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Ingestible Pill for Heart Rate and Core Temperature Measurement in Cattle

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Abstract — **The livestock industry is an integral part of the United States economy. The continued production of quality beef requires new and improved methods for long term monitoring of animal health. Additional benefits can be realized from this class of technology, such as the ability to identify the presence of disease early and thereby prevent its spread. An important element of health assessment is the ability to monitor vital data such as heart rate and core body temperature. This paper presents preliminary results from the design of an ingestible pill that allows one to acquire heart rate (via a phonocardiograph) and core temperature in cattle. Packaging, circuitry, algorithms, and the wireless link are addressed.**

Keywords— **Auscultation, bolus, core body temperature, phonocardiograph, pill, wearable sensors, wireless communication**

I. Introduction

The livestock industry is an important part of the United States economy and plays a key role in the lifestyle of many millions of people. The industry has suffered significant economic hardships due to factors such as isolated incidents of foot and mouth disease, anthrax exposure, and mad cow disease. On average, Americans eat 67 pounds of beef per person per year [1]. Both national and international customers desire to obtain their cuts of beef from the healthiest animals, although this requirement is currently impractical to meet with existing tools and animal husbandry practices. Additionally, recent terrorist events and dialogue regarding the vulnerability of the livestock industry to disease outbreaks (whether from natural or terrorist events) have raised awareness about animal tracking and the need to control the flow of animals from the farm to the feedlot.

When considering long term monitoring of animal health, heart rate and core body temperature come to mind as an important starting point, since they allow ambulatory measurement to be compared against a history of clinical guidelines. Core temperature alone can provide information regarding an animal's drinking habits, rumination cycles, and food intake. It can also indicate the presence of illness, map to the fermentation of ingested food, and allow one to study the effects of temperature and volumes of water on the living organisms inside the rumen [2]. Fluctuations in heart rate can indicate stress and state-of-health changes [3].

Commercial devices exist that allow determination of core body temperature via a bolus (pill) form factor [4-6]. These devices have battery lives of weeks to months and can transmit their data wirelessly at adjustable time intervals. Belt-based arrangements also exist that employ electrodes to transduce the heart vector in large animals [6-8]. However, obtaining heart rate from cattle via electrodes is especially difficult due to the thickness and large electrical resistance of bovine hide. With implantable electrodes, the potential for infections and biological reactions to the suture material present significant hurdles. Additionally, the electrode paste typically used for electrocardiogram measurements will not endure an outside environment for long time periods. Dry electrodes offer hope, but electrode placement problems limit their long term usefulness. Finally, cattle simply do not like to wear belt-based devices, and belts get easily snagged on trees or can be scratched off. Light based approaches have been attempted on the ear, but the results were inconsistent from animal to animal. Hair, unpredictable vessel patterns, and a lack of perfusion also contributed to measurement difficulties [6].

One solution is to monitor heart rate and temperature using one pill. The reticulum is physically near the heart of the animal, and a bolus form factor gives cattle no discomfort and requires little maintenance from the owner. A feasible option is an adaptation of a phonocardiograph for this purpose using a microphone inside the pill. This document addresses the design of a novel pill-based phonocardiograph and presents initial data sets obtained with the device.

II. Methods

A. Functional Overview

A functional block diagram of the hardware/software used for the acquisition and processing of the phonocardiographic sensor data is illustrated in Fig. 1. Key features include the following:

- **Acoustic Data Acquisition:** A submersible microphone obtains acoustic data from a steer's reticulum.
- **Body Temperature Acquisition:** A simple surface mount temperature sensor obtains a calibrated core body temperature measurement.
- **Heart Rate Peak Detector and Filter:** Analog circuitry detects acoustic pulses and attempts to filter out unwanted noise such as rumination artifacts.
- **Data Preprocessing:** Raw data are converted and ordered in a meaningful way prior to transmission. The analog-to-digital converter in the main processor captures the temperature data, then the processor clock determines the time between heart rate pulses.
- **Wireless Transmission:** Wireless data are transmitted over a radio frequency link.
- **Post Processing:** Smoothing and parameter assessment algorithms are applied to these data.

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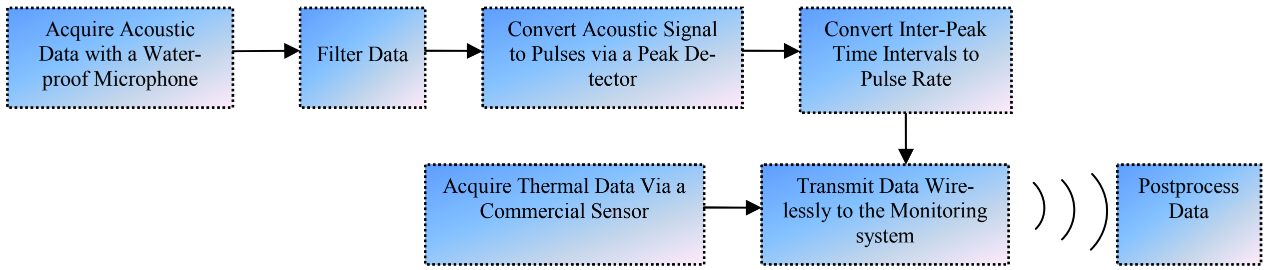

Fig. 1: Functional block diagram for the hardware/software that constitute the ingestible bolus (pill).

B. Data Acquisition Hardware

The current bolus design utilizes peak detection hardware to identify the beginning of each pulse so that the times between consecutive pulses can be determined. These values are then converted into pulse rate. As depicted in Fig. 2, operational amplifiers (op amps) indicate these pulse events to the preprocessor.

The hardware can be analyzed in several stages. Stage one contains the microphone that supplies acoustic signals to the first op amp (U1 – see Fig. 2), which provides modest gain to the signal and serves as an impedance buffer. Stage two embodies the peak detection circuitry, which is comprised of an op amp (U2), a diode (D1), and a capacitor (C1). This is a common peak detector circuit. The negative input of U2 is held at the voltage across the capacitor. When the voltage at the positive input of U2 exceeds the voltage at the negative input of U2, the op amp drives a current through the diode to charge the capacitor as it attempts to maintain identical voltage levels at the two inputs of U2. The diode prevents current from being drained through the op amp while the capacitor is not charging.

Since an op amp theoretically has infinite input impedance, the inputs to op amp U2 should not provide a current path that will discharge the capacitors. However, an actual op amp's input impedance is finite, causing a small amount of leakage current. This small amount of voltage discharge is actually useful; otherwise the circuit would be a maximum detector instead of a peak detector. Over time, the voltage across the capacitor discharges until the voltage at the positive input of U2 again exceeds the capacitor voltage, at which point the capacitor becomes fully charged again. If a more rapid voltage discharge is desired, a simple resistor in parallel with the hold capacitor (C1) will suffice.

The third stage incorporates two non-inverting unity-gain buffers (U3 and U4). This stage is also made up of a network of resistors and capacitors that act as filters and provide a voltage to the final stage, which is an op amp that performs as a comparator. Without feedback, the op amp rails to the positive supply when the voltage at the positive input is larger than the voltage at the negative input; it rails to the negative power supply when the reverse occurs.

C. Communication Link

Establishing a reliable wireless link has posed a significant challenge for this effort. The initial hardware used to implement the wireless link is a development kit designed by Microchip, Inc. The transmitter is an rfPIC-controlled, printed loop antenna with a center frequency of 315 MHz. The receiver is an rfPIC-controlled monopole antenna. More recently, we have been working with LINX Technologies hardware to establish a more reliable link. Link experiences to date are discussed in the *Results* section.

Each data packet transmitted from the bolus contains the following (transmitted in the order given): an identification number for distinguishing between multiple pills in multiple cattle, two bytes of temperature data, 16 bytes of heart rate data, and a checksum. The two bytes of temperature data are later translated into a single value for core body temperature. The heart rate is transmitted as 8 sets of two bytes, each containing the time between two consecutive pulses. These eight values can later be averaged together on the data logger to produce a single representative heart rate value (similar to the manner in which many commercial heart rate units report time averaged numbers). Finally, the simple 8-bit checksum mechanism was added to this transmission scheme to remedy occasional, nonsensical readings received via the communication link.

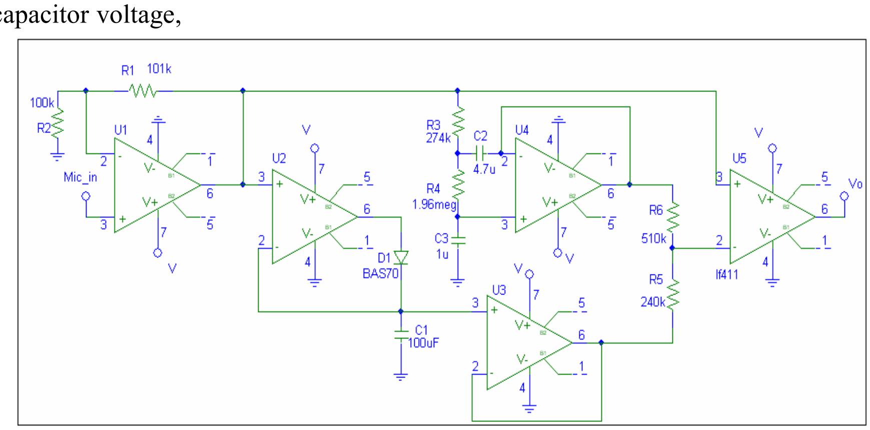

Fig. 2: Schematic diagram for the heart rate peak detector.

III. Results

A. Simulation

After examining the peak detection circuit, one would expect the output of that circuit to pulse high when the voltage at the positive input terminal of U2 rises to a value greater than the current voltage on the hold capacitor. Fig. 3 displays the results of a simulation that affirms this expectation. The acoustic sample (signal 1) was acquired from the reticulum of a steer, via a cannula, using an inexpensive waterproof microphone. The waveform demonstrates a desirable signal-to-noise ratio. Fig. 3 also plots the voltage across the hold capacitor (signal 2) in the peak detection circuit. Note that the peak detector discharges the capacitor slowly, allowing the secondary portion of each acoustic pulse to pass through the system without generating false timing pulses. Finally, Fig. 3 shows a scaled version of the output signal (signal 3). The circuit clearly performs as anticipated: the output briefly pulses at the onset of each heart beat. The preprocessing unit uses an internal clock to assess the time intervals between consecutive output pulses. Once that information is forwarded to the post processing unit, several intervals are averaged to obtain the heart rate reported by the unit. In Fig. 3, the animal's heart rate is ~70 beats per minute.

B. Wireless Communication Link

In a laboratory environment, the monitoring system can reliably receive air transmissions without a significant number of false data sets. However, when using Microchip's wireless hardware, we have had little success establishing a reliable link between the transmitter and receiver modules when the transmitter is inside the reticulum of a cow. Multiple explanations exist for this behavior. First, upon examining the signal-to-noise ratio of the received signal, it is apparent that the transmitted signal has been attenuated almost to the point of nonexistence. This is due to the attenuation properties of tissue at this transmission frequency. Since the bolus rests in a pool of rumen fluid when inside the reticulum, the transmission medium is dominantly water over the entire transmission path. However, water is a poor transmission medium for electromagnetic wave propagation at this frequency. One way to remedy this problem is to maximize the power supply voltage to the transmitter. Additionally, one can change the controller software to provide a slower bit rate, thereby doubling the effective transmission bandwidth and allowing the receiver to better detect the center frequency.

Two additional remedies could be employed. First, since the circuitry near the receiver on the monitoring system may be interfering with the receiver, electromagnetic shielding might allow the receiver to be more sensitive to the transmission. Second, the system could be redesigned to employ a lower center frequency. The solution offers the most potential but will require careful antenna design and a significant amount of additional engineering time.

As previously stated, we are attempting to utilize alternative wireless hardware. The new hardware provides a higher output power rating on the transmitter, offers a more sensitive receiver, and requires less real estate. Thus far, this hardware has provided a transmission success rate (from inside the reticulum) that is approximately 10 times better than the previous design. We now successfully receive 25-50% of the transmissions when the receiver is positioned on the side of the animal's neck and 50-80% of the transmissions when the receiver is positioned directly underneath the reticulum of the cow. This compares to a transmission success rate of ≤10% when using the Microchip hardware in the previously mentioned positions.

C. Initial Trials

While the circuit simulations work as expected, real-world trials offer a dilemma regarding the acoustic data acquisition process. When the bolus is in the animal's reticulum, it does not stay in one place, but rather moves from the reticulum to the rumen, where a reliable acoustic signal can rarely be obtained. The microphone on the bolus needs to rest near the bottom of the reticulum, ideally against tissue in order to maximize the quality of the acoustic signal. At-

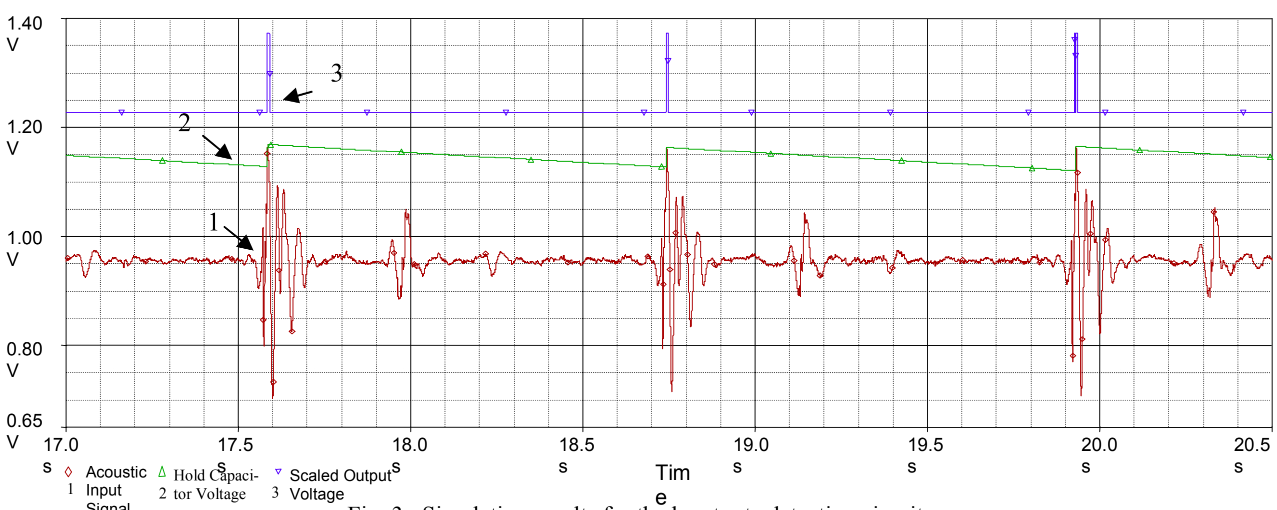

Fig. 3: Simulation results for the heart rate detection circuit.

tempts have been made to add weight to the bolus so that it will not float, but the underlying problem is that the existing bolus design is too large to rest unobtrusively in the reticulum. As the animal ruminates, it contracts its stomach muscles and subsequently squeezes the bolus out to the rumen.

This poses a problem when testing the bolus in an animal for long periods of time. For short experiments, the bolus can be held into place if the animal has a cannula. The only long-lasting solution to this problem is a bolus redesign, utilizing the same hardware but a different PCB layout, thereby allowing the pill to be much smaller. A benchtop alternative for long-duration tests is to set a metronome next to the microphone. In this configuration, the hardware behavior matches the behavior of the circuit simulations.

Finally, when the bolus rests in the reticulum of an animal and that animal begins to ruminate, a substantial amount of rumen fluid and debris passes by the microphone. Additionally, muscle contractions (e.g., during walking or grazing) generate substantial noise in the acoustic signal. These artifacts cannot be avoided, so software algorithms will be needed that (a) separate these artifactual components from the desired phonocardiogram and/or (b) indicate periods of time over which clean signals can be acquired. A good acoustic waveform every few minutes will suffice.

D. Hardware

Fig. 4 shows a photograph of the bolus hardware that incorporates the peak detection circuitry described earlier. In the photograph, (A) and (B) are the Microchip transmitter and receiver modules, respectively, that have been integrated into this system. The milled circuit board (C) hosts the control, data acquisition, and filtering circuitry. The packaging constructed for the bolus is shown by (D) and (E). The cap (D) contains the submersible microphone, and the enclosure (E) is a hollow body that protects the circuitry from water damage.

IV. CONCLUSION

Animal state of health is vitally important when considering both the economic status of the livestock industry and biosecurity. This paper presented a design for an ingestible bolus (pill) that may allow effective and continuous assessment of cattle state of health. The pill incorporates (a) an off-the-shelf sensor to monitor core body temperature and (b) a submersible microphone and peak detection circuitry that facilitate the determination of animal heart rate.

Initial circuit simulations yield promising results given real-world acoustic signals obtained with a microphone held in the reticulum of an animal via a cannula. Early field tests have yielded valid data sets for both heart rate and temperature over a short time interval, but longer term testing will require significant time investments. While simulations operate as expected, real-world tests will require the establishment of a reliable wireless link as well as processing software that can differentiate between heart beats, rumination noise, and movement artifact.

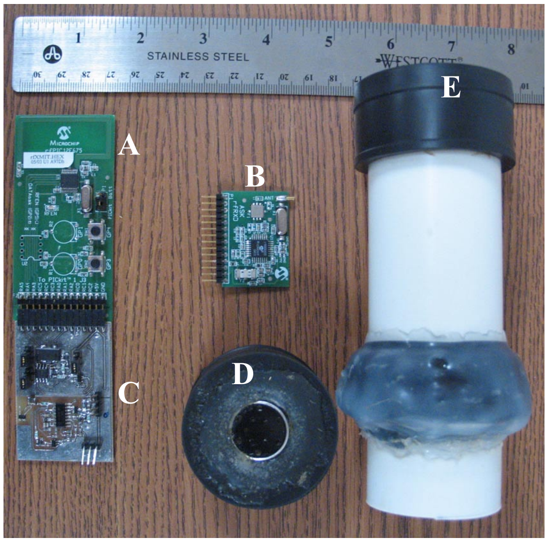

Fig. 4: Photograph of the bolus hardware.

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REFERENCES

[1] C. G. Davis and B.-H. Lin. "Factors Affecting U.S. Beef Consumption," Economic Research Service, United States Department of Agriculture LDPM13502, October 2005.

[2] K. Mayer, K. Ellis, and K. Taylor. "Cattle Health Monitoring Using Wireless Sensor Networks," Communication and Computer Networks.

[3] A. M. Lefcourt, B. Erez, M. A. Varner, R. Barfield, and U. Tasch. "A noninvasive radiotelemetry system to monitor heart rate for assessing stress responses of bovines," *Journal of Dairy Science*, vol. 82, pp. 1179-1187.

[4] "Wireless Sensing Systems and Design," HQI Inc., 2006, http://www.hqinc.net.

[5] "CorTemp Remote Temperature Sensing in the NFL," MedGadget, 2005, http://www.medgadget.com.

[6] S. Warren, L. Nagl, R. Schmitz, J. Yao, T. Hildreth, H. Erickson, D. Poole, and D. Andresen. "A Distributed Infrastructure for Veterinary Telemedicine," 25th Annual Conference of the IEEE EMBS, Fiesta Americana Grand Coral Beach Hotel, Cancun, Quintana Roo, Mexico, September 17-21.

[7] "Televet 100 - The Telemetric ECG and Holter System," Jørgen KRUUSE A/S, 2006, http://www.kruuse.com.

[8] "Polar Horse Heart Rate Monitors," FitMed Incorporated, 2006, http://www.heartmonitors.com/horse/.