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Near-Field Wireless Magnetic Link for an Ingestible Cattle Health Monitoring Pill

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Abstract—**Cattle health assessment is receiving increased attention due to threats that disease and bioterrorism pose to producer profits and to the safety of the food supply. Ingestible pill technology offers a promising means to obtain these physiologic data, since a bovine reticulum is an environment sheltered from outside elements that offers direct access to feed intake and heart/lung data. Traditional radio-frequency links are inappropriate for this application, as water absorption severely limits transmission ranges through tissue. This paper presents the initial design of a communications link that utilizes magnetic induction for signal transport and should be well-suited for a tissue medium. The link consists of a transmitter/receiver pair that employs loop antennae frequency matched at 125 kHz. Optimization of the link design offers the potential to achieve transmission distances of several feet through tissue.**

Keywords—**Cattle health, inductive coupling, ingestible sensor pill, telemetry, telemonitoring, veterinary telemedicine, wireless communications, wearable devices**

I. Introduction

Disease, whether it occurs naturally or as a potential result of bioterrorism, poses a serious threat to the livestock industry. Agricultural profit margins for meat cattle are generally small – often $10 per head in a large feedlot [1]. These economic pressures, coupled with a recently augmented focus on meat quality driven by efforts to ensure the safety of the food supply, have led to an increased desire to monitor individual animal health [2]. The living environments that support most of these animals imply the use of emerging technologies such as radio-frequency identification (RFID) tags [3, 4], environmentally-robust wearable sensing systems [5-12], and electronic animal records [13]. The goal is to establish a life-long electronic record for each animal that chronicles its health data, location, and proximity to other animals.

Wearable sensing systems offer an attractive alternative to hands-on veterinary assessments because of their promise to acquire continuous physiologic data that may lead to new understandings about animal health while at the same time optimizing the time of clinical professionals. These benefits have already been demonstrated in the human health monitoring domain. However, cattle are non-compliant wearers, and sensors can be easily rubbed off on tree branches, fence posts, and other animals. Wind, water, dirt, and debris pose additional problems in this environment, making ingestible sensors an appealing alternative to wearable units because of the predictability and isolation of the environment [14-19].

Sensors in pill-based form factors have shown promise, but transmitting these data out of a large animal is problematic. Traditional radio-frequency (RF) wireless technologies designed for ad-hoc networking environments (e.g., Bluetooth [20, 21], Wi-Fi [22], and ZigBee [23]) do not work for this application, since RF energy at these frequencies attenuates rapidly in tissue due primarily to water absorption. Similar problems have been encountered in deep-sea wireless communication [24, 25], where the solution was to adopt a lower transmission frequency and larger antenna size; an impractical solution for ingestible sensors.

This paper presents the initial design for a wireless link based on magnetic induction that has the potential to transmit data from the inside of a large animal to an external receiver. This link will be used to interface pill designs under development at Kansas State University [14-16] with a wearable, multi-parameter cattle health monitoring system which seeks to record animal heart rate, core body temperature, head motion (three axes of acceleration), absolute position via the global positioning system, and the ambient temperature and humidity of the surrounding environment [5-7, 10]. The following sections describe the design of the prototype link and assess its performance relative to the requirements of this animal monitoring application.

II. Methodology

A. Overall System Layout

The overall flow diagram for the system that will employ this wireless link is illustrated in Fig. 1. As depicted on the left side of the diagram, a sensor pill located in the animal's reticulum, or first stomach, will encode its data (e.g., heart rate and core body temperature [14-16]) into a digital stream which will be passed to the transmitter. Those data, sequences of digital ones/zeros represented by high/low states in the analog circuitry, will be amplitude modulated at the carrier frequency and sent over a wireless magnetic link to a receiver using a one-way communications scheme. The receiver, which will reside on a data logging unit worn by

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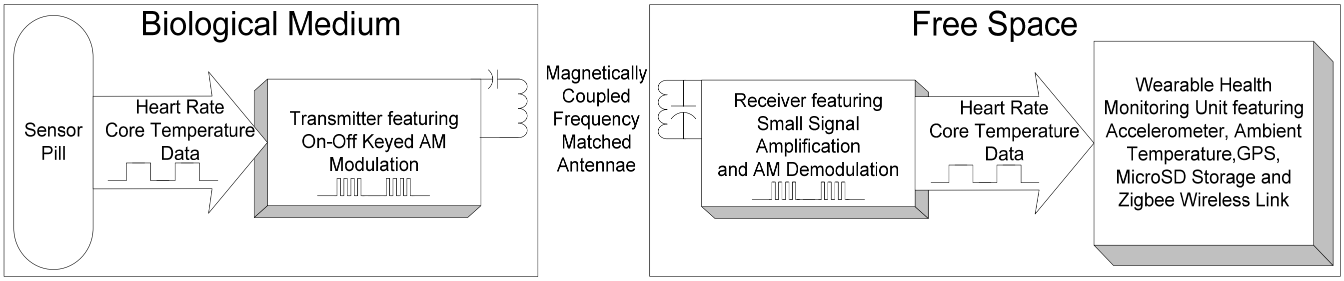

Fig. 1. Overall flow diagram for the pill-based data acquisition platform which will employ the wireless magnetic link.

the animal, will demodulate the data. These data will then be stored on a MicroSD card. When the animal wanders within range of a base station at a feed bunk or water trough, the data will be uploaded to a server and merged with the animal's electronic health record.

B. Transmitter Design

The transmitter block diagram is depicted in Fig. 2. A 125 kHz square carrier wave is generated using an LMC555 CMOS timer. On/off keyed amplitude modulation is applied to the digital signal data by feeding the carrier wave and the digital signal to a dual-input NAND gate. This inverted signal is offered to both inputs of a second dual-input NAND gate to provide a non-inverted signal counterpart. The transmitting antenna is connected to a transistor-based H bridge, where one half of the bridge connects to the inverted, modulated signal and the other connects to the non-inverted signal. The opposing polarity of these inputs allows more voltage and current to be provided to the antenna. With this approach, a 0 is provided as a ground signal, whereas a 1 is a square wave oscillating at the carrier frequency. The frequency of the transmitted signal is always at resonance, and its outer envelope represents the original data.

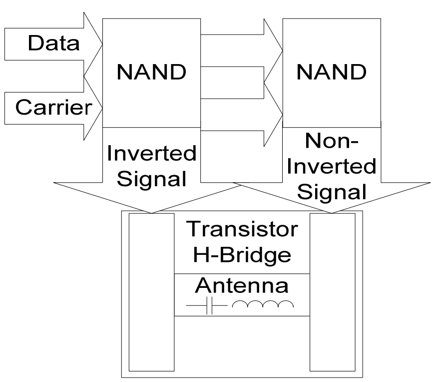

Fig. 2. Transmitter block diagram.

C. Magnetic Link Design

The transmitter and receiver antennae must be tuned to resonate at the carrier frequency, and minor deviations from this frequency affect transmission range. The resonance (carrier) frequency is 125 kHz, which supports a 5 kHz digital data rate at a 33% duty cycle. Each antenna employs a coil of wire around a ferromagnetic core whose inductance, *L*, is paired with a capacitance, *C*, to resonate at a frequency of $1/\left(2\pi\sqrt{LC}\right)$ Hz. This relationship holds whether these components are placed in series or in parallel. The transmitter employs a series relationship to maximize the current through the inductor and therefore the magnetic field strength surrounding the transmitter. Conversely, the receiver utilizes a parallel arrangement to maximize the voltage drop across its antenna.

Antenna coils were made using 28-gauge magnet wire around ferrite rod cores: Fair-Rite 3078990911 manganese-zinc composite ferrites [26] with a diameter of 8 mm, a length of 45 mm (cut to 25 mm), and a relative permeability of 2300, suitable for frequencies ≤ 200 kHz. Inductance values of 5 mH were needed, requiring 500 turns of wire in multiple layers to yield antenna diameters of ~15 mm.

D. Receiver Design

The external receiver converts the quasi-static magnetic field generated by the transmitter to an electric signal whose amplitude can range from volts to millivolts depending on the proximity of the transmit/receive antennae. Small signals must be amplified to voltage levels appropriate for the data reconstruction circuitry. The receiver is relatively more complex than the transmitter; its block diagram is illustrated in Fig. 3. The incoming signal is received by the antenna, whose impedance is isolated from the rest of the circuitry with a triac composed of a pair of anti-aligned diodes. This often-small signal is amplified with an OPA830-based circuit with a gain of 80 that incorporates simple *RC* first-order lowpass and highpass filters with cutoff frequencies of 120 kHz and 130 kHz, respectively. Next, the analog amplitude-modulated signal is converted to CMOS-compatible digital pulses using an LMC311 voltage comparator. The outer envelope of the signal now resembles a 5 kHz digital signal with a 33% duty cycle. Demodulation is performed with a 5 kHz one-shot timer using an LMC555 chip, which also removes the reduced duty cycle. These data can be decoded and stored to memory.

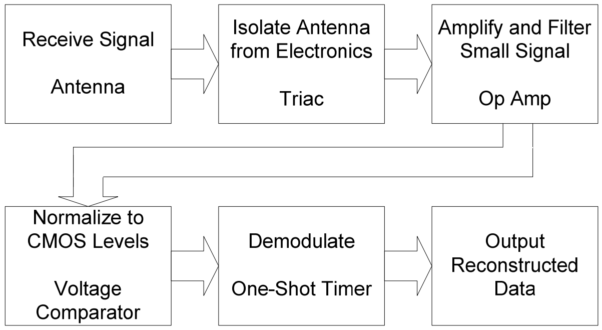

Fig. 3. Receiver block diagram.

III. Results and Discussion

Fig. 4 illustrates signal data captured by an Agilent DSO6104A mixed-signal oscilloscope at various stages in the transport process. The top trace (DATA) is the original digital signal, in this case simulated with an LMC555 timer operating at 5 kHz. The next signal (MOD) is the non-inverted, on/off keyed amplitude-modulated signal. The third signal (TX) is the voltage across the transmitting coil, which is in series with a tuning capacitor. The bottom trace (RX) signal is the received signal after it has been amplified.

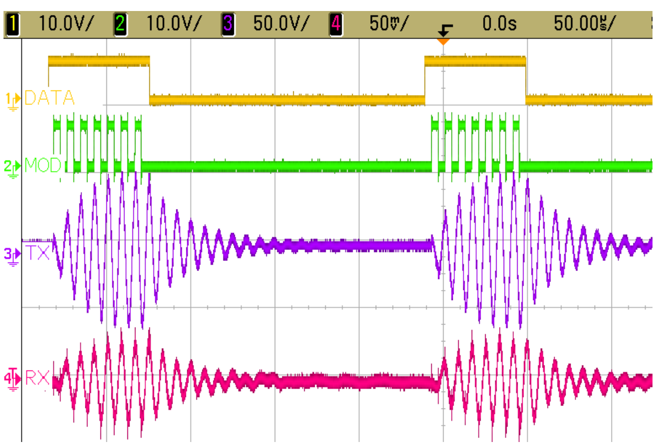

Fig. 4. Inductive link data for a 15-inch separation distance: (DATA) original digital signal, (MOD) modulated digital signal, (TX) transmitted signal, and (RX) received signal.

The effect of the tuning capacitors is apparent; the transmitted and received signals are sinusoidal when compared to the original modulated signal. Also, while the H bridge increases the current through the transmitting inductor, the current takes ~40 µs to reach its full value and ~75 µs to turn off. These delays require the carrier frequency to be at least 10 times larger than the data rate and impose a reduced duty cycle. While higher data rates could be potentially achieved with higher carrier frequencies, the near-field distances achieved by these links (approximately one wavelength) would be smaller because of the inverse time-frequency relationship. In addition, amplification of a small signal at higher frequencies will increase the power consumption and bandwidth requirements for the associated electronics. A further incentive for adopting a carrier frequency of 125 kHz is its role in near-field communications for a collection of ISO standards [27, 28].

In Fig. 4, the peak-to-peak voltage of the received signal is about 50 mV for a transmitter-receiver separation distance of 15 inches. This amplitude varies with separation distance, as illustrated in Fig. 5, which plots the peak-to-peak voltage received as a function of separation distance in both free space and a saline solution (tissue approximation, where the transmitter was in saline and the receiver was in air). The figure also illustrates a scaled $1/r^3$ curve (where r is the separation distance) which aligns well with these data for distances greater than 5 inches. This behavior is anticipated from theory. In cases where the separation distance is greater than the antenna radius, the magnetic flux density, B, at a point in the near field is described by the expression $B = \mu INa^2/(2r^3)$, where μ is the permeability of the core, I is the loop current, N is the number of turns in the coil, and a is the radius of the antenna [29]. While the link appears to perform slightly poorer in saline, the measured voltage disparity in Fig. 5 does not exceed 3%.

Note that ferrite cores play an important role in this link design. Early designs utilized air-core inductors for the antennae, but they required large antenna radii to achieve suitable link distances of a few feet; these radii were unacceptable for use in an ingestible form factor. Commercial, machine-wound inductors were also sought, but commercial units that are practical in terms of size and value employ closed cores to *reduce* the magnetic field.

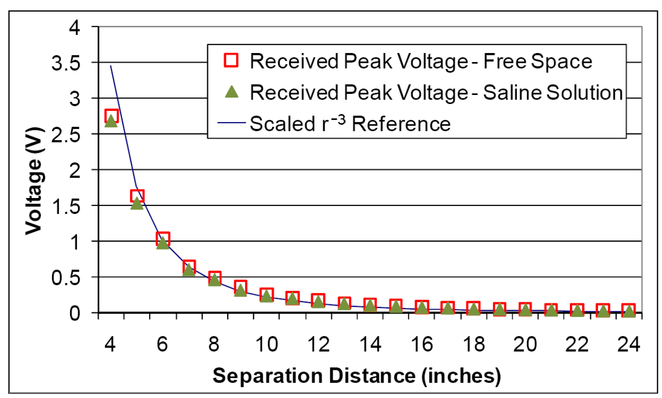

Fig. 5. Received signal intensity versus separation distance.

As depicted in Fig. 5, existing transmitter/receiver separation distances are on the order of 15 to 20 inches; the authors anticipate that this separation distance can be increased substantially with further tuning, hardware optimization, and enhanced signal processing. Once the circuit design is optimized, the layout will need to be updated so that the board can be integrated with sensor pill designs already under development [14-16] and still yield a pill whose form factor can be easily swallowed by an animal (commercial pills are approximately 1 by 4 inches [17]). Battery technology will play a role, as the power needs of this wireless link are substantive; an ingestible pill should operate 12 to 18 months on a single battery in order to be feasible for use with meat cattle. Finally, since one-way communication will continue to be used, a layer of encoding should be done above the physical layer to allow for limited error detection and correction.

V. Conclusion

Ingestible pill technology offers promise for obtaining physiologic data from cattle. The reticulum is near the heart and lungs, and it is an environment sheltered from weather, other animals, and external hazards to the physical integrity of wearable sensors. This paper presented a hardware description and early data for a prototype wireless link that utilizes magnetic induction to couple a transmitter to an external receiver, where the link should be much less susceptible to attenuation in tissue when compared to traditional radio-frequency links.

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