A LOW-POWER WIRELESS MICROINSTRUMENTATION SYSTEM FOR ENVIRONMENTAL MONITORING

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SUMMARY

This paper reports a hybrid microinstrumentation system that includes an embedded microcontroller, transducers for monitoring environmental parameters, interface/readout electronics for linking the controller and the transducers, and custom circuitry for system power management. Sensors for measuring temperature, pressure, humidity, and acceleration are included in the initial system, which operates for more than 180 days and dissipates less than 700μW from a 6V battery supply. The sensor scan rate is adaptive and can be event triggered. The system communicates internally over a 1MHz, 9-line intramodule sensor bus, and outputs data over a hardwired serial interface or a 315MHz wireless link. The use of folding circuit platforms allows an internal system volume as small as 5cc.

INTRODUCTION

The development of highly-integrated "smart" microsystems merging sensors, microactuators, low-power signal-processing electronics, and wireless communication promises to have a significant and pervasive impact during the coming decade [1], finding applications in such diverse areas as industrial process automation, health care, automotive systems, and environmental monitoring. These systems will require the high-density integration of state-of-the-art circuitry, sensors formed using a variety of technologies, and intelligent system management. This paper describes a generic multiparameter sensing system for environmental monitoring that could serve as a prototype for such devices. A block diagram of the system is shown in Figure 1, and specifications for an initial system implementation are listed in Table 1.

The microsystem is built around an embedded Motorola 68HC11 microcontroller (MCU) having on-chip memory, an 8b ADC, a timer, and serial communications hardware. The MCU communicates with the front-end transducers via a nine-line intramodule sensor bus and custom interface circuitry integrated on the transducer chips or on a separate hybrid. Sensor data collected by the MCU is calibrated in-module, stored, and sent out either through an on-board telemetry device or via a hardwired RS-232 I/O port. A custom power management chip performs several functions for minimizing power consumption in the battery powered system. The system employs an open
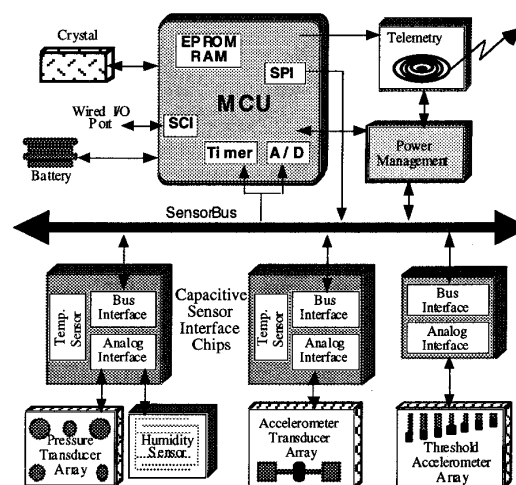

Figure 1: Block diagram of the microinstrumentation system.

architecture that permits it to be populated as desired by transducers using a mix of technologies. Transducers for measuring barometric pressure, altitude, humidity, and acceleration are included in the initial system.

SYSTEM OPERATION

Each transducer has a block of code in the MCU which contains information regarding the sensor characteristics and their digital compensation. The transducers are scanned periodically at a rate determined adaptively based on the variation in the parameters measured. During each scan the MCU communicates with the front-end devices over an intramodule sensor bus described in Figure 2. The sensor bus [2] contains three power leads (ground, a continuous 6V line from the system supply, and a switched 5V reference), four outputs to the front-end circuitry (chip enable and strobe handshaking signals, a 1MHz clock, and a serial data line), and two inputs from the front-end electronics (data out and data valid). The data valid line signals the MCU when valid data is present on the data out line and is also used to initiate interrupts triggered by the front-end devices. Figure 2 also shows the bus protocol for serial data delivered by the MCU, which includes a 4b chip address followed by a 5b sensor/actuator address, 3 command/instruction bits, and up to 12b of input data.

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Parameter	Typical Value
Power Supply	6V, External or Battery
Ave. Power Dissipation*	400-700μW
Lifetime (with battery)*	180-330 Days
Package Configuration	Card or Wristwatch
System Volume	5cc
Packaged Volume	12cc
Sensor Bus Frequency	1MHz
Wireless Range	≥100 feet
Temperature	-20 to +60°C ±0.2°C
Barometric Pressure	600-800 Torr ±25mTorr
Humidity	30-90%RH ±3%RH
Vibration/Acceleration	-2 to +2g ±0.1g
* scan rate dependent	

Table 1. Specifications for the initial version of the microinstrumentation system.

Sensor Bus

GND: Ground	CLK: Clock
VDD: Power	CIN: Serial Input
VR: 5V Ref.	DV: Data Valid
CE: Chip Enable	DO: Data Out
STR: Strobe	

Serial Data (CIN) Format

Chip Address   Element Address Command

Extended Data   Write Data
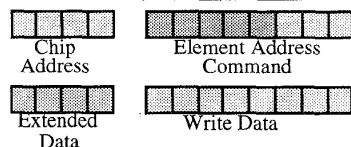
Command Codes

R/W	C1	C0	Input Command (CIN)
0	X	X	Read Element
1	0	0	Write Data, 8bits
1	0	1	Write Data, 12bits
1	1	0	Special
1	1	1	Write to 4b Register

Figure 2: The intramodule sensor bus, serial data format, and command format used in the microsystem.

To interface between the front-end transducers and the bus, a standardized interface chip, shown in Figure 3, has been designed. This interface chip contains switched-capacitor readout circuitry [3] for up to six capacitive sensors with digitally programmable gain and reference capacitance values along with all bus interface circuitry and an on-chip temperature sensor. A photograph of the 2.2mm x 2.2mm 2μm p-well 2M/2P CMOS chip is shown in Figure 4.

The sensor data received during each front-end scan is stored in the MCU's RAM and is output when the data buffer is full. Before being stored, the data is calibrated and digitally compensated for cross-parameter sensitivities (e.g. temperature dependence). Digital compensation algorithms vary depending on each sensor's response but have been

chosen to minimize processing time, power consumption, and MCU memory. The compensation methods currently employed are look-up tables and polynomial evaluation [4].
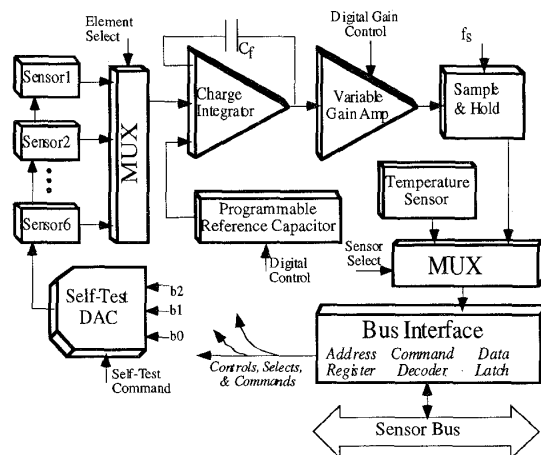
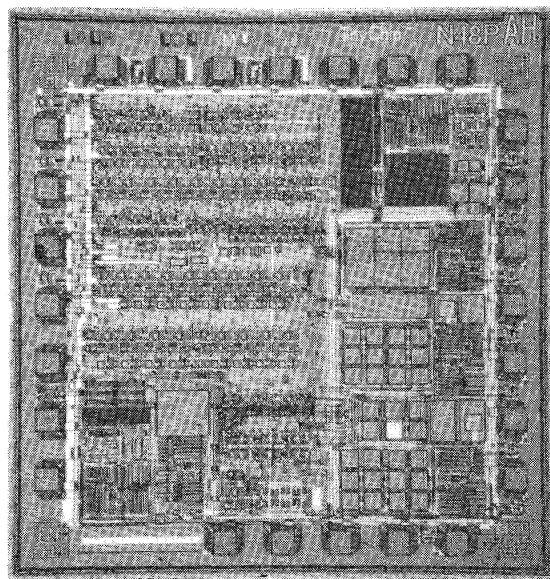Figure 3: Block diagram of the capacitive sensor interface chip.

Figure 4: Integrated CMOS capacitive sensor interface chip for a standardized intramodule sensor bus.

I/O METHODS

The system offers both a hardwired external port and a wireless link. Included in the eight-line hardwired bus are power and ground, four advanced feature selects (e.g. programming toggles), and two lines for asynchronous serial RS-232 communications. For normal data transfer operations this bus can be reduced to four lines. The

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telemetry device on the microsystem is a commercially available 315MHz amplitude modulating transmitter (HX1005; RFM, Inc.) driven at a 3KHz bit rate. This device operates from a 3V supply and requires an average current of 4mA. With a superheterodyne receiver and a one inch loop antenna, a range of over 100 feet has been observed. The message format for wireless transmission consists of eight data bits preceded by a start bit and followed by a parity bit and a stop bit. Additional error checking is handled by software at the receiver end, and some data compression is performed in-module by the MCU. Future additions to the microsystem will include a 2.4GHz link using a micromachined antenna structure expected to produce a range of several thousand feet.

POWER MANAGEMENT

The microinstrumentation system can be powered though the wired I/O port or, as many applications demand, can operate as a wireless, battery-powered system using two 3V, 500mA-hr Lithium batteries. To control power consumption and maximize the life of the battery-powered microsystem, a power management (PM) chip has been designed. Figure 5 shows a block diagram of this chip, which has been fabricated using the same technology as the interface chip above. The primary function of the PM chip is to control and monitor system functions between sensor scans when the MCU goes into a low-power sleep mode and power is removed from all unnecessary components. The duration of this interval is programmed by a 4b coded input from the MCU and can range from 40 seconds to 8 minutes. The MCU adaptively adjusts this interval based on the amount of variation in the sensed parameters. An on-board PM clock generator and counter provide the timing functions that wake the system from its sleep mode. This chip also includes integrated switches for shutting off the voltage reference and the telemetry device. The PM chip also contains circuitry for converting the telemetry data to the necessary 3V level and provides pull-ups at the appropriate MCU inputs.

During the sleep period, only the MCU (in sleep mode), the power management chip, and a threshold accelerometer interface chip remain powered, keeping the continuous power dissipation under 400μW. The threshold accelerometer is a device with three cantilever beam switches that can interrupt the MCU and wake the system from its sleep mode for an event-triggered response. The interface circuit for this device can be programmed to generate interrupts at three different thresholds depending on the environment of the system. The thresholds are 1.5g, 10g, and 100g. The addition of this device to the system allows slowly-changing environmental variables to be scanned at a wide time interval while continuously (and autonomously) monitoring higher-frequency vibration activity. The combination of these functions allows the microsystem to operate using 700μW at the maximum scan frequency, providing a battery-powered lifetime of about 180 days.
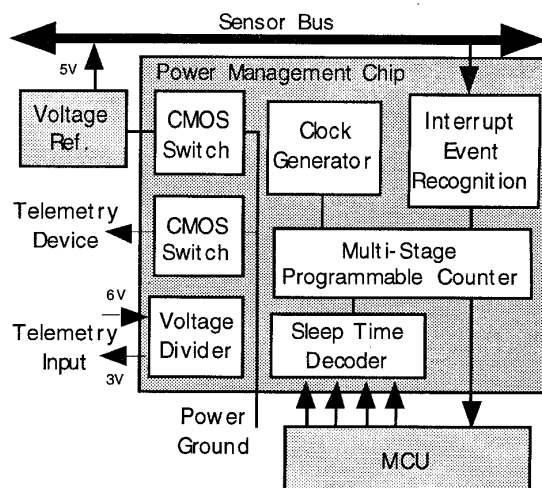

Figure 5: Block diagram of the power management chip and its connections to the system.

SENSORS FOR ENVIRONMENTAL MONITORING

The initial microsystem contains sensors for measuring temperature, barometric pressure, altitude, humidity, and acceleration with the specifications given in Table 1. The temperature sensor, integrated on the sensor bus interface chip, is a simple temperature-dependent oscillator, although a bandgap sensor is being developed for future versions of the system. For barometric pressure, a multi-element, thin-diaphragm, micromachined, capacitive pressure transducer [5] is used. While one diaphragm measures pressure over the entire measurement range, the other elements measure segments of that range with much greater resolution (equivalent to changes in altitude of approximately one foot at sea level). Humidity is measured by a high aspect ratio inter-digitated hygrometer. This capacitive transducer utilizes micromolding [6] and electroplating to form electrodes that are separated by a polymer (e.g., DuPont PI2723) having a moisture-sensitive dielectric constant. Acceleration is measured by a bulk-silicon capacitive microaccelerometer with overrange protection and force feedback electrodes [7]. This device has a bandwidth of 75Hz using a bridge structure with four folded beam supports. Many of these transducers have utilized optimal design of experiments [8] for calibration and testing. Future versions of the system will add sensors for gas type, gas purity, and acoustic inputs, as well as a link for global position sensing. Thus, the device will be able to monitor many aspects of its environment and its position within that environment.

PACKAGING

A major requirement of this system is that it be very small and still compatible with a variety of sensor technologies. The packaging scheme must permit selective environmental access for those sensors requiring

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it and should permit repair or replacement of defective chips during test. In the initial version of the microinstrumentation system, a three-level printed circuit board (PCB) has been used to integrate the hybrid system components. The layout of the PCB is drawn actual size in Figure 6. This "card-like" packaging structure provides access to all system components during testing yet still achieves a volume less than 12cc with two coin cell batteries attached below the board. An o-ring attached to the package lid seals most of the system components from the external environment while still allowing access to the required transducers.
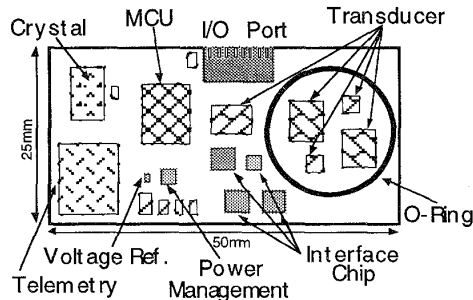

Figure 6: Actual size layout of the printed circuit board version of the system packaging.

An additional package that has been developed to further reduce the system volume is shown in Figure 7 and consists of several micromachined silicon platforms connected by gold-plated silicon ribbon cables. The platforms include sites for a number of sensing chips and, when folded, form three levels: one for the MCU and other system electronics, one for sensors that do not require environmental access, and a final level for sensors that do. The system is populated as desired, tested, and then folded into the required package shape which provides room for large components such as the crystal. The use of silicon platforms allows high-density interconnects, a low-resistance ground plane under the components, the possibility of in-platform switching/buffering, and compatibility with micromachined antenna structures. Figure 8 shows a prototype platform assembly before it is folded into a 5cc wristwatch-size cavity.
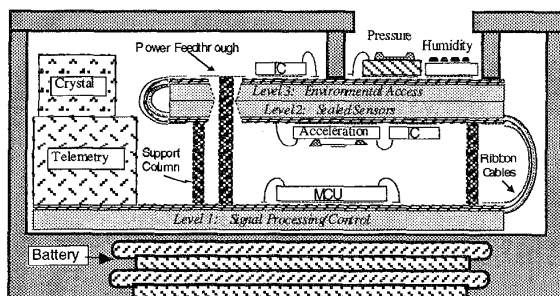

Figure 7: Three-level folding-platform packaging using micromachined silicon platforms and ribbon cables.
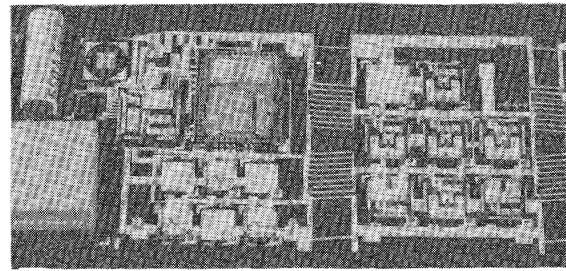

Figure 8: Prototype microinstrumtation system using a silicon micromachined platform assembly.

ACKNOWLEDGMENT

REFERENCES

1. K. D. Wise, "Integrated Microinstrumentation Systems: Smart Peripherals for Distributed Sensing and Control," *Digest IEEE Int. Solid-State Circuits Conf.*, pp. 126-127, February 1993.
2. N. Najafi and K. D. Wise, "An Organization and Interface for Sensor-Driven Semiconductor Process Control Systems," *IEEE Journal of Semiconductor Manufacturing*, pp. 230-238, November 1990.
3. Y. Park and K. Wise, "An MOS Switched-Capacitor Readout Circuit for Capacitive Pressure Sensors," *Proc. IEEE Custom Circuit Conf.*, May 1983, pp. 380-384.
4. S. B. Crary, W. G. Baer, J. C. Cowles, and K. D. Wise, "Digital Compensation of High-performance Silicon Pressure Transducers," *Sensors and Actuators*, A21-A23, 1990, pp. 70-72.
5. Y. Zhang and K. D. Wise, "A High-Accuracy Multi-Element Silicon Barometric Pressure Sensor," *Digest Transducers '95*, Stockholm, June 1995.
6. A. B. Frazier and M. G. Allen, "Metallic Microstructures Fabricated Using Photosensitive Polyimide Electroplating Molds," *IEEE J. Microelectromech. Systems*, 2, pp. 87-94, 1993.
7. K. J. Ma, N. Yazdi and K. Najafi, "A Bulk-Silicon Capacitive Microaccelerometer with Built-in Overrange and Force Feedback Electrodes," *Digest, IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, pp. 160-163, June 1994.
8. S. B. Crary, "Reducing Sensor Calibration Expense using Optimal Design of Experiments," *Proceedings of the Ninth Annual Conference and Exposition of Sensors and Systems*, Cleveland, OH, pp. 475-484, September 1994.

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