time to begin the next refilling operation, or a shutdown signal is received.

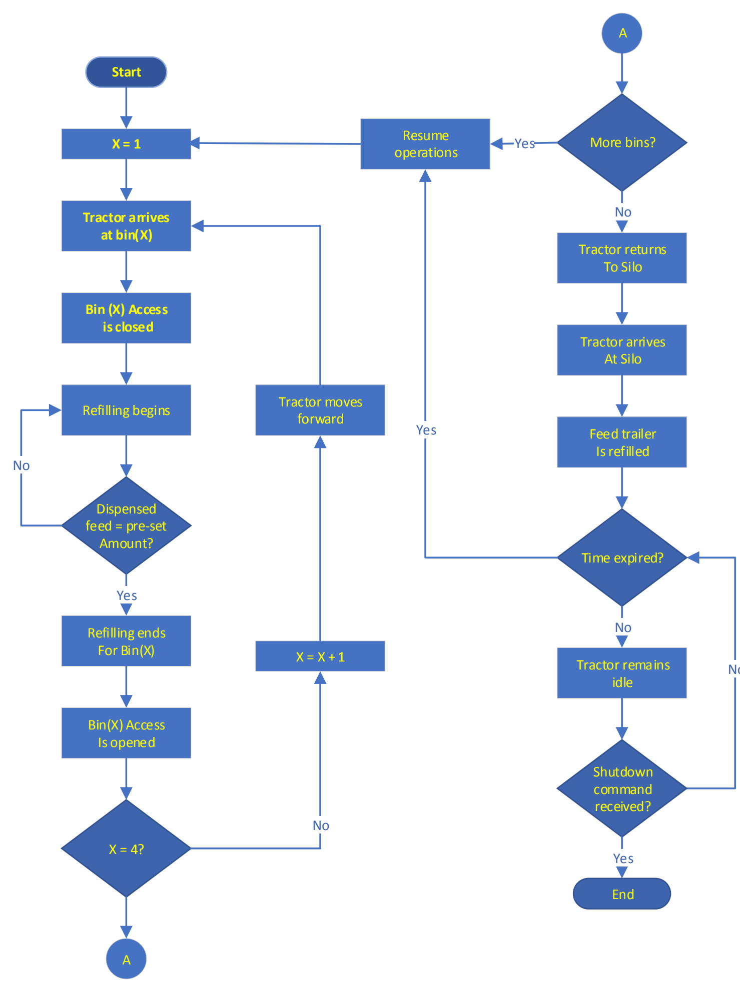

Fig. (2). Refilling Operation.

The refill operation takes about 5 to 10 minutes per bin once the feed loader has arrived at the bin. It is necessary to prevent the animals from feeding during the refill operation[1], because feed consumed during this transition is difficult to calculate. The feed loader is outfitted with a scale of its own to ensure that the correct amount is dispensed. Because the bins are sitting on load cells, the weight of the feed added can be determined and compared to the amount dispensed by the feed loader. This can provide only a rough check of accuracy because the precision of feed loader scales is usually to the nearest pound, while the bin scales are precise to the nearest 0.02 pounds.

Although animals can and do feed continuously throughout the day and night, they most often feed immediately following feed bunk refilling operations. Placing lights near the feed bunks encourages cattle to feed at night and the data show that although some do feed at "off-peak" hours, most follow the same daily routine of feeding for 2 to 4 hours after the bins are refilled. Each bin is constructed to allow only one animal at a time; however, each animal feeds for about 15 to 25 minutes. A single bin will therefore support about 6 to 8 animals over the course of a day. The animals seem to establish a hierarchy among themselves such that the animals at the top of the hierarchy feed first. Because there are fewer feed bins than animals, the animals may contend for a window by nudging each other. Moving from one bin to the next because of the nudging is a common occurrence. The animal hierarchy results from differing temperaments, is readily evident in the data and is another important metric in grading the quality of meat [30].

5. DATA COLLECTION

Cattle feeding is recorded using animal identification data obtained from passive RFID ear tags and weight data from each bin. These data are obtained using multiple instances of a terminal emulator (e.g., PuTTY) running on a single machine. Output from the emulators are written into separate log files locally but are later uploaded to servers that provide centralized processing. The terminal emulator provides a timestamp for each data point, which is obtained from the local computer thus ensuring that recorded timestamps reference the same clock. The log files are currently transmitted to the servers on a predetermined schedule, but could be transmitted as they are collected, in real time. Two log files are recorded for each feed bin for each 24-hour period. One file consists solely of weight data captured from the load cells on the feed bin. The other log file consists of RFID data obtained from the RFID antenna mounted at the feed bin.

Because scale and animal location data are transmitted continuously, the number of data points grows rapidly, but linearly. The total number of data points, which represent the net weight of each bin at a specific time can vary depending upon the frequency of transmission, but a typical day will generate nearly a million independent observations for each feed bin. The total number of data points representing animal presence can also vary, but usually totals 3 to 5 hundred thousand per receiving antenna per day. The actual number is highly dependent upon several factors, such as antenna transmission frequency, and antenna and ear tag placement [31]. A timestamp is recorded for each observation (both animal location and bin weight), and the system matches these time stamps[2] on a per animal basis. The steps in the algorithm are described below and are also shown in fig. (**3**) in algorithmic format for a single bin. The output of this process is written to a file in which each record contains the data shown in table **1**.

1) The RFID log of the first feed bin is read into memory.
2) The ID of the animal in the first record and its timestamp are each placed into variables.
3) Subsequent records in the RFID log are searched sequentially. As the animal continues to feed, the ID will be the same and these records are skipped until another animal is found at the bin. The timestamp for the last appearance of the first animal is placed into a third variable.
4) The scale log for this same bin is read into memory and searched for the two timestamps stored in variables. Weights recorded at these two times are added to two additional variables in memory.
5) The system calculates the time difference and the weight difference and places these values into additional variables.
6) These data points are then recorded as a single entry in a file. The recorded data will have eight components and a sample entry would include the data shown in Table **1** below.

Table 1. Extracted Feed Consumption Data.

Field	Value
Animal ID	3000E2008325251801620120F77E
Bin number	1
Time start feeding	21/10/17 07:23:47.705
Time stop feeding	21/10/17 07:26:38.045
Duration	00:02:50.340
Start bin weight	255.33
Stop bin weight	252.38
Feed consumed	2.95

Note: Weights are measured in pounds, duration is hours: minutes: seconds. milliseconds; Here the data indicate that this animal consumed nearly 3 lbs. in 2 mins. 50 secs.

7) The variables in the RFID log are replaced with the next animal's ID and its timestamp and the process is repeated until all entries in the RFID log have been processed.

1 Animals are naturally attracted to the bins (by sight and by smell) when they are being refilled.

2 Timestamps are matched to the nearest 100 msec.

8) Data on the next feed bin is retrieved and the process repeats until data from all bins have been retrieved, processed and stored.

Algorithm 1: Data Collection

```
Input:    RFID log, Scale log
Output:   Output file (Duration/Consumption)
Initialize variables: animalID1, animalID2,
          timestamp1, timestamp2, timestamp3
          binWeight1, binWeight2,
          duration, weight;
readRFIDRecord
while (RFID log ≠ null) do
    animalID1 ← RFIDrecord.getID
    animalID2 = animalID1
    timestamp1 ← RFIDRecord.getTimestamp
    timestamp2 ← readScaleRecord
    while (timestamp2 ≠ timestamp1) do
        timestamp2 ← readScaleRecord
    end while
    binWeight1 ← ScaleRecord.getBinWeight
    while (animalID2 = animalID1) do
        readRFIDRecord
        animalID2 ← RFIDrecord.getID
    end while
    binWeight2 ← ScaleRecord.getBinWeight
    weight ← binWeight1 – binWeight2
    duration ← timestamp2 – timestamp1
    outputFile.writeRecord(animalID1, duration, weight)
    readRFIDRecord
end while;
```

Fig. (3). Data Collection Algorithm.

Each animal will have a series of non-contiguous entries each day from one or more feed bins that are obtained using the preceding method, and so the application must aggregate them to indicate the total amount consumed by each animal. It must also aggregate the results from all bins because animals may eat from any of them. Doing so yields the daily weight of feed consumed by each animal. These data are stored for additional processing (calculation of feed efficiency) and are then transmitted back to the farmer for viewing.

Another part of the feed efficiency calculation is the animals' weight. Animals should be weighed no more often than once every two weeks, because it is a stressful process that induces weight loss, referred to as shrink [32]. Stress in beef cattle has been well researched [cf. e.g., 33, 34] and in addition to inducing weight loss, is known to adversely affect carcass performance and feed efficiency [34], so there is a tradeoff between obtaining more precise calculations and suffering the ill effects of a more aggressive weighing schedule.

The weight of each animal is then used to calculate its average daily weight gain (ADG) and the metabolic mid-weight gain (MMWT), which is the animal's weight midway through the cycle raised to the 0.75 power. Both ADG and MMWT are generally used in the calculations of residual feed intake, because it is independent of these production traits [35, 36]. Collecting additional animal weight data points in the feeding cycle helps to improve the accuracy of this figure and can also be used to show trends and to spot potential health problems. The feeding cycle is expected to be for a minimum of 70 days [37], which would allow for at least 5 weight measurements in the cycle.

Animal weights and feed consumption are used to determine feed efficiency. The prototype system currently uses RFI as its computed metric but could easily be programmed to use other metrics as well. RFI is defined as the difference in actual feed consumption with expected feed consumption, that is, the residuals computed from the regression of feed consumed on weight gain (ADG and MMWT) [38, 39]. The farmer can use the feed efficiency calculation for genetic selection in the hopes that future generations will inherit the trait and thereby reduce the amount of feed needed for production and maintenance [8, 38].

The condition of each animal and its feed efficiency are sent to the farmer for display on software generated dashboards. Selectable dashboards are capable of displaying individual animal statistics and/or aggregate statistics for the entire herd. Details included in the display for individual animals are current weight, average daily gain, feed efficiency, and times and amounts related to feed intake. Diurnal rhythms are monitored and displayed so that the farmer will know if one or more animals is not eating to allow for intervention as necessary. Eating order can also be displayed so that the farmer can discern animal hierarchy. As mentioned previously, established hierarchies can assist in grading animals [30].

Additional data is collected from the feed silo and the feed replenishment trailer. The weight of feed remaining in the silo indicates the inventory of feed immediately available. When this weight reaches a predetermined amount, it must be replenished. The predetermined amount is dependent on a number of factors:

1) The time delay involved in replenishing the feed, which includes order processing and delivery time,

2) The aggregate daily consumption rate, which increases as animals grow, and

3) The quantity ordered.

These factors affect both farmers that order feed from a supplier and those that grow their own feed. The only difference between them is the way costs are calculated and paid. The system can generate orders automatically based on the silo weight data and notify either the supplier or the farmer. In a horizontal market, invoices and payments can be automated as well. In a vertical market, the cost calculations can be made and used later by the farmer to determine total costs of production.

In a fully automated cattle operation, silo and replenishment trailer weights are used to dispense and deliver the correct amount of feed to each bin. As the trailer receives feed from the silo, these weights are used to stop the flow of feed once it has reached the predetermined amount needed to fill all of the feed bins. Next, as the trailer moves past each bin, its weight is used to fill the bin to the correct amount.

Each farming operation can incorporate its own IoT system and collect and analyze data autonomously; however, a more economical solution is to centralize the system so that a number of farms can be serviced at once. All data can be uploaded to the system and analyzed in different ways. The data for each farm can be provided back to the farmer through user interfaces and dashboards that allow the farmer to view either his overall operation or the information on each animal or groups of animals. Aggregate data can be further analyzed by animal scientists and veterinarians for behavioral and health assessment research. One such research effort concerns determining the best metric for feed efficiency, as the inputs from both phenotypic and genetic factors must be accounted for, and some metrics, such as RFI, are independent of phenotypic regressors in the model but are not independent of the genetic factors [40]. Research to best determine how genetic selection for feed efficiency will avoid adverse effects to animals [38] is ongoing and requires the precise measurement of feed intake and weight gain [8] that this system can provide.

6. DATA ANALYSIS

There are two separate but interdependent areas of interest to the farmer that are exposed by the data collected in this system. The first area allows the farmer to make more informed animal husbandry decisions, because it provides a measure of the feed efficiency in each animal. Animal feed efficiency affects the cost of production and more efficient animals can improve profitability. The farmer with knowledge of individual animal efficiency can compete in a tight market more effectively. The second area allows the farmer to better manage feed inventory. Animal feed is organic with a limited life, and so proper storage conditions (especially water content and temperature) are critical to prevent spoilage from molds and mycotoxins [41, 42]. The farmer with knowledge of the amount consumed by his herd is in a better position to provide the feed, unspoiled and as needed to his animals. This is true whether he grows the feed himself or purchases it from a supplier.

Animal feed efficiency is a measure of the biological process of energy conversion into growth, metabolism, body heat regulation and physical activity [43]. Many different measures designed to relate feed intake to efficiency have been developed, such as feed conversion ratio (FCR), residual feed intake (RFI), partial efficiency of growth [44] and residual gain [6]. In fact, the relevant literature has studied and discussed over 2 dozen measures of feed efficiency [40]. Any of these measures can be calculated from the data provided by the sensors in this IoT system simply by adding or modifying some program code. The system currently is programmed to compute RFI. This metric represents the difference between an animal's actual feed intake and its expected feed intake based on its size and growth [45]. As such, it is independent of phenotypic traits and therefore allows the comparison of animals in different stages of production [45]. Animal actual feed intake is computed using the data and methods previously discussed. Animal estimated feed intake is computed by regressing actual feed intake on measures of weight and weight gain. Here we use the Average Daily Gain (ADG) and metabolic mid-weight (MMWT). RFI is the difference between the actual intake and the predicted feed requirements for maintenance and growth. It can be estimated as the residuals of the regression of feed intake on ADG and MMWT [46, 47]. It can also be estimated by computing a standardized daily feed intake and subtracting the expected daily feed intake [39]. Standardized daily intake is computed by taking the total intake of an animal over a period of time, converting this to Dry Matter Intake (DMI) by accounting for water content, converting the result to total energy intake based upon the energy content of the feed consumed and converting back to total standardized feed intake (SFI). Dividing this result by the number of days on feed yields a standardized daily intake. The expected feed intake can be calculated by using ADG and MMWT to model the standardized daily feed intake. The overall form of each regression (standardized and expected feed intake) is expressed in equation (1).

$$Y_i = \beta_0 + \beta_1 ADG_i + \beta_2 (MMWT_i)^{.75} + RFI_i \qquad (1)$$

Yi is the daily SFI for animal i, β0 is the regression intercept, β1 and β2 are regression coefficients for ADG and MMWT for animal i, and RFIi is the error term that accounts for the residual feed intake for animal i. Animals with negative RFI values are more efficient than those with positive values, because a negative value indicates that the animal ate less than was expected. Results for two animals considered representative of the 67 animals that were in the prototype test groups are shown in tables **2** and **3**.

Table 2. Results for Two Representative Animals.

Weight			Days on			
Begin	End	Total Gain	Feed	ADG	$(MMWT)^{.75}$	RFI
481.8	1158.3	676.5	182	3.7	153.24	1.89
426.8	1149.6	722.8	182	3.8	148.76	-2.15

Note: Weights are measured in pounds, RFI in pounds/day.

Table 3. Single Day Feed Consumption for Two Representative Animals.

Animal	Feed Consumed (lbs)
1	12.53
2	8.49

Table **2** indicates that although animal 2 was slightly smaller than animal 1, it gained about 7% more than did animal 1. Table **3** indicates that in a single day, animal 1 consumed 4.04 pounds more feed than did animal 2. These results provide support for the underlying theory of feed efficiency: more efficient animals will consume less in feed to achieve growth similar to less efficient ones [48]. Finishing weight on each animal is close to 1,150 pounds, yet animal 2 consumed an average of 4 pounds less per day.

Feed inventory and consumption rates are also computed from scale data. Total consumption by the herd is taken from the feed bin scale readings that are a part of the normal data stream. Additional inputs for this are the weight of feed delivered to each bin by the feed loader and received from the silo. The silo scale is also used as a check on the other measurements and as an indicator of available feed level. Feed

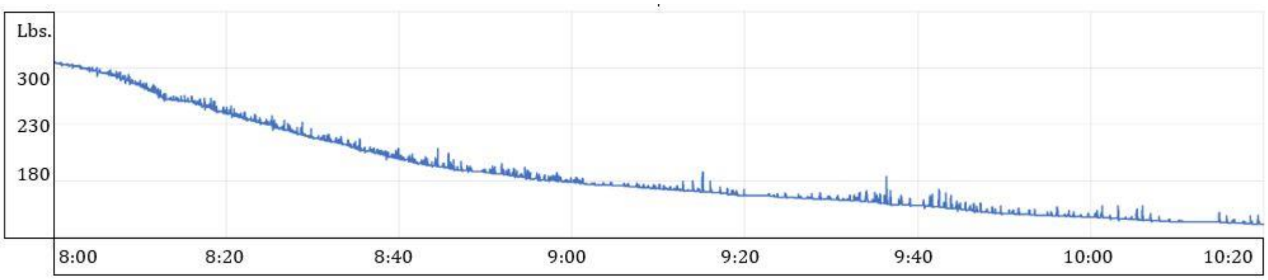

Fig. (4). Two Hour Feed Consumption for a Single Feed Bin.

Table 4. Single Day Feed Consumption.

c	Bin 1	Bin 2	Bin 3	Bin 4	Total	Average	Std Dev
1	37.6	10.2	28.2	25.2	101.21	25.30	11.37
2	31.1	9.4	10.6	9.0	60.06	15.02	10.72
3	27.2	30.5	14.5	19.0	91.10	22.77	7.36
4	30.1	15.1	15.3	5.0	65.52	16.38	10.31
5	16.4	7.8	26.1	30.7	81.05	20.26	10.21
6	7.8	11.9	29.6	35.0	84.40	21.10	13.25
7	16.5	10.9	45.6	17.6	90.46	22.62	15.58
8	14.4	15.3	22.5	26.5	78.74	19.69	5.81
9	10.6	6.7	51.2	17.7	86.20	21.55	20.30
10	6.2	8.4	53.0	25.1	92.69	23.17	21.58
11	22.4	24.9	51.4	0.5	99.18	24.79	20.85
12	9.8	8.6	34.4	24.6	77.37	19.34	12.42
13	23.9	17.4	52.8	16.5	110.52	27.63	17.07
14	25.3	19.6	52.9	2.2	99.93	24.98	21.01
15	19.8	16.8	27.1	4.3	68.11	17.03	9.52
16	2.9	7.7	39.0	16.7	66.36	16.59	15.99
17	6.8	11.4	20.7	24.8	63.78	15.95	8.26
Totals	308.72	232.73	574.77	300.46	1,416.68	354.17	150.96
Average	18.16	13.69	33.81	17.67	83.33	20.83	
Std Dev	10.09	6.57	14.95	10.35	15.03	3.76	

inventory is monitored continuously, and orders can be triggered at pre-determined levels, usually the economic order quantity (EOQ) for a particular farm.

Once computed, both individual animal and summary information can be presented to the rancher. Presentations can take on various forms, from spreadsheets that display tabular data to a more sophisticated output report capable of providing grouped data. Information can also be presented in a more graphical way that can substitute computer generated icons for actual animals who are then shown to visit the feed bin along with the amount consumed at each visit in an animated way. Feed efficiency can directly affect revenues [45], and so a simple scatter plot of the average daily weight gain of animals against feed efficiency can assist the producer in making business decisions.

Information such as this, supplied to the rancher/owner improves the bases for making decisions and results in more efficient cattle production. Feed efficiency, measured with residual feed intake (RFI), is moderately heritable ($.24 \leq h2 \leq .58$)3. Knowledge of individual animal RFI would allow the farmer to segregate animals and help to produce lines of more efficient cattle. Arthur and colleagues [49] demonstrated an 11% reduction in feed consumed over 2 generations of cattle selected for low RFI.

7. SAMPLE DATA

Although the user interface is still under design, we present some data that are indicative of the type presented to the farmer. Table **4** displays the aggregate feed consumption for a

3 The heritability parameter, h2, estimates the amount of phenotypic diversity due to genetics. It ranges from 0 (no genetic differences) to 1 (100% genetic differences).

single bin in a single day. Seventeen animals are listed along with the amount each consumed from each bin. Totals, averages and standard deviations for each animal and each bin are also included in the table.

Some things are clearly visible in this table:

1) Animals seem to have a preferred bin. Compare animal 4 with animals 16 and 17. Animal 4 seems to prefer bin1, but feeds to a lesser degree from bins 2 and 3, while animals 16 and 17 seem to prefer bins 3 and 4.

2) Animals consume between 60 and 110 pounds of feed per day. This large range is probably due to a number of factors but is clear evidence that some animals require less feed than others, i.e., are more feed efficient. This was the expected result.

3) Bin totals vary also, ranging from about 300 pounds to well over 600 pounds. The total of 1,417 lbs. is about what would be expected for a single day with one refill of the bin.

It is also informative to view consumption over time. Fig. (**4**) displays a graph that shows two hours of feed consumption data for a single bin. The horizontal axis is time and shows that the graph begins at 8:00 AM and ends around 10:20 AM, while the feed bin weight decreases from slightly over 300 pounds to less than 180 pounds. We chose this period as it is representative of continual feeding, occurred right after the bins were filled, and shows that the rate of consumption tends to slow down after about two hours.

Fig. (**4**) also shows a moderate amount of fluctuation in the data stream. These fluctuations result from the animals pushing against the bin as they feed and is not the result of noise caused by wind or other external factors. We know this because the scales tend to flatten out within a short period after the animal has completed feeding and withdraws from the bin. As we discuss in the next section, each animal creates a unique pattern manifested in this fluctuation so that, given a pattern matching technique, each animal could be identified based solely on this fluctuation.

8. CONCLUSION

This paper set out to provide details on a cattle feed monitoring system that was designed with various separate components to communicate as an interconnected network in order to monitor and control feed dispensed to cattle. The system is able to use these data to calculate and display the feed efficiency of each calf in the herd. The system collects, stores, and analyzes data on a central server and this allows the monitoring of multiple herds simultaneously. The analysis is transmitted back to the farmer and includes the daily feed consumption of each animal and additional items as they become known, such as animal weight, average daily gain and metabolic mid-weight. These data points are used to calculate feed efficiency for each animal, which is also transmitted to the farmer or animal husbandman. Knowledge of feed efficiency on a per animal basis not only helps to reduce costs of production, but also provides input to animal husbandry decisions, such as genetic selection and determination of optimal harvest ages. This system can also provide needed information for researchers seeking to isolate factors of feed efficiency and health in animals.

We provided the overall architecture of such a system along with its various components and explained its normal operation and data collection and analysis tasks and techniques. We justified the system by linking the results it produces to the business of cattle production. The beef cattle industry accounted for $78.2 billion in cash receipts for the year 2015 with an inventory of 92 million head of cattle producing 41.5 billion pounds of meat [50]. In a market of this size, a small savings per animal can have a major impact on the entire market.

Research on feed efficiency is an essential element in beef cattle industry improvement. Additional sensors can be used on cattle that may yield more insight on cattle growth and meat quality. Motion sensors with accelerometers can be attached to cattle to track activity levels. Weather sensors can also be included to discover and control for these effects on cattle behavior. While the heritability of the metrics of feed efficiency, such as RFI, are closely studied, more data needs to be gathered to better predict its genetic effects and help to improve line building decisions. The goal is to improve animal health and the quality of meat to the consumer.

Digitizing animal behavior and analyzing the resulting data brings an exciting opportunity to engineers, data scientists and IT personnel. Simply attaching ear tags to an animal, reading its movement and linking behavior to feed consumption is helpful, but analyzing the data can provide a much richer experience because new discoveries can be made from these data. For example, this study is focused on individual feed consumption, which necessitates unique identification for each animal. Currently this is done with individualized RFID tags; however, this may not be necessary. Each animal behaves differently and distinctions in behavior, though subtle, can be readily discerned from a data stream of great enough length. The algorithms used herein could be modified to identify an animal based solely on its head movement at the feed bin. Head movement is detected by analyzing the fluctuations in the scale data as an animal feeds. Once thought to be noise in the data stream, these fluctuations are caused by the animal pressing and releasing his snout against the feed bin and is completely normal. After careful analysis, these fluctuations represent unique animal behavior, which is enough to distinguish one animal from another much like a fingerprint or a DNA sample. Additional research is needed to help discover the meaning and effects of nuances in animal behavior.

As the world population grows, the task of feeding people takes on an increasing amount of importance. The knowledge gained from animal behavior monitoring is a step toward ensuring that this task can be done.

ABBREVIATIONS

ADG Average Daily (weight) Gain

NFL	National Football League
DMI	Dry Matter Intake
RADG	Residual Average Daily (weight) Gain
RFI	Residual Feed Intake
GPS	Global Positioning System
IoT	Internet of Things
RFID	Radio Frequency Identification
EOQ	Economic Order Quantity

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest.

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