CUSTOM WIRELESS SENSOR FOR MONITORING GRAZING OF FREE-RANGE CATTLE

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CHAPTER I

INTRODUCTION

PROPOSING THE PRECISION RANCHING CONCEPT

Oklahoma ranked fifth in the nation for cattle inventory in 2007, totaling 4.5 million head; and has consistently been ranked in the top five states for years.[1] The state's most recent estimated cattle production value was $2.02 billion with a total value of $5.16 billion.[1] In 2007 cattle were the largest agriculture commodity in Oklahoma with a dominating 48% of the total farm income of all agriculture products.[1] Annually, there are approximately 2 million beef cows and 3 million stockers that are spread across some 33 million acres of land used for farms and ranches, which is 73% of the state's entire acreage.[1] Oklahoma's 2007 national GDP ranking was 45th, or 0.98% of the national GDP,[2] whereas Oklahoma's cattle and calves made up 5.6% of the nation's total cattle and calves gross income.[1] Texas has long been the leader of cattle production and leads the top five states with 15% of the national cattle and calves gross income.[1] In fact, the top five states (Texas, Nebraska, Kansas, Colorado, and Oklahoma) together contribute 53.4% of the nation's cattle production.[1] Clearly Oklahoma shares a major role amongst few states in national beef production as well as having significance to its own local economy.

Oklahoma's cattle industry is unarguably a considerable part of the state's economy and strongly contributes to US agriculture production. Preserving competitiveness and increasing productivity is needed to meet unavoidable changes in the industry's evolving requirements and outlook. Functions involving traceability, quality, efficiency, and production history are all on the forefront of new market concepts and demands. Other influences reside in rising oil prices (energy costs) and displacement of feed grain for fuel

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[1] Data from United States Department of Agriculture, Agriculture Statistics Services and Oklahoma Department of Agriculture.
[2] Data from United States Department of Commerce, Bureau of Economic Analysis.

production. It is trivial to comprehend the direct needs for better managed and more efficient production systems that can offset these influences.

The most prevalent economic influence on US beef production in the 21st century is believed to be the discovery of bovine spongiform encephalopathy (BSE) in December 2003. The United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS) responded to the BSE event in November 2004 with formation of a traceable animal identification system termed the National Animal Identification System (NAIS). Electronic radio frequency identification (RFID) was considered one of the primary technological vehicles to implement such a system along with a modern electronic database. To an industry of strong conventional and proven methods that are culturally established, a modernized approach such as this has proven to be challenging. Although traceability has its merits from the perspective of disease outbreaks and national security, it is also practically perceived as a non-recoverable cost to the producer not only because of newly required equipment, but also because of needed management changes. Additional value is apparently needed if a system requiring these kinds of technological tools is to be integrated. It is proposed by the author that the mindset and operational adjustment required for the NAIS easily extends to everyday production areas where firm improvements can be realized.

Systems requiring operations to incorporate items, such as traceability and enhanced quality, need assistance from newer technologies that promote rapid data collection, analysis, and transfer in a highly automated or transparent fashion. Moreover, new kinds of data never before used in conventional production methods are now poised for use. For instance, grazing information has historically been evaluated on whole pasture and herd bases. New focuses are being directed to sensing individual animal foraging in unison with site-specific forage production as well as grazing cattle waste excretion monitoring focused on surface water quality (see Chapters 4 and 6). Information based systems using algorithmic and empirically proven strategies will be an important part of augmenting decision support for multi-product and dynamic market pressures driven by both consumer demands and environmental citizenship.

Oklahoma ranchers and farmers inhabit a large range of environments spanning from highly improved pastures, large acreages of native prairies, to remote rugged terrain deep in mountainous or cross-timber country. The USDA's National Agriculture Statistics Service (NASS) most recent consensus showed that an average Oklahoma farm was 165 ha (408 ac), where woodland covered 6.7% of farmland and 72.3% of pastureland. This indicates that large amounts of agricultural land likely used for cattle production, are not amenable to technologies utilizing electronic wireless systems or site specific methods. Infrastructure limitations are mostly a product of non-developed agriculture land where rugged terrain dominates the possibilities of improvements. Efforts to handle and manage livestock in farms and ranches with fastidious equipment and facilities are increased when compared to locations that are better developed. Organizational structures formed by producers have evolved mostly as a result of the physical environments in which their livestock inhabits. Ranchers utilizing large tracts of native lands will undoubtedly have different operating procedures compared to those grazing distinct acreages of wheat pasture. Cow-calf producers must also operate differently than background[3] systems simply because of the nature in that stage of beef production. However, the opportunity for cattle production still remains in non-contemporary environments indicated by continual vast usage of these lands and inherent production style of free-grazing cows and yearling cattle. Proposing use of new technologies and methods calls for necessary research and product development addressing variables not only associated with environments but also with various production stages in the industry.

As profit margins continue to shrink and input costs rise, re-evaluation of management will become more common. Both improved productivity and additional product value will be assessed and innovative methods will be explored. Advanced technologies specifically supported by miniaturized and micro-sized electronics will be at the center of these pursuits. Rugged remote agriculture settings present significant challenges with respect to radio transmissions and electrical power supply. Fortunately technologies in a large number of applications across other industries have faced similar feats and now offer transitional knowledge for the cattle industry.

Electronic sensor and wireless communication technologies are primed for adoption in agriculture. Agriculture commodity production is ready to reap the benefits of the technology's versatile growth and cost effectiveness. The Oklahoma cattle industry is a prime candidate for such an adoption. Stocker, cow-calf, and feed yard operations all have great potential to effectively implement these available and

[3] Backgrounding is where young cattle recently weaned are subjected to grazing with the intent of both maturing and physical weight gain. This stage of production is valuable in that it utilizes forage as a cheaper food source compared to grain. Most background cattle are finished with 30-90 days of grain feed.

innovative technologies. Following is a scenario illustrating how electronic sensors and wireless communications can affect a single producer and essentially the entire industry:

> Farmer Joe was getting his morning coffee at the local coop when his cellular phone rang. He looked at the phone and noticed it was a text message. The message was sent from the base station of his wireless precision ranching system, and read "Watertower South, Out, North, ID# 52, 31, 12". He immediately knew after reading the message that three of his stocker calves had just escaped from their pasture. Specifically he knew the location (Watertower South), which border of the pasture they breeched (North), and the specific identity of each animal (52, 31, and 12). He then jumped in his truck and started the 10 mile trip to the field. While driving he entered the three ID numbers into his PDA (Personal Digital Assistant), which was mounted to the dash of his 1998 converted farm truck. Immediately a physical description of each animal (two red steers and a black motley face) was shown on the screen. As he approached the field he saw the three dots appear on the PDA's screen. The steers (dots) were directly ahead about a mile down the road. As he neared the steers' location he found them barely noticeable standing amongst tall weeds in the ditch. Fortunately they had only made it about half a mile from the field. Joe easily turned them around, heading the steers back from where they escaped. Upon reaching the field, he observed that 15 more steers were just about to walk through the break in the hotwire fence that the three fugitive steers had probably created. Thankfully, he arrived just in time before more cattle escaped.
>
> Since Joe was already at the field he decided to do a full pasture check. After a couple of taps with the PDA's stylus, an immediate head count was given. Thirty seconds later he was prompted with identification numbers and physical descriptions of animals that were possible sick cases and exactly where the sick animals were located in the field. In fact, he viewed every animal's current movements on the PDA's screen, with virtually instant updates of location and health status. With another tap of the stylus he was shown a map illustrating the last seven days worth of grazing patterns for the entire heard, and for each individual steer.

Joe then decided to evaluate his forage condition and determine if fertilizer should be applied, and if so develop an application prescription. With the aid of a proven cattle foraging and grain production algorithm a prescription fertilizer application map was created. This was generated by using various inputs such as beginning stocker weight, total days grazing, and crop measurements (i.e. NDVI). The prescription was now in a form that could be immediately downloaded into his spreader (sprayer) or be given to a commercial application service. The algorithm either optimized forage growth or grain production given Joe's objectives for that particular field.

Joe then wanted to check the field's current performance of both grain crop and stocker cattle, which the algorithm has already assessed. Tap, tap, and accounts were given for stocker growth performance and potential grain yields. This information aided in deciding how long grazing should continue and when the cattle should be sold, while maintaining maximum profit from both grain and cattle. All the mean time, information and any decisions made were stored for record keeping and final evaluation.

POTENTIAL ECONOMIC IMPACT

The Oklahoma stocker industry is comprised mainly of winter/spring and summer/fall grazing periods. Wheat and other small grains are primarily grazed in winter/spring. An estimated 1.9 million head of stockers were grazed in Oklahoma the 2004-2005 winter/spring.[4] Native grasses and other forages are primarily grazed for summer/fall. An estimated 1 million stockers were grazed in the summer/fall for 2004.[4]

Average stocker investment is comprised of labor, death, veterinary/medical, pasture/forage, and purchase price. Given the use of an advanced technology to manage stocker health and prevention, along with decreasing the need for labor and time consuming tasks, the percent cost for labor, death and veterinary/medical may be estimated for a 50% reduction. If these costs were estimated at $20/head, there is a potential savings of around $10/head.

Added growth performance and increased profits are also likely. New technologies and applications have the potential to prevent weight loss by detecting animal sickness earlier, thus providing

[4] USDA, NASS.

an earlier window for corrective action. Growth performance data such as rate of gain per animal may provide avenues for sales premiums. These dollar additives may increase profits anywhere from 1-10% ($0.80-$8.00 per head for $800 sales price).

Spatial management of dual purpose winter wheat provides better grazing performance as well as maximizing potential for grain production. This is accomplished by evaluating stocking rates and timely decisions for feed supplements and grazing rotations. There is roughly 3.2 million acres of dual purpose wheat in Oklahoma.[5] Poor management decisions potentially effects harvesting of as much as 1 million acres of wheat due to lack of information. Decisions made from incomplete or poor mid-season information effects grain losses due to grazing. An advanced technology system provides a tool to harness such information for addressing these issues.

Savings and increased returns could greatly affect the stocker industry as well as the small grain industry. For the entire Oklahoma stocker industry it is speculated that anywhere from $60-$90 million dollars ($20 - $30 dollars per head) could be saved annually and added as profit. For dual purpose wheat, if $10 per acre were returned because of better management decisions, that would translate to roughly $2 million. This only includes the stocker industry. There are also many more opportunities for savings and profit increases in cow-calf and feed yard operations with this technology.

The development of advanced precision ranching systems in Oklahoma could lead to the creation of manufacturing and service industries. Oklahoma alone could utilize up to 5 million electronic identification-management devices. Along with these devices are components for infrastructure and system interfacing. Setup, application, and training services are all viable necessities needed to support market assimilation. Consulting firms will be needed to assist farmers and ranchers with implementation. If each device averaged $20, then that equates to $100 million of sales. Out of state sales could double, triple, or even quadruple state sales as acceptance is gained through the Southwest, Midwest, and other areas. Also, an approximate life of 5 years for each device with an annual or bi-annual service would be appropriate for either obsolescence or reliability purposes. Oklahoma has both historical and regional potency to support a precision ranching industry. Manufacturing and service of precision ranching devices and systems could provide an obvious benefit to Oklahoma.

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[5] USDA, NASS.

NEW TECHNOLOGY PROSPECTIVE

Advanced technology is at the point where it is economically feasible to consider use of wireless electronic sensors and communication in a herd, confined yard, or transportation environment. Applications such as instantaneous remote animal monitoring of health, position, activity, and growth may now be accomplished. Management at the individual animal level can be deployed, improving animal performance and reducing everyday labor. Animal identification and tracking are also within realm of this technology.

Other precision farming technologies can be coupled with a precision ranching system to optimize both animal and plant crop production. Commonly a producer in Oklahoma grows grain and grazes stockers. Small grain crops have been shown manageable using remote sensing strategies for well over a decade. When forage production is also a purpose of these crops, remote sensing strategies are compromised due to unaccountability of plant biomass removal and added stress. One of the key aspects of a grazing sensor system is to now provide measurability of this removal along with indicators for forage production variability within a field. Essentially, animals' preferential grazing characteristic functions as a crop sensor for both quantity and quality. A complete system that aids in precisely managing the producer's grain crop (planting, nutrient applications, irrigation, etc.) and simultaneously manages stocker operations (health, stocking rates, foraging changes, supplemental feed, etc.) while interconnecting data of both operations for optimum benefit, would provide substantial productivity improvements.

Systems being tested for animal identification and monitoring have considerable limitations for free range and transportation uses. New technology exists that could remove these limitations with development and application. Wireless technology is common in miniaturized cost effective packages with broadcasting ranges anywhere from hundreds of feet to miles. Power conservation and reusability are also key features that are now available to support improvements and broaden applications.

CHARACTERIZING NEEDS AND IDENTIFYING PROBLEMS

Production costs and homeland security needs are greater than ever in the cattle industry. Investments for medical treatments, mortalities, labor, interest, and pasture are significantly increasing. Instantaneous animal identification and tracking, along with secure and reliable information exchange, has become essential for food and homeland security. Monitoring free range animals for either everyday management or security is difficult due to characteristically large areas over which the animals travel and spend most of their time. Interstate and intrastate transportation of cattle and other products is also difficult to effectively and accurately monitor. Farmers and ranchers need systems that consist of both hardware and timely decision making methods to reduce increasing costs and meet future security mandates. Technology is now available to meet these needs, but research and development for application and design improvements are necessary.

In some instances, researchers and scientists have been studying and developing management techniques with methods and tools that have become outdated. It has been difficult for researchers today to aid farmers and ranchers because of costs and obsolete monitoring tools. A system for enabling researchers to collect precise data on free-range beef animals has become necessary to keep up with the producer's reliance on the researcher's discoveries. Researchers, veterinarians, and producers also need to be enabled to take advantage of revolutionary advances in the medical field. A system that consists of wireless sensor and communication technologies with proven application techniques can fill a need and more importantly help build a sophisticated foundation for producers and researchers alike.

A few methods and procedures that have been considered advanced include controlled stocking rates, select supplemental feeds, forage growth selection, systematic rotational grazing, herd monitoring, individual animal health/performance monitoring, and structured data recording. Some studies have included observing animal grazing locations relative to supplemental feed placement, water, etc. Other studies have attempted to monitor feed intake while grazing on a per animal basis. Examining weight gain and growth rate relative to size, age, and transition periods has always been very important to productivity, but has always been time and labor intensive measurements. These methods have often been limited in both capacity and resolution.

Proposed Sensor System

A custom wireless sensor for monitoring free grazing cattle is proposed. This system coheres to the concepts recently presented. Determining foraging characteristics extends from evaluating food intake efficiency with respect to weight gain, to intelligent detection of morbidity cases. Other near applications includes spatial fertilizer application of improved forages and cooperative analysis for grain production in dual production systems. Animal identification and records keeping can be provided and managed by the system. System architecture can be briefly described as a combination of field hardware, management software, and a select amount of items for communication infrastructure. Still the first steps are to address the base functions of a grazing sensor, data synthesis, and data transmission.

RESEARCH OBJECTIVES

Applied research is essential to validating acceptance and performance, especially in the cattle industry. Experiments must determine the viable use of a precision ranch management system using advanced electronic equipment and methods. Design and application of new technologies is highly dependent on quality experiments with directive implications. Research is needed to define and demonstrate the benefits of using new technologies for the purpose of precision ranching. The overall objectives of this research were:

1. Identify a sensor and sensing strategy to detect foraging characteristics.
2. Implement sensor on a miniaturized electronic wireless platform that can be concealed on an animal in a non-invasive manner.
3. Investigate the general implications of using a short range radio device in an agriculture environment for the purpose of a grazing sensor.
4. Develop a manufacturable device and the associated firmware for use in grazing experiments.
5. Explore other possible applications for wireless sensing devices and cattle production systems.

CHAPTER II

Physical Aspects of Applying Wireless Sensors in Agriculture: Technical Background and Basics

Chapter Preface

The material in this chapter was written for publication in the American Society of Agricultural and Biological Engineers, *Resource* magazine. The article submitted was a condensed version of the material presented in this chapter. The intent of the article was to address agriculturalists and biosystems engineers not familiar with wireless sensors. The submission for review was made in October 2008. For inquiry of acceptance or publishing, please check with *Resource* magazine at least six months after the submission date. http://www.asabe.org/resource

Introduction

Responsiveness is an inherent and essential characteristic to agriculture production. Producers respond to plant or animal needs based on some form of information feedback. Preparedness is another key aspect producers articulate from past experiences and proven methods. Quality of preparedness and ability to respond, in most respects, determines productivity. Even though the general concepts of agriculture production do not change, needs and abilities do. Changes are undoubtedly occurring with the application of advanced electronic technologies to address challenging needs while providing innovative ability. New technology is providing the ability to respond more efficiently and accurately; and in most cases far beyond traditional human observation techniques and technologies of the recent past. This chapter intends to sort out and expose some of the common details that can determine effectiveness of applying these new technologies, especially wireless sensor devices. Important details of wireless device operations are often disregarded due to lack of time to become better educated, rapid changes in product, “black box” perspective, and the fact that most electronics can be marginally utilized.

Complex algorithmic data processing and networking schemes gathered in the digital realm of integrated circuitry often dominates the world of wireless sensors. However, no wireless device is useful unless it can establish a physical radio link amidst challenging environments found in agriculture. The part of wireless sensors often overlooked is the interface of radio waves, antennas, and carrier frequencies. Appropriate application relies on understanding operational limitations and needs relative to this interface, and not necessarily complex features (i.e. network protocols, modulation schemes) designed by electronic and telecommunication engineers. Researchers, engineers, students, and producers not familiar with fundamental radio operations, can better apply wireless sensors by understanding the following key areas.

So why are wireless sensors so great? They provide the ability to sense phenomenon in a manner never before possible. It does so by having less need for wired infrastructure and an increase in sensor population. For instance, status update and control of irrigation pivots have become available via cellular communication methods. Now, either soil or crop specific information is being wirelessly fed into irrigation controllers from field scattered sensors. Irrigation controllers use this information to automatically respond to real-time soil moisture and crop conditions. Livestock are also being equipped with wireless sensors for monitoring reproductive cycles or the occurrence of digestive problems. In some cases, free-range livestock have had GPS devices and integrated sensors attached to provide near real-time mapped foraging information (Figure 1). Whether it is grazing cattle, irrigation control, or any other agriculture production system, efficiency seems to be more important now than ever and often with heightened environmental accountability. Wireless sensor functions are an obvious fit for modern challenges.

Figure 1. Heifer fitted with instrumented test halter grazing in an open range wheat pasture. Halter style is standard nylon turn-out, and is equipped with micro-GPS and grazing activity wireless sensor (915 MHz carrier frequency).

WIRED SYSTEM

In lieu of realizing the pervasiveness of electronics today, this chapter only targets wireless devices as it is speculated they will be the most prominent advancements in the near future of agriculture. However, respect must be given to other progressions such as wired communication standards, low cost/low power electronic components, robust sensors, and task specific controllers. Agriculture equipment has distinctively been advanced via wired communication systems. ISOBUS[6] compliant equipment and the consolidation of controller interfaces into a single virtual terminal located inside tractor cabs, have made a significant mark on agriculture. Engines, implements, sensors, and controllers from different manufacturers are becoming easier to integrate as a result. Consumers are now offered more operationally transparent systems, but not without a significant need for adequate product support and specialized training. Most high level electronic agriculture equipment is not as simple as flipping a switch or pushing a button. A respectable amount of learning is required to understand operational mentality and how an automated or controlled function achieves the task at hand. Rarely is a piece of equipment purchased without a training session and an exchange of technical support's phone number and online help forum address.

The largest limitation to wired systems is the need for physical infrastructure, which is usually accommodated by the mechanical structures of equipment. Wires can be routed along steel frames and booms like most preexisting power buses, and be quickly connected between tractors and implements. ISOBUS enhances wired systems via a standardized networking approach thus resulting in less wires and the ability to integrate various controllers, actuators, and sensors on a common network control platform. However, applications where preexisting structures or power busses are not available present a completely different outlook on how electronic sensors and controls are to be employed. Battery powered electronic modules with radio communications provide the best remote solutions. Although, replacement of equipment based wired systems with wireless devices may not be an appropriate objective. It is more reasonable to route a robust communication bus along with a power bus over and through a tractor's frame and extended structures. Trying to utilize wireless devices in this metallic and electromagnetic wave impeding environment would be riddled with reliability challenges. A more appropriate strategy would be

[6] ISOBUS is the implementation of International Organization for Standardization (ISO) standard 11783 directed for agriculture and forestry equipment. Standard addresses needs of an open interconnected system via a control area networked bus modeled after the Bosch 2.0 CAN protocol.

to devise enhancements with off-board wireless sensors, or have wireless sensors located where wiring has proven to be problematic or is clearly not an option.

BASICS OF ELECTRONICS

Before delving into the ins and outs of wireless devices, it is necessary to review the nature of electronics and how they exist today. Electronics are made up of two basic elements: hardware and software. Hardware refers to the physical electronic components and assemblies that can be held and seen, such as circuit boards, integrated chips, sensors, and module assemblies. Software can neither be held nor seen, at least other than in the lexicon of a coding language or through a user interface screen. Hardware and software both have to be designed and built in relation to each others' specifics. However, there is a vast array of categories further dividing these two groups into a plethora of divisions defined by cost and ability. The intermingling of software with hardware, and vice versa, promotes the surpassing nature of the tech industry's obsolescent trends. By now, most of the public understands what software and hardware updates are and knows the frequency at which they are provided.

For some, this information is elementary. However, the need to touch on the basics is apparent. Quite often people use electronic devices but have little understanding of what it is they are using. This is because most electronic devices are specifically designed to provide the option of marginal use (may also be understood as having novice to expert levels of use), thereby reaching many more users in the market. End users confidently understand what the device can do for them relative to marketed tag lines and shortened specification sheets. But they don't know what else the device can do beyond advertisement claims or how it can do what it does better; and with a lot less disappointment when problems occur and expectations are not met. Misplaced expectations developed from minimal and partially understood information are common fallacies that derail users' perception. One of the most common points of confusion with commercial wireless devices is effective communication links, which depends on numerous factors including distance, power, orientation, antenna type, carrier frequency, propagation path, etc. And all this is additional to figuring out device configuration and operational procedures.

Truth be told, current wireless devices have a sensitive nature resulting in poor performance or even complete failure when operational parameters are violated. The catch is when users sometimes cannot detect strains on operational compliance. This suggests that there needs to be an effort to better prepare those having only a superficial understanding of the technology, and are interested in utilizing electronics with wireless features. Inefficient and misapplied uses are uninhibited and need to be addressed so that negative and vulnerable outlooks are less prominent in the agriculture industry, in which wireless devices are almost becoming necessary to meet current demands.

ELECTRONICS WITH WIRELESS ABILITY

So why focus on wireless systems? For one, there is an obvious reduction in wires. Secondly, communications with minimal need for physical infrastructure greatly increases possibilities wherever sensors and controls may be useful (i.e. stream monitoring, on free-ranging livestock, irrigation systems). The theoretical use of fewer electrical infrastructures equates to faster deployment and enhanced sensor information. Most of the advantages are intuitive and have already been realized. Precision automatic vehicle steering is one of the most popular recent successes in wireless agriculture technology. Wireless connections play an overly significant role in its operation not only with the use of space satellite to ground receiver communications, but also with position correction information via a ground base to tractor radio link. Radio frequency identification (RFID) is another example of popular wireless applications making new trends and opportunities in agriculture. Animals with RFID tags are traceable by an identification number and can have production related information stored in tag memory thereby following each animal wherever it may be transported throughout the production process.

Understanding how radios work, or at least a refresher on the physics and methodologies involved is needed. The days of high powered citizen band radios in tractors and farm trucks are past. Daily functions and decisions are now being supported with cellular communications, personal global positioning systems, electronically accessible information databases, and low-cost wireless sensors. Wireless technologies are no longer just a means of voice communication, they are also sensing and control. However, today's low-power, functionally specific, quick to market, and destined to become obsolete wireless systems can be quite contrary, especially when reliability and robustness are needed. Researchers, scientists, and producers are offered great opportunities to enhance their abilities with wireless devices, but may be faced with unforeseen challenges and disappointments when ill-prepared. When considering employment of a wireless system, the question "what is needed to make it work?" should be asked with equal emphasis as the question, "what all is it designed to do and how does it do it?" Wireless devices have been demonstrated to do unparalleled tasks, but only with additional learning effort and sometimes expensive product support. Investing in this kind of equipment can be quite a frustrating experience when there is not sufficient comprehension upfront. For instance, one common drawback to animal RFID systems is that tag readers are very expensive and usually require extra installation costs, not to mention training to learn how to use the manufacturer's software accompanying the reader. Some software may even come with annual subscription costs. Tag readers (more correctly referred to as interrogators) are not typically owned by average producers, but by someone that allows producers to use it as a service or benefit. This part of the system isn't always understood because marketing focuses on how cheap the tags are and not what it actually takes to implement their use.

Like wired communication systems, time will produce more transparent and user friendly wireless systems for agriculture. That amount of time may be longer than expected while the benefits wireless devices offer are presently needed. In light of this reasoning, the best current action is increased dissemination of knowledge.

Wireless Re-introduced

The term "wireless" is commonly spoken as a one word descriptor for electronic devices, although it is actually referring to an electronic communication scheme. Communication schemes can have many layers defined by physical and functional operations. Wireless communications are unsurprisingly facilitated without wires, or more precisely by electromagnetic (EM) waves also referred to as radio frequency (RF) waves. RF waves have virtually replaced wires as a media to transport information. Just because RF waves cannot be seen, unlike wires, doesn't mean that there is not something physically between two wireless devices providing a communication link. Also, like a wire that can be damaged or cut, EM media can also be disrupted thus compromising the communication link. Advantages of using RF waves include the ability to freely bend around obstacles, go through objects, reflect off structures, and they exist as a pre-installed component. These facts support rapid deployment and the ability to densely sense agricultural phenomenon despite previous physical limitations common to wired systems. For instance, soil sensors can now be arbitrarily placed throughout a field without worry of installing obtrusive wires to each device's location. Devices can be quickly relocated in the field and able to immediately report information to a base receiver. These advantages don't come without a new set of impediments though.

Not all objects can be fully penetrated by RF waves resulting in an attenuated signal, or propagation loss. These kinds of objects are referred to as lossy media. Bending around and reflecting off structures are not necessarily supportive traits as they can result in counter effects to the RF signal. However, some structures may form enhancements by guiding or reflecting waves to a receiver that does not have a clear unobstructed view of the transmitter. It is worth the time to become aware of all structures within and nearby the communication path between wireless devices.

Understanding the basic behavior of RF wave propagation is an important part of practical application. Light is a good example of illustrating the physical aspects of EM radio waves. Light cannot pass through materials (i.e. brick wall) that are not considered transparent (i.e. glass windows). Semitransparent materials are used to control or distort light waves. Similar to light, RF waves cannot pass through conductive materials known as shields (i.e. metal buildings), and are decreased by energy absorbing/dissipating materials (i.e. water, vegetation, animal flesh) because of molecular relaxation and resonance. All material in the pathway between transmitter and receiver, including moisture and dust particles in the air, will affect RF waves' ability to propagate. Permittivity and conductivity describe the physical characteristic of materials encountered by RF waves. Material will either conduct electric current thus depleting energy from the wave or permit the EM radio wave to pass.

In an agricultural environment, and all other practical scenarios, clear air is the best medium for RF waves to traverse. Free line-of-sight is a phrase used to describe open air situations where receiver and transmitter propagate RF signals in a straight unobstructed path. Dense vegetation, metal structures, and animals are some of the worst attenuators. For instance, two devices located on opposite sides of a herd of cattle, wide strip of trees, or metal barn, will experience signal attenuation when trying to send and receive messages (packaged information) over an RF link (Figure 2). These kinds of situations are remedied by repositioning the devices where they are closer together or have a clearer line of sight, which isn't always an option.

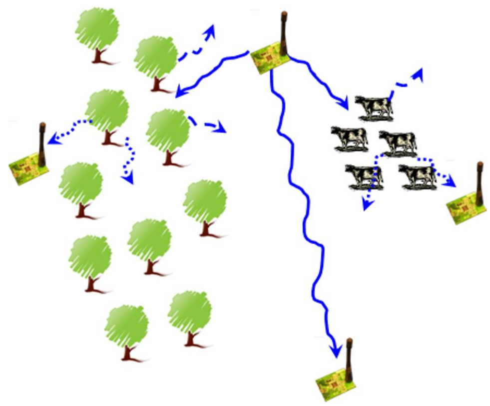

Figure 2. RF wave propagation paths between wireless sensor devices encountering common agriculture obstructions. Clear line-of-sight path has strongest signal and has ability to transmit farther.

Another important factor is that Earth ground can coordinate significant attenuation. Earth ground acts as a dielectric either reflecting or absorbing waves. Reflected ground waves are the most concern. Ground absorbed waves are only applicable to through-earth applications. Transmission through a mountain or from underground obviously sustains severe attenuation. It is not likely that low power short range wireless devices will attempt to transmit through a large mountain, but it may be desirable to transmit from a buried soil sensor. Device antennas located near the ground will experience signal attenuation because of two main reasons: 1) induced current in the antenna from nearby reflected electromagnetic waves and 2) signal interference from reflected waves. Antennas located near the ground could experience an induced current. When an antenna transmits an EM radio wave it may be reflected back to the antenna such that it induces a significant current in the antenna. The effect will cause a change in the antennas radiation because the additional current will either increase or decrease transmitted power along with potential alterations of the antenna system's electrical characteristics (i.e. detuning). Signal interference can also be caused from a ground reflected wave at lateral distances in the antenna's far field region. At shallow reflection angles, ground reflected waves change phase and polarization and can result in a cancelling effect on stronger non corrupted waves. The higher the antenna the greater the reflection angle and the less cancelling waves transpire; and the less opportunity for nearby reflected waves to cause induced current in the antenna. For short range wireless systems, it is best to not place devices directly on the ground. Many novice users make this mistake because it is easy to install a device close to the ground as opposed to elevated on a vertical structure. Correct above ground positioning can be determined by the operating frequency wavelength. A 900 MHz device has an approximate wavelength of 0.33 m (1.08 ft).

A suitable height would be greater than at least one wavelength of the operating frequency; and the safest heights would be at multiples of the operating frequency (i.e. 1 m (3.28 ft) height for a 900 MHz device).

Understanding the differences between RF waves is essential. Two important constituents of RF wave communications are the carrier frequency and transmission power. Carrier frequency is the chosen EM radio band selected to impose modulation techniques upon. The width of the band is simply referred to as bandwidth and is an important feature pertaining mostly to data rate and number of modules managed on the same network. If a 915 MHz carrier frequency was selected with a 10 MHz bandwidth, then the carrier frequency would encompass bands from 910 to 920 MHz. Selected carrier frequency is also referred to as the center frequency of the noted bandwidth. Transmission power is the amount of power applied to the device's antenna in order to generate EM energy in the form of RF waves. Carrier frequency selection and transmission power relate mostly to the physical aspects and needs of a wireless sensor application.

OEMs design and build radio devices to withstand interferences from other radio devices and equipment having EM emissions in the same bands. This is accomplished by way of modulation and media (airway) access control. In the United States most short range wireless sensors are designed using unlicensed radio bands in compliance with the Federal Communications Commission (FCC) to be used for industrial, scientific, and medical (ISM) purposes. Other countries may regulate ISM frequencies differently, but for the United States the FCC is the governing division. The International Telecommunication Union Radiocommunication Sector provides standards and regulations as an international coordination of radio communications and is adhered to by manufacturers having an international customer base. The advantage of ISM bands is that formal licensing is not needed thus indicating the requirement for interference handling. Wireless sensor devices using ISM bands are usually considered low power short range radio devices in accordance with Part 18 and Part 15 of the FCC regulations. As designated by Part 15, ISM bands are 902-928 MHz, 2.400-2.4835 GHz, and 5.725-5.875 GHz with a maximum 1 W transmitter power using an antenna with maximum 6 dBi directivity.

So why is it important to be aware of the frequency band a device uses? For a given transmitter power, a lower frequency device is able to transmit further than a higher frequency device because it is less affected by attenuating media in the RF wave's propagation path (Figure 3). It was mentioned earlier that being aware of all obstacles in the transmission path is recommended. It was also mentioned that radio waves can bend around and go through objects. The size of the radio wave and the size of objects in the propagation path partially dictate performance. Radio waves are more apt to bend around objects that are not larger than one wavelength. Frequencies in the 2.4 GHz range have a wavelength on the magnitude of 12.5 cm (4.9 in). Objects in the propagation path of a 2.4 GHz signal that are larger than 12.5 cm (4.9 in) potentially will cause more attenuation than smaller objects. Higher frequencies can also transmit at higher data rates than lower frequencies thus being able to send the same amount of information in a shorter period. This means that high frequency devices' transmitters would need to be turned on for less time effectively saving power. A higher frequency device also has to have more power to transmit the same distance as a lower frequency device. Antenna size and design are related with frequency selection. Lower frequencies typically need a larger antenna than higher frequencies. Since small size and concealment are often important to wireless sensors, antenna characteristics may play a significant part in frequency selection. When selecting a wireless system it is imperative that the tradeoffs related to power usage, carrier frequency, data throughput, and size be understood so that an appropriate deployment and management strategy is constructed.

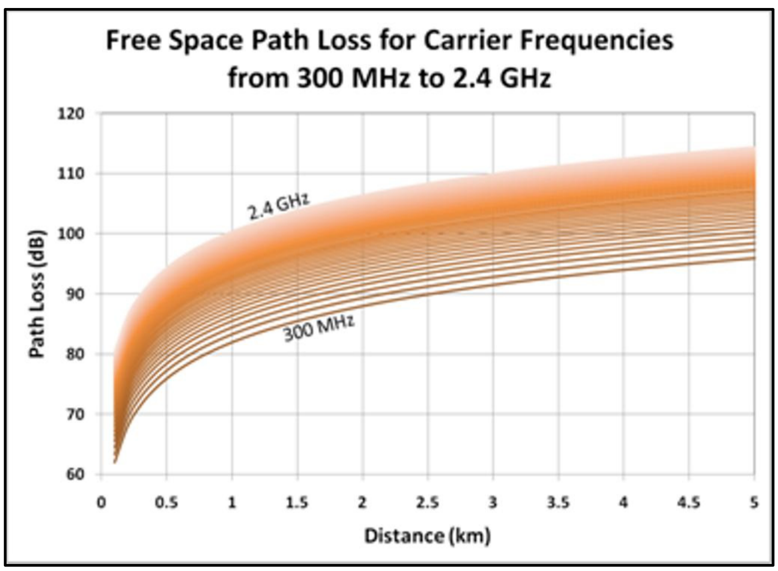

Figure 3. Signal loss of radio waves between 300 MHz and 2.4 GHz. Path loss calculated for theoretical free space. Lower frequencies have less path loss per distance when compared to higher frequencies.

ANTENNAS AND ORIENTATION

Every wireless device has an antenna even if it can't be seen. Size and shape of antennae depends upon radio frequency, regulated transmission power, and application specifics. Wireless sensor antennas are often designed with a small form factor for concealment purposes. A large number of antenna designs have been integrated as copper traces on circuit boards or as board level surface mounted components not visible to normal users (Figure 4). More conventional antenna shapes exist as small stubs or short wire like protrusions (Figure 5). Monopole designs resemble a short straight wire extension and are commonly referred to as "whip" antennas. Passive animal RFID devices often use a long thin strand of wire wound in a small circular pattern providing both a radio antenna and EM induction tool for power generation. A great deal of design, both mechanical and electrical, is put into antennas to achieve performance goals. However, this is one of those areas where marginal operation can occur. Most antennas have directional radiating features where performance varies relative to orientation and displacement from the antenna. Theoretical guidelines are provided for antenna selection and use but practical knowledge reveals the extent of workable limitations. For example, an RFID tag in an animal's ear has an unpredictable orientation when an animal moves past an RFID tag reader. The animal's head and ear may be bobbing, turning, up/down, etc. However, this application expects a general orientation of the RFID ear tag so that it and the tag reader can communicate. Ideally the tag would be read with any orientation, but this is not possible indicating the reason why RFID system specifications list probable failure rate or percent accuracies.

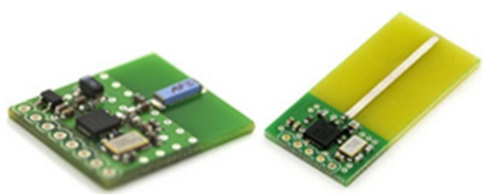

Figure 4. Circuit board integrated antennas. Chip style shown on left (blue chip component on end of board). Monopole antenna fabricated into board as copper trace is shown on right. Board level antennas are used for high frequency, short wavelength systems; and require some isolation from other board components. www.sparkfun.com

Figure 5. Common antenna designs for UHF devices. Quarter wavelength monopole whip antenna shown on the left, patch style shown in upper right, and solder mount helical stub shown in the lower right corner.

The antenna's primary purpose is to provide a physical means of transmission and reception. Antennas convert energy from an electronic transmitter to radiated electromagnetic energy, or electromagnetic energy from an RF wave to voltage and current fed into a receiver. Transmitting antennas must radiate in such a way that the receiving antenna can accept the signal. Likewise, a receiving antenna requires positioning so that it can interface correctly with a signal.

RF signals lose energy with distance (Figure 3). Enough power must be directed to the area where a receiver is located. Antennas provide the ability to direct transmitted power to the right area. Radio signals and antennas depend upon orientation and direction for these reasons.

Other than orientation, size and design must be considered. If the antenna was designed for a high frequency signal then it would have difficulty receiving low frequencies. All this concludes to the fact that antennas and signals are meant to be used within prescribed working parameters.

Receiving and transmitting devices do not have to exclusively have the same type of antenna. Different styles of antennas can send and receive signals to each other usually with a decrease in performance. It is best to have similar types of antennas on all devices (possibly excluding stationary base stations) with similar orientation and radiation patterns. For example, a wireless sensor module with a ¼ wavelength whip antenna is positioned with its antenna vertically aligned. Whip style antennas are designed to radiate a signal in an omnidirectional pattern. However, it must be understood that omnidirectional only refers to a 360° pattern in the horizontal plane parallel to the surface of the Earth. A vertical whip antenna radiates very little signal, if any, in an upward/downward path known as null directions (Figure 6). Figure 7 illustrates best whip antenna positioning between a transmitting device located at the center of its toroid like radiation pattern, and a receiving device located in the rightward direction. A line perpendicular to these paralleled antennas can be drawn, indicating the receiver is well located in the horizontal plane of the transmitter's radiation pattern. Two non-receptive devices are also shown in Figure 7. One is located directly above the transmitter in a null region and the other is rotated 90° to the transmitter while still in the horizontal plane of the monopole's radiation pattern.

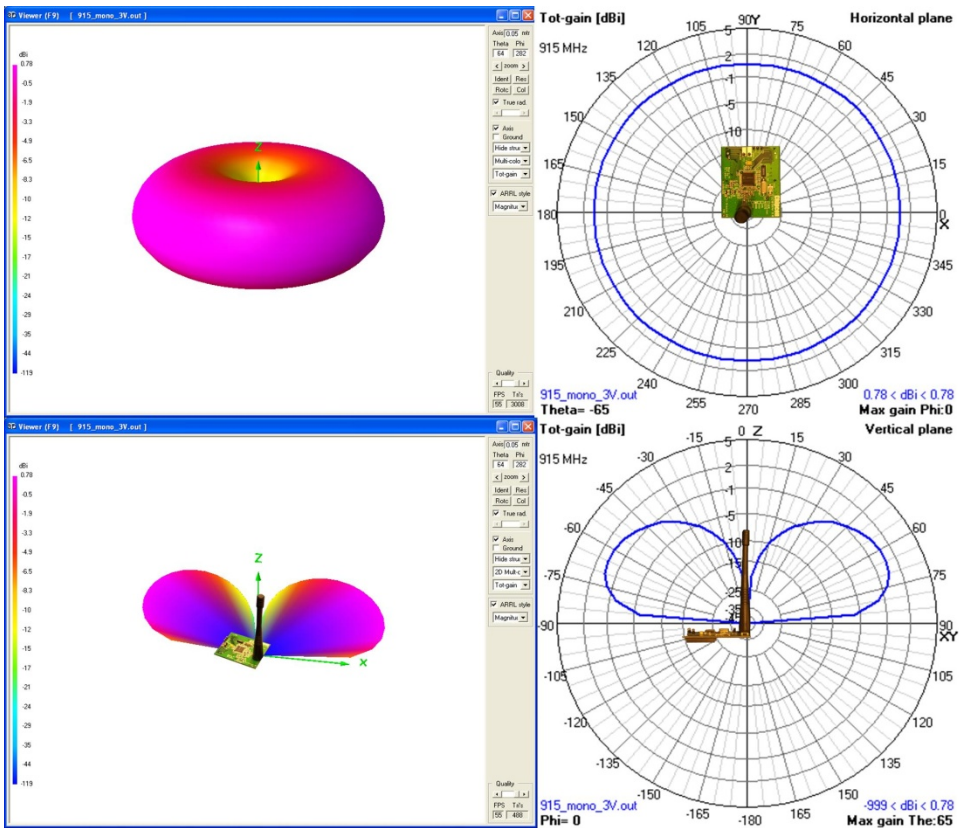

Figure 6. Radiation pattern for monopole 1/4 wavelength antenna on wireless sensor device. Omnidirectional 360 degree half donut shape shown upper left; vertical cross section pattern shown lower left; 2-D horizontal and vertical patterns shown on right. Maximum directivity is in all directions in the horizontal plane and in only the 45 to 75 and -45 to -75 degree windows of the vertical plane. Note that upward and downward directions along z axis are null.

However, strict enforcement of whip antenna orientation is not all that necessary as most modules can be partially rotated and placed at varying heights while still maintaining a functional RF link. Other positioning possibilities may result from reflected waves. The idea is to know the boundaries of where and how the wireless device can be physically placed for any given application environment. Miniaturized

GPS devices are another example of orientation dependency. Handheld and vehicular GPS devices commonly use "patch" antennas made of two square copper patches separated by a ceramic plate (Figure 4). This style of antenna is meant to lay horizontal with the receiving patch facing upwards (and ground plane patch facing downward) so that satellites in the upward hemisphere can be viewed. This antenna is designed to have an upward directivity when horizontally aligned. In order to receive signal from the greatest number of satellites in the upward hemisphere, this antenna also has a broad pattern resembling a wide angle cone. The broadness of an antenna's transmission/reception pattern width is known as beam width. Signals from satellites located on the horizon are hard to receive, but satellites transmitting signals at shallow angles above the horizon (i.e. 30°) can usually be received. If the GPS antenna is oriented such that the receiving patch is vertically aligned, the number of viewable satellites will be greatly reduced to less than those located in ½ of the upward hemisphere. In this case an accurate position fix is unlikely. Agriculture research applications, such as tracking cattle, have obvious concerns with GPS orientation due to animal mobility and body positioning. GPS devices should be fixated to the animal so that antenna orientation is within acceptable view of satellites for time durations defined by application requirements. This may also affect power consumption because some GPS device configurations use more computational and receiver power when usable satellite reception is infrequent. Scenarios involving metallic livestock trailers, forest canopies, and canyons must also be considered. Newer micro-GPS antenna designs have recently been introduced that are more lenient to orientation issues.

Polarization is a term used to describe the movement of the electric field radiated from an antenna. Propagation is the direction and path a radio wave travels whereas polarization describes the electric field vector along the propagation path. Linear, circular, or elliptical are the standard expressions used to describe polarization. Linear is where the electric field is aligned in a single plane, whereas circular and elliptical refer to a spiraling electric field vector along the propagation path. Antenna-signal polarized matching is affected by both antenna orientation and physical design. Antennas can be designed to have a particular polarization. Like threads on a screw and nut, they must match to work together. If a screw had right hand threads, then a nut with left hand threads could not be fastened to the screw. Wireless communications are similar in that an antenna with right hand circular or elliptical polarization would have difficulty receiving a reverse polarized RF signal. Furthermore, a vertically polarized antenna (i.e. whip antenna with vertical orientation) would have difficulty receiving a horizontally aligned RF wave (i.e. whip antenna with horizontal orientation). Both antennas are linear polarized, but vertical and horizontal linear polarized signals are incompatible.

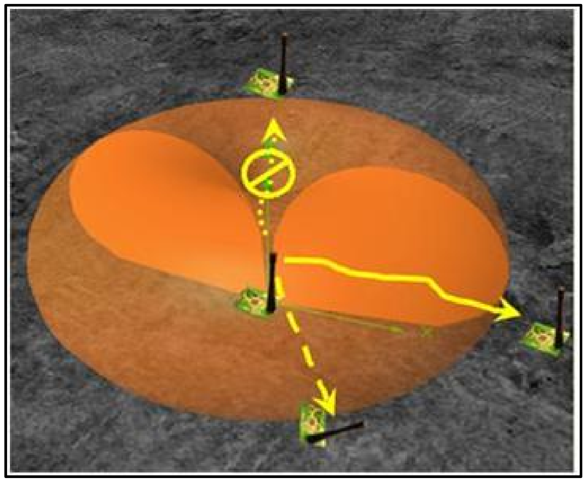

Figure 7. Considerations for antenna orientation respective of polarization and placement. Only like polarized antennas in direction of sufficient radiated power will acquire a proper communication link. Mismatched polarized antennas and signals, or devices placed in null directivity, will experience communication problems and failure.

Optimized antenna orientation promotes best wireless communication performance. But when physical position alterations are made a noticeable degree of improvement or performance decrease is not always the case, unless the user is well equipped with sophisticated RF instrumentation. One can facilitate marginal performance and not necessarily be aware of it until more strenuous dynamic events occur such as increased data requirements or forage growth changes in the propagation path. For instance, a vertically aligned whip antenna with a vertical linear polarization would ideally receive a vertically polarized RF signal at the same height above ground. However, as Figure 6 shows, this type of antenna radiates within the horizontal plane an omnidirectional pattern. The radiated doughnut like pattern also has a significantly noticeable beam width. The axis of the donut pattern is collinear with the whip antenna. Beam width is defined as the angle where at least half the maximum gain (3 dB) remains in the radiated field. Antennas located at various heights that are within reason of the beam width can effectively communicate. Still, the strongest communication is achieved when antennas and waves have matching polarization, aimed in a clear path direction, and at similar heights.

The concept of beam width and wide operating parameters provides a basis for other designs common to wireless sensors (i.e. multipath systems). Cellular phones are one of the most common wireless devices that rely on multipath signals. Cell phones are placed in bags, pockets, drawers, etc. and manage to receive and transmit signals sufficiently. A multipath cellular phone system depends on reflected radio waves from all directions while likely giving a direction preference while in the "talking" position. There are many defining differences between cellular and wireless sensor systems but the principles and general tactics are basically the same.

Reflected waves and waves passing through various dielectric media can have polarized and phase alterations imposed. When this occurs, the receiving antenna best suits the application if it can accommodate these changes. For example, a linear polarized antenna radiates a linear polarized radio wave that is reflected off nearby structures or passes through various media such as brick walls. The linear signal is time varied and rotated in an unpredictable manner along the propagation path, thus becoming re-polarized and phase shifted. A circular polarized or multipath type antenna would be more likely to receive the signal when compared to a matching linear polarized antenna. This concept is structured around the idea that catching some signal is better than catching none of the signal. Even though antenna mismatch may prevent communication failure in this sense, it is still known to reduce efficiency relative to free line of sight matched antennas. The useful tradeoff is additional operability in multiple directions, but at shorter distances.

An isotropic antenna is an ideal theoretical antenna that performs equally in all directions. When transmitting it radiates equally in all directions, and when receiving it has equal reception in all directions. Isotropic antennas provide a basis to develop a measurable quantity describing how well an antenna can perform. This concept suggests that performance measure for wireless communications is always relative. A benchmark is selected and everything else is compared to that benchmark, usually in the form of a logarithmic ratio. Decibel is the name of the unit used for this relative measure. However, decibel (dB) alone does not provide meaningful information unless it is clear what base level is used. Wireless sensors are commonly rated using dBi and dBm. The unit dBi indicates decibels with an isotropic radiator as the base comparison, whereas dBm indicates a base of 1 mW fed into a 50 Ω impedance (common for wireless sensor systems). Decibel is a tricky unit to understand because it has multiple parts and services to consider. Simply reading 5 dB from a specification sheet does not really mean anything unless there is understanding of the measurement reference and how the value is intended to be applied.

Directivity, efficiency, and gain all need to be considered to best comprehend decibel transmission/reception ratings of a wireless device. Directivity describes how well an antenna radiates EM radio waves in a particular direction as compared to an isotropic radiating antenna. For example, if a test antenna's planar radiation pattern exhibits greater than 0 dBi for 180° in the forward direction and then less than 0 dBi for 180° in the rearward direction, then the test antenna can transmit further than an isotropic antenna in the forward direction, and less in the rearward direction. Zero dBi indicates the test antenna radiates the same as an isotropic antenna. The antenna's directivity is basically describing the effectiveness of the antenna when aimed in a designated direction. Directions of high directivity indicate capability of longer transmission distances whereas low directivity indicates shorter transmission distances, but in more usable directions.

The ideal part of an isotropic antenna is its uniform spherical radiation pattern. All real antennas have non-spherical patterns. When comparing directivity of an isotropic antenna to a real antenna, it is necessary to understand that they are transmitting the same amount of total power. The real antenna normally distributes the power differently. This redistribution of power is where antennas attain their directive characteristics.

Antenna efficiency is the power input of the antenna relative to the power that actually gets transmitted. The product of directivity and efficiency yields antenna gain. It is common to expect antenna gain and directivity to be practically the same because well designed antennas' efficiencies are regularly near 100%. Directivity, or antenna gain, are normally provided in the form of a two dimensional chart (Figure 6). The chart is polar and shows dBi measures for a full 360°. Two charts, one for horizontal and one for vertical, are often provided as a specification to represent 3-dimensional transmission. Some refer to the charts as E-plane and H-plane respective of electric and magnetic components of the electromagnetic field. Directivity-gain charts are used to match application needs. There is an apparent tradeoff to be understood with antenna gain and directivity. When an application needs long distance it will need an antenna with high gain (remember that distance can also be achieved with higher transmitter power or lower carrier frequency selection). But if the application also needs multiple directions, an antenna with a lower gain and multidirectional radiation pattern is needed. High gain antennas and multidirectional radiation patterns do not come in the same package. The user must choose which kind of antenna system best supports the application. For long range multidirectional applications, a networking system of intermediate range devices may be more appropriate.

Power measurements, such as sensitivity, are usually indicated by dBm values. Sensitivity is the minimal amount of power needed to be fed into the receiver in order to process a signal. Bit error rate concerns demodulation failure and is typically integrated with sensitivity rating. For instance, a GPS device specified at -140 dBm sensitivity is better than one with -120 dBm because -140 dBm indicates better ability to receive weaker signals. Alternatively, if transmission powers were being compared then a higher dBm value is more desirable as it indicates a stronger transmission signal. Sensitivity and transmission dBm values are exactly opposite in the interpretation of their performance values.

The specified transmission range on data sheets are in all probability based on a clear line of sight situation, with a sufficient height above ground, in the maximum gain direction, and at maximum transmission power. In other words, distance specifications should be assumed the best case scenario unless stated otherwise. Conservative measures should always be exercised when evaluating specified transmission distance. Expectations of achieving data sheet values are usually not met outside of a laboratory environment.

Networked Wireless Sensors

Like most communication schemes, staged routines are used to logically divide the necessary steps needed to make both hardware and software extract meaning and designate reaction from the information being exchanged. Communications are governed either by an industry standard or proprietary framework. In many cases a standardized protocol with proprietary allowances are used so that manufacturer specific devices can communicate with other manufacturers' devices while retaining certain proprietary features, which is the practical intent of standardized communication in a large competitive electronic market. Although, significant proportions of today's wireless sensor devices communicates in a proprietary fashion because standardization has not maturely developed nor been significantly adopted for commercial uses. The reason why standardization has not come to fruition is somewhat opinionated, but revolves around the issues of the type of data sensed, power consumption, and networked devices. The practical thing to know here is that when a standardized form of communication is used there is concern for power consumption, potentially less sensor data, increased need for technical support, and more advanced skills required of the user.

Transmitting information between two devices is actually a simple and inexpensive task. Complexity quickly rises when multiple devices are needed to communicate amongst themselves or with management devices, thus creating a wireless sensor network (WSN). When using a WSN, it is important to understand the taxation networking tasks have on each of the modules referred to as nodes. Most WSN strategies use a proportional amount of memory and power so that real time data and responses driven by sensed phenomenon can be handled. This leaves less power and memory for data sensing and storage. However, WSNs can provide advantages that extend sensing ability. For instance, a sensor node may be placed far away from a base receiver beyond RF transmission range or behind severe lossy media (Figure 8). This node can transfer its information (sensor data) to neighboring nodes between it and the base, effectively hopping the sensor data to the base; a tactic commonly used in WSNs. Also, data aggregation is a popular WSN strategy. Data from a group of associated sensor nodes are collected and processed resulting in an aggregated representation of the sensed phenomenon and can then be stored using less long term memory or sent to a far located base using less transmission energy.

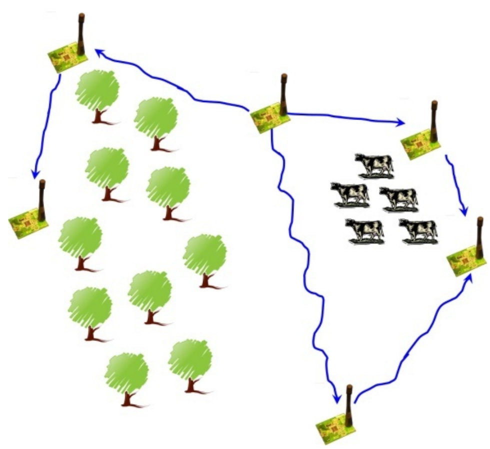

Figure 8. Wireless sensor network relaying (hopping) messages from a central node to other nodes. Transmission is allowed around obstacles because of message hopping technique.

The best way to grasp wireless sensor networks and understand application concerns is with an example. Take a 32.4 ha (80 acre) corn field with 800 m by 400 m (0.5 mi by 0.25 mi) dimensions for instance. The intended application is to measure soil surface temperature and canopy temperature for every ten square acres. For the sake of simplicity, only one sensor module will be used for every ten acres. Realistically, a more appropriate sampling scheme should be used to properly represent average temperature over each ten acre region. At least eight wireless sensor modules are needed. A base station is to be placed in the corner of the field where a remote cellular link is provided for further data transmission. Transmission distance between each sensor device is roughly 200 m (656 ft). Transmission distance between base device and furthest device in the opposing field corner is roughly 750 m (2470 ft). Temperature readings are to be reported to the base receiver every hour.

A 2.4 GHz wireless sensor is selected. The device's antenna cannot be visually seen so it is assumed that it is either a chip antenna or board trace completely enclosed in the device's weather proof non-metallic enclosure. A metallic enclosure is not sensible as it would shield RF wave transmission and reception. Non-conductive enclosures and mounting fixtures are necessary. Mounting directly to a steel structure is not recommended as strong reflections will likely interfere with the wireless module. Each device has two temperature sensors connected by cables that run into the device's enclosure. This is good because it allows the sensors to be placed elsewhere than the radio transmitting part of the sensor system. Batteries are two AAs contained in the device enclosure and provide all power. Modules are deployed immediately after planting and are expected to last at least 90 days.

The first thing to consider is: can the modules transmit to the base receiver? The answer is: it depends! Start with identifying what will affect transmission between base and each node at every ten acre region. Distance, foliage, height above ground, antenna characteristics, and transmission power should be the immediate items to investigate. Product documentation claims each device has an antenna gain of 2 dBi, 1 W transmission power, and 400 m transmission range. From this information it can be assumed that the device has significant directional characteristics because of the 2Bi rating. Since a grid like formation is evident, each device will have four neighboring devices 90° apart. Hopefully the antenna is something like a dipole or monopole that has a horizontal omnidirectional pattern and can accommodate a full 360° horizontal communication direction. However, care must be taken to align a dipole or monopole vertically and not horizontally. Horizontal alignment would allow front-to-back or side-to-side directionality only and would not include 360° vision of all neighboring nodes. If the antenna type cannot be determined than directionality should be determined with the manufacturer's help, or by rudimentary testing.

The specified transmission range is in all probability based on a clear line-of-sight situation, with a sufficient height above ground, in the maximum gain direction, and at maximum transmission power. In other words, the distance rating should be assumed the best case scenario unless stated otherwise. Nodes that are placed near the ground will not be able to achieve this performance for two main reasons: ground reflections and attenuation from the growing corn crop (Figure 9). The obvious solution is to fixate the nodes so that they will always be a few wavelengths above the crop's maximum canopy height. Conservative measures should always be included when evaluating specified transmission distance. Expectations of achieving listed transmission distance are usually not met. Using either 1/2 or 3/4th the specified transmission distance will help prevent data loss and frustration, but may also add a little cost in purchasing extra nodes to decrease node-to-node separation.

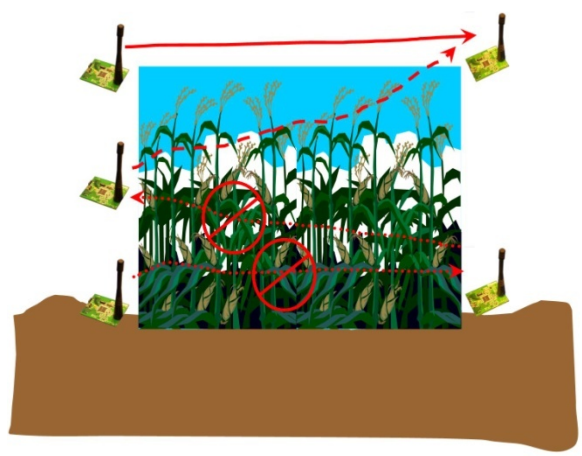

Figure 9. Wireless sensor nodes placed at various heights in a corn field. Nodes located close to ground will experience transmission failures. Nodes should be placed above crop canopy for best communication.

Even if maximum transmission could be achieved in all directions, there are numerous nodes farther from the base receiver that will not be able to establish a radio link because of distance. The solution is networking. Neighboring nodes can pass information to each other thus "hopping" the information all the way back to the base receiver. Intuitively, the most effective procedure is to use a shortest routing method. The node located in the far corner of the field would have the shortest path back to the receiver via all the nodes that lay in a direct line between it and the receiver. But what if the devices have directional antennas that only allow communications in two directions, 180° apart? A diagonal path would only be possible if the antennas of each node were directionally aligned, which causes communication failures for those nodes located at other angles. In this case it is imperative that an omnidirectional antenna be used; otherwise weird and inefficient routing patterns will exist.

Nodes closest to the base receiver will experience more power usage as opposed to far located nodes. This is because close nodes have the obligation to “hop” data from far located nodes back to the base receiver, thus increasing the closer nodes’ receive and transmission time. Aside from hopping other nodes data to the base receiver, each node must have built in intelligence that allows it be part of a network. This intelligence is in the form of firmware (software) and memory. Cost and power consumption are increased with an increase in firmware and memory. Memory used for network operations is not available for data storage and may present other application concerns for intensive data sampling regimes. Networking power consumption also rises when nodes must frequently update their routing knowledge. This is not the case for the proposed corn field temperature sensing scenario as it uses stationary devices, but is a definite concern for applications where nodes are highly mobile, such as on livestock or equipment.

Power consumption is dictated by data requirements, transmission/receiver power usage, and effective routing structure. Battery exchange during mid-deployment is undesirable and efforts should be made to maintain power for the duration of a seasonal task. Calculating exact power requirements is a complicated feat. A good question to ask manufacturers and distributors is: “what are the power requirements relative to node density and data rates, or sampling?” If this cannot be adequately answered more investigation is needed. One should definitely identify nodes that experience high traffic rates due to message hopping requirements so that battery replacement schedules can accommodate.

Not all networks use a “hopping” strategy. Some networks forbid communication between nodes and mandate each node only communicate with the base receiver. This type of network does not have the need for intelligent routing features. Probably the biggest difference with base-to-node only networks is that distance is limited. Multi-hop networks are in some respects not limited by distance because a string of nodes can always be made between base and the end sensor node. Power consumption is imaginably less using direct base-to-node communications, unless a higher powered transmitter, high gain antenna, and lower frequency are specified to accomplish longer distances.

It would be unjust for this wireless sensor network discussion if mention of current standardization efforts and commercial products are not made. The two that are arguably the most prevalent today are

Zigbee® and TinyOS. Zigbee is devised by an industry consortium called the ZigBee Alliance, to facilitate more marketable products that not only cross manufacture lines but also achieve integration with both higher and lower level systems. TinyOS is somewhat different as it offers an embedded operating system existing on a wireless module framework. TinyOS originated from the University of California, Berkeley, California. Wireless networking is a tool or function set within the TinyOS platform. Zigbee is network and application layers that are added on top of the Institute of Electrical and Electronic Engineers (IEEE) standard 802.15.4 physical and media access control layers. Zigbee is sometimes commonly referred to as 802.15.4, but is actually an addition to the standard.

As stated earlier, no mature wireless sensor networking standard actually exists. This is largely in part due to the huge variability of application needs that are targeted with wireless sensors. What does exist are variants of systems revolving around a common set of problem definitions and parameters; where some choose to address few detailed issues to maintain simplicity while others attempt to have a complex serve-all system.

APPLICATION CHECKLIST

The following list is provided for those agriculturalists wishing to begin use of a wireless sensor system, evaluate an existing system, or to reference for future needs; granted that some new understanding has been gained via the leading discussion. Questions instead of statements are used to summarize important points and items presented. However, this list is not meant to be conclusive. The reader will undoubtedly need to converse with manufacturers and distributors in addition to referencing product literature. If customer support is poor or product literature is deficient, then seek a new product. For the amount of time and money needed to implement wireless sensor systems, not having decent help is inexcusable.

1. What is the maximum transmission range between any two devices? What is the maximum range between base and node/tag device? How does this change with available carrier frequencies?
2. What is the ideal transmission/reception pattern? Are highly directional antennas suitable for the application, or is omnidirectional better?

3. What carrier frequency is needed? Does the antenna need to be very small or can it be moderately small? Can an unlicensed ISM band be used?
4. What are the obstacles in the propagation path between all communicating devices? How will the selected carrier frequency perform relative to these obstacles? Will these obstacles require extra nodes and networking features?
5. Is networking needed? Is it necessary to have extended range via networking? How difficult is it to setup a networked system to achieve the overall application goal?
6. How much power will be used, or how often will the batteries need to be changed? If in a building environment or on powered equipment, can power be obtained by other means (may require AC/DC or DC/DC conversion and wiring)? Are charging systems available?
7. What is the desired data rate? Does the data need to be real time?
8. Are the devices stationary or mobile? How does this affect directionality, distance, and data requirements?
9. How will wireless modules be positioned? Will there be interference from reflected waves possibly from mounting structure, ground, or nearby obstacles?
10. Are there any other operating radio devices in the same area that are radiating a significantly strong signal? What is the frequency of the wave and how close is it to the selected carrier frequency of the device under consideration? How well does the device handle interference originating from other devices?
11. Is there sufficient product support and literature to help achieve the intended application goal? Does the wireless system do much more than what is needed? Does this make the product more difficult to use?
12. Are all the product specifications understood? Are there specifications missing? Are the gain and power specifications ambiguous?

CHAPTER III

PHYSICAL DESIGN CONSIDERATIONS AND HARDWARE SELECTION FOR A CUSTOM WIRELESS SENSOR: A PLATFORM FOR MONITORING CATTLE GRAZING ACTIVITY

CHAPTER PREFACE

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The author served as the corresponding author for the submitted manuscript. The contributing author was Aaron Franzen, research engineer with Oklahoma State University, Biosystems and Agricultural Engineering Department, Stillwater, Oklahoma. All sensor, hardware, and software design performed and discussed within the manuscript was work done by the author. The author also completed all product testing and evaluations made. The contributing author provided editorial and revision support.

ABSTRACT

This research involved the design of a custom wireless sensor to monitor free-range cattle grazing activity. The proposed device afforded a platform supporting variable research application needs. Specific design considerations were made for sensor type, radio configuration, voltage regulation, memory, and developer ability. The focal point of the designed device/platform was the microprocessor selection. The CC1010 microprocessor-transceiver IC was chosen based on available resources, integrated features, development environment, function variability, and low power operation. The sensor selected for grazing detection was the ADXL330 3-axes accelerometer. This selection was based on the characteristics of

grazing motion and integratability at the PCB level. Maximum sensor sampling rate for the CC1010's three ADC channels was shown to be 53 Hz during low power operation. Radio frequency signal propagation losses were estimated using log-distance method and information found in previous literature. Link budget analysis was conducted using the chosen carrier frequency 915 MHz, embedded helical antenna, and transceiver power and low noise amplifier settings. Transmission distance was estimated to be 282 m (925 ft) in line-of-sight conditions, and as little as 17 m (55 ft) in severe attenuating environments. Large data storage capacity was added as an external data flash memory chip, which also provided ample storage for future data processing algorithms and wireless network functionality. Board layout was primarily determined by antenna and transmission line positions concerning the potential for interfering digital circuitry. The radio's transmission line was sized using the PCB's dielectric properties and material dimensions. Multiple board layers were used for noise suppression, dense signal line routing, and small form factor retention.

INTRODUCTION

Application of new wireless technologies and non-invasive sensory devices are speculated to significantly advance agriculture research in areas such as detection and quantification of foraging cattle in a free-range environment. Miniaturized electronic circuitry, embedded wireless communication techniques, and low-cost printed circuit board (PCB) prototyping now enable multi-level development of wireless sensors and make custom equipment more obtainable for a number of agricultural research initiatives. Researchers and engineers with applied sensor, hardware, software, and RF knowledge can now utilize today's design tools and IC components to implement custom applications without prerequisite formal training in embedded systems development. Although pre-packaged wireless sensor development kits exist, these systems come burdened with a steep learning curve that often limits researchers' capabilities or project scope. Researchers frequently require versatility when applying a sensing device or prototype communication system. Off-the-shelf wireless sensor products rarely support this kind of variability at the levels most valuable to the researcher (i.e. data sampling, analog to digital converter control, wireless network communications, algorithm/data compression development, etc.). Wireless sensor devices and development platforms that balance researchers' goals with applied electronic development skill are needed.

The authors present the development of a wireless sensor device (and platform) built upon the concepts mentioned above, while concentrating on a particular sensing application. The objectives of this research were to design and fabricate a custom wireless sensor/platform that detects cattle foraging in free-grazing experiments, while also outlining significant areas of custom wireless sensor development for novice to mid-level researchers designing, modifying, or applying wireless sensor systems.

ON-ANIMAL SENSORS

Advancements in geographical information systems (GIS) and global positioning systems (GPS) software and hardware have made it feasible to track free-ranging animals. Wireless devices such as GPS, radio frequency identification (RFID) tags, and implantable boluses provide valuable information and potential uses in advanced livestock management programs. Bailey (2001) monitored hill climbing and bottom dwelling breeds of cattle with GPS-equipped collars to investigate breed selection for improved grazing distribution. Turner et al. (2000) laid groundwork for the use of GPS collars on free-ranging cattle to study improved management techniques related to best management programs. Ganskopp (2001) analyzed data collected from GPS collars to assess cattle movements relative to water and salt supplement locations in large pastures. Ungar et al. (2004) used collars equipped with GPS and motion sensors to distinguish between grazing, traveling, and resting activities. Koostra et al. (2004) followed Turner's work by investigating GPS data obtained from collared cows to show beef cattle interactions with streams. Other impressive electronic devices include control collars that used persuasive stimuli (shock or sound) to herd cattle while grazing. Embedded electronic devices, assembled with a GPS receiver, have been used to enable location-based triggering of behavior-altering stimuli (Agriculture Research Magazine, 2000). Malpas (2005) started a "Telemetry Project" that uses Bluetooth wireless technology to develop a data acquisition system for monitoring physiological indicators via implantable devices.

GPS has not been the only electronic front when investigating cattle monitoring. Stobbs (1970 used a vibracorder to record the length and periodicity of grazing Jersey cows on pure stands of tropical grass and legume pasture. Later, Stobbs et al. (1972) utilized electronic micro-switches and mercury switches to record jaw movements and bites taken during grazing and rumination for different sward structure and composition. Horn et al. (1979) constructed an Animal Weight Telemetry System using "hoof-boots" equipped with pressure transducers and radio transmitters to remotely measure changes in animal weight in hopes of indicating overall forage uptake. Chambers et al. (1981) electronically recorded total time grazing, jaw movement, and head movement for both cattle and sheep grazing tall and short swards. Forwood et al. (1985) measured passage of boli within the esophagus of cattle via a cannulas equipped with a pressure and conductivity transducers. Phillips et al. (1988) showed variations in dairy cows' grazing behavior by correlations between pedometer and vibracorder measurements. Matsui et al. (1989) used displacement sensors, attached to a cow's jaw, foreleg, and chest, to identify grazing and rumination. Later, Matsui et al. (1991) employed a transducer, pulse generator, and heart-rate memory unit to indicate bolus swallowing and regurgitation in free-ranging cattle. Rutter et al. (1997) used a noseband sensor that was fitted over the muzzle of sheep, and employed a digital recorder, to assess mastication and bite prehension during grazing. Laca et al. (1999) recorded acoustics via a head mounted microphone on cattle grazing differing types of turves to determine chewing, biting, and intake.

These past studies have shown sensory devices are a viable means of monitoring free-ranging animals. Wireless communications coupled with this type of technology provides more efficient and effective means of data collection and management of experiments. However, efforts focused on wireless sensor applications and developments in agricultural environments are commonly stifled by lack of equipment that sustains custom research needs. Agriculture based electronic development platforms that target lower level sensor and communication development such as transducer type investigation, algorithm construction, and development of communication protocols are needed.

WIRELESS SENSOR PLATFORMS

Wireless sensor network (WSN) platforms are currently a hotbed research area, both in academia and industry. As new products become available to address the shortfalls of previous generations, new application needs continue to push the limits of available hardware. As of this writing, no platform exists that can fill the needs of every application. Karl et al. (2005) explained that variability in wireless sensor applications is multifaceted such that developing a standardized communication system is an extremely difficult challenge. In fact, standardization of wireless sensor communications will likely not be in the form of a single framework, but multiple configurations targeted at different data characteristics and application divisions.

Two very popular efforts to standardizing wireless communications and application methods are ZigBee® and TinyOS. ZigBee is a networking and application protocol developed by an industry consortium, known as the ZigBee Alliance. The alliance designed ZigBee to provide low power and low latency sensing and control via wireless mesh networking. Industry often refers to ZigBee as the IEEE 802.15.4 standard, which delineates the medium access control (MAC) and physical (PHY) layers for wireless sensor networks. The more correct understanding is that ZigBee targets wireless use of sensor and actuator interface in personal area networks (PANs). ZigBee and IEEE 802.15.4 are different in that ZigBee corresponds to the network (NWK) and application (APL) layers built on top of IEEE 802.15.4 MAC and PHY layers.[7] ZigBee focuses on wireless products in markets particular to home automation, building structure sensors, medical device monitoring, etc. Integrated hardware modules and chips are abundantly available for developing ZigBee capable products, but generally require manufacturer specific development environments with limited application objectives. Researchers interested in custom formulated data collection schemes may not find ZigBee conducive to their task.

The University of California- Berkeley originally developed TinyOS; and has since shared their work with Intel Corporation, Santa Clara, California, and the open-source community. TinyOS is an embedded operating system consisting of task modules for sensing, control, and mesh networking. It configures sensor nodes based on their specific tasks by linking sensing and control modules in software. TinyOS binds the sensing and control functions, and allows different sensor nodes to communicate in the mesh network environment. The development environment for TinyOS is the result of many research projects that combine different goals to give users many facilities for deploying a new WSN. While this is convenient for researchers working on the fundamentals of wireless sensor networking, it also presents challenges for researchers wanting to apply WSN techniques to real-world problems. These challenges often include bloated and poorly documented development material along with version-riddled firmware. This results in a steep learning curve that is difficult for new would-be WSN users to manage.

The main disadvantage of technologies such as ZigBee and TinyOS lays in their complexity and reliance on software integration skills. Frustrations, unwanted consulting costs, and expensive training sessions inhibit researchers desiring custom sensor experimentation via WSN technologies. Current

[7] Refer to Open Systems Interconnection Basic Reference Model for a theoretical layout of layered communication systems (ISO/IEC JTC1).

generation ZigBee and TinyOS devices are difficult to configure, and offer no guarantee of time-determinant operation. Until these popular architectures reach a more easily deployable status, other rudimentary and direct solutions are appropriate.

SUPPORTIVE INFORMATION FOR HARDWARE SELECTION

SENSOR TYPE AND PARAMETERS

Locomotion and position of an animal's head and muzzle can be used to identify cattle grazing activity. Grazing is defined by front to back muzzle movement in which an animal grasps a clump of grass with its tongue, pulls the clump into its mouth, then slightly jerks thereby sheering grass stems and leaves against its upper incisors. Researchers have long exploited this phenomenon for monitoring foraging activity of ruminating livestock (Stobbs, 1970; Stobbs et al., 1972; Chambers et al., 1981; Luginbuhl et al., 1987; Matsui et al., 1989; Rutter et al., 1997).

Reed et al. (2007) exhibited a proof-of-concept device using a halter-mounted miniaturized data logging module that used a dual-axis accelerometer as the sensing mechanism. During their experiment, raw acceleration data was collected and correlated with time synchronized video (Figure 10). Reed et al. (2007) defined accelerometer selection criteria as a dynamic range of ±750 m*g* and a minimum static range of ±2000 m*g*. They also noted that ±250 m*g* was the dynamic range consisting of the most useful working data; and recommended this static range for sensing tilt respective of head elevation. Their work showed that the sensor-device sampling regime should have a minimum 120-ms sampling interval per axis for bite rate detection. However, this interval was intended for minimal sampling that targeted average muzzle movement frequencies during grazing, which Figure 10 illustrates to be approximately below 2 Hz. The result of their study was that an accelerometer could be used to effectively characterize grazing activity (i.e. head position, bite rate, bite intensity, and individual bites).

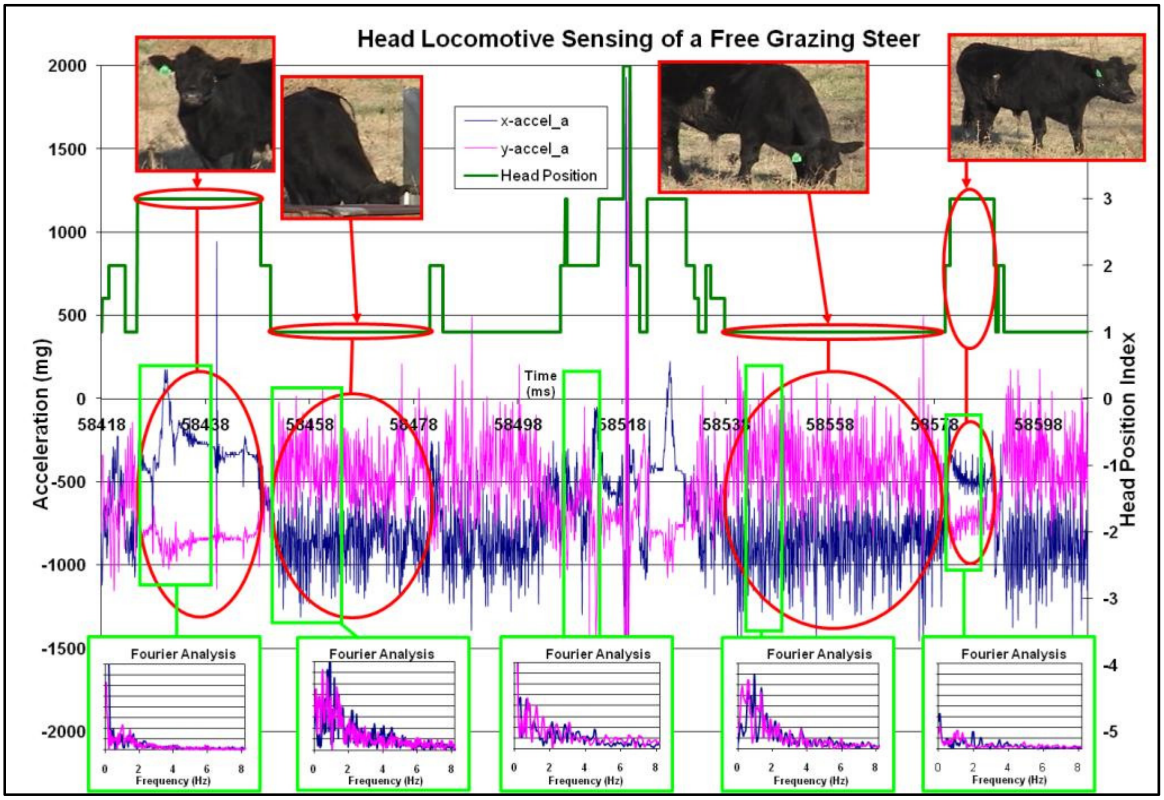

Figure 10. Chart of raw accelerometer data and preliminary Fourier analysis representing a grazing animal. Image obtained from Reed et al. (2007).

MICROCONTROLLER AND DEVELOPMENT NEEDS

The major considerations in selecting a microcontroller (MCU) were unit performance, power consumption, peripheral features, physical size, and availability of well-documented development tools. Embedded designers have many options available when selecting an MCU, ranging from 8- to 64-bit, RISC or CISC architectures, and clock speeds from 4 kHz to 4 GHz. MCU power consumption can range from sub-milliwatt to hundreds of watts, and generally trends proportionally with performance. Many microcontrollers include integrated peripherals, allowing the MCU to provide features that would otherwise require additional ICs. MCU's are available in a wide array of physical packages ranging from the rather large Plastic Dual-Inline Package (PDIP) to the diminutive Micro Small Outline Package (MSOP). Finally, different MCU's offer varying levels of development support, such as source code, programming examples, and documentation. Mature product lines can offer designers with improved debugging and programming support when compared to recently introduced MCU's.

Experimenters and developers desire wireless sensor modules to combine small size, low power consumption, modest computing power, and ease of deployment. As such, a selected MCU should integrate many peripherals to reduce PCB size requirements, and should be a mature product with easily accessible development tools enabling novice to mid-level embedded designers targeting applied wireless sensor research.

WIRELESS COMMUNICATIONS

Radio communication theory has long used the concept of free-space path loss as a starting point for determining the physical capabilities of wireless communication systems. Most modeling techniques revolve around cellular and radio communication systems where a base antenna is positioned high in the air (i.e. 30 m) and a mobile device is close to the ground (i.e. 1-2 m) (Agrawal et al., 2003). Little research supports modeling near-ground systems such as wireless sensor applications, where both receiving and transmitting devices are at similar low heights (i.e 0-2 m). However, recent studies address this void (Molina-Garcia-Pardo et al., 2005; Sawant et al., 2007; Comeau et al., 2008; Tate et al., 2008). Many empirical models have been offered to delineate urban, suburban, indoor, and open space environments but have not been confidently established to represent near-ground, short-range wireless devices (Hata, 1980; Rittas et al., 2004).

Near-ground wireless communications are extensively concerned with Fresnel zone interference. Fresnel zones represent the space adjacent to line-of-sight paths where interference may occur because of diffraction. When Fresnel zone boundaries are crossed or aligned with interfering media, signal losses are expected to occur. Empirical methods are commonly used to value interference levels associated with Fresnel zones. More sophisticate methods of evaluating electromagnetic alterations of a radio wave are extremely difficult and often inaccurate thus warranting empirical approaches. Molina-Garcia-Pardo et al. (2005) illustrated that near ground path losses can be best modeled with a two-slope log-distance model that accounts for near-ground and ground cover attenuations after a breakpoint distance has been surpassed. Comeau et al. (2008) used a two-part evaluation where wireless sensor network clusters could be defined by free-space path loss alone when node-to-node distances were shorter than the breakpoint. Beyond the breakpoint, they used a log-distance equation to model propagation losses. These breakpoint distances are related to first Fresnel zone interference and media type, which are both evident in near-ground wireless sensor applications.

Besides ground-based interferences, other biological attenuators are common to outdoor applications and have also been empirically characterized. Seker (1995) provided theoretical and experimental attenuation measures for a Florida forest recognizing both horizontal and vertical polarized transmissions along with obstructions from tree trunks, leaves, needles, and branches. Seker concluded that vertically polarized UHF frequencies above 400 MHz encountered a cumulative 0.263 dB/m attenuation. Tate et al. (2008) noted experimental losses of 5 dB and 10 dB for rain and cornfield environments, using a 2.4-GHz device at a 1.5-m height and 100-m transceiver spacing. They also collected data for 50- to 200-m device spacing, and at 0.5- to 2-m heights, and showed that approximately 10 dB could be lost from a 0.5-m height decrease. Path loss appeared to lessen for heights above 1.5 m and at distances beyond 200 m; and an average 0.12-dB/m attenuation rate was estimated from Tate's grassy field data. Molina-Garcia-Pardo et al. (2005) evaluated on-ground 868-MHz devices for smoothed-soil ground, building area, and grass lawn. They estimated attenuations for each environment at 1.89 dB/m, 0.41 dB/m, and 0.52 dB/m, respectively. These values were high, mostly because on-ground antenna placement and the associated Fresnel zone interference. For agricultural and outdoor environments, a wide range of attenuators can be conservatively assumed to contribute 0.1 to 2 dB/m losses, in addition to free-space loss.

DATA STORAGE NEEDS

Monitoring cattle in a free-range grazing environment presents a situation where data download from on-animal sensors might be infrequent, and must be handled in an opportunistic fashion. Wireless sensor deployments with long-duration experiments require a substantial amount of on-board storage to prevent data loss between download opportunities. This is largely due to the mobility of animals in their grazing environment, as the transmission distances of low power short-range devices (i.e. Tx distances < 300 m) do not match the perimeters and physical areas ordinary to inhabited pastures. For instance, grazing cattle can commonly be at distances greater than 800 m away from the nearest communicating device because many pastures cover extremely large areas. When an animal comes within range of an interrogating device, all information previously stored should be downloaded at that opportunity. Because of these constraints, a wireless sensor module must possess facilities to store data for a lengthy interval, until the animal moves within range of an interrogating data sink.

VOLTAGE REGULATION

Radio link quality is highly dependent on power-supply noise characteristics, and often requires great efforts in supply filter design. Furthermore, wireless data transmission usually consumes more power than any other function in a wireless sensing device, which demands designs that are conscious of power efficiency. Two kinds of regulators commonly used in wireless sensors are switching and linear low dropout (LDO) types. Switching regulators are often used to achieve better power conservation. They are easy to implement in constant-current applications, but tend to produce noisy signals when operating at a small fraction of their rated current. Alternatively, linear regulators are easy to implement, stable over varying current levels, and are solid providers of low noise power. However, they can be somewhat inefficient if poorly implemented.

The common advantage of a switching regulator is efficiency, and in some cases, a buck-boost design can be implemented to extend usable range of a battery to below the regulated output voltage. A switching regulator is, in essence, the combination of a switch, capacitor, diode, and an inductor. The regulator operates by maintaining a voltage drop across the device while preserving potential in the capacitor and current in the inductor. Displaced energy is recovered during the discharge phase of the switching cycle, and is essentially a phase change in the current with respect to voltage. The regulated voltage is characterized by a cyclical, yet tolerable, varying voltage that is centered on the target output voltage. More complex switching regulation methods are based upon this simplified interpretation.

A linear regulator use resistive mechanisms to drop voltage while dissipating energy in the form of heat. One of the advantages of a linear regulator is that a steady regulated output voltage is easily achieved. LDO regulators are a subclass of linear regulators, and are distinguished by the narrow difference between input and output voltages in which regulation is maintained. A greater portion of a battery's energy is therefore used because the battery's voltage is dropped to a lower level than is possible with an ordinary linear regulator. Additionally, the narrow difference between battery voltage and regulated output voltage allow for less heat loss, thereby requiring less energy dissipation improving efficiency. Normal linear regulators are somewhat less efficient than LDOs as they require larger input voltages and more heat dissipation, not to mention their inability to use battery voltages slightly above the regulated output voltage and less of a battery's energy profile.

LDOs have an advantage over switching regulators in that they can operate more smoothly at very low current levels. This is important for wireless sensor systems, especially in cases where low current, power-saving modes are employed. LDOs also operate more consistently over wider current draw ranges than do switching regulators. However, switching regulators provide advantageous performance when used for a constant current draw application where the current is within a specific range. To combat situations where switching regulators face varying currents, control loops are designed into switching regulator circuitry to help maintain an optimum switching frequency. An unfortunate affect of varying currents imposed on switching regulators is enhanced noise in the regulator's output voltage because of its switching operation. Alternatively, an LDO is relatively insensitive to current variation while maintaining efficiency and low noise output.

These differences are pertinent to wireless sensor devices controlling a radio transceiver that often causes variable current requirements on the magnitude of a few milliamps upward to tens of milliamps. This presents a significant concern for power conservative systems as well as noise sensitive operations like transceiver modulation or demodulation.

CHOOSING/VALIDATING COMPONENTS AND CONFIGURATION DETAILS

SENSOR AND SAMPLING

Based on Reed et al.'s (2007) work, the authors determined that an accelerometer sensor was an appropriate selection for the proposed miniaturized PCB grazing sensor. A low-voltage motion and tilt measurement sensor from Analog Devices, Inc., Norwood, Massachusetts was selected. The chip model is ADXL330 and is available in a small chip scale package (CSP),[8] measuring 4 mm X 4 mm X 1.45 mm. The ADXL330 is surface mountable, operable from a 3-volt supply, has three orthogonal axes with ±3 *g* range, and has a 300 mV/*g* resolution. The accelerometer's operating parameters are compliant with the selection criteria discussed previously. This selection also supports further sensor development as opposed to the two-axis device used in Reed et al. (2007). The sensor's third dimension represents side-to-side motions of the head/muzzle, which may possibly correlates with bite/grazing intensity.

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[8] Modern chip manufacturing technique where final component is fractions larger than the underlying chip die. See Institute for Interconnecting and Packaging Electronic Circuits (IPC) J-STD-012 for specifics.

A passive bandwidth filter was implemented to condition sensor output prior to the ADC. Manufacturer documentation specified the noise densities of the sensor's z-axis to be 350 μ*g*/√Hz, and 280 μ*g*/√Hz for x- and y-axes. Documentation also provided Equation (1), which yields minimum detectable acceleration change by using both noise density and bandwidth.

$$\text{rms noise} = \text{noise density} * \sqrt{\text{bandwidth} * 1.6} \tag{1}$$

For instance, a 25 Hz bandwidth relative to the z-axis yields a minimum detectable acceleration change of 2.2 m*g*, an exemplary quantity regarding the ±250 m*g* dynamic range criteria. This also equates to a minimum usable voltage change of 0.66 mV fed into the ADC.

Reed et al. (2007) illustrated spectral results for various animal activities and the ability of Fourier analysis to characterize grazing. Fourier analysis requires appropriate sampling relative to band limited applications, finite sample sets, and near-continuous signals. Grazing bite rate was discussed in Reed et al. (2007) to exist in the range 0.5-8 Hz. Therefore, the authors chose 8 Hz as the maximum possible biting frequency, which would require at least a four-times sampling rate (32 Hz) for Fourier analysis. Sample rate is directly related to sample size and has been evaluated relative to memory capacity, phenomenon characteristic, and processor performance. Additionally, a 50 Hz bandwidth filter was used and includes a larger frequency range considering the 32-Hz desired sampling rate. This allows for investigating higher frequencies in support of future sampling and filter development, while maintaining an adequate noise level of 3.13 m*g*.

MICROCONTROLLER, CLOCK FUNCTION, AND DEVELOPMENT TOOL

The Chipcon[9] CC1010 was chosen to be the wireless device's MCU. The CC1010 is a low power, integrated single chip unit consisting of a radio transceiver, analog to digital converter (ADC), serial peripheral interface (SPI) master, dual universal asynchronous receiver/transmitter (UART), and real time clock (RTC). The device supports dual-system clock operation, along with having an industry proven 80C51 processor core. The MCU contained a considerable amount of code and data space with 32 kB of flash programmable memory, 2 kB of external RAM, and 128 bytes of internal RAM. This was a sizable

[9] Texas Instruments of Dallas, Texas is the provider of Chipcon products. Chipcon AS of Oslo, Norway became a subsidiary of Texas Instruments in 2006.

memory configuration for development of extensive programs custom to wireless networking features and lengthy sensor data processing algorithms. An on-chip radio transceiver was beneficial in that no peripheral transceiver chip-set was required. The radio was controllable via special function registers (SFRs) and associated macro functions rather than a communication bus. The dual-UART and SPI busses enabled easy integration of additional peripheral components. The ADC and RTC further reduced the need for external peripherals, as both functions are required for wireless sensor applications.

Dual clock functionality provided two operating modes: low power and high performance. Low-power mode used the slower clock, while the high performance mode allowed quicker processing of intensive functions such as sensor data algorithms or radio encoding. The two clock-crystal frequencies selected were 32.768 kHz and 14.7456 MHz. The low frequency clock was necessary to reduce power consumption during data collection. The MCU's documentation lists current draw to be as low as 1.3 mA in active processor mode when using the low frequency clock. The current consumption for the fast clock in active mode lists at 12.8 mA. With a 3-V supply, the system expectantly consumes 89.8% less power using the slow clock, but at just 2.2% of the computational speed.

The proposed data-sampling regime was verified to be compatible with the use of the 32.768 kHz clock. Verification procedures included test code that exercised the CC1010's ADC, while driven by 32.768 kHz crystal. Test code polled each of the three ADC channel buffers in sequence, resulting in 18.6 ms (53.7 Hz) total time for the entire three-sequence duration. The maximum read rate of all ADC channels was nearly twice as fast as the required sampling rate (maximum 32 Hz). This allowed for sufficient overhead procedures or faster sampling, if desired.

The primary advantage of the slower clock was its applicability to sampling a near continuous phenomenon such as grazing. As long as the sampling strategy could function with the slower clock, continuous operation for detecting grazing activities would efficiently consume power. Significant inefficiencies would occur in the form of wasted clock cycles if sampling functioned under the fast clock. Essentially, more clock cycles would elapse as wasted energy between sample periods. Alternatively, a fast processing mode was invaluable for processing large amounts of data in the form of complex calculations or intensive data manipulations, not to mention the requirement of a fast clock for radio functions. Combining the use of two clocks offered the best solution for efficient power management proper function execution.

The CC1010's 80C51 processor core provided a proven architecture supported by abundant developer resources. Novices, as well as experienced users, can access documentation that supports diverse applications, from introductory to complex, using this specific single chip processor/transceiver. Development support included a sizable product manual and a large selection of example code that quickly enables device functionality. The popular Keil™[10] integrated development environment (IDE) also supports the CC1010. This research used Keil µvision IDE software, CC1010 development board, and CC1010 development modules as the primary firmware development tools. Embedded C and in-line assembly were the coding languages used. The authors only used assembly in situations where efficient use of clock cycles was necessary.

The MCU's product documentation also offered PCB design guidelines, another enabling feature for novice developers. Documentation provided a board layout example and complete bill of materials for the development module. Adequate documentation and resource availability, such as that found with the chosen MCU, readily accommodates wireless sensor applications for users with basic knowledge of embedded hardware and programming languages. Many other chip manufacturers provide development platforms similar to that used in this research. Novice researchers and developers should select MCU platforms based on their experience and availability of hardware support, software support, and development environment.

TRANSCEIVER SETUP, ANTENNA, AND TRANSMISSION LINE

For novice embedded developers (and even experts), using an integrated microcontroller-transceiver and commercial antenna is unarguably trivial in comparison to radio chip-set integration. Furthermore, this allows actual control and configuration of device radios, where most commercial mote devices have radio settings that are fixed. Experimentation with antenna options is also not possible with most mote devices. In respect to existing commercial systems, users that do not require flexible radio operation can successfully deploy WSN applications. However, many researchers can benefit from having

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[10] ARM® of Maidenhead, UK acquired Keil™ Elektronik GmbH of Munich, Germany and Keil™ Software, Inc. of Plano, Texas in 2005. Keil™ – An ARM® Company offers software development tools for various chip architectures.

flexibility in these areas, as many of their research objectives might be dependent on custom networking schemes or modified radio settings.

The CC1010 radio-processor chip can use a portion of the Industrial, Scientific, and Medical (ISM) unlicensed bands regulated by the Federal Communications Commission (FCC) and International Telecommunications Union Radiocommunications Sector. Developers can configure the radio to operate in the 300-1000 MHz range. The FCC-designated ISM band within the CC1010's configurable range is 902 to 928 MHz. The availability of unlicensed bands was the main determining factor for carrier frequency selection. The authors expected little improvement from frequency selection within this narrow of a band, and arbitrarily chose 915 MHz.

The CC1010 transceiver uses FSK (frequency shift keying) modulation with several encoding options. The manufacturer integrated four encoding modes into the chip's hardware: NRZ (non-return to zero), Manchester, Transparent, and UART. The manufacturer intended use of Transparent and UART modes for testing and customization. NRZ and Manchester are well known encoding techniques. Developers can quickly utilize either mode by setting the appropriate SFRs. The Manchester encoding scheme required twice the bandwidth compared to NRZ, but is typically more robust, allowing for better sensitivity ratings. The manufacturer documentation outlined a sensitivity advantage of Manchester over NRZ to be 2 dBm (58% increased performance) for lower baudrates, and equal performance at higher baudrates. Documentation listed the 868 MHz carrier frequency ratings to be analogous with 915 MHz operation. The modulation frequency separation was also selectable within the range 0-65 kHz. Larger frequency separations provide better communication because of less sensitive bit timing accompanied by reduced interference. However, larger frequency spread also required more bandwidth, which was well suited for low data rates and small network applications. The authors selected a frequency separation of 64 kHz to insure robust operation, and because high data rates and complex networking features were not needed.

MCU used an 8 bit buffer for radio transceiver data handling, where either bit-by-bit or byte-by-byte methods could be constructed. NRZ and Manchester both used byte-by-byte methods. Software development modules supported both these encoding methods, which provided easy to use pre-coded functions and configuration routines. Because of available software, there was no need to program bit-by-bit or byte-by-byte handling of data at the buffer level. This supported rapid development while decreasing the need for extensive encoding knowledge.

The minimum and maximum modulated baudrate settings were 600 baud and 76.8 kbaud, respectively. Authors selected baudrate based on desired performance characteristics relative to sensitivity, carrier frequency, and data throughput. Manufacturer documentation provided frequency separation and baudrate relationships. The authors concluded that 19.2 kbaud would provide adequate data transfer capability along with an acceptable sensitivity level of -96 dBm. Product documentation suggests an expected 2 dBm sensitivity improvement for a one-half baudrate reduction. For instance, reduction of baudrate from 38.4 kbaud to 19.2 kbaud provides an expected 2 dBm sensitivity improvement. As such, baudrate reduction dramatically improves data transmission distance ranges; granted data transfer rate requirements remain low. Complex networking structures or high data rates require that higher baudrates and narrower frequency separations be selected; but with an expected loss of transmission distance and robustness.

The authors used the Chipcon-provided software package, SmartRF Studio[11], to configure the radio and select proper SFR values. Register values were selected using a graphical interface, which could program settings directly to the chip via a development board. The purpose of the program was to support pre-application selection of RF settings and parameters. SmartRF Studio also assisted with impedance matching for the LNA (low noise amplifier) and PA (power amplifier) transmission line components, and selection of the inductor component for the VCO (voltage control oscillator).

The antenna's transmission line was designed for proper impedance matching. The antenna and transmission line impedances were set to 50 **Ω**, in compliance with the manufacturer specifications. Microwave & RF (2006) presented a reduced calculation (Equation (2)) for determining copper trace dimensions on an FR4 PCB material using a calculation from the IPC[12]-2141 standard (Equation (3)).

$$W = \frac{10 * H}{1 + \varepsilon_r + \frac{T}{H}} \tag{2}$$

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[11] Free development software distributed by Chipcon (see second footnote) to customers for the support of integrated radio transceiver chip models.

[12] IPC, originally named Interconnecting and Packaging Electronic Components, now is the Association Connecting Electronic Industries®.

$$Z_o = \frac{87}{\sqrt{\varepsilon_r + 1.41}} * \ln\left(\frac{5.98 * H}{0.8 * W + T}\right) \quad (3)$$

W, H, and T were trace width, height, and thickness, respectively. The dielectric constant of FR4 material is ε_r, and Z_o represents impedance. The trace width was calculated to be 307 µm (12 mil) using 35.6 µm (1.4 mil), 178 µm (7 mil), and 4.6 as T, H, and ε_r respectively. The board manufacturer provided trace thickness, dielectric thickness, and dielectric constant.

Antenna selection was based on concealment needs and radiation pattern. An an omnidirectional antenna that supports near-random positioning was desired. The common antenna types considered were whip, helical, and board trace. The authors expected that a copper trace would require difficult tuning methods, and a whip style antenna was too large for concealment purposes. Monopole whip antennas are often used in wireless sensor systems, but are too large for the desired level of concealment. A commercial, permanent-solder-mount antenna was selected for its durability and easy integration. A ¼-wavelength, compact-helical antenna was used in the final design. This kind of antenna could be mounted perpendicular to a board or at a 90° orientation from the board's edge. A 90° configuration was selected to maintain the lowest profile while providing a usable radiation pattern. The selected antenna was 14.5 mm (0.57 in) long and 7.0 mm (0.28 in) in diameter, and was operable with a 916-MHz carrier frequency, 30-MHz bandwidth, 50-Ω impedance, and a -2.16-dBi maximum gain with a near-omnidirectional azimuthal pattern. It was reasoned that a 916-MHz carrier frequency and 30-MHz bandwidth were sufficient for a 915-MHz configured transceiver with 64-kHz frequency separation. A larger bandwidth and gain could potentially be accomplished with a monopole whip-style antenna, allowing for more complex networking abilities and higher data rates. However, such added complexity was not deemed necessary for the proposed system.

Propagation Loss, Transmission Power, and Link Budget Estimate

The Friis equation (Equation (4)) is widely known and used to calculate free-space path loss. The log-distance method (Equation (6)) is an extension of the Friis equation where environmental obstructions can be accounted for via an efficiency parameter that increases path loss with distance (Rappaport, 2002). Even though a two-slope log-distance model and other combined models were shown to describe particular attenuating scenarios, a one-slope model (Equation (6)) was used to illustration propagation losses for a 915 MHz carrier frequency (Figure 11). Equation (6) is a result of Equations (4) and (5). Equation (5) is an evaluation of Equation (4) using 1 m as the base distance, d. Wavelength, *λ,* is equal to the speed of light (2.998E8 m/s) divided by the carrier frequency, *f*, in MHz. An attenuation factor is represented by *n* and is equal to two in the case of free space; values greater than two are for environments with larger attenuating effects. Figure 11 illustrates varying values of *n*, starting with free-space path loss and increasing *n* values up to five for severe attenuating environments.

$$PL = 10 * \log\left(\frac{16 * \pi^2 * d^2}{\lambda^2}\right) \quad (4)$$

$$PL_{d0} = -27.55 + 20 * \log(f) \quad (5)$$

$$PL = PL_{d0} + 10 * n * \log(d) \quad (6)$$

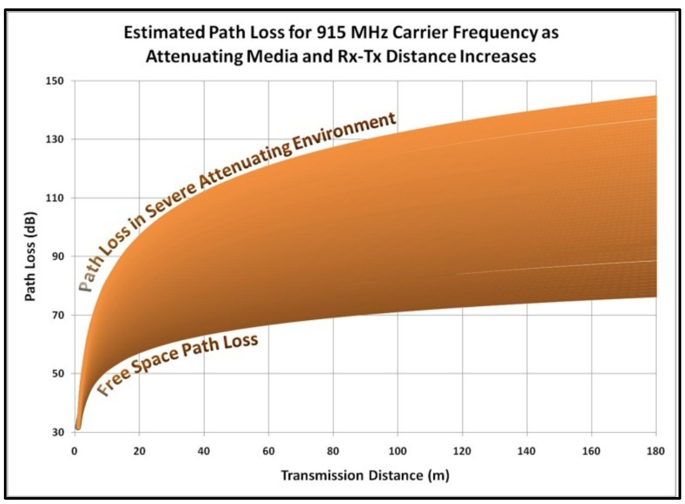

Figure 11. One-slope path loss model using the log-distance method.

In addition to propagation loss, transmission distance and data throughput are two heavily weighted variables determining device use. These two parameters are closely related to a device's transceiver power settings. In order to achieve a robust maximum-length RF connection, the power setting must be high enough to propagate through imposing media. Environment characteristics and experimentation needs will determine whether or not power settings are sufficient or if lower settings can be used. Maximum settings were chosen so that communication limits would always be evaluated first. If transmission could not occur at maximum power settings then improvements are needed in other variables; likewise, if transmission is possible then power conservative methods could be implemented using lower settings. Maximum output power using the 915 MHz carrier frequency, and with a 14.7456 MHz system oscillator, was specified in the manufacturer's documentation to be 4 dBm (2.5 mW). At these settings, a total MCU-transceiver current consumption was expected to be 38.5 mA (115.5 mW for a 3-V system). For an antenna gain of -2.16 dBi, transmission power of 4 dBm, and 3-m free space path loss of 41.2 dBm (calculated using Equation (6)), an estimate for equivalent isotropic radiated power (EIRP), not including transmission line loss, was -39.36 dBm (4.37E-37 mW).

Understanding the propagation and radio configurations are essential to device deployment. Link budget is an accounting method used to match wireless systems with operational needs by including both device and environmental factors. Transmission power, receiver sensitivity, antenna gains, and free space path loss were used to determine an expected link budget. It was assumed that adequate polarization matching and sufficient first Fresnel zone clearance existed with the antenna positioning of both transmitter and receiver. Link budget was calculated using Equation (7), where P_{Tx} was transmitter power, G_{Tx} and G_{Rx} were antenna gains, and PL was path loss.

$$LB = P_{Tx} + G_{Tx} + PL + G_{Rx} \tag{7}$$

Receiving and transmitting antenna gains were considered the same and have been previously identified as -2.16 dBi. Maximum PA setting was 4 dBm and receiver sensitivity has been identified as -96 dBm. Free-space path loss is dependent on distance and was shown as the lower curve in Figure 11. It was evident that antenna gains and transmission power was significantly dominated by path loss and that link budget was easily determined by shifting up the curves found in Figure 11 by 0.32 dB. An arbitrary, yet common value of 15 dBm was used to account for noise in addition to the receiver's rated sensitivity. Including noise, an -81-dBm signal level must be present at the receiver input, or -78.84 dBm at the device location when also including receiver antenna gain. This equates to a maximum acceptable path loss of 80.68 dB. An acceptable path loss of -77 dBm was determined using Equation (7), where G_{Rx} was -78.84 dBm, P_{Tx} was 4 dBm, and G_{Tx} was -2.16 dBm. By using Equation (6), and the acceptable path loss, an estimated transmission distance of 282 m was determined for line of sight conditions. However, for a severe attenuating factor of four the estimated transmission distance would be shortened to approximately 16.8 m.

MEMORY ALLOCATION

The CC1010 MCU has a sizable bank of volatile on-chip memory. However, an additional memory chip was required to allow for data logging during long-duration experiments. Atmel Corporation's (San Jose, California) AT45DB64 data flash memory chip was selected. This device was easily integrated via an SPI interface and powered by a 3-V supply. The chip had 8.4 Mbytes of memory space in total, and was capable of retaining data through power cycle events, a feature not present with CC1010 on-chip data storage. Retention of data through power cycles was valuable for network management functions such as device identification storage, time re-synchronization, and network failure analysis.

A large amount of peripheral non-volatile memory was necessary to provide sufficient data storage periods between potential downloads. It was discussed earlier that the sampling rate may be 32 Hz for each axis. Using single byte values, three bytes are to be stored every 31.25 ms. A total memory space of 8.4 Mbytes could then contain approximately 24.3 hrs of data if sampled continuously. A 16-Hz sampling frequency would provide 48.5 hrs of continuously sampled data. This is well within reason for developing grazing sensor algorithms, as grazing bout durations are thought to be well below either of the periods noted for 16- or 32-Hz sampling regimes. Further sampling strategies could be deployed allowing for intermittent periods when data is not relevant to grazing, thereby lengthening the total sensing period prior to a required data download. The sizable memory chip selected also provides the capacity to store data from multiple integrated sensors after algorithmic and data compression techniques are employed.

COMPARISON OF VOLTAGE REGULATORS

Two voltage regulators were investigated. Each regulator was evaluated relative to radio transmission and power efficiency. A switching regulator configured in a buck-boost application was first assessed. Two operating modes were investigated: low noise and high efficiency. High efficiency mode proved exceptionally noisy, with an approximately 380-mV amplitude, high-frequency noise imposed on a 230 mV saw-tooth output signal (centered on a 3.3-V output while supplying 15.2 mA). The regulator's documentation showed efficiency at this current level and mode to be approximately 85%. Low noise mode resulted in a ringing characteristic exhibited by the regulator's output. This noise profile was best described as a 250-mV spike occurring every 22 ns followed by a 60-mV ripple at a 180-MHz frequency. The regulator's data sheet claimed an efficiency of 68% for ~15 mA current output when in this mode. For best switching regulator noise and efficiency performance with this regulator, a current output between 50 and 500 mA and low noise mode should be configured. This was unlikely because the MCU consumed 38 mA when using the radio transceiver; and the transceiver was to be momentarily activated. Otherwise, the MCU was intended to operate with lower power while collecting and processing data. These low power operations are outlined by the CC1010's documentation to be between 1.3 and 15 mA. Because the current requirements change in magnitudes greater than 50% and are at low levels, the switching regulator is obviously challenged in areas dealing with both noise and efficiency.

Basic RF communication tests using single transmitting and receiving devices revealed both low noise and high efficiency modes of the switching regulator inhibited RF communications. The test was conducted by setting up the CC1010's transmitter with Manchester encoding, a 4-dBm PA output, 9600 baudrate, and single-byte data packets. Both receiver and transmitter were positioned one meter off the ground and oriented to insure matching antenna-signal polarization. Distance between each device was gradually increased while successful reception was confirmed by serial output from the receiving device. The test environment was conducted in an open laboratory where minimal RF interferences were assumed. Successful transmission was only achieved for distances less than a few meters when using the switching regulator. Neither low noise nor high efficiency regulator modes provided a stable power supply capable of adequate radio functionality.

An LDO regulator was used to replace the switching regulator in the next generation PCB. The LDO regulator specifications included a 150-mA maximum current, 20-μV noise, and 270-mV dropout. Efficiency of an LDO regulator can be determined by the ratio of output to input voltage. Inefficiency occurs when using a battery with a nominal voltage much larger than the desired regulated voltage. In addition, a gradually sloping battery discharge profile is preferred so that change in efficiency is minimized. An optimum battery would have a nominal voltage slightly larger than the drop out voltage and with a small discharge rate.

A 16-mV amplitude output voltage was measured to confirm noise performance of the LDO regulator. The measured noise level exceeded data sheet specifications, but was well below noise levels experienced when using the switching regulator. Repeating the simple RF communication test described earlier, revealed good performance in radio transmission and reception. Tests included consistent packet reception for 100-m line-of-sight conditions, and up to 150-m packet reception. For distances farther than 10 m, tests were conducted outdoors with typical turf grass and asphalt ground covers.

Efficiency levels of the LDO were estimated for a lithium ion battery having a discharge profile starting at a full charge of 4.2 V down to 3.5 V, before reaching the drop out voltage level (~200 mV above 3.3 Vreg). At 4.2 V, an efficiency of 78% was estimated whereas 94% efficiency was possible at the drop out voltage. Provided that a standard lithium ion battery gradually decreases in voltage in a nearly linear manner under normal usage, an approximate average efficiency of 87% may be realized. This average efficiency was comparable to situations where the switching regulator experienced larger and more adequate current draw in accordance with its specifications. However, the LDO's expected efficiency proved superior to the switching regulator because of low current operations in addition to improved radio operation. More performance was further achieved using the LDO regulator because the drop out voltage decreased significantly with lower current requirements, according to manufacturer documentation (i.e. 210 mV at 50 mA; 150 mV at 10 mA). The LDO regulator proved to be an easily integrated, sound performing regulator that was compliant with the wireless sensor device's current consumption range. Conversely, the switching regulator performance was far from passable, with poor efficiencies for low current applications, and noise levels that rendered radio communication nearly unusable.

ADDITIONAL ADC

Wireless sensor devices are often required to incorporate multiple types of analog sensors. The MCU used on the proposed design included an integrated, three-channel ADC that was controlled through SFRs. The accelerometer sensor required use of all three ADC channels, one channel for each of its three axes. Many versions and models of peripheral ADC chips are available. An additional ADC chip would facilitate the addition of other types of sensors. An additional ADC was selected based on availability, power requirements, resolution, number of channels, interface method, and versatility.

The additional ADC had 10-bit resolution and could be interfaced using a three- or four-wire serial communication link. Channel selection was achieved through a multiplexed address method when in single ended mode; or the channels were configurable to be a differential input. A simple RC filter was added to each input channel per data sheet recommendations. Filter can be changed easily using basic surface mount soldering techniques, in the case that different filter characteristics are preferred. A through-hole, fine pitched array was added to board layout allowing for attachment of a header connector, or for direct wire soldering of sensor devices. The array included two power-ground connections along with two signal inputs, one for each ADC channel.

PHYSICAL PLATFORM AND PCB LAYOUT

The sensor board was required to have a small form factor for installment on a standard nylon turnout halter described in Reed et al. (2007). Nylon straps on halter were measured to be 25.4 mm (1 in) wide by 4.76 mm (0.1875 in) thick. Ideally, the board size would be narrower than the halter strap width and have the lowest possible profile. Free-range cattle typically perceive a halter as foreign and a nuisance thereby subjecting it to forceful acts of removal until the animal reaches a point of acceptance. During Reed et al.'s (2007) experiment, it was noted that an acclimation period of approximately one week was necessary before actual data logging could commence. In order to sense grazing activity, as well as other potential phenomenon such as morbidity, it was essential that the animal not be diverted from normal behavior. Instituting an acclimation period prior to experiment deployment contributed to decreased animal irritation, and a decline in unwanted behavioral alterations. A sensor with a small form factor and low profile, combined with animal acclimation to the halter, work to prevent sensor damage caused by forceful rubbing on hard structures or other animal-caused halter removal.

A sensor designed to mount directly to a PCB, which is commonplace in wireless sensor architectures, was desired. A halter strap, located on the side of the animal's face along its jaw structure, was the preferred sensor attachment site. Therefore, the device was strategically positioned on a test halter to capture appropriate animal head movements as discussed previously (Figure 12). The halter side strap ranged from 12.1 cm (4.75 in) to 14.6 cm (5.75 in) in length, depending on halter model, with dimensions listed for yearling- and cow-sized models, respectively. It was determined that a yearling-sized halter should be the target design platform, as a device built to fit the smallest halter would be easily implemented on larger harnesses. Thus, dimensions for a yearling-sized halter were used to determine maximum size criteria for device enclosures, and thus for the sensor devices themselves.

Figure 12. Standard nylon turnout halter equipped with custom enclosures. Custom wireless sensor and miniature GPS module are shown.

The sensor board was attached to the halter using a custom-made enclosure. The enclosure was constructed from common PVC pipe material using rudimentary heat-forming methods. Two parts were devised in a manner that allowed one to be seated inside the other, while the connection was sealed with a rubberized gasket (Figure 13). The ends of each part were compressed and drilled with mountable fastener holes. Halters were equipped with threaded inserts for securely fastening the enclosure to the halter. Fastener tabs were formed on the end of each part of the enclosure and required at least 4.8 cm (1.9 in) of space on the halter strap. This left approximately 7.3 cm (2.87 in) for the PCB and antenna to be housed inside the enclosure's cavity.

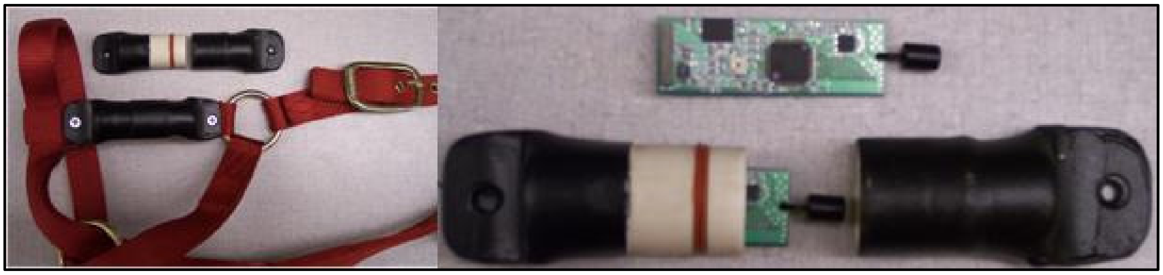

Figure 13. Custom two-part PVC enclosure designed to fit wireless sensor, mount to test halter, be environmentally sealed, and impact resistant. Placement on halter side strap (left) and sensor positioning in enclosure (right) are shown.

Additional to available halter space, IC and passive component layout was a significant influence on PCB dimensions. Since the device included both digital and analog systems, as is customary for wireless sensors, attention was given to component placement with respect to the antenna system so that transmission performance could be preserved. The antenna circuitry was located on the opposite end of board with respect to other peripheral components such as the voltage regulator, data flash memory, ADC, etc. The antenna, transmission line, and impedance matching components were all located toward one end of the board away from most other digital IC components (Figure 15).Ground plane layers and ground fill areas were incorporated to aid in protecting against potential digital noise issues. The antenna's specifications provided guidelines for location and ground plane size. However, it was noted that ideal ground planes are rarely achieved with wireless sensor devices due to board size constraints.

The MCU was positioned in a central location on the board, as it has features that requires multiple connections to a large number of peripheral components. The most challenging part of the MCU layout was its high-density package, consisting of four-sides, 64 pins, and 0.5 mm (0.0197 in) pin pitch. Connecting serial and I/O connections to a chip of this structure demands an orchestrated layout, especially on a small rectangular board when component/circuitry isolation was a necessity. Because of the MCU design and peripheral component needs, the PCB was designed to have six layers (Figure 14). Three layers (top, fourth, and bottom) were designated as signal layers and were constructed with significant ground fill areas. This provided ample ability to connect all components with the MCU while preserving digital/analog isolation as best possible. The second and fifth layers were ground planes, whereas the third layer was the power plane that was connected directly to the output of the voltage regulator circuit. All the ground planes were connected to battery ground. All ground planes and ground fill areas were also connected by a generous number of vias simulating a faraday cage in order to minimize any noise originating from the board or from external sources. A more precise ground design could be implemented with sophisticated design software, but this approach was deemed sufficient for novice level designers without access to such equipment.

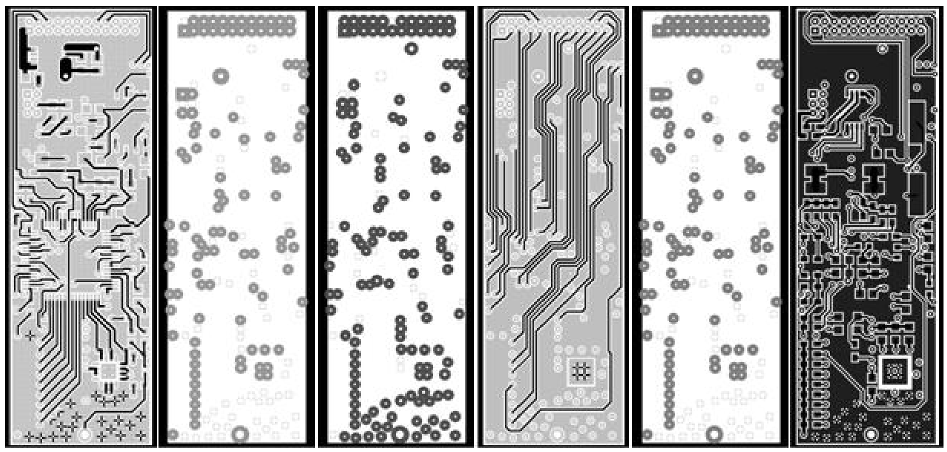

Figure 14. Board layers for custom wireless grazing sensor. Layers from left to right are: top, ground plane, power plane, signal, ground plane, and bottom. Top and bottom layers are both populated with surface mount components.

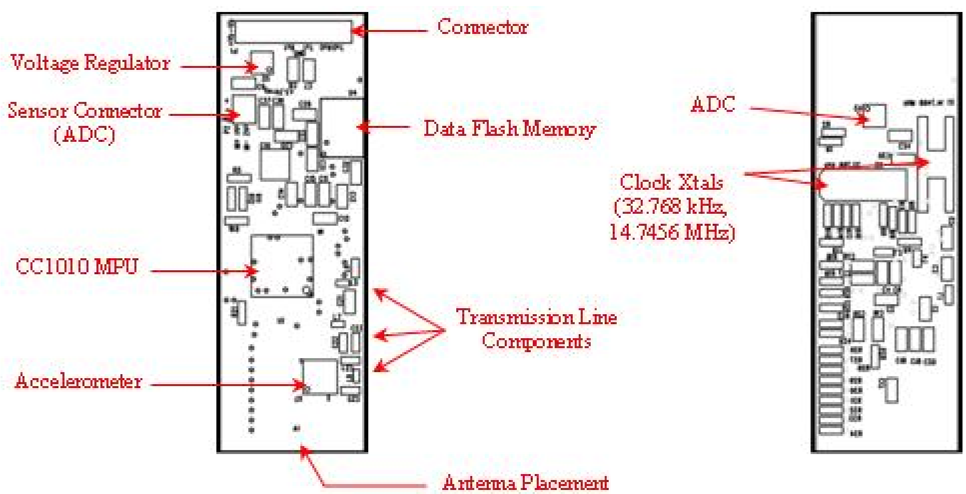

Figure 15. Silk screen layers for custom wireless grazing sensor. Primary components are identified. Top (left) and bottom (right) are shown.

A utility connection was added for programming and debugging functions in conjunction with the manufacturer's evaluation board's connections. This connection also provided a means for external battery power connection. The evaluation board provided a PC connection through a 3.3-V TTL-to-RS232 convertor, in addition to various input and output components such as switches and LEDs. The evaluation board was also equipped with potentiometers for simulating variable analog signal sources. The connector was a high-density dual-row header with a1.52 mm (0.06 in) pitch, a 2 X 12-contact array, and a profile height of 4.1 mm (0.161 in) above board surface. The next sizable component significant to profile height was the antenna. The antenna measured at 7.1 mm (0.28 in) above board surface and was located on the opposite end of the board away from the utility connector.

The final unpopulated board was 19.6 mm (0.77 in) wide by 58.5 mm (2.31 in) long. The fully assembled sensor dimensions were 19.6 mm (0.77 in) width, 71.8 mm (2.83 in) length, and 11.0 mm (0.43 in) thick. Overall board dimensions were extended the most by antenna length and thickness, whereas the 14.7456 MHz crystal determined overall height.

CONCLUSION

A miniaturized wireless sensor PCB was designed and built for monitoring grazing activity of free-range cattle. The significant design criteria and considerations were:

- Sensor selection with respect to sensed phenomenon
- Microprocessor and related development support
- Radio transceiver application and operability
- Memory storage for both sensor data and wireless network functionality
- Voltage regulation and power consumption efficiency
- Additional sensor integrations
- Physical apparatus for deployment
- Board size and component layout

Preliminary performance characteristics were calculated for the proposed sensor data sampling method, memory storage, radio communication, and power consumption. Data sampling rates were concluded from information provided by Reed et al. (2007), and determined to be in the range 16-32 Hz. The maximum possible sampling rate using the CC1010 microprocessor was measured to be 53 Hz, well above the required rate. A non-volatile memory chip was added to the board for the purposes of opportunistic data downloading strategies and retention of information in the event of power cycles. The memory chip could contain 24 or 48 hours of raw accelerometer data sampled at 16 or 32 Hz respectively. Radio transmission estimates were outlined for both transceiver configuration and propagation losses. Transceiver was configured with Manchester encoding, 64 kHz frequency spread, 9600 baudrate, and 4 dBm PA setting for robust operation. Antenna performance and propagation losses were evaluated using log-distance method and link budget analysis. A maximum possible transmission distance of 282 m (925 ft) was calculated for line-of-sight conditions and 17 m (55 ft) for severe attenuating environments such as near ground antenna placement or dense foliage. Switching and linear LDO voltage regulators were assessed. The LDO regulator proved to be the best choice, matching current consumption needs and low noise operations, while providing an estimated average power efficiency of 87%. The switching regulator was shown to produce radio-transmission-inhibiting noise levels and less efficiency for the expected current consumption. Component layout and board size was determined based on usage of multiple board layers and electrical separation of analog radio circuitry from digital parts and communication lines. The radio transmission line and antenna were located on the end of board away from other components; and multiple ground planes and ground fill areas were used to attenuate any noise issues that may occur. Final assembly size was 19.6 mm (0.77 in) width, 71.8 mm (2.83 in) length, and 11.0 mm (0.43 in) thickness.

ACKNOWLEDGMENTS

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CHAPTER IV

Foraging Detection of Free-grazing Cattle using a Wireless Motion Sensing Device and Micro-GPS

Chapter Preface

The material in this chapter was constructed for a professional presentation presented at the American Society of Agricultural and Biological Engineers, Annual International Meeting, Minneapolis Convention Center, Minneapolis, Minnesota, June 17-20, 2007. Presentation slides are included in Appendix A.

Author served as corresponding author and sole presenter. Dr. John B. Solie, Oklahoma State University, Biosystems Engineering Department, Stillwater, Oklahoma was the contributing author. Dr. John Solie assisted in development of initial research objectives and revisions concerning final material presented. Majority of work and writing were performed by the corresponding author.

Abstract

Quantification of specific animal activities within grazing herds of cattle is currently obtained by difficult and labor intensive means that are often obsolete. An on-animal wireless sensor device was designed and built to detect normal activities such as grazing, walking, and standing. These activities were detected using a low power electronic accelerometer sensor. A micro-GPS device was included in the test apparatus to provide geo-referencing capabilities for the purpose of creating grazing maps. Radio transceiver was also integrated for future implementation of remote control and device interrogation. Animal head locomotion was recorded over lengthy sensor deployment periods at sampling rates of 30, 116, and 120 ms. Experiment sampling periods entailed a large range of normal animal activities such as grazing, walking, standing, eating food supplements, drinking, fighting, chewing, urinating, etc. Raw accelerometer data was analyzed using basic discrete signal processing techniques (e.g. Fourier analysis).

Preliminary signal processing algorithms were investigated for the purpose of developing real-time sensing methods. Accelerometer data was compared to recorded video for truth-verification of animal activities. Grazing bouts consisting of only a few bites over a period of a few seconds were shown to be detectable using an accelerometer sensor. Bite rate was measured to be within 0.5 to 3 Hz (bites/sec) for cattle. Both frequency and amplitude of raw accelerometer signals illustrated distinct differences between animal activities. Single axis accelerations ranged from ±250 mg to ±1000 mg during grazing and ranged less than ±250 mg while standing. Grazing maps were generated from data collected with micro-GPS and accelerometer sensor. This research illustrated that grazing bouts and bite rate could be readily detected. Large amounts of accurate grazing information could potentially be collected near real-time using a wireless accelerometer sensing device, and with minimal labor and human-animal interaction.

INTRODUCTION

Application of new wireless technologies and non-invasive sensory devices are speculated to significantly advance cattle grazing research and management. Miniaturized electronic circuitry and wireless communication protocols have progressed, enabling wireless sensory devices to become conceivable and practical for use in free grazing cattle research. Advancements in GIS and GPS hardware have made it feasible to track free ranging animals. Wireless devices such as GPS, RF tags, and implantable boluses have been shown to provide valuable information and potential uses for advanced management programs. Bailey et al. (2001) monitored hill climbing and bottom dwelling breeds of cattle with GPS equipped collars to investigate breed selection for improved grazing distribution. Turner et al. (2000) laid groundwork for the use of GPS collars on free ranging cattle to study improved management techniques related to BMP programs in Kentucky. Ganskopp et al. (2001) analyzed data collected from GPS collars to assess cattle movements relative to water and salt supplement locations in large pastures. Ungar et al. (2004) used collars equipped with GPS and motion sensors to distinguish between grazing, traveling, and resting activities with up to 84% accountability. Koostra et al. (2004) followed Turner’s work by investigating GPS data obtained from collared cows to show beef cattle interactions with streams. Other impressive electronic devices include control collars that used persuasive stimuli (shock or sound) to herd cattle while grazing. Embedded electronic devices, assembled with a GPS, enabled location based triggering of behavioral altering stimuli (Agriculture Research Magazine, 2000). Malpas et al. (2005)

started a “Telemetry Project” that uses Bluetooth wireless protocol to help develop a data acquisition system monitoring physiological signals via implantable devices.

Considerable research and development efforts have applied sensory devices for managing free range grazing cattle. A vibracorder was used by Stobbs et al. (1970) to record the length and periodicity of grazing Jersey cows on pure stands of tropical grass and legume pasture. Stobbs et al. (1972) later utilized electronic micro-switches and mercury switches to record jaw movements and bites taken during grazing and rumination for different sward structure and composition. Horn and Miller et al. (1979) constructed an Animal Weight Telemetry System using “hoof-boots” equipped with pressure transducers and RF transmitters to remotely measure changes in animal weight in hopes of indicating overall forage uptake. Chambers, Hodgson, and Milne et al. (1981) used an electronic device to record total time grazing, jaw movements, and head movements automatically for both cattle and sheep grazing tall and short swards. Forwood, Hulse, and Ortbals et al. (1985) measured passage of boli within the esophagus of cattle via cannulas equipped with a pressure transducer and a conductivity transducer. Correlations between pedometer and vibracorder measurements were made by Phillips and Denne et al. (1988) to show variations in grazing behaviors of dairy cows. Matsui and Okubo et al. (1989) determined that grazing and rumination behavior could be automatically identified using displacement sensors attached to a cow’s jaw, foreleg, and chest. Matsui and Okubo et al. (1991) later employed a transducer, pulse generator, and heart rate memory unit to indicate bolus swallowing and regurgitation in free ranging cattle. Rutter, Champion, and Penning et al. (1997) used a noseband sensor fitted over the muzzle of sheep with a digital recorder to assess mastication and bite prehension during grazing with 91% accuracy. Laca and WallisDeVries et al. (1999) recorded acoustics via a head mounted microphone on cattle grazing differing types of turves to determine chewing, biting, and intake.

Other research related to monitoring livestock using electronic sensors include an implantable telemetry device that measured deep body temperature and heart rate, to monitor stresses in poultry and calves during transportation (Mitchell et al, 2001). Luginbuhl et al. (1987) used a contact switch embedded in a halter to determine ruminating, eating, and resting periods of stalled steers.

Use of sensory devices has been long perceived as a viable means of monitoring free ranging animals. However, data collection methods and maintenance of such devices have been less than optimum due to energy requirements, size constraints, technological support, and adaptability. Stobbs et al. (1970) discussed difficulties attaching a vibracorder to a grazing animal. Stobbs was forced to use multiple fastening straps and a complex weight balancing apparatus buckled around the animal's neck. Data was manually read from vibracorder. Matsui and Okubo et al. (1991) used a custom manufactured transducer stretched around an animal's muzzle. Data recording device was attached to a collar and had wires running to it from the transducer. Rutter, Champion, and Penning et al. (1997) used a transducer similar to Matsui and Okubo, but had a large "recorder pack" saddled around the body of a sheep. Wireless communication coupled with sensory devices should promote a more efficient and effective means of data collection and unit maintenance.

Packaging and application of wireless sensory devices for free grazing cattle presents a wide range of developmental needs. Wireless technologies are advancing at a rapid rate thus creating susceptibility for new devices to become obsolete quickly, while allowing insufficient time to validate their applied use in agricultural environments. Continuous evaluation and knowledge acquisition of advancements relative to wireless technologies and tracking, needs to be established. It is ideal for a new technology to adopt appropriate standards necessary to ensure industry wide compatibility as well as longevity.

Minimal efforts have been put forth to deal specifically with identification of sensor specifications and application methods in free grazing beef cattle production systems. Research data is needed and sensor application methods need to be explored for structuring parameters for design and development relative to a free grazing environment. This research utilized a specific sensor and integrated platform design for prototype wireless sensors coupled with a micro-GPS logging device. A new design for a grazing sensor device is proposed and uses available micro sized integrated circuit technology for sensory, management, and logging features. The three objectives of this research were:

1. Demonstrate that a micro sized IC accelerometer sensor is viable for accurately detecting grazing information in a free-range production system.
2. Show that geo-referenced grazing information can be constructed from grazing sensor and micro-GPS data for spatial analytical use.
3. Show that micro sized grazing sensors can now be practically designed and built for use with advancing wireless technology.

Materials and Methods

Ruminants grazing freestanding grass forages are characterized by head locomotion different from other normal activities such as walking, standing, drinking, and laying. Grazing is characterized by muzzle extension into a sward structure while protruding and wrapping the tongue around a gathering of plant stems and leaves. Plant material is then pulled into the mouth, by the tongue, while being pressed against ruminant's incisor teeth. Forage mass is also clasped between the mouth's dental pad and incisors. A motion combined of pulling and jerking of the head then causes plant material to be sheared against the incisors (Griffiths 2003). Distinct motions during grazing activity are detectable with motion sensors such as accelerometers.

Grazing may also be characterized by infrequent walking patterns. Grazing cattle typically take a small number of bites of grass between steps and travel across pastures in linear and zigzag paths, in a walk-graze-walk pattern. Number of bites taken between steps and movement pattern across a pasture while grazing may be related to forage uptake and/or grazing intensity. Head mounted accelerometer devices can provide ample information for distinguishing between these acts therefore providing important grazing information.

Preliminary Evaluation of Grazing Parameters with Video

Previous studies showed biting rates for domestic livestock ruminants, primarily including sheep and cattle, ranged from 0.5 to 8 Hz. To validate these findings and compare others' results with cattle in this region, video was recorded of grazing cows in a nearby herd owned and managed by Oklahoma State University in Stillwater, Oklahoma. Short video clips were recorded with a Sony digital camera at 30 frames per second. Video analysis included bite duration, distance of muzzle movement, and biting intensity. Bite duration was defined as the time between muzzle direction changes for each full bite taken. Biting intensity was defined by a custom three level index: strong head jerk, medium head pull/jerk, and nibbling. Muzzle movement distance was estimated. Muzzle movement distance and bite duration were combined to provide a general account for sensitivity and range of an accelerometer sensor. This information coupled with review of other similar research devices provided decent guidelines for specifying sensor and data logging design parameters.

Micro-electronic Accelerometer Data Logging Device, GPS, and Test Halter

An economic proof of concept design was needed to validate use of a halter mounted micro-electronic accelerometer and GPS logging device. This was a necessary step before more expensive resources could be allocated toward design of a robust fully integrated system. A custom micro-electronic accelerometer data logging device was constructed to collect high resolution data of head and muzzle movements for grazing cattle. Parameters for this device were identified from results of earlier studies and evaluation of short video previously mentioned. The goal of this design was to exhibit the ability of a simplistic halter mounted device for sensing grazing motion and GPS locations. The initial design variables included high sampling rates, multi-dimensional movement, adequate sensor sensitivity, micro sized device, easily interchanged mounting platform, and long sensor deployment periods.

The logging device was constructed from a PIC16C57 microprocessor, Memsic 2125 dual-axis accelerometer, Atmel AT45DB041B Data Flash memory, and a Maxim DS1302 real time clock. Code was written in PBASIC for the BASIC Stamp 2X interpreter supplied by Parallax, Inc. The microprocessor was interfaced with accelerometer, data flash memory, and real time clock. Programmable data log intervals were defined along with prescribed "sleep" and "wake-up" periods. All data was recorded and time stamped in data flash memory for later retrieval via serial connection. Figure 16 shows a flowchart of implemented code routines and overall operation.

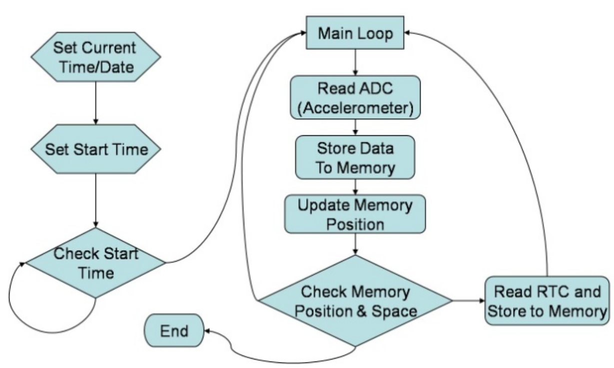

Figure 16. Flow chart of general code routines for accelerometer data logging device.

GPS data were collected. GPS fixes synchronized with accelerometer grazing data provided spatial information for forage management and grazing behavior studies. GPS device was sized for attachment to a standard nylon halter, as was the accelerometer logging device. A commercial vehicle tracking device was selected. These types of devices are readily available and can often be easily altered to fit most application.

Model G30-L GPS vehicle logging device with WAAS (wide area augmentation system) capabilities was purchased from Laipac Technology, Inc. of Canada. The GPS receiver was modified with a linear voltage regulating circuit enabling power supply from a standard +9 V battery instead of a vehicular +12 V system. Device configuration included one minute position fixes (with differential correction) logged continuously for at least three hours powered by a 1200 mAh 9 volt battery. Unit came with software for configuration, data retrieval, and graphical display of logged GPS data via serial communication.

A test halter was purchased from a local farm supply store. This halter is commonly known as a nylon “turn-out” halter and is intended for lengthy wear periods in a free grazing or open range environment. Both GPS and accelerometer logging devices were attached by T-nuts and 8-32 stainless machine screws. Accelerometer and power supply battery were enclosed in a custom PVC housing and attached to the halter’s side strap (Figure 17 b). Positioning the accelerometer to the side of the animal’s head was essential for proper accelerometer axes orientation relative to head tilt and movement while grazing. X axis was aligned lengthwise to animal’s head. Y axis was orthogonal to x axis in a perpendicular direction outward from top of the animal’s nose/muzzle. Axes positioning enabled sensing of head tilt, extension, and rotation while grazing. GPS was attached to halter’s buckling strap, positioning it behind the animal’s poll (Figure 17 b & d). Attaching GPS in this manner provided an upward facing position of the device’s antenna for least obstructed view of satellites. Power supply battery for GPS was encased in a PVC enclosure attached to opposing side strap (Figure 17 b). Battery positioning provided weight balance between left and right sides of halter. Power wires were routed through the halter’s nylon straps.

Figure 17. Instrumented proof-of-concept halter. a) Side view of test halter, b) top view, c) accelerometer data logging device, and d) GPS logging device

EXPERIMENTATION WITH PROOF-OF-CONCEPT DEVICE

Two experiments were conducted using a proof-of-concept micro-electronic accelerometer data logging unit. First study consisted of a large framed 900 lb yearling steer grazing a one acre bermuda grass pasture. Test halter was equipped with only the accelerometer data logging device. Grazing status, bite frequency, and bite intensity were shown by head tilt measurement and frequency analysis of accelerometer data. Video was collected to provide “ground-truth” information.

Second study combined both accelerometer and GPS logging devices. The test halter was outfitted to a medium framed 550 lb steer calf grazing 160 acres of winter wheat pasture. A color scaled map was created from accelerometer and GPS data showing both grazing intensity and location. Live observations were manually recorded on a time basis to provide “ground-truth” information. Video was not obtained in this experiment.

NEW WIRELESS SENSOR DESIGN

Following preliminary experimentation with accelerometer and GPS logging devices, a new wireless sensor was designed. Design requirements included extensive data storage memory, RF transmission capability, three axes accelerometer sensor, real time clock, micro-sized single board form, and low power consumption (using regulated +3 volt supply). Data storage memory was allocated relative to deployment period and sampling strategy. Sixty four megabits of data flash memory were selected (Atmel AT45DB64). At 10 Hz logging interval and for three axes accelerometer readings with 8 bit resolution, this memory device can store approximately 3.25 days of non-compressed grazing motion data. For the initial design, raw information was stored. A three axes accelerometer sensor from Analog Devices (ADXL330) was selected to provide six degrees of freedom measurement for both head position (tilt) and movement. The ADXL330 accelerometer sensing range was ±3 *g* with a calculated sensitivity of 39.1 m*g*/bit (for 256 bit range and +3.4 V source). A real time clock was necessary to synchronize accelerometer data with GPS and video. Microprocessor was a Chipcon CC1010. This device included many built in features such as three 10 bit ADC channels, real time clock, and ISM/SRD band radio transceiver (315, 433, 868, and 915 MHz). Sensor size was designed to accommodate a ¾" wide nylon strap commonly found on turn-out halters. Sensor size limitations were defined to be ¾" X ½" X 3" not including enclosure dimensions. Figure 18 shows a fully populated prototype sensor PCB. Prototype PCB design included a six layer board (three circuit layers, two ground layers, and one power layer) with both IC and passive components assembled on top and bottom layers. Surface mount components were dominantly used except for the connector and antenna. A total of 84 surface mount components were assembled using reflow solder method. Exact board dimensions were 0.77 in X 2.305 in.

Custom firmware was written and flashed into the embedded wireless sensor device. Firmware was generated using C code and compiled with Kiel µ-vision 3 development software. PCBs were programmed using a flash programmer provided by Texas Instruments. A serial downloading scheme was devised using hyper terminal connection to a PC and a series of activation switches responsible for triggering download and reset features. Future design implementations will involve complete wireless download using the microprocessor's built in radio transceiver. At this time, it is necessary to only download information through a wired serial connection.

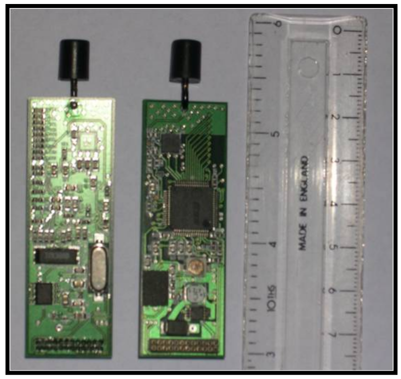

Figure 18. Fully assembled PCB with top (right) and bottom (left) layers shown. Antenna is located at the top of picture and connector is at the bottom.

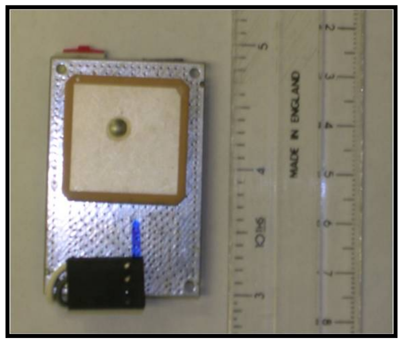

Figure 19. Micro-GPS tracking device commonly used on avian species.

A new GPS logging device was selected. GPS performance was required to be longer lasting while maintaining the smallest size possible. A unit commonly used for tracking avian species was purchased from NewBehavior AG of Switzerland. This particular GPS system is configurable for accuracy, logging interval, and power utilization. Logging intervals of at least one minute with five meter accuracy were specified for this application. The device was required to have enough memory storage for at least three days of continuous operation with one minute logging intervals. Various settings were briefly tested. Intensive evaluations of GPS configuration would be necessary to optimize GPS performance. It was suspected that placement of a micro-GPS device on a normal sized beef animal might result in RF signal degradation due to either antenna orientation or attenuation caused by animal flesh or neighboring foliage. Also, when animal is grazing and GPS device is brought closer to the ground due to head position, RF signals may be attenuated by earth surface interactions. This could be remedied by alternative placement of GPS device besides behind the animal’s poll. More complex testing apparatuses would then be necessary, and potentially more cumbersome to manage. More study is needed to verify animal, earth, and foliage interactions with GPS signal reception. Figure 19 illustrates the actual size of the GPS tracking device.

Lithium polymer batteries were selected as power sources for both accelerometer and GPS logging devices. These batteries were chosen because of availability, power density specifications, and ability to be recharged. Multiple sizes of these batteries with various power ratings are commonly available.

EXPERIMENT WITH NEW WIRELESS SENSOR DESIGN AND GPS

Three test halters were assembled with new wireless sensor and micro-GPS tracking devices. Power wires were routed through halter's nylon straps from battery enclosure to both GPS and accelerometer devices. Assembled halters were tested in a static environment for three days to verify functionality of firmware and GPS performance. Real time clock was checked against other standard clocking devices to validate timing sequences and stamping method. After static test was completed, storage memory was cleared and batteries were recharged.

Figure 20. Heifer with test halter in wheat pasture field.

An experiment was devised to field test new accelerometer data logging and micro-GPS devices. Three 700 lb heifers were randomly selected from a nearby Oklahoma State University herd in Stillwater, OK. This was a commercial type herd consisting of all heifers dominated by the Angus breed type. Herd was being backgrounded on approximately 80 acres of winter wheat pasture. Experiment was designed to last for three days due to length of allocated storage memory and GPS battery supply. It was assumed that none of these animals had experienced wearing a halter. Heifers were equipped with training halters until they became accustomed to wearing halters. Acclimation was expected to take at least one week. Once heifers were acclimated, test halters were then prepared and deployed. Heifers were identified by both numbered and colored ear tags. Figure 20 shows one of the heifers equipped with a test halter. Battery enclosure is on opposite side of the heifer's face, whereas accelerometer logging unit is clearly displayed on left-face side. GPS is located on buckled strap behind the animal's poll.

Two video recordings were made with a Sony digital video recorder and were time stamped using the camcorder's date features. Both samples were collected in a manner to provide ample evidence for grazing, walking, standing, and other various activities.

At completion of the three day test period, halters were collected and data was downloaded using a serial connection. Accelerometer information was extracted and converted from raw signal form into discrete time series data using m*g* units ($1g = 9.8$ m/s^2). Extraction and conversion were performed with Matlab software (version R2006a). Post processing involved basic DSP techniques, such as Fourier analysis, were conducted. Video data was analyzed and time stamped. Video data and accelerometer data were compared to verify specific signal patterns with animal activities. Three activities primarily considered were grazing, walking, and standing.

Results and Discussion

Characterizing Grazing Parameters with Video

Short video clips were used to determine initial sensor parameters for grazing motion. Specifically, head movements while grazing were evaluated. Thirteen short video clips of grazing cows were collected and analyzed for three parameters: bite duration, bite intensity, and muzzle movement distance per bite (Table 1). Frame-to-frame evaluation during a single bite motion was the procedure used. Three bites from each video clip were selected and analyzed. Estimates for velocity and acceleration were calculated using muzzle distance movement and bite duration. Both acceleration and velocity are plotted in Figure 21. Plot suggests there is a sinusoidal pattern characterizing muzzle acceleration. The sinusoids period was approximately 0.5 seconds (2 Hz). Even though this was a rough estimate of muzzle acceleration and bite rate while grazing, it still provided adequate information for determining accelerometer sensor parameters and sampling techniques.

Table 1. Evaluation of short video clips for determining grazing motion parameters.

Video	Intensity Level	Distance (m)	Time (ms)	Velocity (m/s)
1457	1	0.10	667	0.15
	2	0.05	533	0.10
	3	0.05	867	0.06
1458	1	ND	ND	ND
	2	ND	ND	ND
	3	ND	333	ND
1459	1	0.08	767	0.10
	2	0.15	367	0.42
	3	ND	333	ND
1460	1	0.25	633	0.40
	2	0.10	600	0.17
	3	0.03	367	0.07
1461	1	0.13	600	0.21
	2	0.10	500	0.20
	3	0.03	333	0.08
1462	1	0.15	633	0.24
	2	0.05	467	0.11
	3	0.05	500	0.10
1463	1	0.10	400	0.25
	2	0.10	200	0.51
	3	0.03	300	0.08

Video	Intensity Level	Distance (m)	Time (ms)	Velocity (m/s)
1464	1	0.25	467	0.54
	2	0.20	267	0.76
	3	0.05	500	0.10
1465	1	0.13	600	0.21
	2	0.03	533	0.05
	3	0.08	467	0.16
1466	1	0.13	500	0.25
	2	0.10	567	0.18
	3	0.03	800	0.03
1467	1	0.30	833	0.37
	2	0.08	567	0.13
	3	0.05	533	0.10
1468	1	0.13	367	0.35
	2	0.05	367	0.14
	3	ND	600	ND
1469	1	ND	ND	ND
	2	0.10	600	0.17
	3	0.05	467	0.11
Minimum		0.03	200	0.03
Maximum		0.30	867	0.76
Average		0.10	512	0.21
Range		0.28	667	0.73

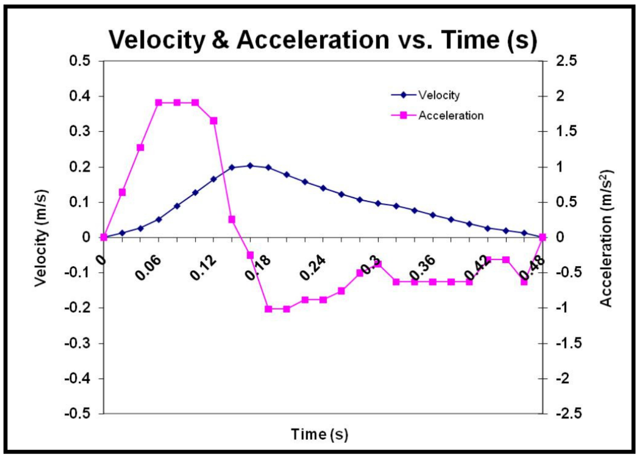

Figure 21. Estimated motion of a grazing beef animal determined by short video clips.

It was concluded from analysis of short video that average bite rate for a cow is 2 Hz (bites/second) and that muzzle acceleration occurs in a sinusoidal pattern (Figure 21). Nyquist sampling theory suggests that a minimum of two sample points per period must be taken to represent a given frequency. Following Nyquist sampling theory, a sampling period of 0.25 seconds would be sufficient to represent a 0.5 second biting pattern. However, it was concluded that a sampling period of at least 100 ms should be implemented in order to detect each bite taken during the act of grazing. This high sampling rate eliminated chances for aliasing effects and enabled possible detection of faster bite rates. It was determined that an accelerometer sensor must be sensitive enough to detect at least half the peak shown in Figure 21. This equates to approximately 1 m/s^2, or 100 m*g*. Most electronic accelerometer sensors are sensitive to less than 100 mg.

PROOF-OF-CONCEPT SENSOR DEVICE

Accelerometer data was collected at a high sampling rate during proof-of-concept experiment. High resolution data enabled better frequency analysis. Movement patterns of an animal's head during the act of grazing were observed with frequency analysis. Data collection was performed at 30 ms intervals, which was more conservative than 100 ms interval identified during short video analysis. It was concluded that most biting frequencies occurred between 0.5 to 1.5 Hz (bites/sec). Ground-truth data was collected using a digital video recorder collecting images at 30 frames per second. Video was processed and analyzed against accelerometer data to evaluate bite rate, and grazing status (Figure 22). Evaluation of 30 ms sampled data proved that an accelerometer data sampling rate of 100 - 120 ms is sufficient for future experiments, which is also vital for preserving memory and power requirements of wireless sensory devices.

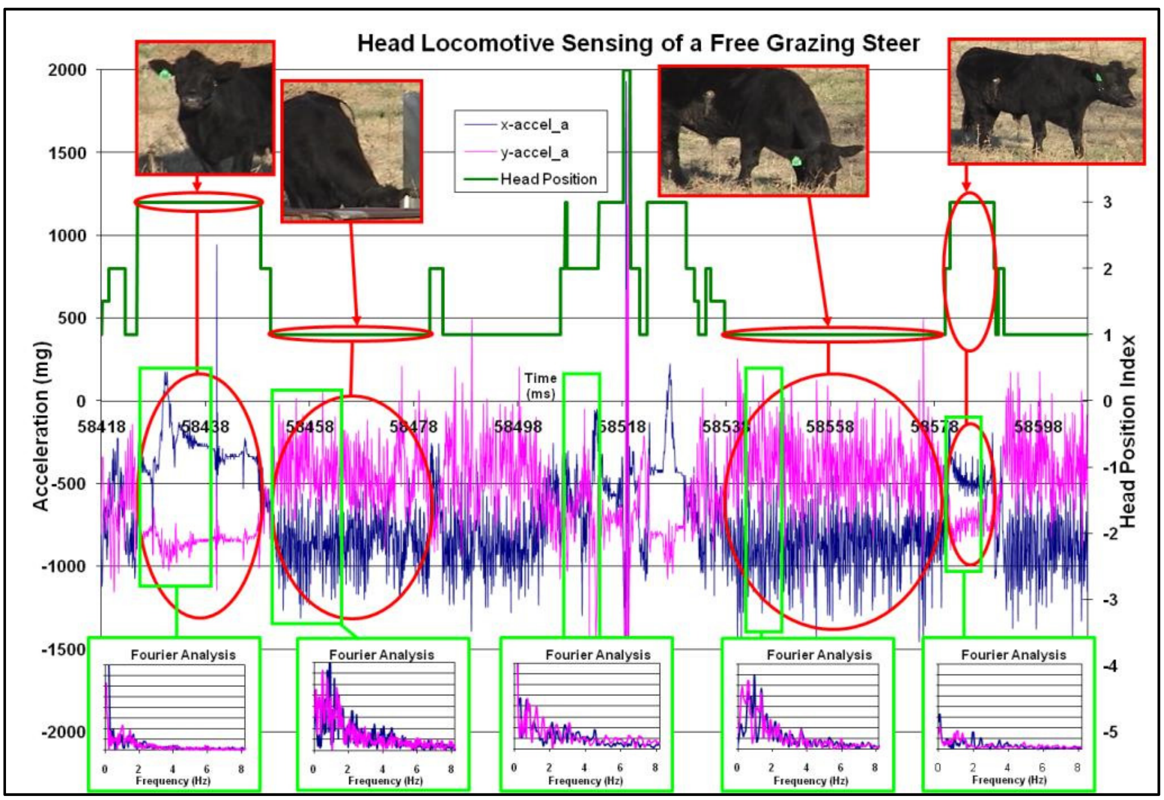

Figure 22. Head position and locomotion of a free grazing steer determined by video and logged accelerometer data.

Raw acceleration values for both x and y axes are shown (Figure 22). Signal patterns for grazing, walking, and standing animal activities were identified using video. Acceleration values were observed to have a range of ±250 m*g* on average, and occasionally ranging as high as ±750 m*g*. Earlier video analysis suggested 500 m*g* accelerations, which is in agreement with these findings. Head position data was determined by ground truth video, and is charted as "Head Position" in Figure 22. Notice the strong relationship between ground truth and raw accelerometer data. Both head position and motion portray specific acts of grazing. Fourier analysis exhibited distinct locomotive frequency differences for grazing vs. standing and walking.

Second part of experiment involved correlation and synchronization of accelerometer and GPS data. Personal observations were logged on a time basis to provide ground-truth information. It was shown that correlations between head accelerations, head tilt, and GPS position provides accurate grazing characteristics. Grazing characteristics were indexed from 0 to 3, 0 being "no grazing" and 3 being "most intense grazing." Indices 1 and 2 were denoted as "light grazing" (associated with fast walking) and "light to heavy grazing" (associated with slow walking), respectively.

Figure 23 shows raw accelerometer data logged at 120 ms intervals and walking speed determined from GPS data. For the period prior to 7:55 AM, data was not valid for analysis because steer was captured and haltered during this time, thus indicating that normal behavior began after 7:55 AM. No acclimation time was given in this experiment. The steer's actions, observed immediately after haltering, suggested that acclimation periods would be beneficial for future experiments. Figure 23 provides distinct relationships between head locomotion and grazing characteristics as well as significant correlations between grazing activity and walking speed.

A forage map of test field was generated from previously collected NDVI data. NDVI data were not a timely account of actual forage, but did aid in illustrating grazing-forage mapping capabilities. Acceleration data was geo-referenced and imposed onto NDVI map as shown in Figure 24.

Results from this experiment validate sensor parameters relative to sensitivity, sampling technique, and potential filtering/compression methods. An accelerometer with a range of ±2 *g* was shown to be adequate to distinguish head motions of a grazing animal, as acceleration signal amplitudes were observed to be mostly between 250 m*g* and 1000 m*g*. A sampling rate of 120 ms was shown to be sufficient for capturing sinusoidal head motions of grazing. Fourier analysis showed potential for providing data compression and other filtering mechanisms indicative of distinguishing grazing parameters such as bite rate and intensity.

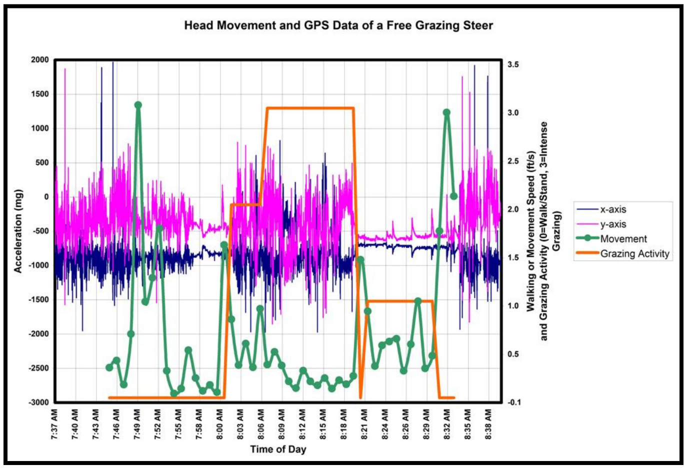

Figure 23. Head locomotion and GPS data for a free grazing steer.

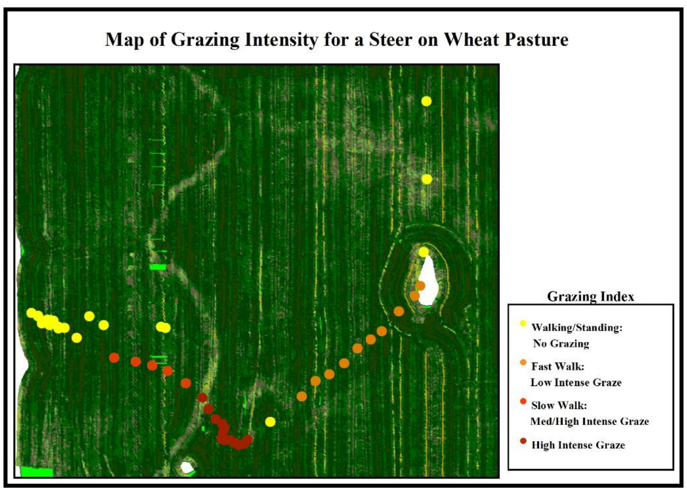

Figure 24. Grazing intensity map generated from test halter with accelerometer and GPS data logging devices.

PROTOTYPE WIRELESS SENSOR

Three halters were assembled with prototype wireless accelerometer logging devices and micro-GPS units were deployed for three days on three grazing heifers. Accelerometer logging devices were configured to collect samples for all three axes at 116 ms intervals. Sampling interval chosen was limited by microprocessor clock speed, and complied with the previously determined 120 ms interval. Halters were collected on last day of experiment and data was downloaded.

Data flash memory consisted of 8192 pages of 1024 bytes each. Each memory page was stamped (current time was stored into last 24 bit data field of each memory page) with a time value obtained from the microprocessor's internal RTC. During data download, time values were evenly distributed to give a discrete time series data set of accelerometer information. This method of time stamping was proven to be accurate during static testing.

Video was recorded at two different sessions during three day experiment. First video was 42 minutes and second was 1 hr and 28 minutes in length. Each video was manually converted into discrete data sets using Panasonic Motion DV software. Frame-by-frame analysis enabled precise determination of all targeted parameters. Parameters recorded from video were grazing, standing, and walking activities. Other information extracted from video were individual bites, head position, laying, fighting, and urinating. The analysis focused on grazing, standing, and walking activities.

Video analysis showed long periods of standing and intermittent periods of walking and grazing. Typically, each animal had resting periods that entailed either standing or lying. Resting periods rarely involved frequent head movements common to walking or grazing. As previously discussed, grazing acts consisted of lowered head position with extending/jerking cyclical motions. Walking was characterized by what is commonly referred to as "head bobbing" as the animals' head gradually and repetitively moved in an up-down and side-to-side motion. Walking and grazing motions were easy to identify using video.

Acceleration data was collected for entire three day period. Approximately three million data points for each axis were collected. Figure 25 shows a graph of each axis over 24 hour period within experiment's three day period. Notice that there are distinct periods where shifts in acceleration and signal frequency change. It was concluded from visual evaluation of raw accelerometer data that approximately 13 significant grazing bouts occurred during the 24 hour period shown (Figure 25). Further research where 24 hour periods of video are collected should confirm these conclusions. A grazing bout was signified by a distinct shift in average acceleration and increased magnitude of cyclical motions. X and y axis data show nearly matching results, as expected, whereas z axis data showed little contribution to distinguishing grazing motion. Perhaps other motions such as post-graze rumination can be observed with z axis as lateral movements of the bottom jaw may excite more z accelerations. These characteristics were also observed in proof-of-concept experiment (Figure 23 and Figure 24).

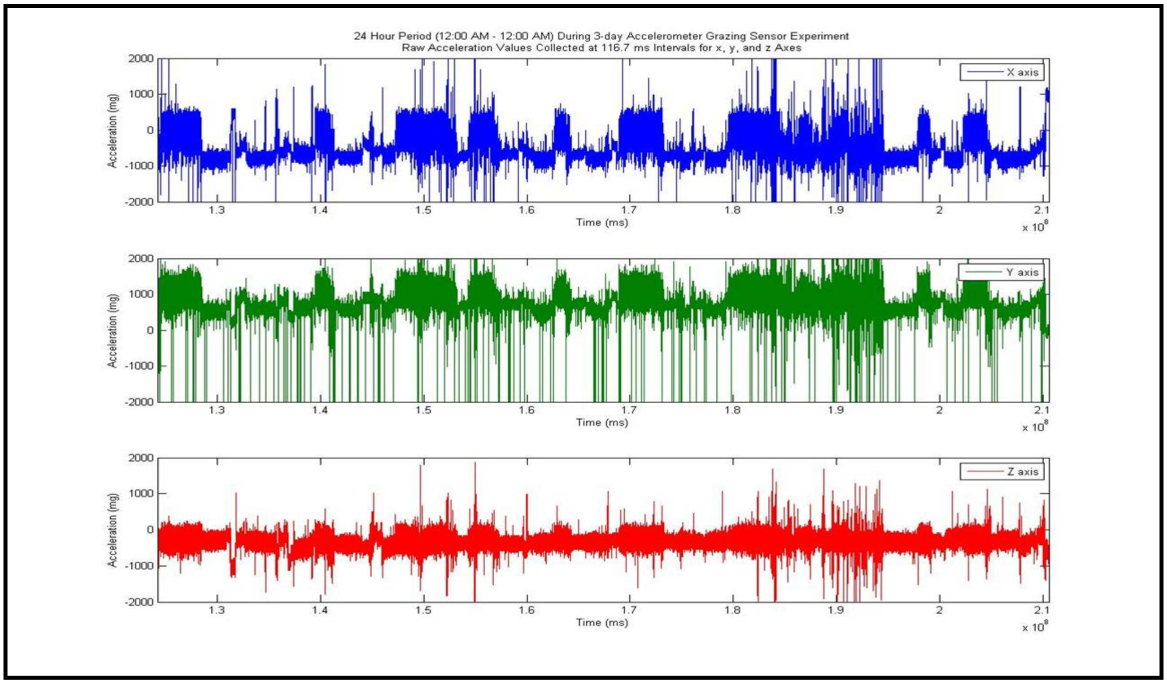

Figure 25. Raw acceleration data for a 24-hour period during a 3-day grazing experiment.

Video and acceleration information were synchronized and plotted (Figure 26, Figure 27, and Figure 28). For time periods where grazing was predominant, a noticeable change in signal bias and frequency were observed for both x and y axes accelerations. Z axis information showed little change in most cases and was inconsistent when changes occurred. However, trends in z axis signal were observed for short periods following grazing bouts (Figure 25). Perhaps this trend of increased sideways motion can be related to chewing or ruminating activities. Animals were not always observable during video recording and thus no activity could be identified for various time periods. Only observable time periods for grazing, walking, and standing are shown in Figure 26, Figure 27, and Figure 28.

Short time periods for grazing, walking, and standing were chosen as sample sets for Fourier analysis. A one sided frequency spectrum was generated for each sample using Matlab's signal processing features. Power magnitudes and patterns were observed. Frequency analysis for standing was clearly repetitive and different from walking and grazing. Powers for all frequencies faster than 0.25 Hz were below 0.5 for standing (Figure 30). Average power magnitudes for grazing were greater than walking. However, there were some occurrences in which walking and grazing frequencies were indistinguishable for either the x or y axis.

Analysis involving combined axes, such as vectoring acceleration data, may have ability to sense various activities with more precision. Still, this data shows that there is potential for halter mounted accelerometers to detect grazing characteristics accurately and over longer periods of time when compared to conventional observation methods or short lived electronic devices used in the past. Grazing acts as short as a few seconds were easily identified by basic analysis of signal frequency and magnitude. More intensive filtering methods may prove to provide information such as bite rate and grazing intensity.

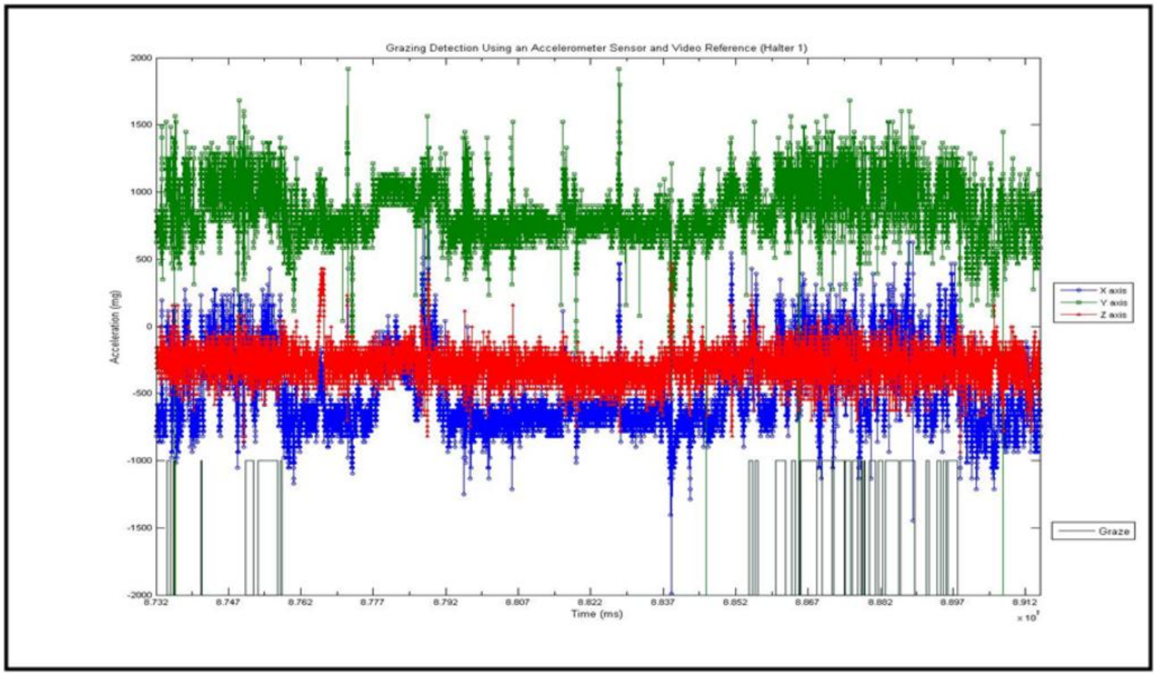

Figure 26. Grazing information obtained from video analysis compared to raw accelerometer data.

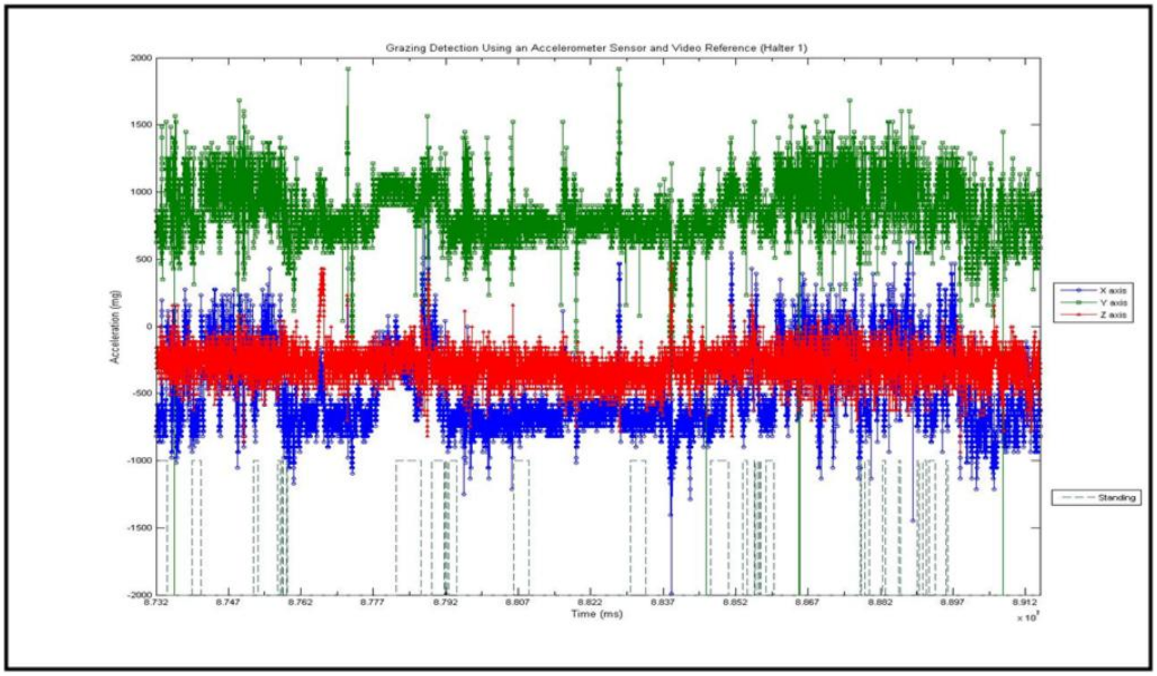

Figure 27. Standing activity obtained from video analysis compared to raw accelerometer data.

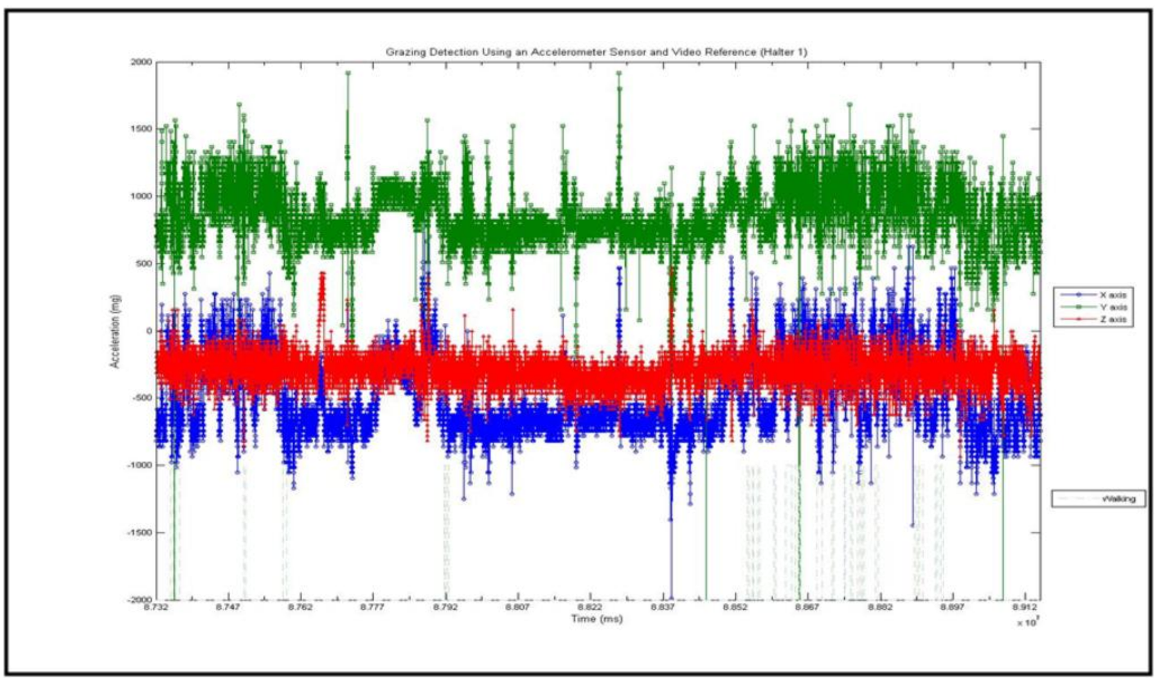

Figure 28. Walking activity obtained from video analysis compared to raw accelerometer data.

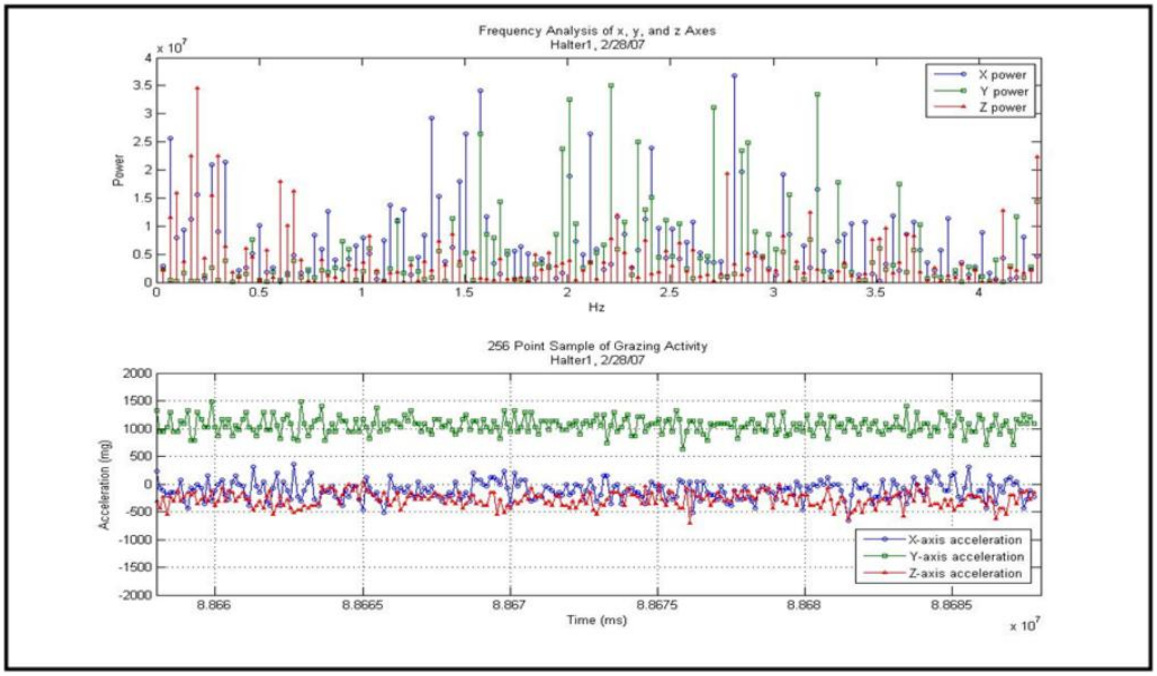

Figure 29. FFT analysis for grazing activity.

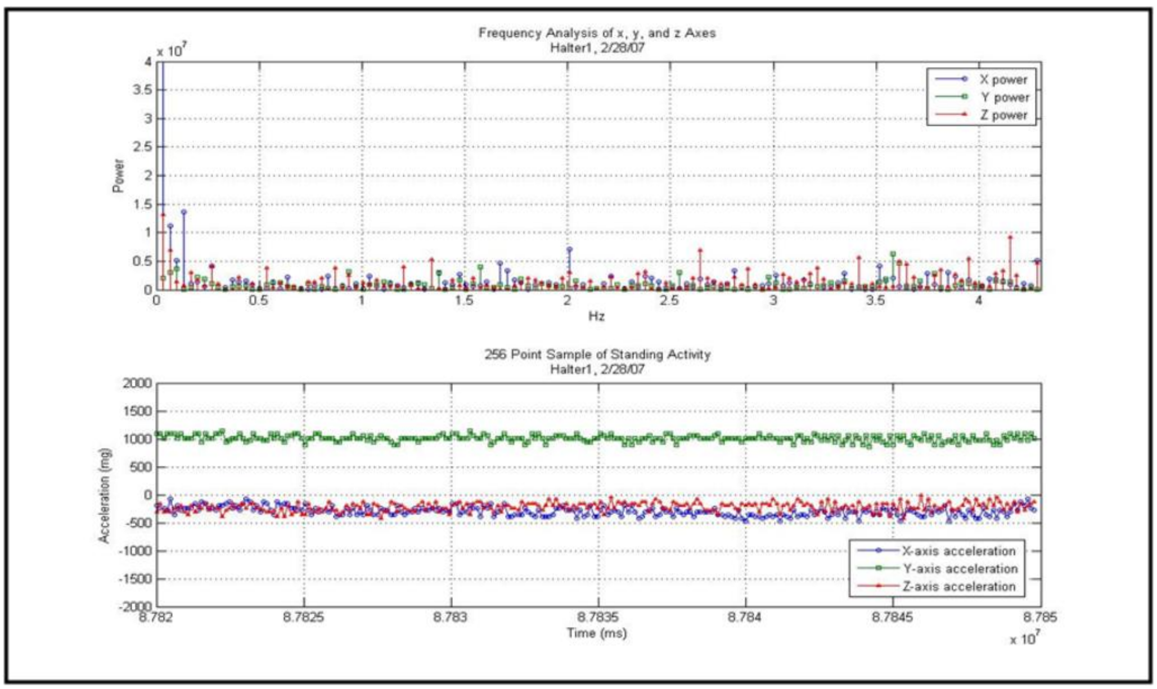

Figure 30. FFT analysis for standing activity.

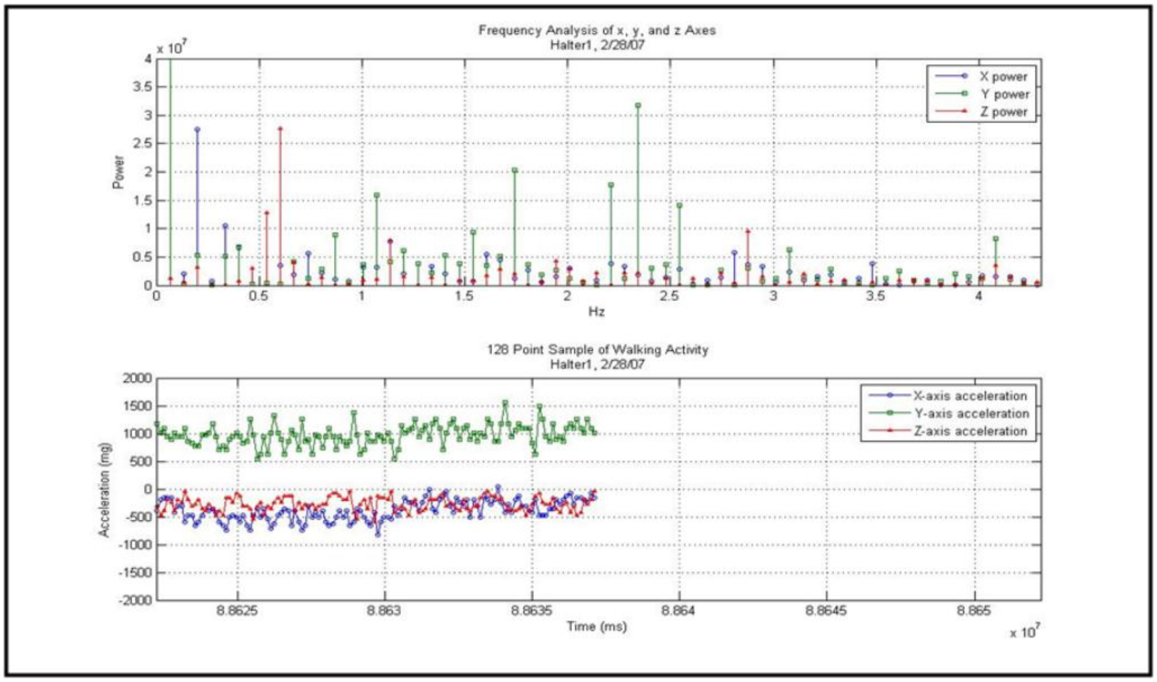

Figure 31. FFT analysis for walking activity.

CONCLUSION

A wireless accelerometer sensory device was successfully designed and built. High resolution acceleration data was collected at 30, 116, and 120 ms intervals using either two or three axes accelerometers. Analysis of accelerometer data showed that grazing, walking, and standing activities could be sensed. Typical acceleration signal amplitude experienced during grazing activity ranged from 250 m*g* to 1000 m*g*, whereas signal amplitude for standing was observed to be below 250 mg. Head accelerations during walking were larger than that for standing, but had lower frequency response than grazing. Grazing bouts were easily identified by using both signal shift and frequency measures. Grazing periods were detected on the order of a few seconds in length. Recorded video provided validation data and was compared against logged accelerometer data. Review of past research and collected video verified that bite rate for grazing cattle could commonly range between 0.5 – 3 Hz (bites/second). Fourier analysis of x and y axes accelerometer data also suggested that bite rate was approximately within the same range.

GPS data were used to geo-reference grazing data while illustrating capability to generate grazing maps. Grazing map showed that walking patterns could be used to potentially determine grazing activity. It was commented that traveling patterns across a pasture may help indicate grazing activity. GPS information could provide relevant information for grazing while simultaneously using accelerometer data to increase detection accuracy. Once an accelerometer based sensing algorithm is fully developed, future research can then address correlations between movement patterns (collected with GPS) and grazing activity sensed by a head mounted accelerometer.

Radio frequency hardware was included into sensor design and can be used to develop a near real-time grazing sensor system where grazing activity and location information may be readily provided. This research demonstrated that it is possibly to use an accelerometer sensor and GPS device to produce valuable grazing information for the purpose of advanced research and management.

Future research needs to be conducted to address development of specific algorithms to delineate not only grazing from walking and standing, but also to determine bite rate and grazing intensity. Other information involving certain behavioral characteristics may be extracted from using head mounted accelerometers and should be studied. Future use of wireless sensors on cattle will undoubtedly lead to more urgent needs for firmly defining hardware, software, and integrative parameters relative to a grazing environment and production system.

Real time foraging data of a free grazing beef animal enables monitoring individual animal growth, spatial forage utilization, preferential grazing, forage uptake, and behavioral changes (i.e. indicative of health problems). This research showed that it is possible for animal scientists to collect valuable information more efficiently as compared to conventional methods and past attempts where electronic sensing devices were used to detect grazing activities. Research involving growth and health studies including native forages, improved pasture, supplemental feeds, growth implants, vaccination drugs, rotational grazing programs, genetics, and many other areas can be readily evaluated with precision and in large scale via sensory systems like the one deployed in this study.

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CHAPTER V

EMBEDDED GRAZING SENSOR ALGORITHM

INTRODUCTION

The act of grazing was characterized in chapter four as distinct head movements detectable with an accelerometer sensor mounted to a standard nylon halter. However, for best wireless sensor performance a sensing algorithm was needed. Sensing algorithms can provide a number of functions including noise filtering, pattern recognition, data compression, and combining with other data. Regardless of an algorithm's specific duty, its main purpose is to make data more useful than in raw form.

In this research it was necessary to define algorithm function and parameters in alignment with sensed phenomenon characteristics and ability of the proposed electronic sensing platform. Prototype sensor designs typically evolve from rudimentary characterization of a phenomenon (i.e. synchronized video depicting animal head movement) and matching those characteristics to sampling and storage capabilities of select hardware. An iterative process is used to achieve a mature sensing device, where hardware specifications are modified when new phenomenon characteristics are revealed. These new characteristics expand the initial understanding of what is being sensed; and are generally undetectable at the onset of device prototyping. Chapter 4 depicts two devices: one that was hand-crafted using a Basic Stamp module as the processor, and the other where a miniaturized PCB, with CC1010 microcontroller/transceiver, was designed based on results from the hand-crafted device.

Only after raw-data investigations are made can sensor hardware changes be identified. Review of raw sample data can divulge new requirements for sampling rates, sensor range, or data storage needs. Adjustment of sampling rate capabilities, microprocessor speeds, and memory size/usability are common areas where hardware and software are improved allowing for more accurate data collection and interpretation to be made possible. Because of these adjustments, sensing algorithms are also increased in performance and/or elegance to accurately meet particular sensing and processing objectives.

Battery-powered wireless sensors are sensitive to power conservation, which is strongly related to the amount of information sent over a radio link. Algorithmic compression of data into easily transmittable sizes, while maintaining useful meaning, is a primary concern in developing wireless sensors. Compressing data potentially requires a significant amount of processor time, which also expends a considerable amount of energy. Efforts allocated to data compression, for the purpose of decreasing amount of data transmitted, can lead to no net value in energy conservation if there is an equal trade between compression and transmission procedures. Care should be implemented so that schedules for both radio and compression tasks are constructed in the most efficient manner possible, thereby avoiding an equal offset. Task schedules and energy usage should also correspond closely with the sensing application. Besides radio/compression energy management, sensing ability must be preserved. This embarks on the close relationship energy consumption has with process time and phenomenon characteristics. Time spent downloading/uploading data over the radio would utilize device resources that otherwise could be devoted to data sampling or processing. When data sampling procedures are interrupted, there is potential for information loss. This concept must be adhered to during design of the sampling scheme as well as the data processing method so that large intermittent intervals do not cause a significant loss of phenomenon information. Large processing times may present situations where phenomenon occurrences go un-sensed. Additionally, large or intensively involved algorithms tend to require lots of processing time that requires significant amounts of power. An obvious remedy would be parallel type processing where both sensing and processing could occur at the same time. However, most low cost or novice level devices, similar to that discussed in Chapter 3, has little opportunity for parallel processing features. Likely solutions exist in the proper identification of required, raw-sample data and the amount of energy expenditures necessary for both data processing and radio transmissions.

Considerations for developing the sensing platform were discussed in both Chapters 3 and 4. These considerations focused on four main areas: sampling rate, memory, sensor, and radio communications. The former two were central to developing an effective algorithmic scheme. Due to the nature of grazing and analysis of raw data collected previously, the frequency analysis of the animal's cyclical head motion was determined to provide the best information. Frequency binning constructed by using a Fast Fourier Transform (FFT) was outlined as the final data-compression mechanism where suitable grazing information would be preserved. Frequency binning is described as the specification of frequency bands for the purpose of averaging spectral power over a narrow frequency interval. This method inherently allowed for sample size versatility and quick modification of bin structures. For instance, FFTs can be conducted on various sample sizes by simply altering a few variables, and bin number and widths can be changed programmatically as well. However, these positive features are only obtainable within the memory capacity of the data logging and processing module. Sample size may be limited by the amount of memory storage and by the amount of memory required to perform an FFT calculation. Sampling rate is related to the desired range of frequencies to be analyzed as well as the sample size to incorporate in the FFT calculation. Both sample rate and sample size must be compliant with the sensed phenomenon's characteristics, despite the FFT, so that meaningful information is retained in the sensor algorithm's output.

The focus of this chapter was to illustrate the first algorithm developed in support of condensing raw accelerometer data for the purpose of grazing detection. Use of a microcontroller, on-board memory, and sampling rates are thoroughly represented. The goal of the algorithm developed here, was to provide a field-experiment deployable sensor that also collected enough detailed information to advance future grazing sensor strategies.

LOCATING THE FFT ALGORITHM

In a networked or remote sensing application, location of data processing is sometimes optional. Certain components and devices are designated for collecting raw sensor information while others are meant for processing data and communications. This is especially true for wireless sensor systems and data processing functions. Two options for locating data processing are prevalent with wireless sensors: on-board the sensing device, or within another designated module such as a base transceiver or non-sensing device. Processing speed, memory storage, data-logging requirements, and data-transmission limitations all drive the selection of a data processing location.

Raw data usually cannot be transmitted in a practical and continuous manner over a wireless link. Some sensing strategies may allow large intermittent periods for data dumps as opposed to continuous transmission. Large data dumps may be necessary in situations where a wireless device does not have sufficient resources to adequately process raw sensor data. Large chunks of raw data may be transferred to another networked wireless module that can further process the data. Processed data can then be re-transmitted in a condensed form. In either case, the battery power involved to operate the radio during either method will be significant. A bulky amount of data throughput will also be required, even if it is for a relatively short period. Extensive data throughput over wireless communications further challenges the ability to have multiple devices in a wireless sensor network. In this sense, management functions for wireless sensor networks would surely compete for the bandwidth consumed by large sensor-data transmissions.

Memory storage is often an influential factor in locating where data processing can occur. Memory is needed first for storing raw data for later processing. Memory then becomes extremely valuable in terms of performing data processing functions. On-board memory can exist in multiple locations. Two on-board memory locations considered here are on-processor and as a peripheral component. On-processor memory is more readily accessible than a peripheral memory device. Most peripheral memory chips are accessible by a wired bus and serial communications. This method of data transfer is much slower than on-processor memory that is accessible by a code variable or pointer. The major difference is the time and resources necessary to communicate with the peripheral device over an external bus, not to mention that pointers must also be externally managed for the peripheral memory space. Time sensitive data processing procedures are usually not amenable to external memory storage because of these differences, unless the sensing strategy can allow for data sampling loss during interaction with the peripheral device. On-processor memory provides a much more efficient data processing method granted that enough memory space is available.

More sophisticated sensing designs, requiring elaborate data processing, often utilizes a peripheral component solely dedicated to data processing ahead of any communication tasks. Digital signal processing (DSP) integrated circuits (IC) can include analog to digital conversion of a transducer's output, digital data storage, and data processing in one automated package, thereby quickly condensing data into a more usable form. Complex mathematical processing strategies implemented with DSP chips can be conducted in a parallel manner without worry of other tasks common to a normal microcontroller and wireless communications. A microcontroller can then utilize output information from a DSP chip directly without any further processing. This approach is generally incorporated after a sensor algorithm has matured to the point where no further refinement is needed. DSP algorithms are usually first implemented in microcontroller software and then transferred to a DSP chip after algorithm design and parameters have been established. More advanced approaches utilize a hardware description language and programmable hardware (i.e. VHDL and field-programmable grid arrays (FPGA)), but also require more sophisticated training and development tools. The speeds and cost savings apparent with DSP chips are warranted best in a commercial product manufacturing stage.

An appropriate amount of data processing must be handled on-board the wireless grazing sensor module. Raw sampled data must be converted into a form that is more storable in non-volatile memory and transferable over the radio link. On-board processing time should not exceed periods where loss of raw sensor information is detrimental to detecting the phenomenon's characteristics of interest. One may ask the questions: what is a sufficient number of bites to sample, and how meaningful is the associated sample period to detecting grazing activity? To answer these questions one must consider animal behavior and the potential meaning grazing information has to a manager or producer. These considerations have already been discussed and are now expounded upon with the more intricate and functional details of FFT code development.

SAMPLE SIZE AND RATE

Grazing was characterized as an animal having cyclical head movements, and was representable with an acceleration measurement. These movements were identified to range between 0.5 to 8 Hz (see Chapter 4). A sensing algorithm that could quantify selected frequency bins within this range was desired. Spectral powers at select frequencies are indicators of bite rate activity as well as relative bite intensity, or grazing intensity. Bite intensity and grazing intensity differ in that bite intensity refers to an individual occurrence where an animal collects and sheers a single gathering of forage. Grazing intensity refers to a combination of both bite rate and bite intensity over a significant period.

An FFT approach was selected so that multiple frequency bins could be constructed and recorded using only two values per bin: bin frequency (or center frequency) and spectral power averaged over the respective bin width. For instance, a sample set consisting of 512 sequential data values could be condensed into anywhere from six to twenty values depending upon the bin size and desired range within 0.5 to 8 Hz. Figure 32 is a depiction of raw x-axis acceleration data collected during the proof-of-concept experiment discussed in Chapter 4. This data was a 256-point sample set collected at 33 Hz, and covering a 7.76-sec time interval. During this interval, the animal was verified to be grazing via video, and with a head movement of an approximate > 300-m*g* amplitude and period of < 1-sec. Figure 33 illustrates the resultant FFT of the data shown in Figure 32. One-hertz bins ranging from one to eight hertz are also shown. Bins representing 1-2 Hz and 2-3 Hz showed the most grazing activity, and indicate a bite rate that ranges between one and three bites/sec.

Additionally, a grazing intensity level may be extrapolated by summing the areas of these bins, or characterizing the entire 0.5- to 8-Hz frequency band. Further research is needed to validate this inference. Once bin values were structured in this way, simple thresholding could be implemented in a logic-based detection scheme appropriate for managing long-term data logging, or integration into more conclusive sensing regimes (i.e. total forage consumption, feeding pattern changes, etc.).

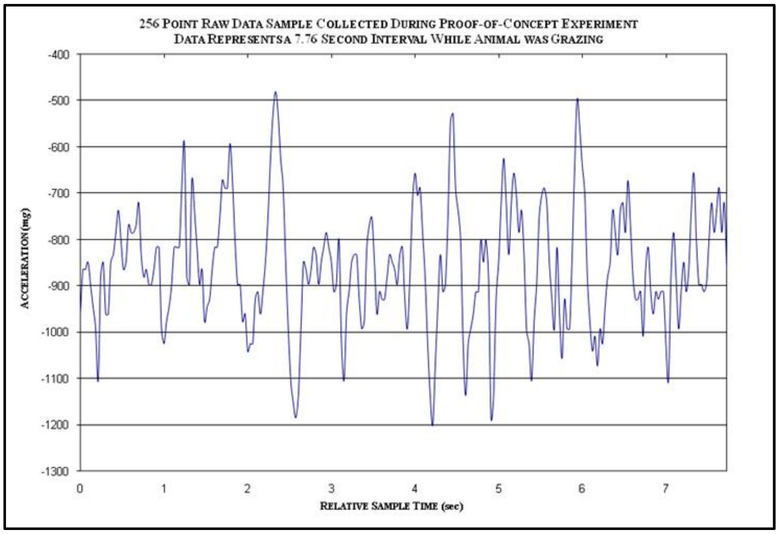

Figure 32. Raw data sample of accelerometer readings during experiment. Sample represents grazing motion.

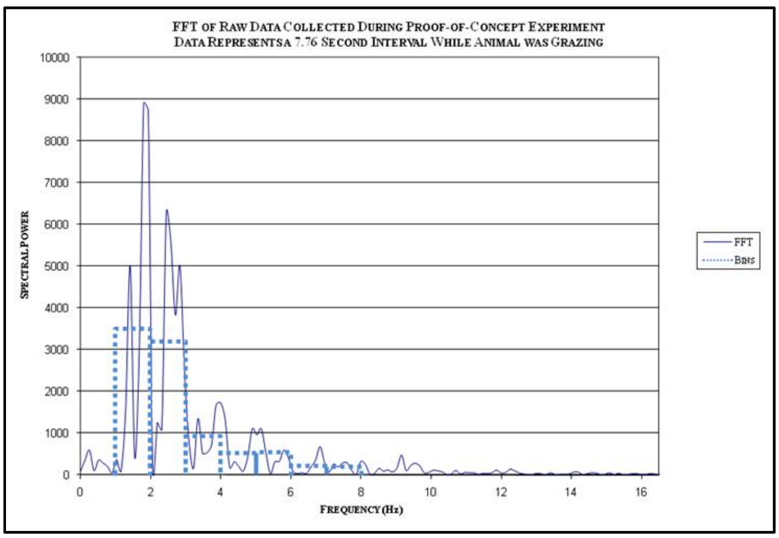

Figure 33. FFT of raw data sample and corresponding frequency bins.

Sample size was considered an extremely important factor. As sample size increases, more information is available to accurately assess true frequencies of a signal. However, an increase in sample size is accompanied with an increase in memory usage and computational processes. Since it was known that the range of bite rates existed between 0.5 and 8 Hz, then the sampling period should be based on the desired number of bites (or periods) to capture. Therefore, at least 5 periods (bites) per sample set was chosen to be captured in a single sample set. At 0.5 Hz, 5 periods resulted in a total sampling time of 10 seconds; and at 8 Hz, there was a sampling time of 0.625 seconds. The lowest frequency rate was used as the determining factor because higher frequencies would have a sufficient number of captured periods in a low frequency's sampling time.

Sampling rate was the other majorly important parameter to define. Sufficient sampling of the fastest bite rate known (8 Hz) would encompass all slower bite rate frequencies of interest. This provided guidelines for an appropriate sampling rate objective. At least four times the maximum target frequency was chosen as an adequate sampling rate (Nyquist theory suggests 2 times the target frequency for band-limited applications). An 8-Hz target frequency would then require a 32-Hz sampling rate. For an approximated average bite rate of 4 Hz, sampling would be 8 times the average rate using the 32-Hz rate. A near ideal sampling rate that accurately characterizes both signal energy and frequency would be ≥ 10 times the target frequency.

A period of 10 seconds to a grazing animal or herd manager is relatively insignificant. Grazing bouts are commonly on the order of minutes to hours in length. Figure 25 of Chapter 4 portrays approximately 12 grazing bouts illustrated by the clumps of heightened accelerometer activity shown throughout the 24-hr interval (see also slide 33 in Appendix A). Characterizing a single grazing bout may only require a few minutes or seconds of samples collected at spread intervals. A 10-sec sample period would at least provide minute-level accuracies for grazing detection. If only the start and stop time of a grazing bout was desired, then identifying grazing bout periods would be accurate within one minute. More intense analysis pertaining to an animal's vigor while grazing would require more frequent sample set periods throughout a single grazing bout. Spreading sampling intervals will be one of the more significant parameters to future applications using sub-minute sampling intervals.

A 32-Hz sampling rate and 10-sec sample window yields 320 samples, per axis, to be stored prior to FFT processing. Three accelerometer axes sampled at this rate would require 960 samples stored in memory and an axis-to-axis sampling rate of 96 Hz. It was previously discussed that the fastest analog to digital conversion (ADC integrated in CC1010) occurred in an 8.6-ms interval for each ADC channel (see Chapter 3). It was important to recall that this was measured when using the 32.768-kHz crystal to drive the microprocessor's system clock. A faster crystal would allow faster sampling rates. When all three ADC channels were polled sequentially, it took a total of 18.6 ms (53.76 Hz) to read the ADC registers and store the values in a defined variable. Further measurements revealed that three times the sampling rate for an individual channel was larger than when sequentially polling all three channels. This was because no timer or looping code structures were necessary to read the ADC channels sequentially. Sequential reading was conducted within a single loop or interrupt (see Appendix B). If a loop were used to read each channel separately, then the total time would have been on the magnitude of three times the 8.6-ms interval.

To illustrate the importance of sampling rate further, data was collected at a lower frequency than that shown in Figure 32. Figure 34 shows a 256-point sample set collected at 8.57 Hz, nearly 1/4th of the 33-Hz rate used to create Figure 32. Even though this sample set included a much larger period that also captured excessive biting events, the decreased sampling rate inhibited the ability of an FFT to appropriately depict bite rates or bite intensities as shown by Figure 35. The accompanying FFT offered little information that helped delineate a dominate bite rate. However, the cyclical and large amplitude appearance of raw data strongly confirmed that grazing was apparent, compared to periods where grazing was not occurring. Figure 26 through Figure 31 supported this conclusion by characterizing the acts of walking, standing, and grazing. The obvious worth in this analysis was that a shift or tilt measurement could be used to confirm relative head position while heightened accelerations provided evidence of potential grazing activity. Even though quantification may not be achievable with a slower sampling rate, detecting the act of grazing was still within reason.

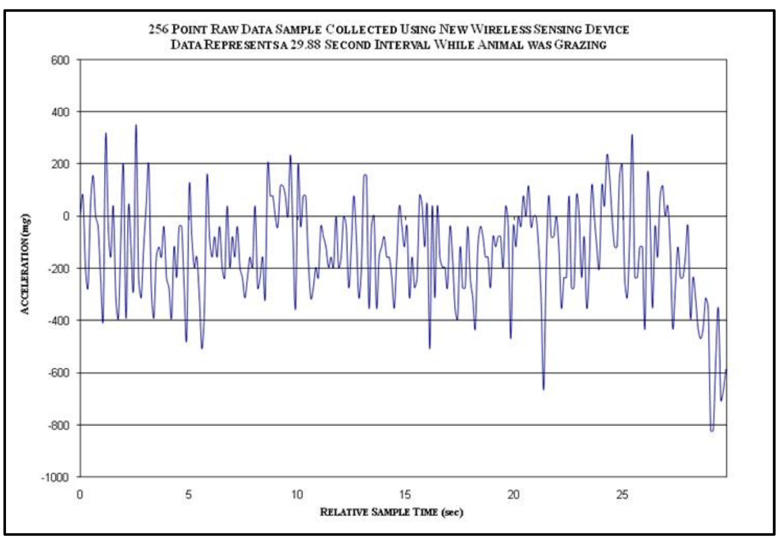

Figure 34. Raw accelerometer data collected at 8.57 Hz. Data was collected using new wireless sensor device deployed on a free grazing heifer in a wheat pasture environment as indicated in Chapter 4.

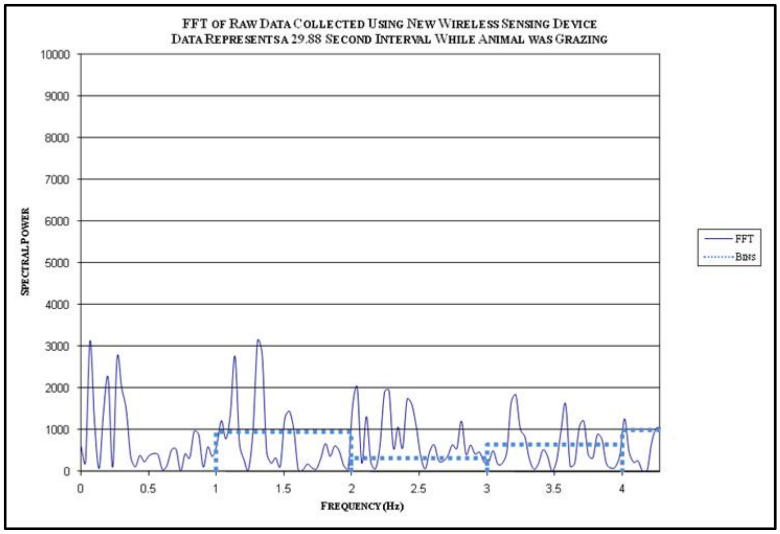

Figure 35. FFT of data collected at 8.57 Hz.

A significant amount of overhead was expected when integrating the ADC sampling routine into a full system necessary for managing both wireless communications and data processing functions. This would involve a procedural method where state control of other functions particular to transceiver usage and other necessary operations would potentially slow the sampling rate. After implementing state control features, 46 ms (21.74 Hz) was recorded as the fastest data-logging period possible. This was below the desired 32-Hz rate mentioned previously. A 10-sec window at 21.74 Hz equated to 217 data points. FFT calculations are best conducted with sample points incremented by 2^n. The next highest sample number meeting this increment was 256 (2^8), and would cover a sample period of 11.78 sec, which still encompasses at least 5 bite periods at an 8-Hz bite rate. The new sampling rate was only 2.7 times the maximum 8-Hz target, but was expected to still yield valuable energy-frequency information at that rate. Do to this change in sampling rate abilities, the sampling rate parameter was redefined to > 16 Hz (4 X 4 Hz and 2 X 8 Hz bite rate). A bite rate range of 1 to 4 Hz was the presumed range with the most value. Rates faster than 4 Hz were considered to occur at infrequent periods and probably represented only nibbling and partial bite actions, which contribute a small fraction of total forage consumption. Full bites were speculated to occur at rates less than 4 Hz because most animals require at least 0.0625 seconds (1/4 of the total period representing both head motion and bite) to gather a significant amount of forage in their mouth prior to sheering. Preliminary evaluation of sample video supports this reasoning (see Chapter 4).

FFT Calculation and Efficiency

Fourier analysis has been an extremely useful signal processing tool for decades. It is generally understood as two separate representations of a phenomenon: one in real time terms and the other as a set of periodic functions. By theory, a physical function can be decomposed into a set of periodic functions that consists of multiple frequencies with separate energy levels. When this decomposition takes place, the resulting information is known to be in the frequency domain. Alternatively, when the signal is represented in real form it is known to be in the time domain. Figure 32 and Figure 34 are both time domain representations whereas Figure 33 and Figure 35 show the frequency domain.

Discrete sampling is essential in any sensing strategy where an analog (continuous) signal is needed in digital form for mathematical manipulation. Continuous and discrete forms of the Fourier transform are shown in Equations (8) and (9) respectively (Press et al., 2007).

$$H(f) = \int_{-f_c}^{f_c} h(t) e^{2\pi i f t} dt \tag{8}$$

$$H_n \equiv \sum_{k=0}^{N-1} h_k e^{\frac{2\pi i k n}{N}} \tag{9}$$

H represents a signal in the frequency domain whereas h is for the time domain. The two variables f and t are frequency and time respectively. N is the number of discrete values collected from sampling a finite period of a continuous signal regulated by a sampling interval. The discrete representation of the Fourier transform does not depend on the sampling interval only the number of finite samples indexed by k. Note that Equation (9) is evaluated for n discrete frequency values up to N, or in the range $-N/2$ to $N/2$, which represents continuous evaluation over the range $-f_{sample}/2$ to $f_{sample}/2$ ($f_{sample}/2$ is the same as the critical frequency f_c). It is important to realize that n and k vary the same allowing the same number of outputs from the Fourier conversion as the number of input sample points. For instance, if 512 sample points were provided in the time domain and then converted to the frequency domain, then the result would be 512 spectral values matched with 512 equally incremented frequency values between $-f_c$ and f_c. The frequency interval can be found by dividing f_{sample} by N. If the sampling rate was 32 Hz and total samples collected were 256, then the frequency interval of the discrete Fourier transform would be 0.125 Hz. For this case, n

would be incremented by 0.125 Hz multiplied by the integer index k and would range from -16 Hz to 16 Hz.

Symmetry also plays a very important role in performing embedded Fourier calculations. Most sensor signals are considered real or at least contain the most important information in their real component. When phase analysis is required, the imaginary component must be included. The proposed grazing sensor was presumed to deal primarily with real data. The Fourier transform provides advantages because of the data's real and symmetric properties. The Fourier transform, $H(f)$, of a set of real values, $h(t)$, is known as being conjugate symmetric, $H(f) = H^*(-f)$. The real part of the transform is also known as being even, $H_R(f) = H_R(-f)$. Because of this, only the transform values between zero and f_c are needed (Oppenheim et al., 1999). The example where 256 points collected at 32 Hz would then yield a transform ranging between 0 and 16 Hz with 128 real spectral values. Memory storage reduction is evident because of the symmetric real and even properties.

The discrete calculation of the Fourier transform requires N^2 complex calculations, indicated by a real sample set multiplied by a complex (Equation (9)). The Fast Fourier Transform (FFT) enabled calculation of the Fourier transform in $N\log_2 N$ calculations, many orders less than the original discrete form. More efficient processing of the discrete Fourier transform was basically achieved by adhering to symmetric and periodic properties while splitting the calculation into sets of smaller discrete Fourier computations. Equation (9) shows that the complex coefficient is periodic in n with period N (Press et al., 2007).

Earlier, an FFT calculation was mentioned to be the most efficient when the input sequence of values was 2^n in size. This, along with the understanding that the input sequence is conjugate symmetric and periodic, provides the basis for manipulating the Fourier calculation in such a way that smaller Fourier transforms can be conducted on subsets of the original sequence. Because the sequence and its subsets are also divisible by two, each subset can be generated by separating the odd and even indexed values, then repeating the procedure on each new subset until there are only pairs of samples left (i.e. recursion). This is widely known as the Danielson-Lanczos lemma (Press et al., 2007; Oppenheim et al., 1999). The applicable worth in the Danielson-Lanczos lemma method is that the Fourier transform eventually becomes a one-point transform, where the stored location of a sample value is defined and only multiplied by the corresponding complex coefficient. After the one-point transform, upper level pairs are combined and then a two-point transform is performed. This combination and multiplication procedure continues until addition of the odd and even subset for $N/2$ points is accomplished, resulting in the completed transform. The ensuing number or complex calculations are $N\log_2 N$, where the value $\log_2 N$ represents the number of stages or subsets.

By recursively dividing data into even and odd groups, an order known as bit reversal is realized. Bit reversal takes the binary index values of the sequence and exchanges the least significant bits with the most significant bits creating a new ordering of the input sequence. The more valuable part of bit reversal is that it can be accomplished with no additional storage memory. Only pairs of values are swapped during bit reversal requiring displacement of only one single value at a time while the paired value is relocated into the former value's original sequence.

Memory storage is further conserved because of a procedure known as butterfly computation. Because of the way subsets are staged and subset Fourier transforms are performed, a butterfly effect occurs. Essentially, at the first or most divided stage two adjacent samples are used to complete a Fourier transform. The reversal affect from odd and even division of the next stage requires that the first stages' results replace the original sample values with the resulting two-transform values in a one-for-one type procedure. What this creates is an efficient use of memory storage in that no extra memory is required to store each new array of transformed values of at each butterfly stage. This is known as in-place computation of an FFT (Oppenheim et al., 1999).

IMPROVING THE FFT

Fourier transform of a finite set of data is necessary for sensor applications because it is impossible to analyze a complete continuous signal. Sections of a continuous signal are used to represent the entire continuous signal, or at least a period of a targeted occurrence. It was discussed earlier that a bite is the occurrence, which is to be sensed. Collecting a period that extends over multiple bites will provide the best data set for FFT processing. Five bites at 0.5 Hz sampling rate was the guideline in which to build the sample set. Multiple representation of an occurrence strengthens the possibility of an FFT revealing its energy dominance in the resulting spectral output. Even though a number of occurrences are to be captured, there still exists some problem with calculating the FFT because of spectral leakage and an open-ended signal. When extracting a finite number of points from a continuous signal there is discontinuity at the beginning and end of the sample set. This discontinuity presents anomalies that mathematically affect the results of the FFT calculation. In a theoretical sense, spectral energy of non-true frequencies leaks into the true frequencies of the signal because of the windowed data-slice that was discretely taken from the true continuous signal. The FFT sees the distinct start- and end-points as an abrupt periodic occurrence and thereby includes its un-true signal energy in the analysis.

A procedure referred to as windowing is used to redistribute leaked spectral energy in a more controlled manner such that relative analysis of the true frequencies can be correctly interpreted. Without windowing, target frequencies may, or may not, be accurately or consistently represented especially when transforms are to be made and compared respective of different sets of samples. Windowing methods can be categorized by range and sensitivity. A window with large range has the ability to evaluate signals with large differences in spectral energy. However, large range windows are not as sensitive because when two signals of near frequencies exist, information about their differences is compromised. A rectangular window (same as using sample set in its original form) provides the best sensitivity but has a low range because signals with similar amplitudes become hard to distinguish from each other spectrally. Windows that diminish end affects by ramped scaling create better distribution of leaked spectral energy while maintaining moderate range and sensitivity. These windows are developed to match the exact number of data points in a sample set and are intended to provide multipliers that scale down the abrupt end portions of the sample set while curving upward to the center of the sample set. The center sample values are usually retained in whole value as they are more insulated from end-effects, and are thereby thought to provide the truest information of the data set. A Hanning window is one such window where moderate levels of range and sensitivity are retained (Oppenheim et al., 1999). Equation (10) was used to provide Hanning window coefficients to be multiplied with sample data.

$$w_n = 0.5 - 0.5\cos\left({}^{2\pi n}/_{N}\right) \tag{10}$$

Discrete signal sample sets that have a nonzero mean or are not centered on zero have an undesirable impulse at the zero frequency. When the signal mean is far displaced from zero, the zero frequency impulse leaks into low frequency signals distorting them beyond usability (Oppenheim et al., 1999). To alleviate this problem a sample set of data is zero-centered by subtracting the set's mean value from each discrete point.

Process Layout and Code

Particulars for data sampling, data preparation, and calculating the FFT have been discussed. Figure 36 illustrates the overall processes the sensor performs to acquire grazing information. The accelerometer sensor feeds three analog signals, one for each axis, into the ADC through an analog bandwidth filter that is implemented on each signal line. Data is then taken from the ADC's data registers and sequentially stored in three vector arrays, one for each axis of the accelerometer. The CC1010 memory map consists of 128 bytes of variable space RAM and 2 Kbytes of external RAM (xdata). Xdata memory presented the best storage solution for in-place processing of the FFT because of its capacity and on-chip status making it accessible by indirect addressing. Two-hundred and fifty-six data points were stored for each accelerometer axis in xdata memory for each sampling interval, totaling 768 bytes. A vector variable declaration was made to setup the three 256-byte arrays as a single 768-byte data buffer.

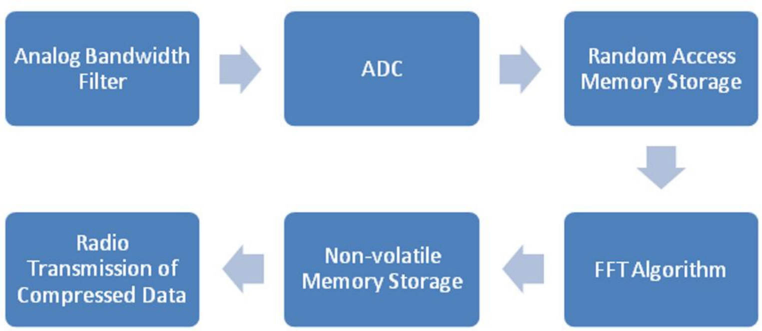

Figure 36. Flow diagram of grazing information through the overall processes of grazing sensor.

It was imperative that the initial storage of accelerometer data was in xdata memory so that timely processing could occur via random access type memory. Internal variable space RAM presented far too little capacity, and peripheral data flash memory access time was excessive because of its serial interface. Since the CC1010 had an ADC, core processor, and xdata all on the same chip platform, transition of data from analog signal to a stored digital form was much more efficient when compared to a layout having ADC and memory storage as peripheral board components accessed either by serial or parallel methods.

The FFT algorithm process presented in Figure 36 can be divided into sub procedures related to computational details and data preparation tasks discussed earlier. These processes were customized from framework presented in Press et al. (2007) and Oppenheim et al. (1999). Appendix C exhibits coding for these FFT calculation procedures, and Figure 37 illustrates the corresponding steps. Appendix E (Main code routine) illustrates the manner in which data is logged and how each axis's data vector is processed. One data vector is processed at a time, but data for all axes are logged in the ADC routine (Appendix B) simultaneously. A state-machine process has been structured in Main (Appendix E) for further implementation of other code routines (i.e. radio transmissions).

As shown in Figure 37, data vectors were first converted to engineering units and zero-centered. Next, vectors were scaled by the Hanning window. A look-up table was used to perform the windowing function. A look-up table prevented excessive instructions and calculation procedures when considering the trigonometric operation shown in Equation (10), and accompanying floating-point math operations. After data were zero-centered and windowed, the bit reversal operation was performed followed by the Danielson-Lanczos butterfly calculation. Both bit reversal and the butterfly calculations were performed in-place and required a final reordering of the data vector.

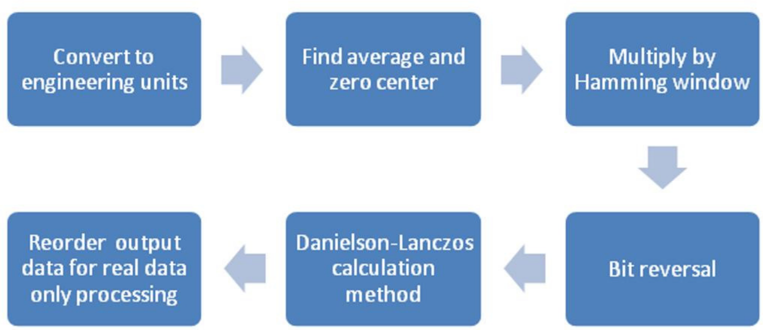

Figure 37. FFT algorithm procedures.

Both the bit reversal and Danielson-Lanczos portion of Figure 37 are structured for processing complex arrays of data where both real and imaginary parts are sequentially stacked in a 1 X 2N array for N complex values. Because of the butterfly structure, the real and imaginary parts of the input array are individually processed as smaller FFTs half the size of the input array. This presents concern since the acceleration data logged is always real data having no imaginary component. Use of the bit reversal and butterfly computations, as is, would require restructuring the existing data vectors to a length 2*N* and fill each imaginary slot with a zero value. The output vector would then result in a proper array of complex transformed values. However, this also presents a situation where unnecessary process time is endured. Fortunately, due to methods outlined in Press et al., (2007) and Oppenheim et al. (1999), processing of real data sets can be done more efficiently with less time and required memory. The fact that the finite data sets collected are real and conjugate symmetric, offers usable features where redundant operations can be eliminated. It also turns out that sub-processing the original vector in two parts, one as real and one as imaginary, also supports the ability to recombine transformed real data into its proper form. The proposed method entails utilizing the real data set in its original 1 X *N* structured sequence, but processing it as an array of 1 X *N*/2 complex values (two values for each index) where real values are positioned at even index numbers and complex components (in this case are real sampled values) are at odd index values.

Because of symmetry, only half of the transformed values are actually needed and are contained in the same sized 1 X *N* output array thereby not requiring extra memory. To arrive at the final transformed result, reordering of the output array must be conducted since the FFT process assumed that the input array was complex instead of all real sequential values. Drawing from how the bit reversal and butterfly computation were conducted, the FFT of real valued inputs was reconstructed after performing the Danielson-Lanczos operation (Appendix C). The result after reordering was a 1 X *N*/2 complex array of the spectral values for all positive frequencies (negative frequencies were excluded because of symmetry).

Spectral power was considered more valuable than complex spectral data for determining grazing characteristics. Spectral power indicates signal amplitudes, or energy, within the finite data sample set which are inferred to reflect dominant phenomenon features such as biting frequency. Therefore, the next step was converting the 1 X *N*/2 complex array (two values for each index) into a 1 X *N*/2 real array (one value for each index) of discrete frequency spectral powers.

The method used to calculate spectral power included normalizing for both sample size and windowing. Various methods of normalizing are discussed in Press et al. (2007) and are most all derived from Parseval's theorem.[13] Squared-amplitude was calculated for each frequency value using Equation

[13] Parseval's theorem states that the sum of squares of a function is equivalent the sum of squares of its Fourier transform over an infinite period. Frequency specific power, or energy, can be determined by determining the squared magnitude of the transform and normalizing it by the data set's sample size.

(11), where C_k was the real, and C_{k+1} was the imaginary components. Since a windowing method was implemented to minimize spectral leakage, a sum of squares normalizing factor for the window was also calculated (Equation (12)); and used in Equation (13) to yield a resulting vector of normalized spectral powers.

$$A(f_k) = \frac{|C_{2k}|^2 + |C_{2k+1}|^2}{\frac{N}{2}} \qquad k = 1, 2, \ldots . \frac{N}{2} - 1 \tag{11}$$

$$W_{ss} = \sum_{j=0}^{N-1} \frac{1}{2}\left[1 - \cos\frac{2\pi j}{N}\right] \tag{12}$$

$$P(f_k) = \frac{A(f_k)}{W_{ss}} \qquad k = 1, 2, \ldots . \frac{N}{2} - 1 \tag{13}$$

Now that data has been converted into a more usable vector array of real values, final compression for storage and radio transmission purposes could be done. Each axis's data array was now the size of 1 X N/2, or 128 sequential values representing frequencies between 0 to $f_{sample}/2$. Note that for zero and cutoff frequencies ($f_{sample}/2$), a slightly different form of Equation (11) must be used because of symmetry properties. When k equals zero or N/2, the N/2 denominator becomes N. It was discussed earlier that a frequency binning method was chosen for data compression. It was determined that half-hertz bin widths ranging between 1 and 9 Hz would provide exemplary experimental data for further research initiatives. This would compress data from 128 values to 16, an 87.5% reduction in non-volatile memory storage. The code for frequency binning is shown in Appendix C.

Long-term memory storage, or non-volatile memory, used for periods between radio transmission data upload to a base receiver, provided an effective means of time stamping each processed sample set. Appendix D outlines the process in which real time clock values along with binned power spectrum data were packaged before data flash memory storage. A time stamp was included at the beginning of each 48-value (three axes each with 16 values) data vector. The packaged data vector was then transferred to data flash memory and relevant pointers were updated. Time stamps and non-volatile memory storage pointers were also continuously stored in a designated non-volatile memory location so that both memory usage and recent time could be remembered in the event a power cycle occurred; and for uploading stored data over the radio.

TESTING OVERALL CODE PERFORMANCE

Code performance was tested in two areas: one was for rounding error and the other was for time efficiency. Rounding error was a concern given the many floating and double precision variables required to conduct the FFT algorithm. To test computational accuracy, similar code was generated using Microsoft Excel VBA (Appendix F), and the built in FFT function of Matlab R2007a was used to process a sample data vector. A data set was collected using the sensor device and then ported to both Excel and Matlab for processing while also being processed using the embedded algorithm (Appendices B through E). To do this, the data vector was captured via hyperterminal and manually transferred into the Excel program and Matlab. The sensor device's power spectrum output was also captured by hyperterminal and transported into Excel for graphing against the VBA and Matlab generated power spectrums. During sampling, the sensor device was manually moved in a periodic motion to mimic grazing. Figure 38 is a 256-point sample collected during this exercise. Figure 39 shows calculated power spectrums for the embedded FFT algorithm, Excel VBA code, and Matlab function. Excel and Matlab showed nearly identical results. They also showed to calculate slightly higher spectral powers for the two frequencies where spectral energy was clearly significant. For very small frequencies, Excel and Matlab appeared to show some spectral leakage, but were not considered a noteworthy concern. These three power spectrum series compared well indicating that rounding error in the embedded code computations was minimal.

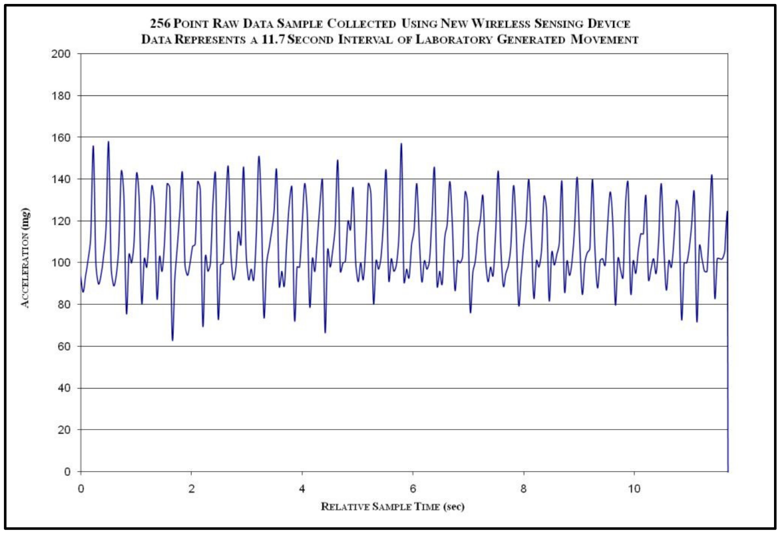

Figure 38. Laboratory sample collected for validating embedded FFT code.

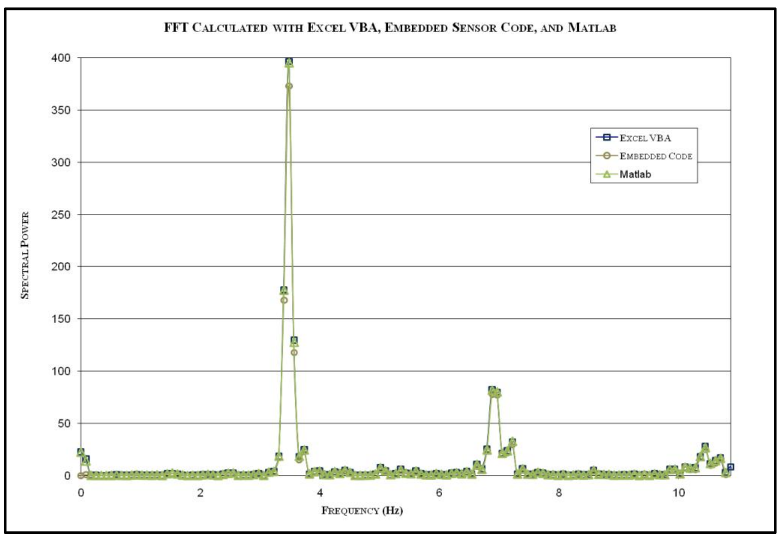

Figure 39. Comparison of FFT calculated with embedded code, Excel VBA, and Matlab.

Time efficiency was determined using an oscilloscope and LED indicators on the CC1010 development board. An LED was driven to toggle at each "sample-process-time stamp-store" cycle. Time to collect an entire data sample for all 3 axes, 256 samples each, was approximately 11.76 seconds. Total cycle time took approximately 17.04 seconds and included a system clock change from 32.768 kHz to 14.7456 MHz. The faster clock was used to expedite the mathematically complex FFT algorithm. Approximately 5.28 seconds was required to process the FFT algorithm and store the frequency-binned values in non-volatile memory. Given that algorithm processing and storage time was 31% of the total cycle time, this concluded that 69% of wireless sensor device's time was devoted to sampling the targeted phenomenon. Ideally, 100% sampling time would provide the most accurate sensing strategy, but given the nature of grazing and the accuracy required to achieve sub-minute levels, this amount of sampling was considered adequate.

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CHAPTER VI

BOVINE URINE AND DEFECATION DETECTION USING A WIRELESS LOCOMOTION SENSOR

CHAPTER PREFACE

This chapter was written as a part of a cooperative student research project lead by undergraduate student Cortney Timmons, Oklahoma State University, Biosystems and Agricultural Engineering Department, Stillwater, Oklahoma. Timmons was awarded an undergraduate student research scholarship to pursue a research project of personal selection, and with the guidance of a mentor. Timmons chose project and mentors relative to her area of interest: environmental issues in animal agriculture and sensors. Selection was partially based upon availability of wireless sensor device exhibited in previous chapters. The intent of the scholarship was to provide extracurricular hands-on research education for exemplary undergraduate students. The author served as the primary mentor for the student, whereas Dr. John Solie acted as faculty mentor.

Specific duties of the author were:

1. Instruct student how to collect literature resources and conduct a review.
2. Train student how to utilize custom wireless sensor device.
3. Handle embedded software and actual configuration of device while exposing student to embedded electronic systems.
4. Help student develop an experimental deployment apparatus.
5. Instruct student how to devise an experimental procedure.
6. Instruct how to select proper data sampling strategies using a specific type of sensor.

7. Instruct student how to determine total operation time respective of battery life for a wireless sensor device.
8. Instruct student how to perform basic frequency analysis.
9. Suggest contacts from other relevant disciplines such as Soil Science and Animal Science for the purpose of cross-disciplinary interaction.
10. Assist student with generating a research publication paper.
11. Review presentation and report material developed by student.

The student's responsibilities were:

1. Conduct a literature review.
2. Develop research proposal in accordance with scholarship application guidelines.
3. Develop specific project objectives related to student's interest.
4. Develop and carry out an experimental procedure.
5. Inquire other disciplines about particular challenges dealing with the project.
6. Construct a poster presentation and present at both the scholarship's presentation event and the American Society of Biological and Agricultural Engineers, Annual International Meeting undergraduate student poster competition.
7. Collect experimental data and analyze with respect to project objectives.
8. Learn the basic aspects of using a wireless sensor device involving sampling strategies, power consumption, data download, and harsh environment enclosures.
9. Develop a basic understanding of embedded systems concerning hardware and software.
10. Participate in generating a publishable applied research article.

ABSTRACT

Temporal and spatial identification of bovine urination and defecation in riparian zones is a topic that has not been extensively explored. Research that measures timing and placement of bovine waste deposits has only been accomplished through visual observations carried out over short periods. The objective of this project was to investigate application of a wireless sensor device using an accelerometer to detect bovine urination and defecation. Wireless sensor device was attached to the tail of free moving animals (one steer and four heifer yearlings). Sensing of tail movement in the z-direction (front-to-back) provided the most powerful indication of excrementous events, followed closely by y-direction (up-down) movement. Video was used to develop sensor configuration parameters and validate sensing movement. The x-direction (side-to-side) allowed for differentiating non-defecating and non-urinating animal tail movements. Movements in this direction are not customary to the act of waste excretion and are mostly indicative of tail switching and other highly dynamic movements. Tilt proved to be best suited for measuring excretion events by tail position as opposed to movements via acceleration. A sensor resolution of 3.5°/bit (using an 8 bit ADC) was adequate for patterning 54° to 67.5° range of motion depicting animal tail position corresponding to an excretion event. An 8 Hz sampling rate was established to capture tilt measurements over an event time duration of 10 to 28 seconds. A distinct cycle occurred during this time frame and was easily patterned using 0.125 sec sampling intervals. This study showed that unique tail movements can be sensed and used to detect animal waste excretion events. It was proposed that a pattern recognition approach would be best suited for this sensor setup and application. Distinct movement patterns along with event timing were indicated to support further refinement of a detection scheme focusing on the amount of waste being deposited and not simply detecting when an event occurred.

INTRODUCTION

Many studies have been conducted identifying cattle production as a significant contributor to the environmental degradation of lakes, rivers, and streams. Different forms of herd and environmental management have also been researched to alleviate this problem, including vegetative filter strips, weep berm-grass filter strips, feed manipulations, grazing strategies, fencing of shallow wetlands, and water source movement (Lim et al., 1998; Barnett, 2004; Filho et al., 1999; Tamminga, 1991; De Boer, 2002; Kebreab et al., 2001; DeRamus et al., 2003; Collins, 2004; Zeckoski et al., 2007; Sheffield el al., 1997; Bicudo et al., 2003). Evidence can also be found utilizing advanced sensory, GPS, and mechanical technologies for monitoring cattle herds. Sensors and biosensors have been used for a variety of applications, such as respiration rates, grazing frequency, deep body temperature, and milk constituents (Eigenberg et al., 2000; Reed et al., 2007; Hicks et al., 2001; Mitchell et al., 2001; Davis et al., 2003; Wu et al., 2003; Delwiche et al., 2001; Kizil et al., 2001). Temporal and spatial identification of bovine urination and defecation in riparian zones is a topic that has not been extensively explored. Research involving the measurement of timing and placement of bovine waste deposits has only been accomplished through visual observations carried out over short time periods. This method is labor intensive, prone to error because the observer can alter cattle behavior, commonly has shortened observation periods yielding less accurate and inconclusive daily behavior patterns, and generally fatigues observers (Agouridis et al., 2004).

According to Tate et al. (2003), spatial and temporal pattern of feces deposition by cattle grazing annual rangeland watersheds is an important factor determining the risk rangeland beef cattle production poses to water quality. The timing of feces deposition relative to rainfall-runoff events, and the proximity of deposition to watershed areas contributing runoff, such as riparian areas, determines much of the potential for pathogens in fecal deposits to be transported to downstream water-bodies and potentially into drinking water supplies. Advanced sensor and GPS technologies offer a means for more precise, long term identification of spatial and temporal variability of cattle waste deposits, thereby allowing for the improvement of environmental and herd management strategies in livestock production.

Identification of sensing methods that aid in advancing research studies related to animal waste depositions is needed. Many sensing platforms using biological, mechanical, and electronic methods are available to assist this endeavor. The objective of this project was to investigate the application of an existing custom wireless device that utilizes an accelerometer sensor to detect bovine urination and defecation.

LITERATURE REVIEW

ENVIRONMENTAL SIGNIFICANCE

Studies have been conducted to characterize the impacts from agriculture, such as cattle and dairy production, on surface and ground water pollution. Statistically, 39% of rivers and 45% of lakes surveyed across the United States had pollution problems, primarily due to high levels of bacteria, nutrients, and sediments.[14] These pollutants have been associated with agricultural activities and hydrologic modifications.[15] It has been noted that the nation's leading source of river and stream impairment was agricultural activity.[15] A compiled document from all states reported that agriculture was a source of

[14] National Water Quality Inventory, 2000.
[15] United States, Environmental Protection Agency (USEPA), Water Quality Report, 2000.

contamination for 48% of impaired river and stream miles. [15] Approximately 41% of the continental United States (364 million hectares) is dedicated to agricultural production of which 43% is pasture and rangeland. [15] With such a large amount of land dedicated to a practice identified as one of the main contributors to stream impairment, methods for determining and managing the effects of livestock on the environment must undergo careful consideration.[16]

Nitrogen and phosphorus have been considered two of the prominent factors in water quality as well as necessary elements for cattle and dairy production systems. Powell et al. (2004) labeled dairy manure components with the ^{15}N isotope to provide a research tool for direct measurement of N flow in feed-dairy cow-manure-soil/crop continuum. Bohlen and Gathumbi (2007) studied nitrogen cycling in subtropical cattle pastures and found that intensive summer grazing of wetlands in improved pastures reduced soil N cycling by lowering soil organic matter relative to less intensive winter grazing practices of wetlands in semi-native or unimproved areas. McDowell (2006) performed a study that showed an increase in phosphorus and sediment loading in a catchment due to winter forage grazing by dairy cattle. Each of these studies gives insight to the impacts of cattle operations related to nitrogen and phosphorus loadings in agricultural lands and watersheds. Macronutrients are important components of healthy land management strategies, but nutrient concentrations outside the optimal level could produce adverse effects on soil and water ecosystems. It is important to understand and quantify nutrient loading potentials in beef and dairy cattle operations. However, what these studies have not done is address the spatial and temporal factors imposed by the natural and semi-unpredictable deposition of livestock waste in a free-range environment.

Some research has been conducted on the impacts of livestock urination pastoral environments. Monaghan (1992) stated that urine deposition is an important source of N in grazed pastures. Nitrogen turnover in urine patches is intense, and the potential for environmental losses is significant, depending on urine composition. Decau et al. (2003) studied the fate of cattle urine during a grazing season, and found that nitrogen leaching is directly correlated to climate and soil type. Richards (1997) described urine patches in grazed pastures as harsh environments that are potentially stressful for soil organisms. N-scorching vegetation is known to occur, depending on deposition rate and urea concentration (Haynes,

[16] 1997 Census of Agriculture as reported by the EPA Office of Water 2000.

1992). Day and Detling (1990) found that natural and simulated bison and cattle urine increased above ground biomass and root mass and decreased root/shoot ratios during two growing seasons in a northern, mixed prairie, and aboveground herbivore utilization was also greater on urine patches than on the surrounding vegetation. Peterson (2004) found that carbon and nitrogen transformations are intense in pasture soil affected by urine. Urine has an adverse effect on soil microorganisms, which was indicated by a stress response of nitrifiers to urine deposition.

Studies have identified urine and feces constituents as well as some of the implications of these constituents on the soil environment. In most cases these studies are on a micro level that does not attend to the larger ecosystems within a range or pastoral cattle production operation. A method that records the location and abundance of livestock urination and defecation would strongly build upon this past research. Availability of this kind of data would give agriculturalists and environmentalists a better macro understanding of soil fertility, nutrient utilization efficiency, and surface water contamination prevention. A larger scale approach may also institute more practical means for new production applications.

Other studies present methods of monitoring and mitigating agricultural pollutants. Lim et al. (1998) discussed the viability of vegetative filter strips as a form of cattle manure runoff mitigation, and suggested that even relatively short filter strips can markedly improve quality of runoff from grassed areas receiving cattle manure. Barnett (2004) researched the effectiveness of a weep berm-grass filter riparian control system to alleviate pollution in our lakes and streams that has been attributed to agricultural practices, with bacteria, nutrients, and sediment being the primary pollutants. Design of these mitigating structures can be arbitrary and governed by estimates. Spatial and temporal data for manure deposition would definitely help refine the structures developed and improve their placement effectiveness.

The plant-animal interaction at the interface of water availability, agriculture productivity, and negative environmental impacts has also been a focal point for research. Management practices using water access control have been implemented to evaluate both herd production improvements and reduced environmental influences. Collins (2004) observed cattle are not attracted to larger deeper wetlands but prefer smaller shallower wetlands both in summer and in winter. This contributes to higher concentrations of fecal contamination in the form of E. coli in these areas. The study suggested fencing off shallow wetlands to yield improvements in bacterial water quality by managing fecal distribution. This approach also indicated improved utilization of available forage as an additional benefit. Zeckoski et al. (2007) collected information from cattle producers in Virginia who use stream exclusion practices to protect surface water quality in and around their property. It was determined that agriculturalists with stream exclusion practices also experienced an increase in cattle weight gain (beef operations) or milk production (dairy operations) and decrease in disease. Sheffield et al. (1997) studied the effectiveness of using a water trough to reduce stream bank erosion and improve water quality improvements. Spatial and temporal logging of actual cattle waste deposition would properly validate the concerns brought forth by these studies.

As shown above, research has been done to quantify and analyze the utilization, implications, and mitigation of livestock urination and defecation after animal excretion. However, little research exists to determine when, where, and how often bovine urination and defecation are actually excreted and introduced into the soil and/or water environment. Tools and methods that provide a more preemptive basis to cattle free range waste management are needed.

In any case where feed or water alterations are made, the practicality of the concern must be validated. It is customary to acknowledge a decrease in surface water contamination is a positive endeavor, but lack of developing a conclusive scope of the situation can have unwarranted ramifications. The studies recently presented would benefit from assessing spatial waste distribution data along with their feed based nutrient control so that more conclusive implications can be drawn.

Advanced Sensory, Mechanical Technologies, and GPS

Temperature sensing has been a popular monitoring regime that can be indicative of multiple morbid or production sensitive traits. Hicks et al. (2001) compared dairy cow body temperature readings using ingested and implanted sensors and rectal thermometers. Mitchell et al. (2001) deployed a multi-channel, surgically implantable radio-telemetry system for the continuous remote monitoring of deep body temperature and heart rate of broiler chickens and calves in transit. Davis et al. (2003) measured core body temperature of steers continuously for 6-9 days at three sites on each animal: rectum, near the tympanic membrane and peritoneal cavity.

Other sensing strategies have been orchestrated around electromechanical platforms. Eigenberg et al. (2000) designed, fabricated, and tested monitors from commercially available thin-film pressure sensors and a small battery powered micro-computer for the continuous measurement of cattle respiration rates and the evaluation of stress responses associated with environmental conditions.

Animal locality has become a prime feature in spatial analysis for both animal mobility and food forage consumption. Turner et al., (2001) reviewed the application of GPS for cattle monitoring in pasture, and presented data assessing location of cattle on pasture as considering slope, aspect, and soil type. According to a study by Agouridis et al. (2004), GPS collars on grazing cattle generally provide data with horizontal accuracies of 4 to 5 meters when operated in the field. Davis et al. (2005) developed a low-cost, automatic, and continuous Herd Activity and Welfare Kit (HAWK), mounted on cattle above the shoulders, to collect GPS positions and analog sensor data at a user-specified sampling frequency to monitor the movements of cattle.

These studies show that advanced sensory, mechanical, and GPS technologies are valuable means of monitoring livestock in various applications. They provide technical and intuitive support for other sensor applications such as urination and defecation detection.

TEMPORAL AND SPATIAL IDENTIFICATION OF BOVINE URINATION AND DEFECATION

The spatial and temporal patterns of feces deposition by cattle grazing rangelands within watersheds are essential to determining the risk cattle production poses to water quality. Timing of feces deposition relative to rainfall-runoff events and the proximity of deposition to watershed areas contributing runoff (i.e. riparian areas) determines much of the potential for pathogens in fecal deposits to be transported to downstream water-bodies and potentially into drinking water supplies (Tate et al., 2003). Successful management of cattle feces distribution to reduce risk to water quality requires an understanding of the management and environmental factors determining the spatial distribution of livestock feces across grazed watersheds.

Tate et al. (2003) used visual observation to measure associations between daily fecal load per season, livestock management, and environmental factors on 40 m^2 (47.8 yd^2) permanent transects distributed across a 150.5 ha (371.9 ac) pasture in Madera County, California. White et al. (2001) determined the distribution of feces and urine from 36 lactating dairy cattle managed in a rotationally grazed 0.74 ha (1.83 ac) endophyte-free tall fescue white clover pasture using 24 and 13.5 hr visual observation periods. Tate et al. (2001) also developed a regression relationship to predict fecal deposit dry weight by rank. This method provided a rapid, simple method for estimating spatial and temporal livestock fecal loading on rangeland watersheds. Shima et al. (2006) used visual observations to study the correlation of cattle stocking density to total nitrogen (TN) and total phosphorus (TP) concentrations in a watershed and found that the loads of TN and TP increased with grazing time.

While some studies have developed methods to determine temporal and spatial distribution of bovine urination and defecation, most rely on visual observation for data collection. While these methods are applicable, they are labor intensive, can only be carried out over a short periods in small sampling areas, and are prone to significant error. An automated sensory method for detecting bovine urination and defecation could be useful in determining urine and fecal loadings over a larger area. Using wireless sensors would produce unbiased data, decrease labor and dependence on visual observations, and reduce the potential for error.

Sensor Preparation and Experiment Setup

Preliminary Video Analysis

Livestock urination and defecation occurrences are described as the animal's tail quickly moves up to a certain angled or arched position, remains motionless in that position for a period of time, and then slowly falls back down to the original starting position. Following this understanding, a sensing strategy and basic parameters were established using frame-by-frame video analysis (Figure 40). To develop a general consensus of locomotion during urination and defecation events of free-moving animals, animals with different genders were analyzed. Captured video included events for steers, bulls, heifers, and cows. It was observed through video that when cows and heifers excrete waste, tail position followed a general pattern similar to that of defecation by steers and bulls. Tail movements typically followed this pattern during an excretion event regardless if the animals were walking or standing.

Along with motion, event timing was evaluated in the preliminary video investigation. Determining the length of an event was imperative to developing a proper sensor data sampling strategy. A single urination/defecation event mostly occurred in the time the tail remains in a motionless, raised position. This period plus beginning and ending tail movements were considered distinct movements in which a sensing device should be able to detect.

Bovine urination and defecation parameters related to the approximate distance, time, and tail position were manually recorded in half-second intervals during each of the video captured excretions. Sensor tilt measurement range was between -1 to 1 *g*, where 0 *g* represented horizontal axis orientation and -1 *g* represented vertical axis perpendicular to the Earth's surface. Tail tilt began at -1 *g*, and approached the 0 *g* horizontal position before falling back to vertical (Figure 40). Acceleration measurements were made possible by estimating velocity of tail movement using frame time and approximate distance moved, then deriving acceleration. A sample of these results is plotted in Figure 41 to graphically characterize bovine excrementous events. Figure 42 and Figure 43 correspond to the information shown in Figure 41. Figure 42 depicts only tilt whereas Figure 43 includes both tilt and acceleration and shows to be nearly the same as Figure 42. During this urination event tail tilt remained constant for approximately 28 seconds and is shown by a constant horizontal position.

Figure 40. Tail movement captured by video during an urination event.

It was concluded from video analysis that tilt is the dominant feature providing the best measurable information for determining an excrementous event. Acceleration may potentially provide features that support a sensing regime beyond the use of tilt. A sensor sampling rate was required to be frequent enough to capture at least a 28 second cycle such as that shown in Figure 42. Figure 41 suggests that accelerations could occur within a one second time frame thereby requiring even a faster sampling rate for capturing more dynamic features associated with the beginning and ending tail movements. Therefore, a sampling rate of 8 Hz was chosen to encompass both tilt and acceleration measurement needs when configuring the locomotion sensor.

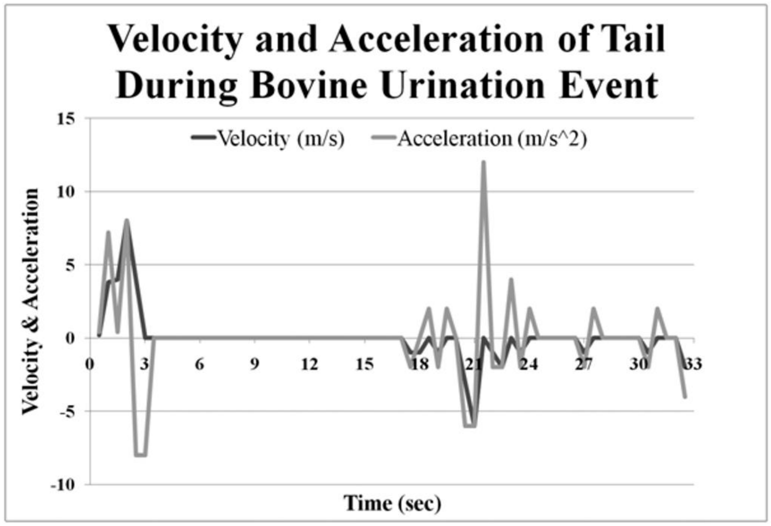

Figure 41. Modeling tail velocity and acceleration using a video-captured urination event.

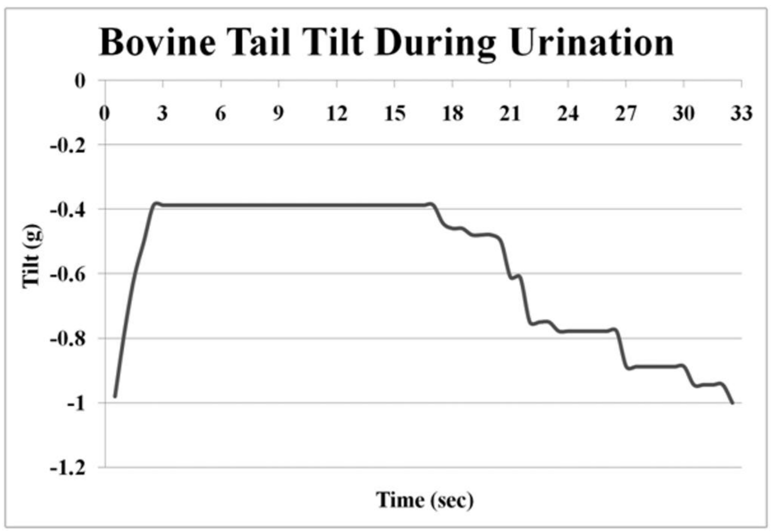

Figure 42. Tail tilt for a video-captured urination event.

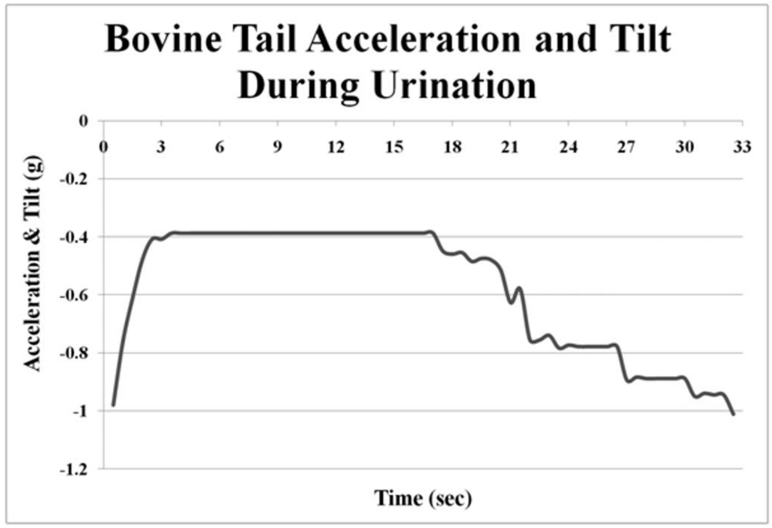

Figure 43. Tail tilt and acceleration for a video-captured urination event.

THE PROPOSED SENSOR

Reed et al. (2007) used a custom wireless sensor device equipped with an accelerometer to detect grazing activity of free-range cattle. The device used was proposed as the platform to collect tail movement data pertinent to detecting urination and defecation events as described earlier. This device consisted of a 3-axes accelerometer with ±3*g* measurement range and 300 mV/*g* resolution; and operable on a 3 V battery supply. A 10 bit analog to digital convertor (ADC) was integrated into microprocessor chip, but was configured for only 8 bit resolution. Using the accelerometer sensor specifications, power supply, and ADC configuration noted, a resolution of 25.6 bits/*g* was calculated. This device also included a real time clock and thereby was capable of time stamping logged data.

An accelerometer logging device capable of capturing grazing movements between 0.5 and 8 Hz, as stated in Reed et al. (2007), was deemed appropriate for capturing much slower tail movements indicative of waste excretion. Wireless sensor device was customized with data logging code to sample all axes every 125 ms (8 Hz). Code was prepared to sample and immediately store data to on-board non-volatile memory. At this rate data could be stored for up to 97 hrs using its 8-Mbit data flash memory.

Additionally, tail movements have been discussed to be best measured with tilt as opposed to acceleration. Because of this reasoning, sensor resolution was evaluated more for positioning than for dynamic movements. Tilt sensor measurement range was between -1 to 1 *g* for each axis, where 0 *g* represented horizontal axis orientation relative to Earth's surface. Assuming that tail positioning will rarely exceed a 90° change from vertical to horizontal only a 1-*g* range was required. This is well within the ±3-*g* range of the proposed sensor. At 25.6 bits/*g* resolution a total usable sensor range was estimated to be only 10% of the ADC range. However, this also yielded a detectable 3.5°/bit, which was considered sufficient for this investigation. The amount of movement expected in this study was shown in previous video analysis to be between 1 and 0.4 *g*, or 54° from vertical to horizontal (Figure 42 and Figure 43). More precise positioning measurement may be appropriate for further studies where benefits can be realized concerning quantification and event-to-event modeling. And because the proposed sensing device was capable of providing both tilt and acceleration, allowances for better inferences to be drawn in support of a refined sensor detection strategy were also possible.

TRIAL RUN LABORATORY EXPERIMENT

A laboratory experiment was conducted to verify an 8 Hz sampling rate and 3.5°/bit resolution were appropriate for field experiment deployment. Wireless sensing device was connected to a small 3 V lithium ion battery, placed in a nylon pouch enclosure, and attached to the author's arm just above the elbow. Arm movements were made to mimic the motion of a tail during a urination or defecation event. Figure 44 shows data collected during the laboratory exercise. Figure 45 is a 256-point Fast Fourier Transform (FFT) calculated using data in Figure 44. An FFT was calculated to explore spectral frequency characteristics similar to that done in Reed et al. (2007). Direct evaluation of Figure 44 proved sufficient for determining pattern characteristics particular to time and tilt magnitude. FFT analysis was concluded to have little added value at this stage. To better utilize FFT analysis larger sampling periods would need to be implemented so that multiple occurrences could be captured in a single sample set. Simulated tail movement shown in Figure 44 is a discrete occurrence and thus does not occur in a periodic fashion, which is also necessary for FFT utilization. An alternative method such as pattern recognition may be a more appropriate sensing approach as opposed to spectral frequency analysis.

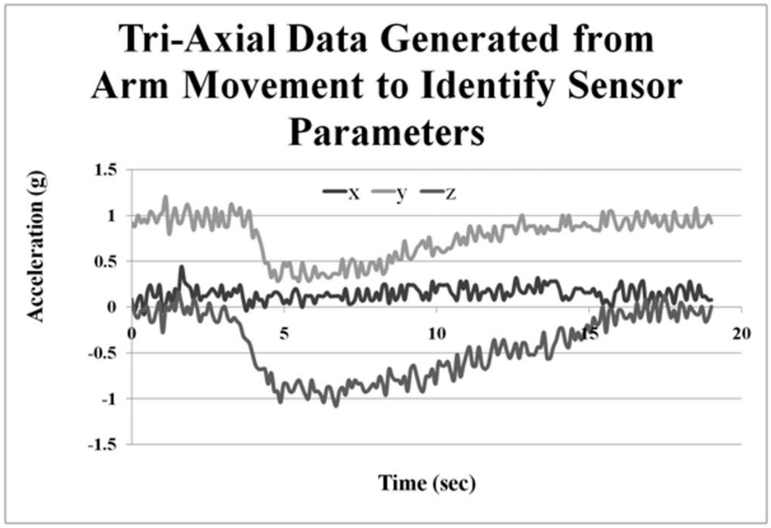

Figure 44. Laboratory experiment data validating sensor configuration settings and apparatus use.

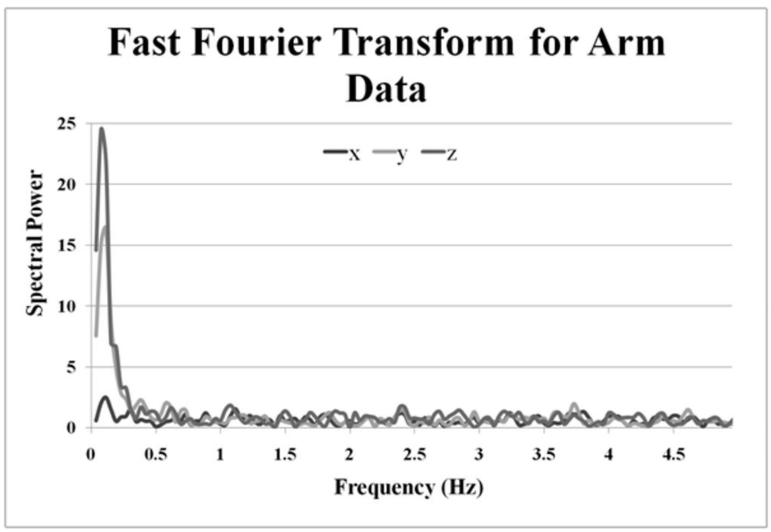

Figure 45. An FFT of laboratory experiment data for exploring spectral frequency uses.

FIELD EXPERIMENT

Four yearling heifers and one yearling steer, each with a weight ranging from 400 to 450 kg (880 to 990 lbs) were used for trial runs as well as final data collection experiments. These animals were domesticated show competition calves managed by a cooperating agricultural secondary education program. Experiment environment was an open five-acre plot already familiar to the animals. It is acknowledged that applying a sensor for the detection of bovine urination and defecation would be most useful in a free range grazing operation of a much larger scale. However, for this experiment, it was necessary to keep the test subjects in a more confined and controlled area. This smaller area allowed for constant visual observation and video recording of the cattle when needed.

Devices were connected to power supplies and placed in customized water-proof PVC casings. Casings were slightly larger than the sensing device and had 8.89 by 3.18 by 2.54 cm (3.5 by 1.25 by 1 in) outer dimensions. Battery was external to enclosure and measured 5.08 by 3.81 by 1.27 cm (2 by 1.5 by 0.5 in). Battery and sensor casing were placed end to end, parallel to the animal's tail, midway between tail tip and tail head. Prior to deployment, a steel rod of approximately the same size and weight of sensor device and battery assembly was attached to each animal for a one week period. This acclimated the animals to having a foreign object attached to their tail; otherwise the first few hours of an experiment would experience unnatural tail switching.

All animals were secured in a normal fashion during their daily wash and coat preparation. At this time elastic veterinary medical tape was used to attach the sensor casings and battery packs to the animals' tails in a non-invasive manner. Tails were prepped with a standard curry comb to remove all debris in the tails' mid-section where the sensors were to be secured. Elastic medical tape firmly secured and protected sensors while also providing a means of easily removing the devices due to the tape's flexible non-permanent adhesion.

Video was collected at various times throughout the sensor deployment period. At device power-up, time and date were recorded for the purpose of cross referencing with validation video. After device-battery connection and enclosure sealing, both battery and device-enclosure were fastened to the animal's tail as described earlier. Sensors were powered for approximately 46.5 hrs, and video was taken in one to two hour increments randomly throughout the time of deployment. Manual time recordings were made each time an urination or defecation event was recorded with video.

Once data logging memory was filled or device operation was terminated by removal of power source, data was then downloaded through a custom serial connection to a PC. Standard terminal software was used to capture the incoming data stream in the form of an ASCII text file. Text file was organized relative to data flash memory structure. This required post-processing for proper alignment with sampling time and division of each axis's respective data. Post-processing was performed using Matlab® R2007a software.[17]

Results and Discussion

Video Confirmation and Sensor setup

An important parameter to consider when sensing bovine urination and defecation was the actual time in which an event occurred, which not only determined the length of the event but also indicated the amount of waste excreted. Preliminary video investigation provided proper characterization and quantitative evidence of cattle tail movement during waste deposition. Tail tilt began at -1 *g* and began to approach the 0-*g* position reaching approximately 0.4 *g* before falling back to the -1-*g* position (Figure 42). Initial tail movement occurred rapidly in most cases, followed by periods of no movement and steady movement back to the original tail position. Urination and defecation always occurred during the "no movement" periods. Twenty eight seconds was observed as an urination event. This gave a good indication of approximately how long urination and/or defecation events could last. Measuring this time period may also help indicate the amount of waste excreted.

In order to generate a usable model, acceleration and tilt were combined and plotted versus time to represent the bovine excrementous event. Figure 43 shows the data model for tail tilt and acceleration. When an accelerometer senses bovine urination and defecation events, the data curve shape produced should resemble the model above. This model was used as a guide to identifying sensor parameters relative to tilt range, sampling period, and sampling rate.

Figure 46 compares the preliminary investigation model to y-directional sensor data produced during arm movement laboratory exercise that mimicked cattle waste deposition tail motion. When the sensor was placed in a nylon pouch enclosure and attached to the arm, the y-axis of the sensor was aligned vertically with positive direction away from the Earth's surface. In the lab experiment sensor readings started at 1 *g* when the arm was in the down position and approached the 0-*g* position as the arm rotated upward, mimicking tail movement. This was different from the preliminary video investigation, where it was assumed that the tail started at -1 *g* and approached 0 *g*. Both curves still indicate the rapid upward

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[17] Matlab R2007a is a data processing environment where multiple analysis and visualization tools are used. Software is provided by MathWorks, Inc, Natick, Massachusetts

motion, stationary phase, and slow downward motion of the tail during waste deposition. This confirmed that the sensor's configuration for sampling and sensitivity was ready for field experiment deployment.

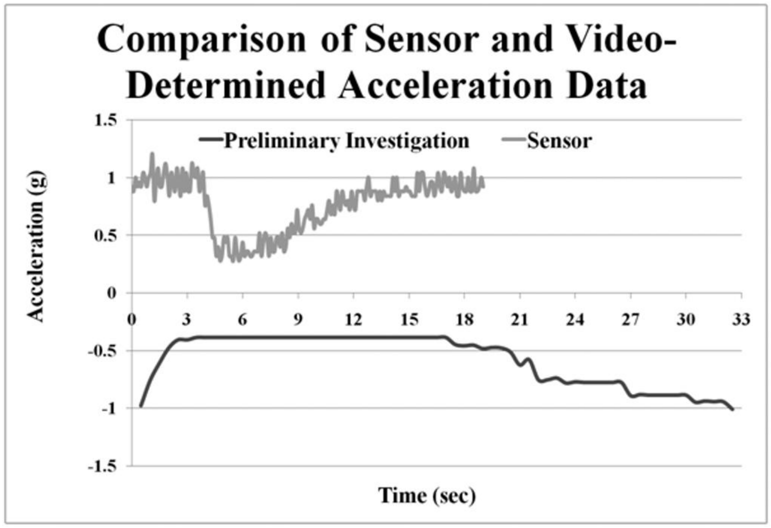

Figure 46. Comparing data generated from video and the laboratory experiment.

APPLIED FIELD EXPERIMENT RESULTS

Acceleration data collected during the applied field experiment provided reliable indications of bovine urination and defecation. Figure 47 illustrates tri-axle data for the steer's tail movement during defecation. Movement in the x- and y-direction (side-to-side and up-down directions respectively) appeared to stay constant during excretion. However, the detection of z-direction (front-to-back) movement provided a strong indication of the defecation event, which occurred over a period of approximately 9 sec. This was also validated with video recordings. A slight depression can be seen in the y-axis curve, but it is unclear why this curve was not a better indicator of tail movement during defecation since laboratory experiments indicated that the y-axis was a stronger indicator. It is likely the device could have slightly rotated around the tail during attachment or that the animal also rotated its tail during the event in such a manner that both the x any axes experienced the same relative yet mirrored positions. This implies that the z-axis (front-to-back) is more reliable for sensing.

Figure 48 shows data for a heifer during urination, and is similar to Figure 47. Again it is shown that the z-axis has the dominant response. Figure 48 also shows a slightly improved pattern with the y-axis and much less dynamic movement at the onset and ending of the event. Events in both these samples lasted between 10 and 15 seconds. Preliminary video showed a much longer period of 28 sec which is evidence of variable time durations possibly related to the amount of urination or defecation excreted. Additionally, a tilt measurement range of 0.75 *g* is apparent in both Figure 47 and Figure 48.

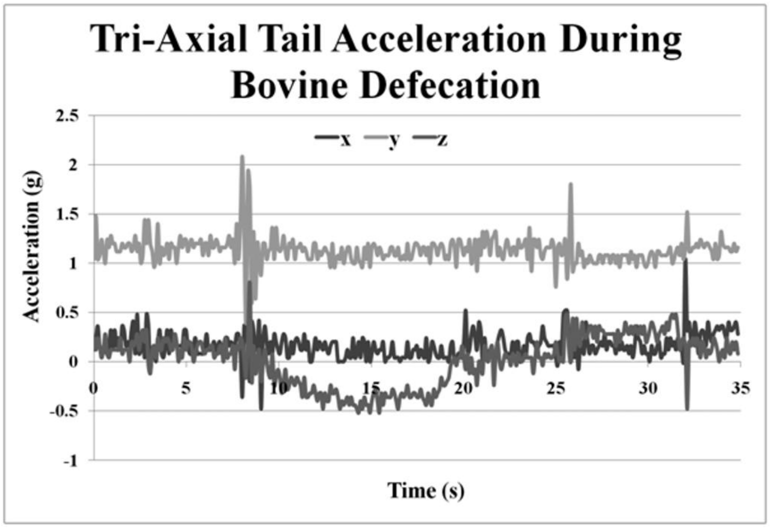

Figure 47. Tri-axial accelerometer data from a steer's tail movement during a defecation event.

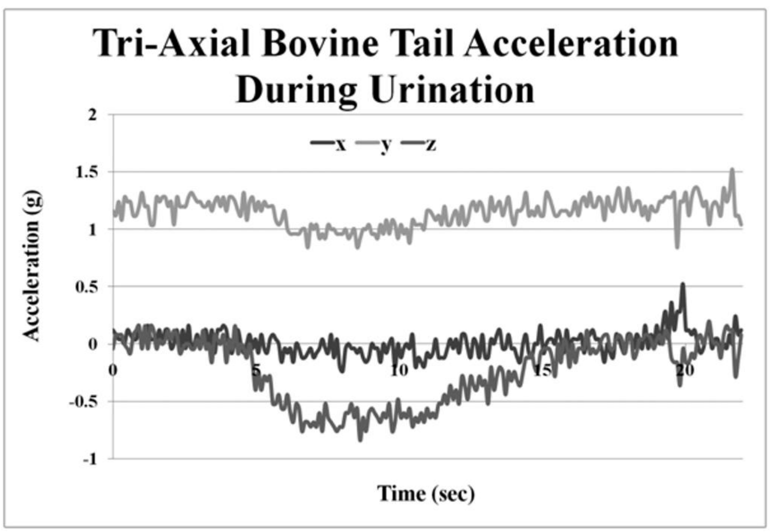

Figure 48. Tri-axial acceleration data from a heifer's tail movement during a urination event.

Data curves like the ones shown in Figure 47 and Figure 48 exhibit how well a wireless tilt sensor can identify bovine urination and defecation. These are two example data sets that occurred for an urination and defecation event of livestock with different gender. While z-directional data provided the most consistent and powerful indication of bovine urination and defecation, it is still important to include detection in the x- and y-directions. Rapid or frequent movement in the x-direction may help identify tail movements during other events, including switching at pests and hyperactive behavior (i.e. running, bucking, fighting, etc.). During these activities, it is possible that the tail moves similar to a defecation or urination event.

Generating a vector from all three axes may prove more sound than focusing on one individual axis. Interpreting dynamic components at the beginning and end of an event may also provide robustness to a sensing scheme. Further research is needed to explore these methods. Usable parameters of a tilt sensing device and a proposed sensing method have been identified to support these research opportunities.

CONCLUSION

Based on the results of this investigation, a miniaturized wireless device with an accelerometer sensor can be used to detect urination and defecation events of free-moving livestock animals such as cattle. Sensing tail movement in the z-direction (front-to-back) provided the most powerful indication of excrementous events, followed closely by y-directional (up-down) movement. Tail movement in the x-direction (side-to-side) stayed constant during urination and defecation, but provided an additional detection mechanism that could assist in identifying non-excretion events. Cattle move their tails in many different directions during non-excretion events like tail switching, which is characterized as a strong side-to-side action. Video was used to validate that only y and z directions experienced explicit tail movement when defecating and urinating, and that distinct logic decision making information was available when combining tilt measurements from all three directions.

Tilt proved to be sufficient for measuring tail movement as opposed to acceleration. Sensor resolution of 3.5° per bit (using an 8 bit ADC) was adequate for patterning a video-estimated 54° range of motion (and maximum of 90°) depicting animal tail position throughout an excretion event. Experimental data showed a tail movement range of 0.75 *g* (67.5°). A courser sensor resolution, achievable with a less expensive tilt sensor, would indisputably provide sufficient data. This is an important parameter for future development of wireless sensor devices specifically targeting livestock waste excretion.

An 8-Hz sampling rate was chosen to capture tilt measurements over an event time duration of 28 sec. A distinct cycle occurred during this time frame and was easily patterned using 0.125-sec sampling intervals. This sampling rate also allowed detection of more dynamic tail movements thereby providing potential to better identify occurrences when tilt information may have been marginal. It is clear that a slower sampling rate would be satisfactory for patterning a near half second cycle. However, more investigation is needed to explore the value of infrequent dynamic features that may be included as part of excretion events.

The data and results presented here not only exhibit the value of using a locomotion sensor to detect urination and defecation events, but also proclaim the possibility of extending this sensing strategy to quantify waste deposition. Timing excretion events along with observing minute dynamics during the event are presumed to be indicative of the amount of urine or feces deposited. Video data showed an event length of 28 sec whereas experimental data showed event lengths ranging from 10 to 15 sec. Recording event frequency is also considered a refining factor for quantifying waste deposition over time. More data collection and analysis will be required to validate these suppositions.

Other research has focused on waste movements after waste material has been deposited by an animal but little work has been done for establishing both temporal and spatial aspects at the occurrence of waste excretion. This is largely in part to lack of sensing equipment and validated methods, which has been addressed by this research. Now that the basic sensing approach has been identified, future work would entail implementation of a sensing algorithm along with a GPS logging component. Reed et al. (2007) implemented miniature GPS loggers to georeference grazing information. GPS information is necessary for future work dealing with spatial analysis of livestock waste deposition and validating areas of environmental concern. The sensor parameters and methods that have been outlined in this work are undeniably valuable for advancing environmental studies in animal agriculture. Past research has recognized similar management and environmental impacts as well as explored various post excretion sensor strategies. However, these efforts did not involve equal ability and opportunity of that realized with the proposed wireless sensor system in this study.

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CHAPTER VII

CONCLUSION

A wireless sensor device and sensing algorithm were designed and built for the purpose of monitoring free-range grazing cattle. The sensor type proposed was a 3-axis accelerometer capable of sensing a grazing animal's head locomotion and tilt positions. A sensing algorithm was shown to determine features pertaining to bite rate, bite intensity, and grazing intensity. A miniature GPS device was simultaneously used to georeference grazing information that resulted in grazing intensity maps, which have potential use with other crop sensing systems (i.e. crop nutrient management). Other than acting as a grazing sensor, the proposed device was designed to provide a custom wireless sensor platform that can be configured to sense other agricultural phenomenon.

The proposed sensing device was 19.6 mm (0.77 in) wide, 71.8 mm (2.83 in) long, and 11.0 mm (0.43 in) thick. The grazing sensor and GPS were concealed on a standard nylon turnout halter using custom-built PVC enclosures. The sensor's MCU was a Chipcon (Texas Instrument) CC1010 module, which entailed an 8051 processor core and chip-integrated peripherals such as a real-time clock, serial peripheral interface master, ADC, and radio transceiver. The CC1010 had ample memory in which data logging and processing were made possible on-chip via RAM. This provided expedient sensor algorithm processing. Dual clock functionality was also capable with the CC1010, and enabled power efficient data collection procedures along with high performance algorithm processing. Combined hardware components on a single chip die not only improved board layout, but also enhanced coding. The advantages are clear-cut when considering multiple, space-consuming, chip-hardware packages that communicate over time costly serial or parallel buses. Furthermore, the CC1010 is a proven microcontroller/transceiver that is accompanied by substantial documentation and development support. Embedded C was used as the coding language and Keil µvision 3 was the IDE.

The sensor's PCB was also populated with extra IC devices such as a sizable 8-Mbit data flash memory chip and additional ADC. The data flash chip provided non-volatile memory storage for post-processed data and other attributes pertaining to network timing, network communication messages, and memory pointer management. The supplemental ADC was added because the CC1010's integrated ADC was completely devoted to the accelerometer sensor. This ADC supported the implementation of future sensor transducers.

A single battery pack was used to power both the GPS and wireless sensor device. The battery was encased separately on the halter apparatus. The sensor operated off a 3-V system using a low-noise and ~87% efficient LDO regulator. The LDO regulator was shown to be better suited for this device with respect to noise level and low-current efficiency, as opposed to a buck-boost configured switching regulator.

A 915-MHz carrier frequency was selected for radio operations. Manchester encoding and a 64-kHz frequency spread were selected as the most robust modulation scheme, that was also built-in and easily implemented on the CC1010. Radio power was set at 4 dBm. An antenna was selected based on size and directivity. The antenna selected was a helical type with a specified maximum gain of -2.16 dBi. The antenna's radiation pattern was near omnidirectional and it had a bandwidth of 30 MHz. The device's link budget was estimated at 81 dBm, equating to a 282-m (925-ft) transmission distance in optimum conditions.

Sensor algorithm specifics were defined with respect to phenomenon characteristics and device operability. Phenomenon characteristics were first clarified using captured video analysis. The video analysis provided initial design parameters for constructing a sampling method when using an acceleration/tilt measurement sensor. An FFT was implemented to provide spectral information related to animal grazing motion. The FFT process was performed in-place using xdata RAM, and 256-point data vectors for each accelerometer axis. The FFT's spectral output was condensed using a frequency binning method. The binning method formed 16 averaged spectral powers over the frequency range 1-8 Hz. The binned results were time stamped and stored in non-volatile memory. Total data collection time was measured to be 11.76 sec and processing/storage time was 5.28 sec. At least 5 grazing bites were required to be sampled in a single period, and that the sample-process procedure would be sufficient for detecting the act of grazing with sub-minute accuracy. Short period (i.e. > 5 min) grazing intensities and bite rates could also be deduced from these sub-minute measures.

Other applications were explored using the developed sensing platform. Grazing animals' waste deposition was discussed to be a viable application where no qualified methods exist to measure when and where these deposits occur. It was proposed to use the locomotion-sensing device attached to an animal's tail thereby monitoring tail movements. These movements were shown to be distinct and measurable using the device. Pattern recognition of tilt was proposed as a possible algorithm that would potentially yield not only an indication of urination or defecation, but also a relative amount of excreted waste. Urination and defecation events were measured to be between 10 and 28 sec. The accelerometer's z-axis (front-to-back) alignment proved to capture the most dominant tail movement features particular to waste excretion.

CURRENT AND FUTURE WORK

Wireless network operability was not implemented in this research. However, the intent of wireless network operability was apparent. Considerations were made at the beginning and throughout the wireless sensor's design phases in regards for future implementation of wireless communications. It was anticipated for a grazing sensor application, that an opportunistic communication scheme within a node-to-base topology would be evaluated. Short-range devices, such as the one developed in this research, are limited in communication strength and ability to perform complex message routing protocols. Therefore, an opportunistic approach that promotes communications only when radio performance and need are established would be a workable method. This would allow for gathering of networking priorities and characteristics in support of developing an elegant system that monitors free-range grazing animals in a timely manner.

Aside from the base-node network level, a full remote operating system was also projected. As an extension of this research, investigations are currently underway for the development of a remote data download and management system using both cellular and internet communication. Figure 49 is an illustration of two possible systems that center on the same application server. The application server functions as both a database and management machine. Two-way communications are required throughout the system. The first system outlines use of any internet-connected terminal, whereas the second is implemented on a laptop for in-field functionality, or in the absence of an internet provider.

Appendix G exhibits a preliminary version of two-way device management via the application server. Four main tasks are core to the application server: change address, time synchronization, data download, and node list management. These tasks pertain to both sensor nodes and base nodes. The gateway device shown in Figure 49 operates merely as a pass-through, and only provides provisions for cellular and TCP/IP communications. Future development may require the gateway module to perform portions of network management functions.

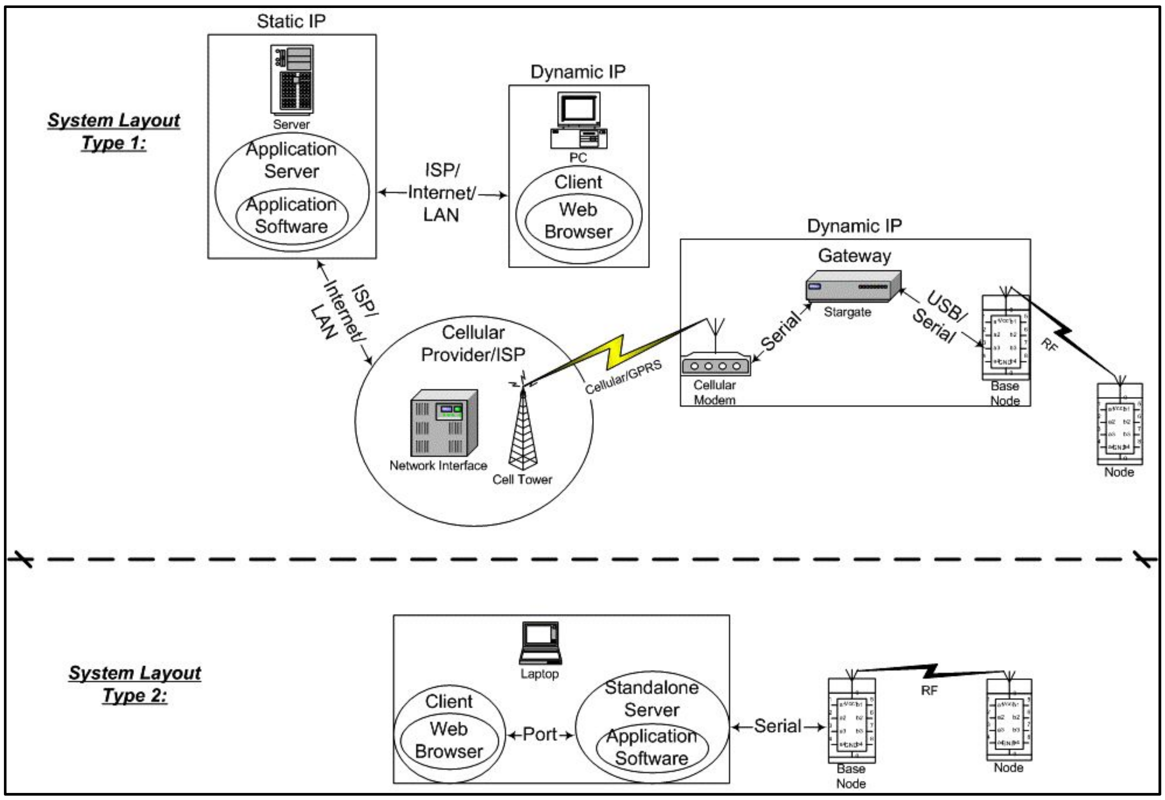

Figure 49. System layout for two-way remote wireless sensor management. System one details internet and cellular connections, whereas system two provides an in-field stand alone application. Both system one and two are intended to use the same application server software.

Multi-leveled system integration is necessary for harnessing the value of developing agriculture sensors. Without these systems combination and use of grazing- and crop-sensor data would not be practical. The importance of enhancing agriculture management practices using sensory devices integrated in conclusive management systems is becoming more plausible as new research tools are being developed. This is facilitated by advanced electronic technologies becoming more feasible to use in studies and by a broader range of researchers with interdisciplinary objectives. The wireless sensor hardware design, sensor algorithm development, and application related parameters presented in this research support these initiatives.

APPENDICES

APPENDIX A

CHAPTER IV: ASABE 2007 INTERNATIONAL MEETING PAPER PRESENTATION SLIDES

Foraging Detection of Free-grazing Cattle using a Wireless Motion Sensing Device and Micro-GPS

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The Importance of an On-animal Foraging Sensor

- Provide data for an individual animal
- Determine in-pasture food consumption
- Indicative of foraging patterns
  - onset of sickness, or breeding cycles
  - forage production temporal variability
  - preferential grazing

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The Importance of an On-animal Foraging Sensor with GPS

- Spatial evaluation of forage use
- Used in parallel with, or as a substitute for, remote crop sensors

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Previous Sensors/Methods for Detecting Grazing Activity

- Live observation
- Vibracorder
- Elastic transducer
- Mechanical switch
- Pressure transducer
- Microphone
- Pedometer

Common Problems
- Laborious
- Difficult to reconfigure and calibrate
- Extensive mounting requirements
- Separate data acquisition system required
- Often cumbersome and heavy to animal

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Conventional On-animal GPS

- Collar apparatus design
  - Expensive ($2000 - $5000), large power requirements
  - Nuisance to animal, cumbersome and heavy, requires acclimation
- Examples of research use
  - Improved grazing management techniques for BMP programs
  - Monitor hill climbing and bottom dwelling cattle grazing distribution
  - Determine grazing, traveling, and resting activities
  - Cattle interactions with streams
  - Controlling grazing location using virtual fences

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Design Constraints for an Integrated Grazing Sensor

- Wireless
  - Remote control and interrogation of sensor device
  - Communication standards: deployable and adaptable
- Sensor Type(s)
  - Single chip or chip set packaging
  - Multiple types per board
- Data storage and handling
  - Large memory storage capacity
  - Ability to conduct real-time data processing
- Power
  - Low power (+3.3 V system)
  - Conservative sensor and wireless functions
  - High density rechargeable batteries

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Research Focus

1. Sensor specification
2. Demonstrate use
3. Complete integration

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Objectives 1 & 2 (proof-of-concept)

1. Demonstrate the ability of an electronic accelerometer to detect grazing activity of a free-range beef animal
2. Show that accelerometer and GPS data provides grazing information useful for spatial analysis

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Objective 3 (full integration of single board wireless sensor)

3. Design and build a micro sized PCB integrating wireless communication and sensing capabilities

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Objective 1:

Demonstrate the ability of an electronic accelerometer to detect grazing activity of a free-range beef animal

Theory:

- Cattle have distinct head movements while grazing (cyclical motion with jerking/pulling action; 0.5 – 8 bites/sec).
- Cattle have particular head positions while grazing (head tilt, up/down).

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Objective 2:

Show that accelerometer and GPS data provides grazing information useful for spatial analysis

Theory:

- Preferential grazing can be related to spatial variables within a field or pasture (i.e. soil nutrient availability, plant species)
- Geo-referenced grazing information can show spatial variable effects

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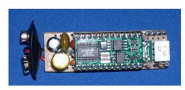
Proof-of-Concept Accelerometer Data Logger

- PIC 16C57 μcontroller (Basic Stamp 2X)
- Memsic 2125 dual-axis accelerometer ($\pm 2g$)
- Atmel AT45DB32 data flash memory (4.3 Mbyte)
- Maxim DS1302 real time clock (RTC)



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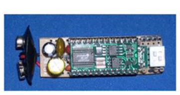
Proof-of-Concept Accelerometer Data Logger



- Sampling rate selectable (33 Hz maximum)
- Serial interface
- Powered by +9V battery (5V regulated)
- 18 hours of data logging

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GPS Device

- Commercial vehicle tracking device (~$150)
- Modified to be powered by a +9 V battery instead of +12 V
- Serial interface
- Interface software for configuration and data retrieval provided
- 1 minute position fix
- < 15 meter accuracy

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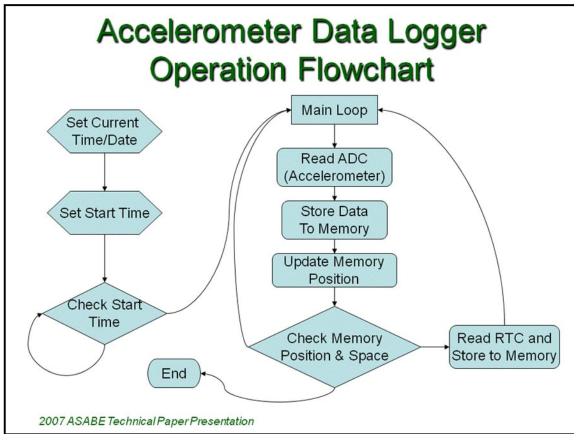

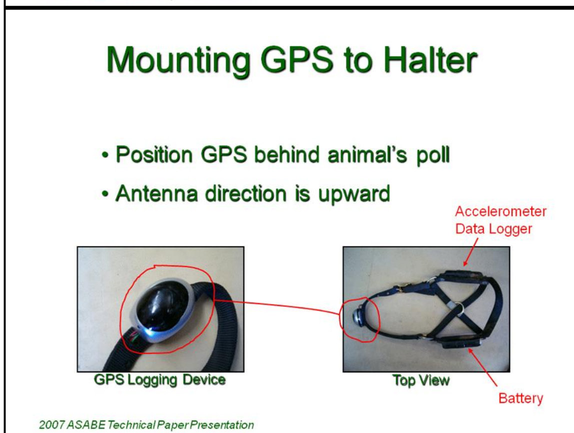

Video Recorder

- Use video to verify animal activity (i.e. grazing, walking, laying)
- Frame-by-frame analysis (bite rate, bite duration)

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Data Synchronization

- Accelerometer data logger time is set during device initialization
- Video recorder time is set at beginning of experiment

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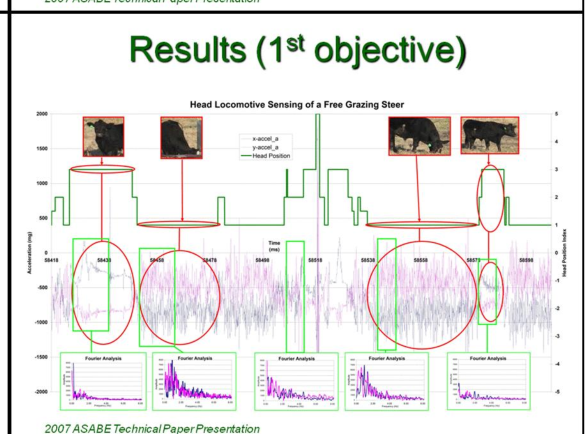
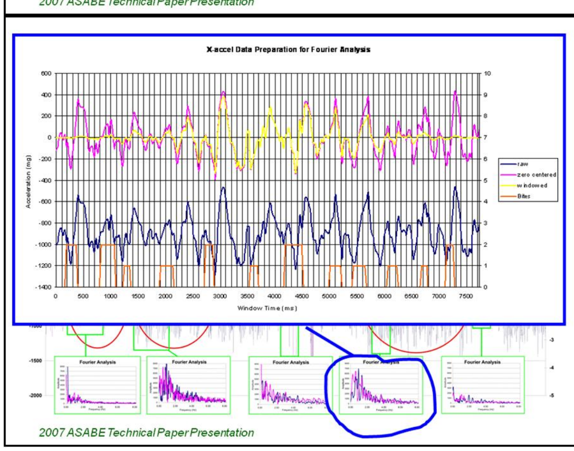
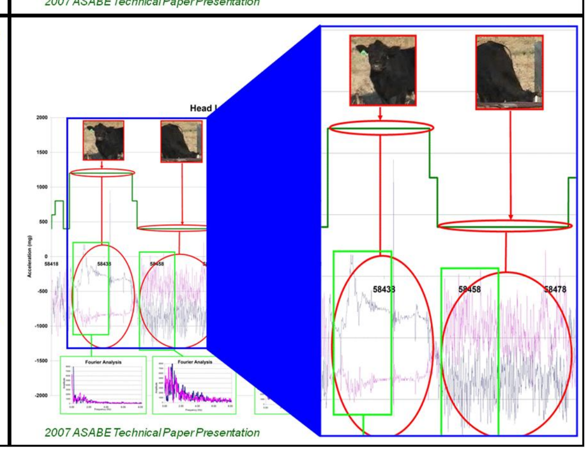
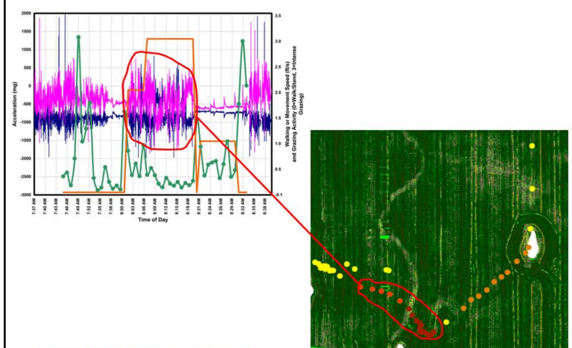






Results (2nd objective)



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Conclusions for Objectives 1 & 2 (proof-of-concept)

- 120 ms accelerometer sampling rate is sufficient
- X and Y axis acceleration frequency, magnitude, and bias can be used to detect grazing activity and characteristics
- GPS and accelerometer data can be combined to create a grazing map

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Objective 3:

Design and build a micro sized PCB integrating wireless communication and sensing capabilities

Supportive Information:

- Micro sized electronic sensors are commonly available and are easily integrated into single board assemblies
- Wireless technology supports implementing sensor systems in a grazing environment
- Integrated wireless sensors are a profound improvement over past systems

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Microcontroller Selection

Chipcon CC1010 (Texas Instruments)

- RTC (real time clock)
- 3 ADC inputs
- Dual oscillator system (32.768 KHz, 14.745 MHz)
- 8051 architecture
- Radio transceiver (300 – 1000 MHz)
- 3 timers
- SPI peripheral device communication
- +3 volt supply
- $11/chip (low quantity)

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Sensor and Peripheral Components

- Analog Devices 3 axes accelerometer (ADXL330)
  - +3 volt supply
  - ±3*g*

1. STMicro switching step-down regulator (L6928)
   - Buck/boost circuit designed for 3.7 to 4.4 V rechargeable batteries
   - ~90% efficiency
2. Atmel data flash memory (AT45DB64)
   - 8.4 Mbyte of memory
   - 3 days of data storage at a sampling rate of 116 ms

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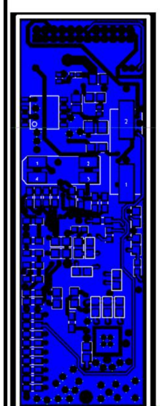
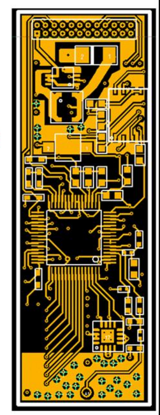


PCB Design

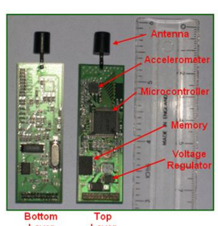
- 0.77 in X 2.305 in
- Two sided (parts assembled on both top and bottom)
- 6 Layers
  - 3 circuit layers
  - 2 ground planes
  - 1 power plane
- 84 SMT or fine pitch through hole parts
- Reflow solder assembly



Paper Presentation

Fully Integrated Wireless Grazing Sensor

- ~$100 for board and components
- ~$100 assembly fee
- Total cost ~ $200/unit
- Other costs include enclosures, batteries, and firmware



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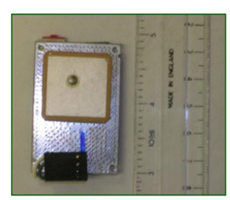
New Micro GPS Device

- Designed to be attached to small animals
- Better performance than vehicle tracking unit
  - longer battery life
  - smaller package
- More expensive



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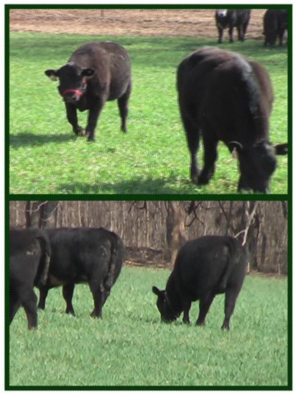
Experiment with New Micro GPS and Integrated Wireless Sensor

- Multiple test halters deployed in a single herd
- 3 days of high resolution data collected (9 million data points per animal)



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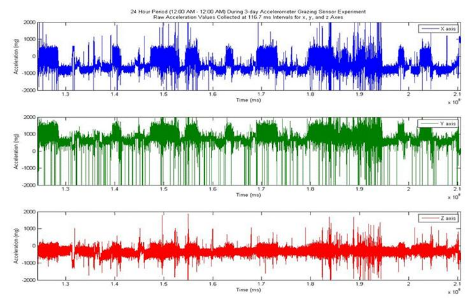
Results (objective 3)



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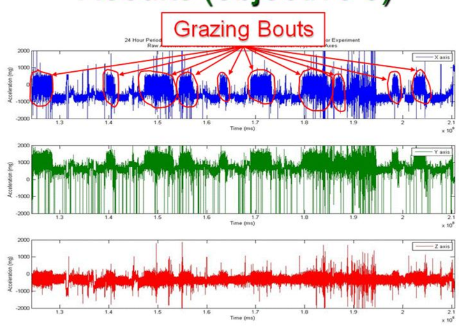
Results (objective 3)



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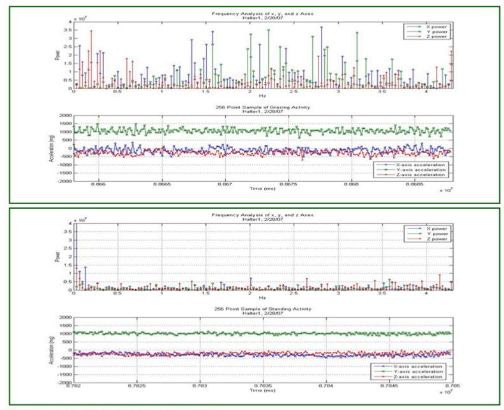

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Future Development and Research

- Develop algorithm for real-time sensing and data compression
- Implement wireless control and interrogation features
- Integrate GPS chip set into current sensor design
- Explore energy harvesting methods
- Investigate adaptation to higher level systems

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APPENDIX B

ADC CODE

```
/*ADC is setup to run only with the 32 kHz oscillator.  Circuit impedence characteristics must change to run with faster oscillator.
ADCON2 values must also be set with faster oscillator.*/
/*--------------------------------------------------------------------------------------------------------------------------------------------*/
#define AtoDON          1
#define AtoDOFF         0
#define xaxis           0
#define yaxis           1
#define zaxis           2
#define     allaxi      3
/*------------------------------------FUNCTIONS-------------------------------------------------------------------------------------------*/
void ConfigADC(byte option)
{
        ADCON2=0x03;                                    //disables interrupt(ADCIE), sets divisor(ADCDIV)
   ADCON=0xA0;                                          //powers down and sets mode(AD_PD)(ADCM)
        ADTRH=0;                                        //sets threshold value

        if (option==AtoDON){ADCON&=~0x80;}              //powers up the ADC, should be turned off when not used
        else if (option==AtoDOFF){ADCON|=0x80;}         //powers down the ADC
}
/*--------------------------------------------------------------------------------------------------------------------------------------------*/
void GetADC(byte option, unsigned int* ADC_ptr, unsigned int x_offset, unsigned int y_offset, unsigned int z_offset)
{
        switch (option)
        {
                case xaxis:
                ADCON=((ADCON&~0x03)|(0x01));           //clears input channel selection then selects new input channel x
                        ADCON|=0x04;                    //starts ADC operation
                        #pragma asm
                                NOP;NOP;NOP;  //waits 12 machine cycles for ADC conversion...4 clock ticks per NOP
                        #pragma endasm
                        *(ADC_ptr+x_offset)=(unsigned int)((ADDATH*64)|(ADDATL/4));
                break;
                case yaxis:
                ADCON=((ADCON&~0x03)|(0x02));
                        ADCON|=0x04;
                        #pragma asm
                                NOP;NOP;NOP;
                        #pragma endasm
                        *(ADC_ptr+y_offset)=(unsigned int)((ADDATH*64)|(ADDATL/4));
                break;
                case zaxis:
                ADCON=((ADCON&~0x03)|(0x00));
                        ADCON|=0x04;
                        #pragma asm
                                NOP;NOP;NOP;
                        #pragma endasm
                        *(ADC_ptr+z_offset)=(unsigned int)((ADDATH*64)|(ADDATL/4));
                break;
                case allaxi:
                ADCON=((ADCON&~0x03)|(0x01));
                        ADCON|=0x04;
                        #pragma asm
                                NOP;NOP;NOP;
                        #pragma endasm
```

```
				*(ADC_ptr+x_offset)=(unsigned int)((ADDATH*64)|(ADDATL/4));
				ADCON=((ADCON&~0x03)|(0x02));
				ADCON|=0x04;
				#pragma asm
					NOP;NOP;NOP;
				#pragma endasm
				*(ADC_ptr+y_offset)=(unsigned int)((ADDATH*64)|(ADDATL/4));
			ADCON=((ADCON&~0x03)|(0x00));
				ADCON|=0x04;
				#pragma asm
					NOP;NOP;NOP;
				#pragma endasm
				*(ADC_ptr+z_offset)=(unsigned int)((ADDATH*64)|(ADDATL/4));
			break;
		}
}
/*------------------------------------------------------------------------------------------------------------------------------------------*/
```

APPENDIX C

FFT CALCULATION, BINNING, AND PACKAGING CODE

```
/*----------------------------------FFT CALCULATION PARAM-----------------------------------------------------------------------*/
unsigned int code interval_ms = 46;
float code start_band = 1.0;
unsigned char code bin_num=16;
unsigned int code nn = 256;
/*-----------------------------------VARIABLES----------------------------------------------------------------------------------*/
extern signed int xdata mem_data[5];
extern signed int xdata i;
double xdata wtemp,wr,wpr,wpi,wi;
signed int xdata j, m, mmax, istep, np3, i1, i2, i3, i4;
float xdata h1r, h1i, h2r, h2i;
/*------------------------HANNING WINDOW LOOK UP TABLE------------------------------------------------------------------*/
float code Wss_han256win = 96;
float code han_win[256] = {0.0,0.000150591,0.000602272,0.001354772,0.002407637,0.003760233,0.005411745,0.007361179,
                           0.00960736,0.012148935,0.014984373,0.018111967,0.021529832,0.02523591,0.029227967,
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                           0.5,0.512270614,0.524533837,0.536782282,0.54900857,0.561205338,0.573365237,0.585480944,
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                           0.992638821,0.994588255,0.996239767,0.997592363,0.998645228,0.999397728,0.999849409,1.0,
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                           0.5,0.487729386,0.475466163,0.463217718,0.45099143,0.438794662,0.426634763,0.414519056,
                           0.402454839,0.39044938,0.37850991,0.366643621,0.354857661,0.34315913,0.331555073,
                           0.320052482,0.308658284,0.297379343,0.286222453,0.275194335,0.264301632,0.253550904,
                           0.242948628,0.23250119,0.222214884,0.212095904,0.202150348,0.192384205,0.182803358,
                           0.173413579,0.164220523,0.155229728,0.146446609,0.137876459,0.129524437,0.121395577,
                           0.113494773,0.105826786,0.098396234,0.091207593,0.084265194,0.077573217,0.071135695,
                           0.064956504,0.059039368,0.053387849,0.048005353,0.042895122,0.038060234,0.033503601,
                           0.029227967,0.02523591,0.021529832,0.018111967,0.014984373,0.012148935,0.00960736,
                           0.007361179,0.005411745,0.003760233,0.002407637,0.001354772,0.000602272,0.000150591};
/*************************************************************************************************
**************************************************************************************************
*************************************************************************************************/
```

```
/*------------------------------------FUNCTIONS-------------------------------------------------------------------------------------------*/
void FFT_alg(signed int* xdata_ptr)
{
	/*--------------AVERAGING & ENGINEERING UNIT CONVERSION-------------------*/
	h1r=0;
	for (i=1; i<=nn; i++){h1r = h1r + *(xdata_ptr+i-1);}			//sums 0-127 of data array...value less than 32768
	mem_data[3]=(signed int)((h1r*39.0625/nn)-5000);			//averages and converts to mg for tilt measurment

	/*--ENGINEERING UNIT CONVERSION, ZERO CENTERING, & WINDOWING---*/
	for (i=1; i<=nn; i++)
	{
		*(xdata_ptr+i-1)=(signed int)(1.953125*han_win[i-1]*(*(xdata_ptr+i-1)-(h1r/nn)));
											//calcs accel in mg/20 and zero centers
	}
	/*--------------BIT REVERSAL---------------------------------------------------------------------*/
	j=1;
	for (i=1;i<nn;i+=2)
	{
		if (j > i)
		{
			istep = *(xdata_ptr+j-1);
			*(xdata_ptr+j-1) = *(xdata_ptr+i-1);
			*(xdata_ptr+i-1) = istep;
			istep = *(xdata_ptr+j);
			*(xdata_ptr+j) = *(xdata_ptr+i);
			*(xdata_ptr+i) = istep;
		}
		m = nn>>1;
		while (m>=2 && j>m) {j-=m; m>>=1;}
		j+=m;
	}
	/*--------------DANIELSON-LANCZOS---------------------------------------------------------*/
	mmax=2;
	while (nn > mmax)
	{
		istep=mmax << 1;
		wtemp=sin(3.14159265359/(float)mmax);
		wpr = -2.0*wtemp*wtemp;
		wpi=sin(6.28318530717959/(float)mmax);
		wr=1.0;
		wi=0.0;
		for (m=1;m<mmax;m+=2)
		{
			for (i=m;i<=nn;i+=istep)
			{
				j=i+mmax;
				h1r=wr*(*(xdata_ptr+j-1))-wi*(*(xdata_ptr+j));
				h1i=wr*(*(xdata_ptr+j))+wi*(*(xdata_ptr+j-1));
				*(xdata_ptr+j-1)=(signed int)(*(xdata_ptr+i-1)-h1r);
				*(xdata_ptr+j)=(signed int)(*(xdata_ptr+i)-h1i);
				*(xdata_ptr+i-1)+=(signed int)(h1r);
				*(xdata_ptr+i)+=(signed int)(h1i);
			}
			wr=(wtemp=wr)*wpr-wi*wpi+wr;
			wi=wi*wpr+wtemp*wpi+wi;
		}
		mmax=istep;
	}
	/*--------------UNPACK AND REORDER FOR REAL DATA-------------------------------*/
	wtemp=sin(3.141592653589793/(float)nn);
	wpr=-2.0*wtemp*wtemp;
	wpi=sin(6.28318530718/(float)nn);
	wr=1.0+wpr;
	wi=wpi;
	np3=nn+3;
	for(i=2; i<=(nn>>2); i++)
	{
		i4=1+(i3=np3-(i2=1+(i1=i+i-1)));
		h1r=0.5*(*(xdata_ptr+i1-1)+*(xdata_ptr+i3-1));
		h1i=0.5*(*(xdata_ptr+i2-1)-*(xdata_ptr+i4-1));
```

```
			h2r = 0.5*(*(xdata_ptr+i2-1)+*(xdata_ptr+i4-1));
			h2i=-0.5*(*(xdata_ptr+i1-1)-*(xdata_ptr+i3-1));
			*(xdata_ptr+i1-1)=(signed int)(h1r+wr*h2r-wi*h2i);
			*(xdata_ptr+i2-1)=(signed int)(h1i+wr*h2i+wi*h2r);
			*(xdata_ptr+i3-1)=(signed int)(h1r-wr*h2r+wi*h2i);
			*(xdata_ptr+i4-1)=(signed int)(-h1i+wr*h2i+wi*h2r);

			wr=(wtemp=wr)*wpr-wi*wpi+wr;
			wi=wi*wpr+wtemp*wpi+wi;
		}
		*xdata_ptr = (signed int)((h1r = *xdata_ptr) + *(xdata_ptr+1));
		*(xdata_ptr+1) = (signed int)(h1r - *(xdata_ptr+1));
}

/*------------------------------------------------------------------------------------------------------------------------------------------*/
void FFT_conv_pkg(signed int* xdata_ptr, byte axis)
{
		/*---------------CALCULATE POWER SPECTRUM------------------------------*/
		for (i=2; i<(nn>>1); i++)
		{
			wr = ((double)*(xdata_ptr+i*2-2))*(*(xdata_ptr+i*2-2))/((nn>>1)*Wss_han256win);
			wi = ((double)*(xdata_ptr+i*2-1))*(*(xdata_ptr+i*2-1))/((nn>>1)*Wss_han256win);
			wr = wr+wi;
			if (wr > 32767) {*(xdata_ptr+i-1) = 32767;}
			else {*(xdata_ptr+i-1) = (signed int)wr;}
		}
		wr = ((double)*xdata_ptr)*(*xdata_ptr)/(nn*Wss_han256win);
		wi = ((double)*(xdata_ptr+1))*(*(xdata_ptr+1))/(nn*Wss_han256win);
		wr = wr+wi;
		if (wr > 32767) {*xdata_ptr = 32767;}
		else {*xdata_ptr = (signed int)wr;}

		wr = ((double)*(xdata_ptr+nn-2))*(*(xdata_ptr+nn-2))/(nn*Wss_han256win);
		wi = ((double)*(xdata_ptr+nn-1))*(*(xdata_ptr+nn-1))/(nn*Wss_han256win);
		wr = wr+wi;
		if (wr > 32767) {*(xdata_ptr+(nn/2)-1) = 32767;}
		else {*(xdata_ptr+(nn/2)-1) = (signed int)wr;}

		/*---------------CALCULATE FREQ BIN VALUES-------------------------------------------*/
		h1r=1000.0/(float)(nn*interval_ms);		//Calculates frequency resolution in Hz per memmory location
		i1=(unsigned int)((start_band/h1r)+0.5);
		i2=(unsigned int)((((bin_num*0.5)+start_band)/h1r)+0.5);

		for (j=1; j<=bin_num; ++j)
		{
			h2r=0.0; m=0;
			for (i=i1; i<=i2; ++i)
			{
				if (((i*h1r)>=(start_band+(0.5*(j-1)))) && ((i*h1r)<=(start_band+(0.5*j))))
				{
					h2r+=(float)(*(xdata_ptr+i));
					++m;
				}
			}
		  h2r=h2r*10.0/m;
		  if (h2r>=32767){h2r=32767;}
		  *(xdata_ptr+j-1)&=~0xFFFF;
		  *(xdata_ptr+j-1)=(signed int)h2r;
		}

		/*---------------PACKAGE DATA----------------------------------------------------------------*/
		for (i=1; i<=bin_num; ++i)
		{
			*(xdata_ptr+bin_num+5-i)=*(xdata_ptr+bin_num-i);		//moves data down 6 places
		}


		*(xdata_ptr+3)=(signed int)axis;
		*(xdata_ptr+4)=mem_data[3];
```

```
		for(i=1; i<=(bin_num+2); ++i)
		{
			*(xdata_ptr+2+i+(axis*(2+bin_num-nn)))=*(xdata_ptr+2+i);		//packs data into first part of mem
		}
}
/*----------------------------------------------------------------------------------------------------------------------------------------------*/
```

APPENDIX D

TIME STAMPING AND FINAL DATA STORAGE CODE

```
/*------------------------------------------------------------------------------------------------------------------------------------------*/
#define ClkFreq1                                14746
/*-----------------------------------DATAFLASH OPCODES--------------------------------------------------------------------------*/
#define buffer1write                            0x84
#define buffer2write                            0x87
#define buffer1read                             0xD4
#define buffer2read                             0xD6
#define buffer1tomemmorywrite                   0x83
#define buffer2tomemmorywrite                   0x86
#define pageread                                0XD2
#define blockerase                              0x50
#define directmemwriteviabuf1                   0x82
#define directmemwriteviabuf2                   0x85
#define mainmemtobuf1                           0x53
#define mainmemtobuf2                           0x55
/*-----------------------------------FUNCTION PROTOTYPES----------------------------------------------------------------------*/
extern void WritetoDataFlashBuffer (byte opcode, int data_bytes, signed int* xdata_ptr);
extern void WriteBuffertoMainMemmory(byte opcode, word page_address);
extern void DirectMemWriteviaBuf(byte opcode, word page_address, word byte_address, int data_bytes, signed int* xdata_ptr);
extern void ReadMainMemmoryPage(byte opcode, word page_address, word byte_address, int data_bytes);
/*-----------------------------------VARIABLES---------------------------------------------------------------------------------------*/
extern signed int xdata xdata_buffer[768];
extern signed int xdata mem_data[5];
extern word xdata buff_add;
extern word xdata page_add;
extern byte xdata bufferwrite;
extern byte xdata buffertomemmorywrite;
extern unsigned char code bin_num;
extern signed int* FFT_memloc;
extern signed int xdata i;
extern byte xdata second;
extern byte xdata minute;
extern byte xdata hour;
extern byte xdata day;
extern byte xdata month;
extern word xdata year;
extern byte xdata maxday;
/**************************************************************************************************
**************************************************************************************************
**************************************************************************************************/
/*-----------------------------------FUNCTIONS---------------------------------------------------------------------------------------*/
/*Stores data after being processed by FFT algorithm.  Data is in the form of three vectors, one for x, y, and z.  A time stamp leads the
vectors.  Total storage for a 256 sample scheme is 114 bytes.  Xdata buffer is used to transfer data to data flash.*/

void FFT_store_data(void)
{
		if (page_add>=8190){return;}

		FFT_memloc = &xdata_buffer[0];
		xdata_buffer[0]= mem_data[0]; xdata_buffer[1]= mem_data[1];	xdata_buffer[2]= mem_data[2];
		for (i=0; i<((bin_num+2)*3+3); ++i)
		{
			if ((buff_add<=1054)&(page_add<8190))
			{
```

```
					WritetoDataFlashBuffer(bufferwrite, 2, FFT_memloc);
					++FFT_memloc; buff_add+=2;
				}
				else if ((buff_add>1054)&(page_add<8190))
				{
					WriteBuffertoMainMemmory(buffertomemmorywrite, page_add);
					halWait(20, ClkFreq1);

					if (bufferwrite==buffer1write) {bufferwrite=buffer2write;}
					else {bufferwrite=buffer1write;}

					if (buffertomemmorywrite==buffer1tomemmorywrite)
					{buffertomemmorywrite=buffer2tomemmorywrite;}
					else {buffertomemmorywrite=buffer1tomemmorywrite;}

					++page_add; buff_add=0; --i;
				}
				else{return;}
		}
}
/*-------------------------------------------------------------------------------------------------------------------------------------------*/
/*Stores time and last memmory location written to in data flash.  Second to last page of data flash (8189) has been designated for data
pointer and time storage.  This can be referenced in the event of power cycle or for other management reasons. Xdata buffer is used to
transfer data to data flash.*/

void store_time_and_dataptr(void)
{
		ReadMainMemmoryPage(pageread, 8190, 0, 16);

		xdata_buffer[0]=((((int)second)<<8)&~0x00FF)|(((int)minute)&~0xFF00);
		xdata_buffer[1]=((((int)hour)<<8)&~0x00FF)|(((int)day)&~0xFF00);
		xdata_buffer[2]=((((int)month)<<12)&~0x0FFF)|(((int)year)&~0xF000);

		if (buff_add==0){xdata_buffer[3]=page_add-1; xdata_buffer[4]=1054;}
		else {xdata_buffer[3]=page_add; xdata_buffer[4]=buff_add-2;}

		if (bufferwrite==buffer1write) {bufferwrite=directmemwriteviabuf2;}
		else {bufferwrite=directmemwriteviabuf1;}

		DirectMemWriteviaBuf(bufferwrite, 8190, 0, 16, &xdata_buffer[0]);

		if (bufferwrite==directmemwriteviabuf1) {bufferwrite=buffer2write;}
		else {bufferwrite=buffer1write;}
}
/*-------------------------------------------------------------------------------------------------------------------------------------------*/
void store_last_com_time(void)
{
		ReadMainMemmoryPage(pageread, 8190, 0, 16);

		xdata_buffer[5]=((((int)second)<<8)&~0x00FF)|(((int)minute)&~0xFF00);
		xdata_buffer[6]=((((int)hour)<<8)&~0x00FF)|(((int)day)&~0xFF00);
		xdata_buffer[7]=((((int)month)<<12)&~0x0FFF)|(((int)year)&~0xF000);

		if (bufferwrite==buffer1write) {bufferwrite=directmemwriteviabuf2;}
		else {bufferwrite=directmemwriteviabuf1;}

		DirectMemWriteviaBuf(bufferwrite, 8190, 0, 16, &xdata_buffer[0]);

		if (bufferwrite==directmemwriteviabuf1) {bufferwrite=buffer2write;}
		else {bufferwrite=buffer1write;}
}
/*-------------------------------------------------------------------------------------------------------------------------------------------*/
```

APPENDIX E

MAIN CODE

```
/*-------------------------------------------------------------------------------------------------------------------------------------------*/
#define UARTON              1
#define UARTOFF             0
#define TurnON              1
#define TurnOFF             0
#define AtoDON              1
#define AtoDOFF             0
#define RLED                P1_2
#define YLED                P1_3
#define GLED                P1_4
#define RLED_OE(x)          {P1DIR=(x) ? P1DIR&~0x04 : P1DIR|0x04;}
#define YLED_OE(x)          {P1DIR=(x) ? P1DIR&~0x08 : P1DIR|0x08;}
#define GLED_OE(x)          {P1DIR=(x) ? P1DIR&~0x10 : P1DIR|0x10;}
#define OSC32K              1
#define OSC14M              0
#define xaxis               0
#define yaxis               1
#define zaxis               2
#define     allaxi          3
#define ClkFreq1    14746   //14.7456 MHz...14746kHz
#define ClkFreq2    32768   //32.768 kHz...32768Hz
#define log_sensor_data     1
#define check_radio_com     2
#define check_time_int      3
#define sync_time           4
/*-----------------------------------DATAFLASH OPCODES-------------------------------------------------------------------------*/
#define buffer1write                    0x84
#define buffer2write                    0x87
#define buffer1read                     0xD4
#define buffer2read                     0xD6
#define buffer1tomemmorywrite           0x83
#define buffer2tomemmorywrite           0x86
#define pageread                        0XD2
#define blockerase                      0x50
#define directmemwriteviabuf1           0x82
#define directmemwriteviabuf2           0x85
/*-----------------------------------FUNCTION PROTOTYPES---------------------------------------------------------------------*/
extern void ReadMainMemmoryPage(byte opcode, word page_address, word byte_address, int data_bytes);
extern void SerialCom0(byte option);
extern void GetADC(byte option, signed int* ADC_ptr, unsigned int x_offset, unsigned int y_offset, unsigned int z_offset);
extern void ConfigADC(byte option);
extern void SwitchOscillator(byte clockmodeselect);
extern void ConfigRTC(byte RTCperiod, byte RTCSwitch);
extern void FFT_alg(signed int* xdata_ptr);
extern void FFT_conv_pkg(signed int* xdata_ptr, byte axis);
extern void FFT_store_data(void);
extern void store_time_and_dataptr(void);
extern void store_last_com_time(void);
/*------------------------------------VARIABLES-------------------------------------------------------------------------------------*/
extern byte xdata clockmodecurrent;
extern unsigned int code nn;
signed int xdata xdata_buffer[768];
signed int xdata mem_data[5];
signed int xdata i;
```

```
signed int* FFT_memloc;
word xdata buff_add = 0;
word xdata page_add = 0;
byte xdata bufferwrite = 0X84;
byte xdata buffertomemmorywrite = 0X83;
unsigned char xdata node_task;
extern byte xdata second;
extern byte xdata minute;
extern byte xdata hour;
extern byte xdata day;
extern byte xdata month;
extern word xdata year;
extern byte xdata maxday;
/*****************************************************************************************************
******************************************* INITIALIZATIONS ***********************************
*****************************************************************************************************/
void StandardInit(void)
{
	/*--System clock is 14.7456 MHz at startup-----Disable the watchdog timer, result is WDT=0x10--*/
	clockmodecurrent=OSC14M; WDT|=0x10; WDT&=~0x08;

	/*---Set optimum settings for speed and low power consumption---------------------------------------*/
	CKCON&=~0x07; FLCON= (FLCON&~0x60)|(0x40&0x60);

	/*---Setup port 0 and SPI settings to interface with ATDB64C1 DataFlash----------------------------*/
	P0DIR=0x05; SPCR=0x30; P1DIR&=~0x80; P1_7=1; P0_3=0;
	halWait(1, ClkFreq1);
	P0_3=1;	halWait(1, ClkFreq1);
	SerialCom0(UARTOFF);

	/*---Setup port 2 for manual SPI interface with LTC1199 AtoD-----------------------------------------*/
	P2DIR&=~0X68; P2_3&=0; P2_5&=0;	P2_6|=1;

	/*---Turns on 32kHz Crystal for RTC and starts RTC-----------------------------------------------------*/
	SwitchOscillator(OSC32K); ConfigRTC(1, TurnON); SwitchOscillator(OSC14M);

	/*---Sets initial settings for evaluation board leds---------------------------------------------------------*/
	GLED_OE(1);		RLED_OE(1); YLED_OE(1); RLED=1; YLED=1; GLED=1;
}
/*****************************************************************************************************
************************************************ MAIN *****************************************
*****************************************************************************************************/
void main(void)
{
	StandardInit();

	node_task = log_sensor_data;

	while (1)
	{
		switch (node_task)
		{
			case log_sensor_data:
				FFT_memloc = &xdata_buffer[0];
				SwitchOscillator(OSC32K);
				ConfigADC(AtoDON);
				while(FFT_memloc<(nn+&xdata_buffer[0]))
				{
					GetADC(allaxi, FFT_memloc, 0, nn, (nn<<1));
					++FFT_memloc; GLED=~GLED;
				}
				ConfigADC(AtoDOFF);
				SwitchOscillator(OSC14M);

				mem_data[0]=((((int)second)<<8)&~0x00FF)|(((int)minute)&~0xFF00);
				mem_data[1]=((((int)hour)<<8)&~0x00FF)|(((int)day)&~0xFF00);
				mem_data[2]=((((int)month)<<12)&~0x0FFF)|(((int)year)&~0xF000);
				FFT_alg(&xdata_buffer[0]);		FFT_conv_pkg(&xdata_buffer[0], xaxis);
				FFT_alg(&xdata_buffer[nn]);		FFT_conv_pkg(&xdata_buffer[nn], yaxis);
				FFT_alg(&xdata_buffer[(nn<<1)]);	FFT_conv_pkg(&xdata_buffer[(nn<<1)], zaxis);
```

```
					FFT_store_data();				store_time_and_dataptr();

					for(i=0; i<(nn*3); ++i){xdata_buffer[i]&=~0xFFFF;}	//Clears xdata_buffer
					node_task = check_time_int;
				break;
			}
		}
}
/*-------------------------------------------------------------------------------------------------------------------------------------------------------*/
```

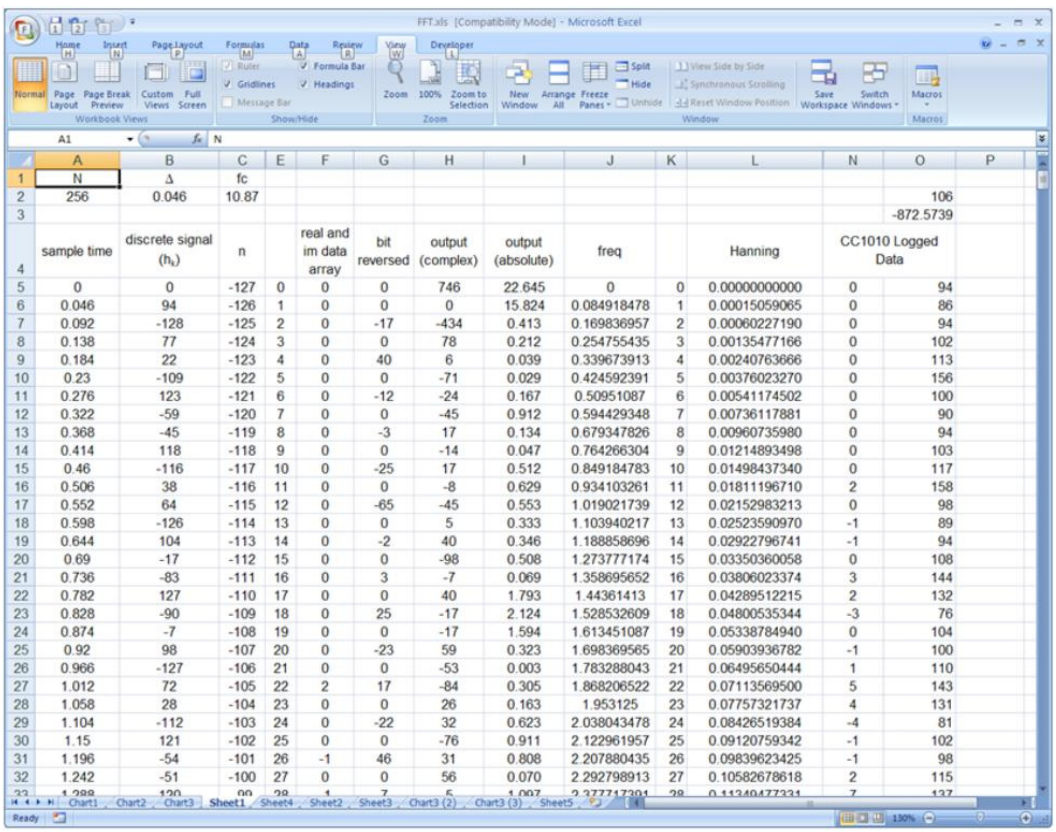
APPENDIX F

EXCEL VBA FFT CODE

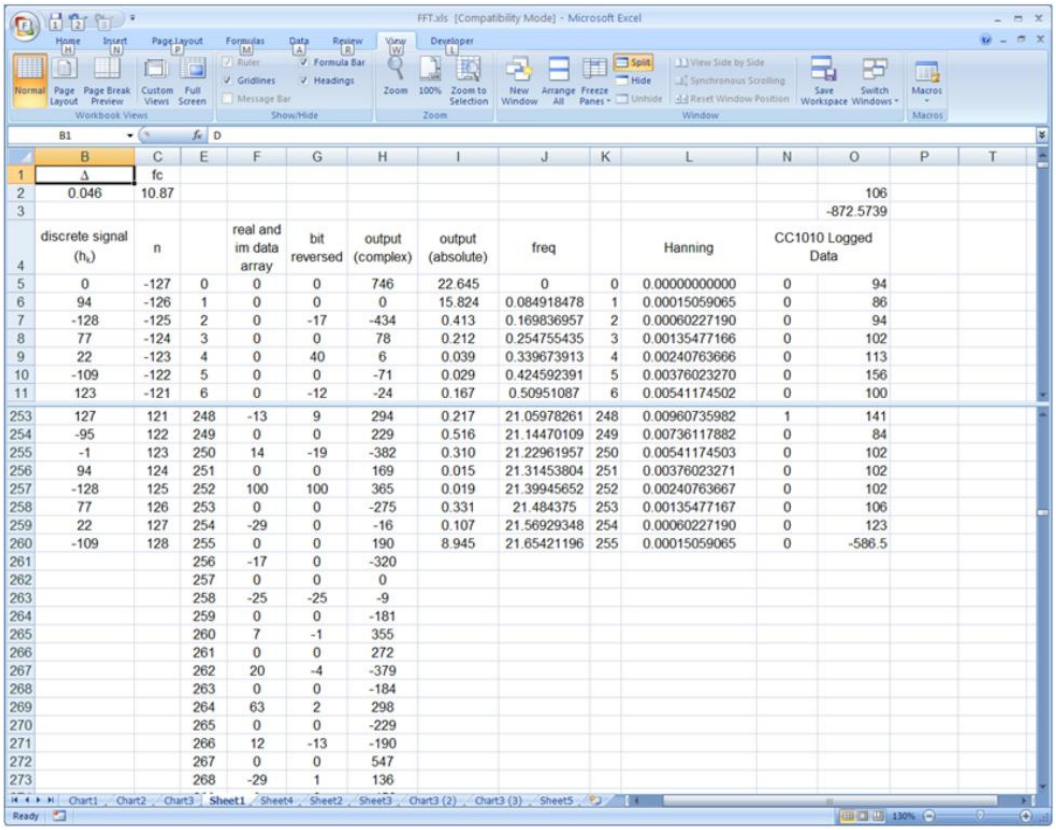
```
'*********************************************************************************************
Sub Bit_Reversal()

    nn = ActiveSheet.[A2].Value
    N = nn * 2                              'n = nn << 1

    ReDim data(1 To N) As Integer

    Avg_data = 0

    For i = 1 To N Step 1
        data(i) = 0
    Next

    'ActiveSheet.[B5].Select
    ActiveSheet.[O5].Select
    'ActiveSheet.[L5].Select

    Avg_data = 0
    For i = 1 To nn Step 1
        Avg_data = Avg_data + ActiveCell.Offset(i - 1, 0).Value
    Next
    Avg_data = Avg_data / nn
    ActiveSheet.[O2].Value = Avg_data
    ActiveSheet.[O3].Value = (Avg_data * 39.0625) - 5000

    Avg_data = ((Avg_data * 39.0625) - 5000) / 20

    For i = 1 To nn Step 1      'Converts to mg/20 and zero centers data
        data(i) = (((ActiveCell.Offset((i - 1), 0).Value * 39.0625) - 5000) / 20) - Avg_data
    Next

    ActiveSheet.[L5].Select     'Windows data
    For i = 1 To nn Step 1
        data(i) = data(i) * CSng(ActiveCell.Offset((i - 1), 0).Value)
    Next

    ActiveSheet.[Q5].Select     'Prints data
    For i = 1 To nn Step 1
        ActiveCell.Offset((i - 1), 0).Value = data(i)
    Next

    For i = 1 To nn Step 1      'puts real value in every other cell of array...im values are all zeros
        data(N - ((2 * i) - 1)) = data(nn - i + 1)
        If i < nn Then
            data(nn - i + 1) = 0
            data(N - (2 * i)) = 0
        End If
    Next

    ActiveSheet.[F5].Select     'Prints data
    For i = 1 To N Step 1
        ActiveCell.Offset((i - 1), 0).Value = data(i)
    Next
```

```
   j = 1
   For i = 1 To (N - 1) Step 2                    'for (i=1; i<n; i+=2)
      If j > i Then
         tempr = data(j)
         data(j) = data(i)
         data(i) = tempr
         tempr = data(j + 1)
         data(j + 1) = data(i + 1)
         data(i + 1) = tempr
      End If
      m = nn
      While m >= 2 And j > m                    'while (m>=2 && j>m)
         j = j - m                           'j-=m
         m = m / 2                            'm>>=1
      Wend
      j = j + m                              'j+=m
   Next

   ActiveSheet.[G5].Select
   For i = 1 To N Step 1
      ActiveCell.Offset(i - 1, 0).Value = data(i)
   Next

End Sub

'*********************************************************************************************
Sub Danielson_Lanczos_Calculation()

isign = 1
mmax = 2
nn = ActiveSheet.[A2].Value
N = nn * 2

ReDim data(1 To N) As Integer

ActiveSheet.[G5].Select
For i = 1 To N Step 1
   data(i) = ActiveCell.Offset(i - 1, 0).Value
Next

While N > mmax
   istep = mmax * 2                  'istep=mmax << 1
   theta = isign * (6.28318530717959 / mmax)
   wtemp = Sin(0.5 * theta)
   wpr = -2 * wtemp * wtemp
   wpi = Sin(theta)
   wr = 1
   wi = 0
   For m = 1 To (mmax - 1) Step 2
      For i = m To N Step istep
         j = i + mmax
         tempr = (wr * data(j)) - (wi * data(j + 1))
         tempi = (wr * data(j + 1)) + (wi * data(j))
         data(j) = Int(data(i) - tempr)
         data(j + 1) = Int(data(i + 1) - tempi)
         data(i) = Int(data(i) + tempr)
         data(i + 1) = Int(data(i + 1) + tempi)
      Next
      wtemp = wr
      wr = (wtemp * wpr) - (wi * wpi) + wr
      wi = (wi * wpr) + (wtemp * wpi) + wi
   Next
   mmax = istep
Wend

ActiveSheet.[H5].Select
For i = 1 To N Step 1
```

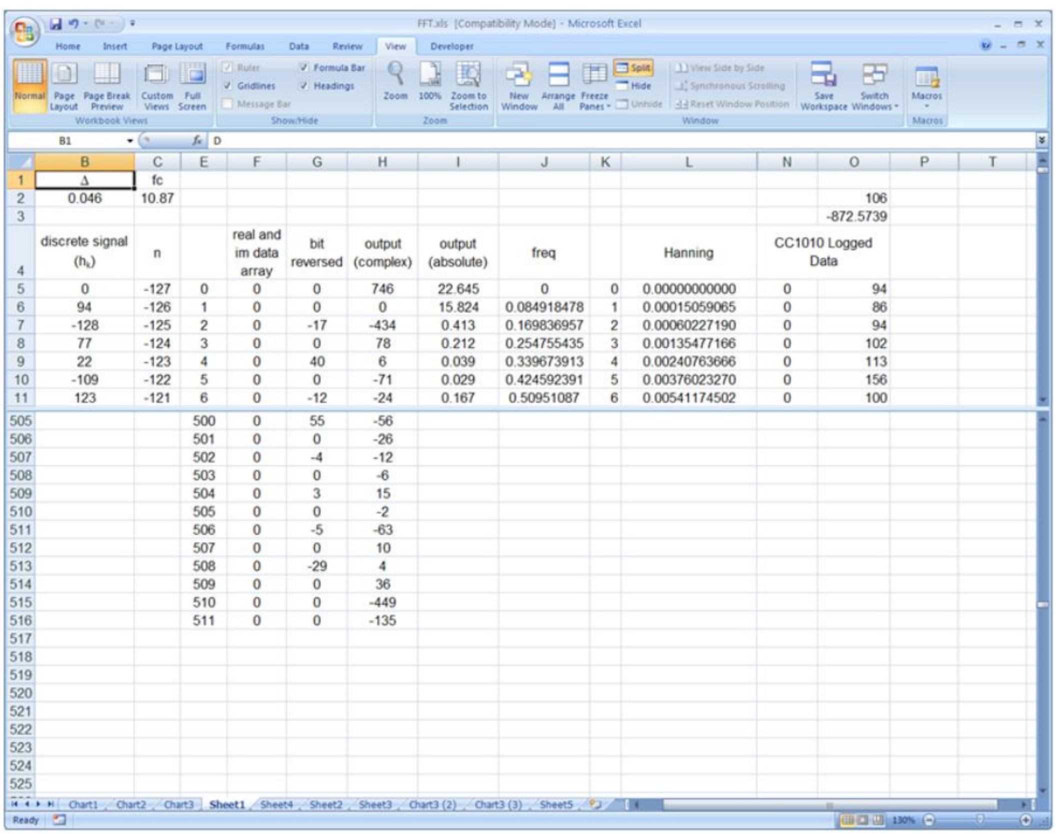
```
    ActiveCell.Offset(i - 1, 0).Value = data(i)
Next

Wss = 0
ActiveSheet.[L5].Select
For i = 1 To (N / 2) Step 1
    Wss = Wss + (ActiveCell.Value ^ 2)
    ActiveCell.Offset(1, 0).Select
Next

ActiveSheet.[I5].Select
For i = 2 To (nn - 1) Step 1
    a = ActiveCell.Offset((i * 2) - 2, -1).Value
    b = ActiveCell.Offset((i * 2) - 1, -1).Value
    ActiveCell.Offset(i - 1, 0).Value = 2 * ((a ^ 2) + (b ^ 2)) / (nn * Wss)
Next

ActiveSheet.[I5].Select
a = ActiveCell.Offset(0, -1).Value
b = ActiveCell.Offset(1, -1).Value
ActiveCell.Offset(0, 0).Value = ((a ^ 2) + (b ^ 2)) / (nn * Wss)

a = ActiveCell.Offset((nn * 2) - 2, -1).Value
b = ActiveCell.Offset((nn * 2) - 1, -1).Value
ActiveCell.Offset(nn - 1, 0).Value = ((a ^ 2) + (b ^ 2)) / (nn * Wss)

End Sub

'*************************************************************************************************
```



	A	B	C	E	F	G	H	I	J	K	L	N	O
1	N	Δ	fc										
2	256	0.046	10.87										106
3													-872.5739
4	sample time	discrete signal (h_k)	n		real and im data array	bit reversed	output (complex)	output (absolute)	freq		Hanning	CC1010 Logged Data	
5	0	0	-127	0	0	0	746	22.645	0	0	0.00000000000	0	94
6	0.046	94	-126	1	0	0	0	15.824	0.084918478	1	0.00015059065	0	86
7	0.092	-128	-125	2	0	-17	-434	0.413	0.169836957	2	0.00060227190	0	94
8	0.138	77	-124	3	0	0	78	0.212	0.254755435	3	0.00135477166	0	102
9	0.184	22	-123	4	0	40	6	0.039	0.339673913	4	0.00240763666	0	113
10	0.23	-109	-122	5	0	0	-71	0.029	0.424592391	5	0.00376023270	0	156
11	0.276	123	-121	6	0	-12	-24	0.167	0.50951087	6	0.00541174502	0	100
12	0.322	-59	-120	7	0	0	-45	0.912	0.594429348	7	0.00736117881	0	90
13	0.368	-45	-119	8	0	-3	17	0.134	0.679347826	8	0.00960735980	0	94
14	0.414	118	-118	9	0	0	-14	0.047	0.764266304	9	0.01214893498	0	103
15	0.46	-116	-117	10	0	-25	17	0.512	0.849184783	10	0.01498437340	0	117
16	0.506	38	-116	11	0	0	-8	0.629	0.934103261	11	0.01811196710	2	158
17	0.552	64	-115	12	0	-65	-45	0.553	1.019021739	12	0.02152983213	0	98
18	0.598	-126	-114	13	0	0	5	0.333	1.103940217	13	0.02523590970	-1	89
19	0.644	104	-113	14	0	-2	40	0.346	1.188858696	14	0.02922796741	-1	94
20	0.69	-17	-112	15	0	0	-98	0.508	1.273777174	15	0.03350360058	0	108
21	0.736	-83	-111	16	0	3	-7	0.069	1.358695652	16	0.03806023374	3	144
22	0.782	127	-110	17	0	0	40	1.793	1.44361413	17	0.04289512215	2	132
23	0.828	-90	-109	18	0	25	-17	2.124	1.528532609	18	0.04800535344	-3	76
24	0.874	-7	-108	19	0	0	-17	1.594	1.613451087	19	0.05338784940	0	104
25	0.92	98	-107	20	0	-23	59	0.323	1.698369565	20	0.05903936782	-1	100
26	0.966	-127	-106	21	0	0	-53	0.003	1.783288043	21	0.06495650444	1	110
27	1.012	72	-105	22	2	17	-84	0.305	1.868206522	22	0.07113569500	5	143
28	1.058	28	-104	23	0	0	26	0.163	1.953125	23	0.07757321737	4	131
29	1.104	-112	-103	24	0	-22	32	0.623	2.038043478	24	0.08426519384	-4	81
30	1.15	121	-102	25	0	0	-76	0.911	2.122961957	25	0.09120759342	-1	102
31	1.196	-54	-101	26	-1	46	31	0.808	2.207880435	26	0.09839623425	-1	98
32	1.242	-51	-100	27	0	0	56	0.070	2.292798913	27	0.10582678618	2	115



	B	C	E	F	G	H	I	J	K	L	N	O
1	Δ	fc										
2	0.046	10.87										106
3												-872.5739
4	discrete signal (h_k)	n		real and im data array	bit reversed	output (complex)	output (absolute)	freq		Hanning	CC1010 Logged Data	
5	0	-127	0	0	0	746	22.645	0	0	0.00000000000	0	94
6	94	-126	1	0	0	0	15.824	0.084918478	1	0.00015059065	0	86
7	-128	-125	2	0	-17	-434	0.413	0.169836957	2	0.00060227190	0	94
8	77	-124	3	0	0	78	0.212	0.254755435	3	0.00135477166	0	102
9	22	-123	4	0	40	6	0.039	0.339673913	4	0.00240763666	0	113
10	-109	-122	5	0	0	-71	0.029	0.424592391	5	0.00376023270	0	156
11	123	-121	6	0	-12	-24	0.167	0.50951087	6	0.00541174502	0	100
253	127	121	248	-13	9	294	0.217	21.05978261	248	0.00960735982	1	141
254	-95	122	249	0	0	229	0.516	21.14470109	249	0.00736117882	0	84
255	-1	123	250	14	-19	-382	0.310	21.22961957	250	0.00541174503	0	102
256	94	124	251	0	0	169	0.015	21.31453804	251	0.00376023271	0	102
257	-128	125	252	100	100	365	0.019	21.39945652	252	0.00240763667	0	102
258	77	126	253	0	0	-275	0.331	21.484375	253	0.00135477167	0	106
259	22	127	254	-29	0	-16	0.107	21.56929348	254	0.00060227190	0	123
260	-109	128	255	0	0	190	8.945	21.65421196	255	0.00015059065	0	-586.5
261			256	-17	0	-320						
262			257	0	0	0						
263			258	-25	-25	-9						
264			259	0	0	-181						
265			260	7	-1	355						
266			261	0	0	272						
267			262	20	-4	-379						
268			263	0	0	-184						
269			264	63	2	298						
270			265	0	0	-229						
271			266	12	-13	-190						
272			267	0	0	547						
273			268	-29	1	136						



	B	C	E	F	G	H	I	J	K	L	N	O
1	Δ	fc										
2	0.046	10.87										106
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4	discrete signal (h_k)	n		real and im data array	bit reversed	output (complex)	output (absolute)	freq		Hanning	CC1010 Logged Data	
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6	94	-126	1	0	0	0	15.824	0.084918478	1	0.00015059065	0	86
7	-128	-125	2	0	-17	-434	0.413	0.169836957	2	0.00060227190	0	94
8	77	-124	3	0	0	78	0.212	0.254755435	3	0.00135477166	0	102
9	22	-123	4	0	40	6	0.039	0.339673913	4	0.00240763666	0	113
10	-109	-122	5	0	0	-71	0.029	0.424592391	5	0.00376023270	0	156
11	123	-121	6	0	-12	-24	0.167	0.50951087	6	0.00541174502	0	100
505			500	0	55	-56						
506			501	0	0	-26						
507			502	0	-4	-12						
508			503	0	0	-6						
509			504	0	3	15						
510			505	0	0	-2						
511			506	0	-5	-63						
512			507	0	0	10						
513			508	0	-29	4						
514			509	0	0	36						
515			510	0	0	-449						
516			511	0	0	-135						
517												
518												
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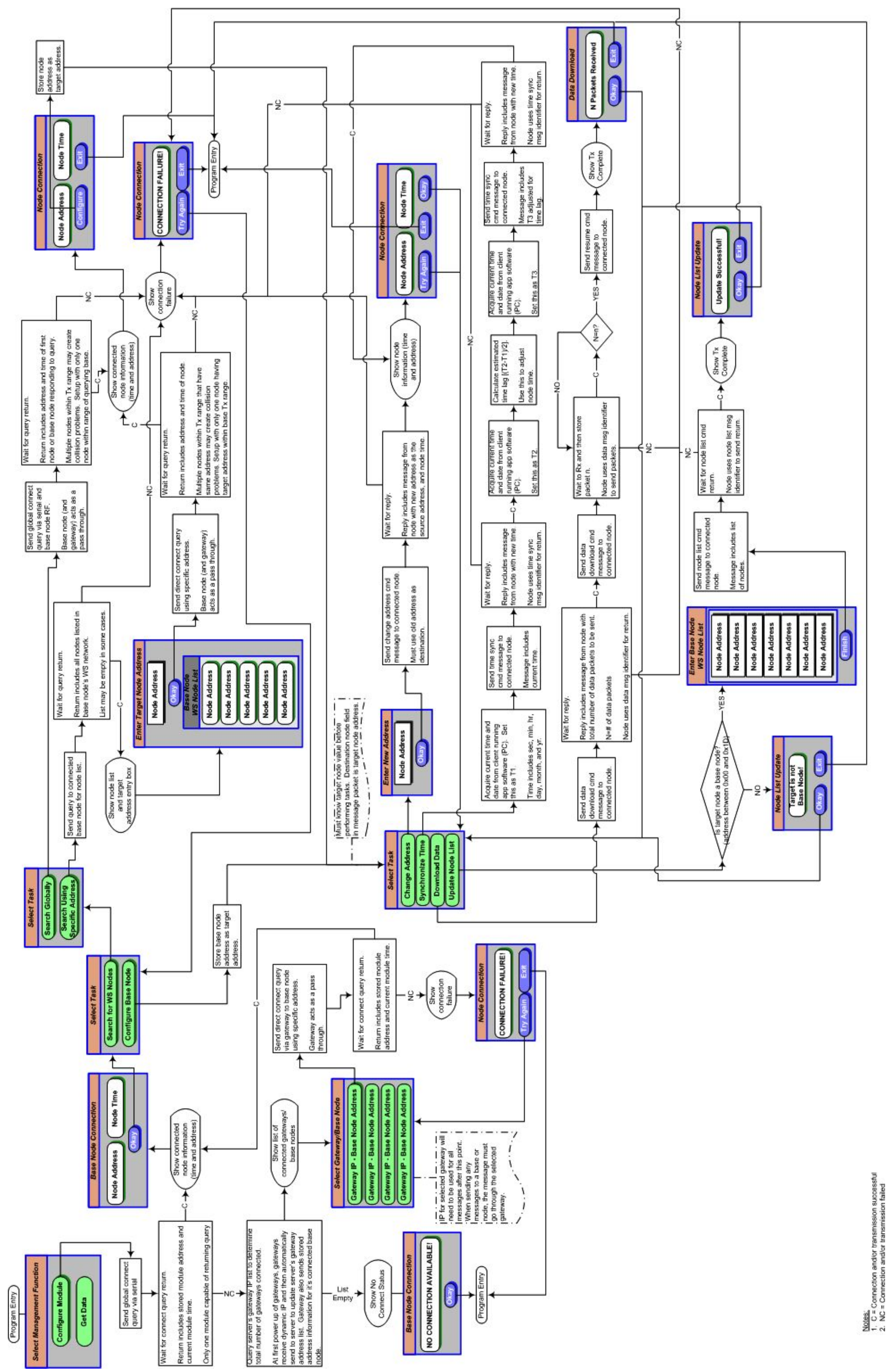
APPENDIX G

APPLICATION SOFTWARE PROCEDURES FOR BASE AND NODE MANAGEMENT

Continued on next page.



Program Entry
Select Management Function
Configure Module
Get Data
Send global connect query via serial
Wait for connect query return.
Return includes stored module address and current module time.
Only one module capable of returning query
Show connected node information (time and address)
Base Node Connection
Node Address
Node Time
Okay
Query server's gateway IP list to determine total number of gateways connected.
At first power up of gateways, gateways receive dynamic IP and then automatically send to server to update server's gateway address list. Gateway also sends stored address information for it's connected base node.
Show list of connected gateways/ base nodes
List Empty
Show No Connect Status
Base Node Connection
NO CONNECTION AVAILABLE!
Okay
Program Entry
Select Gateway/Base Node
Gateway IP - Base Node Address
Gateway IP - Base Node Address
Gateway IP - Base Node Address
Gateway IP - Base Node Address
IP for selected gateway will need to be used for all messages after this point. When sending any messages to a base or node, the message must go through the selected gateway.
Send direct connect query via gateway to base node using specific address.
Gateway acts as a pass through.
Wait for connect query return.
Return includes stored module address and current module time.
Show connection failure
Node Connection
CONNECTION FAILURE!
Try Again
Exit
Select Task
Search for WS Nodes
Configure Base Node
Store base node address as target address.
Select Task
Search Globally
Search Using Specific Address
Send query to connected base node for node list.
Wait for query return.
Return includes all nodes listed in base node's WS network.
List may be empty in some cases.
Show node list and target address entry box
Enter Target Node Address
Node Address
Okay
Base Node WS Node List
Node Address
Node Address
Node Address
Node Address
Node Address
Send direct connect query using specific address.
Base node (and gateway) acts as a pass through.
Wait for query return.
Return includes address and time of node.
Multiple nodes within Tx range that have same address may create collision problems. Setup with only one node having target address within base Tx range.
Send global connect query via serial and base node RF.
Base node (and gateway) acts as a pass through.
Wait for query return.
Return includes address and time of first node or base node responding to query.
Multiple nodes within Tx range may create collision problems. Setup with only one node within range of querying base.
Show connected node information (time and address)
Show connection failure
Node Connection
Node Address
Node Time
Configure
Exit
Store node address as target address.
Node Connection
CONNECTION FAILURE!
Try Again
Exit
Program Entry
Must know target node value before performing tasks. Destination node field in message packet is target node address.
Select Task
Change Address
Synchronize Time
Download Data
Update Node List
Enter New Address
Node Address
Okay
Send change address cmd message to connected node.
Must use old address as destination.
Wait for reply.
Reply includes message from node with new address as the source address, and node time.
Show node information (time and address)
Node Connection
Node Address
Node Time
Try Again
Exit
Okay
Acquire current time and date from client running app software (PC). Set this as T1.
Time includes sec, min, hr, day, month, and yr.
Send time sync cmd message to connected node.
Message includes current time.
Wait for reply.
Reply includes message from node with new time.
Node uses time sync msg identifier for return.
Acquire current time and date from client running app software (PC).
Set this as T2.
Calculate estimated time lag [(T2-T1)/2].
Use this to adjust node time.
Acquire current time and date from client running app software (PC).
Set this as T3.
Send time sync cmd message to connected node.
Message includes T3 adjusted for time lag.
Wait for reply.
Reply includes message from node with new time.
Node uses time sync msg identifier for return.
Send data download cmd message to connected node.
Wait for reply.
Reply includes message from node with total number of data packets to be sent.
N=# of data packets
Node uses data msg identifier for return.
Send data download cmd message to connected node.
Wait to Rx and then store packet n.
Node uses data msg identifier to send packets.
N=n?
YES
NO
Send resume cmd message to connected node.
Show Tx Complete
Data Download
N Packets Received
Okay
Exit
Is target node a base node? (address between 0x00 and 0x1D)
Node List Update
Target is not Base Node!
Okay
Exit
Enter Base Node WS Node List
Node Address
Node Address
Node Address
Node Address
Node Address
Node Address
Node Address
Finish
Send node list cmd message to connected node.
Message includes list of nodes.
Wait for node list cmd return.
Node uses node list msg identifier to send return.
Show Tx Complete
Node List Update
Update Successful!
Okay
Exit
C
NC
Notes:
1. C = Connection and/or transmission successful
2. NC = Connection and/or transmission failed

VITA

STEWART DAROLD REED

Candidate for the Degree of

Doctorate of Philosophy

Dissertation: CUSTOM WIRELESS SENSOR FOR MONITORING GRAZING OF FREE-RANGE CATTLE

Major Field: Biosystems and Agricultural Engineering

Biographical:

Personal Data: Born in Ada, Oklahoma on December 19, 1976, the son of Logan and Brenda Reed of Coalgate, Oklahoma. Married to Ashley (Clarke) Reed on September 27, 2003.

Education: Graduated from Coalgate High School, Coalgate, Oklahoma in May 1995. Received Associates of Science degree in Agriculture from Redlands Community College in May 1997 and Bachelor of Science degree in Biosystems and Agricultural Engineering from Oklahoma State University, Stillwater, Oklahoma in July 2000. Completed the requirements for Master of Science and Doctorate of Philosophy in Biosystems and Agricultural Engineering from Oklahoma State University, Stillwater, Oklahoma in August 2003 and December 2008, respectively.

Experience: Summer intern employment by John Deere Product Engineering Center, Waterloo, Iowa, from May 2000 to August 2000. Employed as a research engineer by the Oklahoma State University, Biosystems and Agricultural Engineering Department, Stillwater, Oklahoma, from August 2000 to July 2002, and from July 2005 to January 2009. Employed by NTech Industries, Inc., Stillwater, Oklahoma, as operations manager/engineer from August 2002 to January 2005.

Professional Memberships: American Society of Agricultural and Biological Engineers, Institute of Electrical and Electronics Engineers

Name: STEWART DAROLD REED Date of Degree: December, 2008

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: CUSTOM WIRELESS SENSOR FOR MONITORING GRAZING OF FREE-RANGE CATTLE

Pages in Study: 162 Candidate for the Degree of Doctorate of Philosophy

Major Field: Biosystems and Agricultural Engineering

Scope and Method of Study: The purpose of this study was to develop a wireless sensor device capable of sensing cattle grazing activity. This included design and build of a miniaturized PCB, sensor specification, data processing, and experimental validation. Experiments were conducted in cooperation with the Oklahoma State University, Animal Science and Biosystems Engineering departments. The primary objective of this study was to provide information supporting the use of an accelerometer sensor for monitoring free-range cattle grazing activity. A wireless sensor platform was also developed for sensor and wireless communication development needs. Secondary objectives included exploring alternative applications, such as monitoring cattle waste excretion events, and identifying wireless network functionality for agricultural environments.

Findings and Conclusions: During this study, parameters for using an accelerometer based grazing sensor were established relative to the head motion of grazing cattle. Initially, a survey of literature and video analysis of foraging livestock animals were conducted, where 0.5-8 bites/sec was confirmed as animal bite rate range. The preliminary video analysis provided guidelines for establishing a sensing strategy. Sensor data processing algorithm development and sampling rate selection were driven by video-provided characteristics and sensor platform capability. The Fast Fourier Transform (FFT) was selected as the core component of the sensor's algorithm. The FFT was able to characterize grazing motions because of the animal's near-continuous periodic head movements. At least five bite cycles and a 32 Hz sampling rate were required for proper algorithm implementation. A sample size of 256 data points were collected for each accelerometer axis, and proved to be adequate for the FFT computations. A revised sample rate of 21.74 Hz was presented once the FFT was implemented in firmware. This new rate retained well performing FFT calculations based on the understanding that bite rates faster than 4 bites/sec were due to nibbling and partial bites. The FFT's Spectral power was binned and stored for the purpose of data compression and reduced wireless transmissions.

The wireless sensor device platform was built using the CC1010 microcontroller/transceiver IC. The CC1010 provided integrated features commendable for fast FFT processing and conservative PCB layout design. The radio was configured for robust operation by using a 915 MHz carrier frequency, Manchester encoding, and 64 kHz frequency spread. A small, helical, and omnidirectional antenna was mounted directly to the PCB. Link budget was estimated to be 81 dBm, which equated to a 282 m (925 ft) transmission distance in optimum conditions. The device's dimensions were 19.6 mm (0.77 in) X 71.8 mm (2.83 in) X 11.0 mm (0.43 in). A custom PVC enclosure was used to house the device. For deploying experiments, the enclosure was fastened to a standard nylon turnout halter. A miniature GPS logger was also attached to the halter, which allowed for constructing grazing maps.

Additionally, the proposed wireless sensor device was used to detect cattle urination and defecation events. This was accomplished by attaching the device to an animal's tail and sensing its elevated movements. Tilt measurements in the z-axis (front-to-back) direction provided the most prominent evidence of a distinct tail movement pattern during excretion events. A pattern recognition strategy was shown as a viable sensing method.

An outline for a multilevel-networked system was also generated. This included cellular and internet communications, along with a customized application software for base/node management.

ADVISER'S APPROVAL: Dr. John B. Solie