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Wearable Sensor System for Wireless State-of-Health Determination in Cattle

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Abstract—**Wearable systems for human and animal state-of-health determination share many design requirements. This paper discusses the design of a remote health monitoring system for cattle that hosts a suite of sensors and communicates wirelessly with a base station via Bluetooth telemetry.**

Keywords—**Animal health, Bluetooth, cattle, component design, microcontroller, wearable sensors**

I. Introduction

Agriculture, including the livestock industry, is vital to the American economy. Currently, the American livestock industry does not track animal identity (as Canada's meat industry does [1]) and has no means to assess past or present animal health. Animals move from farms to huge feedlots, and tracking the locale from which diseased animals originate can be impossible.

The overall goal of this project is to develop monitoring systems that continuously assess cattle state of health in concentrated and distributed herds. These systems will improve the ability of the livestock industry to react to and predict disease onset and its epidemiological spread, whether from natural or terrorist events. There is an obvious benefit to human medicine from this research. In particular, wearable sensor and information technology can have a positive impact on human state-of-health assessment.

In order to monitor an animal's health remotely, it is necessary to design a per-animal unit that will collate biomedical data from several sensors and wirelessly transmit that sensor data to an analysis station. The Bovine Mobile Observation Operation (BMOO) unit is designed to communicate with a variety of commercial and custom sensors and to use Bluetooth links to relay the data back to a farmer, a rancher, a veterinarian, or even an automated analysis system. The heart of BMOO is a MicroChip PIC microcontroller. It is responsible for controlling the various sensors, translating their communication protocols into a common protocol, storing the data until the animal is within range of a base receiving station, and then transmitting the data to the base station. Multiple base stations can exist, ideally located near feed bunks or watering troughs. With a ten-meter wireless range, the animal only has to get reasonably close to a base station for a connection to take place.

With the data obtained by the BMOO unit, a farmer, rancher, or veterinarian can make detailed state-of-health analyses, enabling rapid treatment or early disease detection to prevent spread within or between herds.

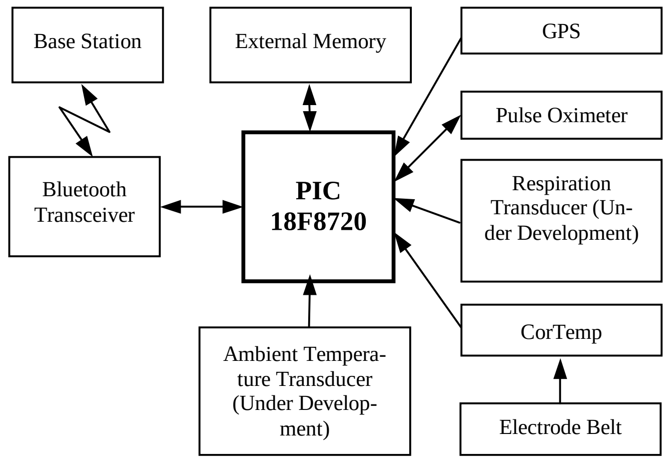

Fig. 1. Block diagram of BMOO unit.

II. Methodology

BMOO is designed to incorporate off-the-shelf and custom-designed sensors and modules to provide cost-effective animal health monitoring capabilities. These sensors and modules include a GPS (Global Positioning System) unit, a pulse oximeter, a core body temperature sensor, an electrode belt, a respiration transducer, and an ambient temperature transducer (see Fig. 1).

A GPS unit yields both animal location and movement data; with this, it is possible to see which fields an animal (and therefore, a herd) is grazing and whether the animal movement patterns are limited or erratic, each of which can indicate disease [2-4].

Next, a commercial CorTemp system monitors core body temperature continuously via an ingestible bolus. The bolus wirelessly transmits temperature data to a receiving unit connected to BMOO. The animal also wears a Polar electrode belt that acquires pulse rate and transmits it wirelessly to the core body temperature receiving unit.

A custom-designed pulse oximeter [5,6] measures blood oxygen saturation and pulse rate from an ear tag that the animal wears. (Optimal ear tag design is a current focus of this effort.) Finally, these data are stored to external memory while the animal is far from a receiver station. In this proof-of-concept system, only 512 KB of external SRAM (Static

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Random Access Memory) is implemented; more memory will be included in a production unit. A BrightCom Callisto II Bluetooth telemetry unit performs the wireless data transmission. This unit will allow connection either with a base station or with a handheld PDA (Personal Digital Assistant). The latter will enable the user to walk around a herd of cattle, checking the health of each animal. Early software written for Windows CE has demonstrated the utility and operability of the Bluetooth connection between BMOO and a PDA.

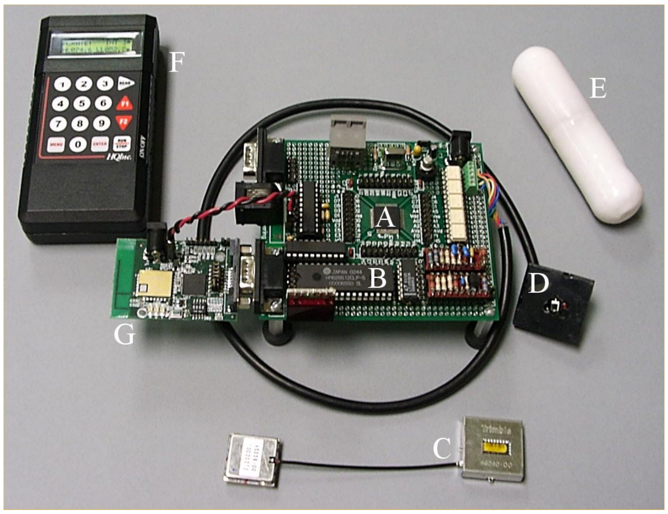

Fig. 2. The prototype BMOO unit.

A PIC microcontroller coordinates sensor operation in the circuit. The PIC 18F8720 (Fig. 2A) is used for this task due to its small size, low cost, low power consumption, and wide variety of peripheral functions. It is flash-memory based, allowing rapid reprogramming for easy product development. Using a Harvard architecture, is has separate internal memory spaces for code and for data; 128 KB of flash program memory and 3840 bytes of data RAM are adequate for complex programs. It includes a 10-bit, 12-channel A/D (Analog-to-Digital) converter for data acquisition from multiple external analog sensor units. Versatile interrupt handling comes from having eighteen interrupt sources and two interrupt priority levels. A 20 MHz clock provides the power necessary to perform complex calculations, such as FFTs (Fast Fourier Transforms). Finally, it has powerful Input-Output (I/O) capabilities, including nine I/O ports and two independently addressable UARTs (Universal Asynchronous Receiver-Transmitters). These varied I/O capabilities allow BMOO to communicate with a large number of sensors.

Programming the PIC requires a combination of assembly language and ANSI C. Because the PIC is only an eight-bit microcontroller with a modest clock speed, some time-critical portions of the program need to be optimized for speed. These code segments, such as the FFT code, are therefore implemented directly in assembly language. However, the overall program flow is too large and complex to represent in assembly language. Additionally, adding or modifying pure assembly language code is error-prone and time-consuming. Because of this, the overall program is implemented in C, using function calls to pre-assembled assembly language routines when greater efficiency is needed. This compromise promotes speed and efficiency while still ensuring ease of debugging and readability.

The memory space in the microcontroller, while adequate for processing and temporary data retention, is not large enough for long-term data storage. During use, the animal will potentially be far out of the range of a base station for many hours, or even days. External memory is therefore needed to store the vital sign data. To this end, 512 KB of SRAM is integrated onto the BMOO board (Fig. 2B), supplying approximately 136 times the amount of on-chip memory native to the microcontroller. The memory organization is that of a FIFO (First-In, First-Out) queue. When new data are fully processed and ready to be stored, they are taken out of on-chip memory and enqueued into the external memory. When BMOO detects the presence of a base station, these data are transmitted out of the queue until it is empty.

In order to monitor animal location and characteristic movements, a GPS unit is incorporated into the BMOO platform. To fulfill the requirements of low cost, small size, and low power consumption, the Trimble Lassen SQ GPS unit was chosen (Fig. 2C, shown with an embedded antenna). Measuring only 26 mm x 26 mm x 6mm and drawing only 100mW of power, the Lassen SQ is the most suitable GPS for this application. The Lassen SQ uses a battery backup to hold ephemeris data (the predicted locations of GPS satellites), allowing rapid re-acquisition of the GPS signal. This allows the GPS unit to be powered down intermittently, but still be able to re-acquire a signal quickly.

This rapid re-acquisition of the GPS signal is very important for efficient power use. When the GPS unit is powered on but has not acquired a signal, battery power is being wasted. The current drain from the GPS unit is not insubstantial, representing a significant portion of the total BMOO power requirements. Practically, it is more efficient (both in terms of energy and memory storage space) to sample the animal's location every few minutes rather than continuously.

A custom-designed pulse oximeter (Fig. 2D) is used to measure blood oxygen saturation and pulse rate. Originally, we implemented the pulse oximeter as an off-board sensor unit communicating through a wired RS-232 connection, but the large size and high power consumption necessitated an improved design. We redesigned the pulse oximeter sensor, and its processing was integrated into the main PIC microcontroller to reduce cost, power, and size. The pulse oximeter sensor will attach to a custom-designed ear tag (under development) that will permanently attach to the cow's ear. To reduce required memory storage space, the PIC performs an FFT on each data set received from the pulse oximeter, storing pulse rate and blood oxygen saturation calculations directly rather than storing the waveform obtained from the A/D converter. This allows vital sign measurement in the field without requiring additional off-board processing or a large memory space.

Core body temperature is an important parameter for assessing cattle state-of-health. To obtain this measurement, an unobtrusive sensor is required, but implanted sensors can be expensive and problematical, and rectal or oral thermometers are likely to be dislodged. In light of these issues, a commercial CorTemp system from HQInc is integrated into the BMOO system. The CorTemp unit consists of an ingestible bolus (Fig. 2E) and a receiver unit (Fig. 2F). The bolus houses a temperature sensor, low-power RF transmitter, and power source capable of providing up to nine months of power. The bolus is designed to lodge in the reticulum of the cow and remain there, not passing through the animal's digestive tract. Once the bolus battery is exhausted, a new bolus can be administered to the animal, with no harm to the animal. In addition, the CorTemp receiver unit acts as a receiver for a Polar pulse rate belt (see next paragraph). It then transmits both pulse and core body temperature over an RS-232 serial communication line to the BMOO unit.

An alternative method to measure pulse rate (i.e., versus the pulse oximeter) is to measure an electrocardiogram directly from the skin surface. Polar, Inc. makes an electrode belt for humans and horses that does this, communicating wirelessly to a separate receiver unit, typically a watch worn by the horse trainer. The belt is not pictured here.

Ambient temperature is easily measured through a thermistor connected to an A/D line on the PIC. (This addition is currently under development.)

Animal respiration can be measured using a thermistor attached to a nose stud in the animal's nostril. When the animal exhales, the temperature of the thermistor increases compared to ambient temperature. Using the PIC's A/D converter, we can detect this change. By noting the number of times per minute the temperature rises and falls, we can calculate respiration rate. (This addition is also currently under development.) Note that respiration can also be determined from pulse oximeter data as well as a separate inductance plethysmograph unit.

Bluetooth technology is used for wireless communication between BMOO and a base station. We chose Bluetooth as our telemetry option because it is a low-power, short-range protocol, ideally suited for battery-powered devices. The ability for auto-detection and auto-connection between a master and multiple slaves is necessary for this setup, where multiple animals will wander in and out of the receiver range. The Bluetooth device used in BMOO is a BrightCom Callisto II development card (Fig. 2 G).

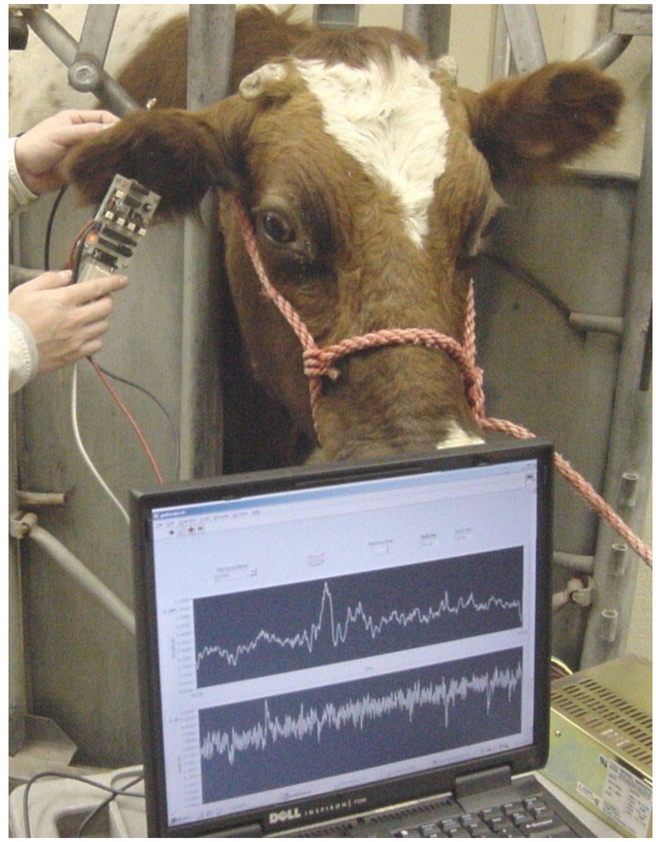

Fig. 3. Initial testing of pulse oximeter on a cow.

III. Results

Initial testing with a Garmin GPS-16L GPS unit showed a very long startup time and high power consumption. This led to a redesign of the GPS portion of BMOO, including choosing a new GPS unit. To compare the two GPS units tested, the Trimble Lassen SQ allows signal re-acquisition in 14 seconds with a battery backup, or 90 seconds without one. In contrast, the Garmin unit initially chosen for this project requires nearly 300 seconds to re-acquire a signal and has no battery backup option. This long re-acquisition time makes switching the unit into a power-saving mode impractical for real-world use. Power drain for the Lassen SQ is 100 mW (133 mW with antenna), while the GPS-16L consumes 400 mW.

In our tests, the CorTemp bolus did indeed stay in the rumen of the cow, and it communicated successfully with the receiver unit. Additionally, the Polar electrode belt returned accurate results when used on a cow, but the belt had to be lengthened to accommodate the cow's girth.

It is important that there is enough time for the BMOO unit to send its stored data while the animal is within range of a receiving station. At a data rate of 115,200 bps (bits per second), it takes approximately 45 seconds for BMOO to transfer a full queue of sensor data. Given the typical amount of time a cow spends at a feed bunk, this transfer time is sensible.

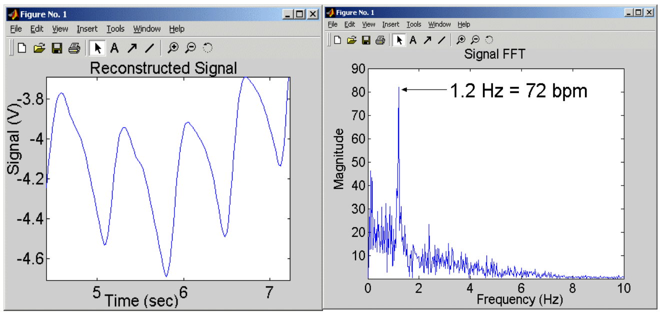

Fig. 4. Reconstructed Pulse Oximeter Signal

Testing of the original pulse oximeter unit on a cow is depicted in Fig. 3. Results were promising, as the reconstructed signal (Fig. 4) agreed with clinical data, and design of a bovine pulse oximeter unit was initiated.

IV. Discussion

An ambulatory animal monitoring system must be low power, small size, low cost, wearable, and exhibit adequate telemetry range. Each of these will be discussed in turn.

Power consumption for BMOO is primarily dependent upon the sensors attached to it. The current high-drain sensors are the pulse oximeter and the GPS unit. To reduce power, it is best to sample the GPS every few minutes rather than once per second, the GPS default. However, the original Garmin GPS-16LVS unit could not be turned off to save power without incurring a 300 second re-acquisition time, which makes GPS data acquisition for short bursts infeasible. Therefore, the Trimble Lassen SQ GPS unit was chosen as a replacement. This unit includes a battery backup to hold ephemeris data, shortening re-acquisition time to only 14 seconds. This allows the GPS unit to be cycled on to sample data for only a few moments before being cycled off again to reduce current drain. The pulse oximeter's power drain can be reduced in a similar manner: only sampling for a short time every few minutes. The other high-current device is the Callisto II Bluetooth transceiver. Again, since cows do not normally move quickly, we can turn it off for most of the time, only turning it on about once per minute to look for a base station. Bluetooth supports a ten-meter range by default, certainly adequate for this application. By installing a base station near a feed bunk or water tank, one can maximize the likelihood that animals will be close enough to a base station for a connection to take place. If a longer range is required, the Bluetooth standard allows for additional power transmitters of up to 20 dBm for up to a 100-meter range.

The current BMOO prototype is somewhat large because the components are hand-wired. However, shrinking the unit would be very simple by creating a custom printed circuit board and using surface-mount components rather than standard dual in-line package components.

The BMOO components are for the most part low cost. The only exception is the CorTemp monitor. However, added market penetration and economies of scale will drive prices down.

Ideally, the entire BMOO package would fit into a cowbell, a collar, or on a belt affixed around the animal's thorax. It is important that the unit be weatherproof and be able to withstand freezing and very warm temperatures. It is also necessary to ensure that the animal cannot roll onto the unit and crush it. Finally, sensors cannot be torn off by wires that catch on branches or fences. Preferably, each sensor would communicate with the BMOO unit wirelessly, but that is a topic for future development.

V. Conclusion

Initial development of the BMOO project focused on finding, developing, and field testing suitable sensors. The next step involved integrating the sensors into a single unit and writing the software necessary to control the sensors with the microcontroller. During this step, some modules proved to be suboptimal or otherwise problematical, and these were re-designed or replaced. The current phase includes adding more sensors and testing the complete unit on an animal.

There are many avenues of research still available to improve the BMOO project. First, the bovine ear tag pulse oximeter sensor requires field-testing. Next, the wires connecting sensors to the base BMOO unit must be replaced with short-range telemetry links to prevent the animal from catching on obstructions and damaging the unit. Finally, the power consumption and physical size of the device must be reduced to make the unit truly portable.

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