A MICROINSTRUMENTATION SYSTEM FOR REMOTE ENVIRONMENTAL MONITORING

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ABSTRACT

This paper reports a hybrid micro-instrumentation 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, nine-line intramodule sensor bus and outputs data over a hardwired serial interface or a 315MHz wireless link. The use of folding platform packaging 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 process 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. The microsystem is implemented in a hybrid fashion as shown in Figure 1. This architecture allows the process technologies for each of the sensing elements and circuit components to be individually optimized and allows high precision sensors to be fabricated without unduly complicating the production of the integrated circuits. Additionally, a hybrid implementation allows commercial components to be used and individual elements to be updated without modifying the entire system.
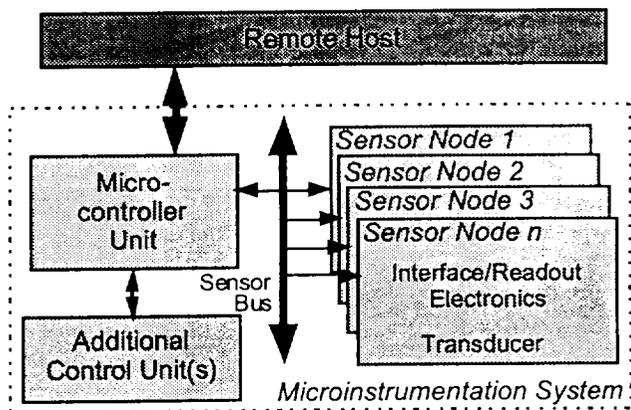

Figure 1: Hybrid system architecture for a microinstrumentation system.

SYSTEM DEFINITION

Based on the generic microinstrumentation system architecture shown in Figure 1, a multi-element sensing system has been developed. A block diagram of the system is shown in Figure 2, and specifications for the prototype system implementation are listed in Table 1. The microsystem is built around an embedded Motorola 68HC11 microcontroller unit (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 a hardwired RS-232 I/O port or via an on-board telemetry device. A custom power management chip performs several functions for minimizing power consumption in the battery powered system. The system employs an open architecture that permits it to be populated as desired by transducers using a mix of technologies. Transducers for measuring barometric pressure, altitude, humidity, temperature, and acceleration are included in the initial system.
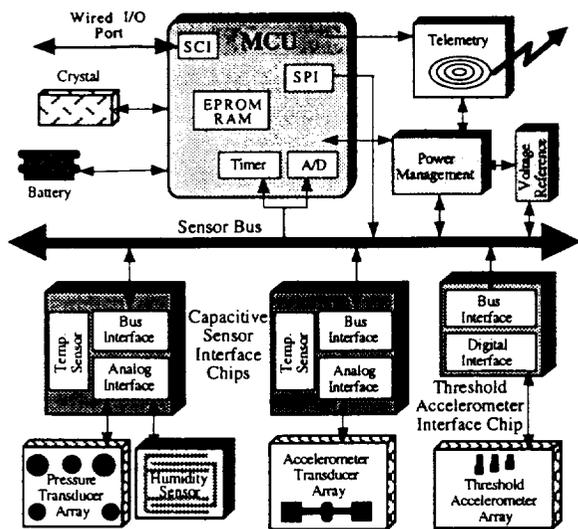
Figure 2: Block diagram of the
microinstrumentation system.

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

Parameter	Typical Value
Power Supply	6V, External or Battery
Ave. Power Dissipation*	400-700µW
Lifetime (with battery)*	330-180 Days
Package Configuration	Card or Wristwatch
System Volume	5cc (wristwatch structure)
Packaged Volume	25cc (card structure)
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	

During normal operation the system runs in a periodic scan mode in which data is collected from each sensing element and stored in the MCU's RAM. Each transducer has a block of code in the MCU which contains information regarding the sensor characteristics, self-test procedures, etc. Floating point software routines allow the sensors to be calibrated and digitally compensated for cross-parameter sensitivities (e.g., temperature dependence) in-module before the data is delivered to a remote host for further analysis. Digital compensation algorithms vary depending on the sensor 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 [2].

Each sensor scan is followed by a sleep period in which the system enters a low power mode. The duration of this sleep period is determined adaptively based on the variation in the sensed parameters with previous measurements. At the end of the sleep period the system is awakened and the cycle starts again with another sensor scan.

INTERFACING TO THE SENSOR BUS

During each sensor scan the MCU communicates with the front-end devices over an intramodule sensor bus described in Figure 3. The sensor bus [3] 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 3 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 bits, and up to 12b of input data. This format allows each microsystem to access up to 16 interface chips which can, in turn, service up to 32 sensors and 32 actuators.

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

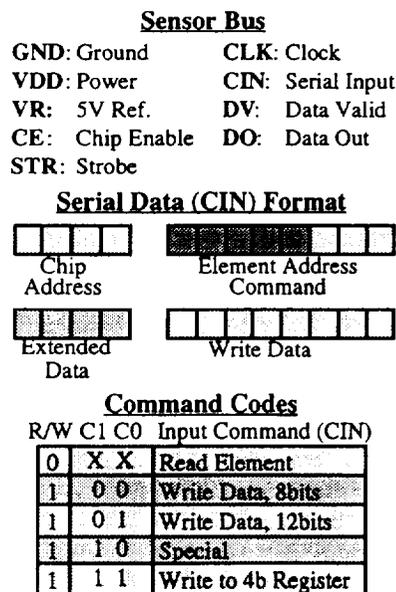| R/W	C1	C0	Input Command (CIN)
0	X	X	Read Element
1	0	0	Write Data, 8bits
1	0	1	Write Data, 12bits
1	1	0	Special
1	1	1	Write to 4b Register

Figure 3: 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 4, has been designed. This interface chip contains switched-capacitor readout circuitry [4] for up to six capacitive sensors with digitally programmable gain and three digitally selected reference capacitors that can be laser trimmed. The chip also contains all bus interface circuitry, a 3b
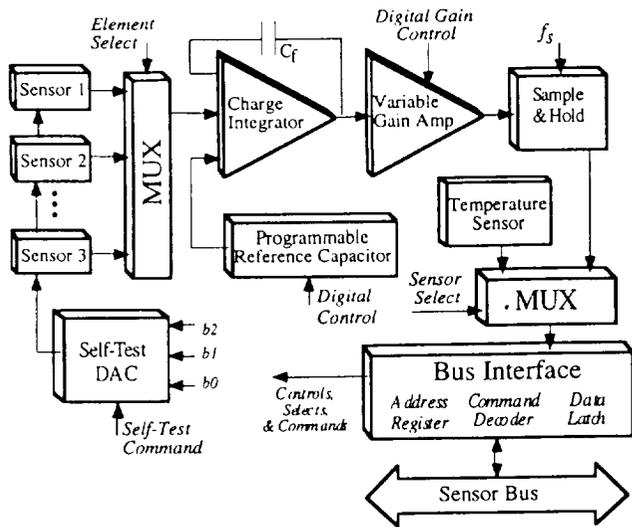
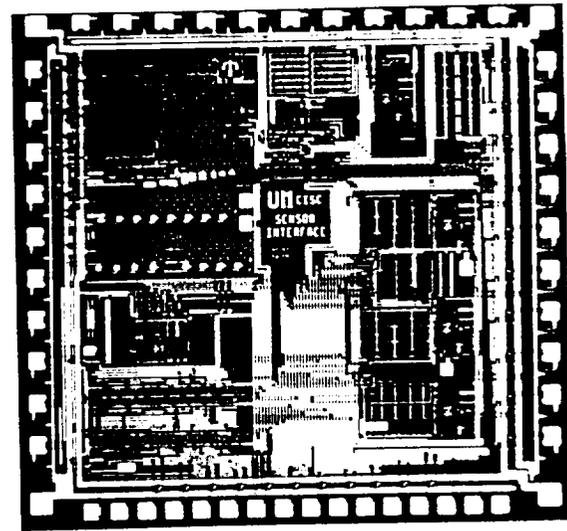Figure 4: Block diagram of the capacitive sensor interface chip.

Figure 5: Integrated CMOS capacitive sensor interface chip for a standardized intramodule sensor bus.

DAC for sensor self-test, and an on-chip temperature sensor. A photograph of the 3.2mm x 3.2mm 3μm p-well 1M/2P CMOS chip is shown in Figure 5. The sensor interface chip operates from a 5V supply at about 400μA.

SENSORS FOR ENVIRONMENTAL MONITORING

The sensors in the initial system and their specifications are listed 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 a global positioning system (GPS). Thus,

the device will be able to monitor many aspects of its environment and its position within that environment.

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, 270mA-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 6 shows a block diagram of this 2.2mm x 2.2mm chip 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 many system 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-chip clock generator and counter provide the PM 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 micromachined device with three cantilever beams that act as switches measuring accelerationat three different thresholds (1.5g, 10g, and 100g). These switches feed to a 2.2mm x 2.2mm threshold accelerometer interface chip formed in 3μm p-well 1M/2P CMOS technology . This chip is programmed by the MCU through the sensor bus to monitor one of the threshold values, latch results, and wake ·the system from its sleep mode for an event-triggered response. The addition of this device to thesystem 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 enables the microsystem to operate using 700μW at the maximum scan frequency, providing a battery-powered lifetime of about 180 days.
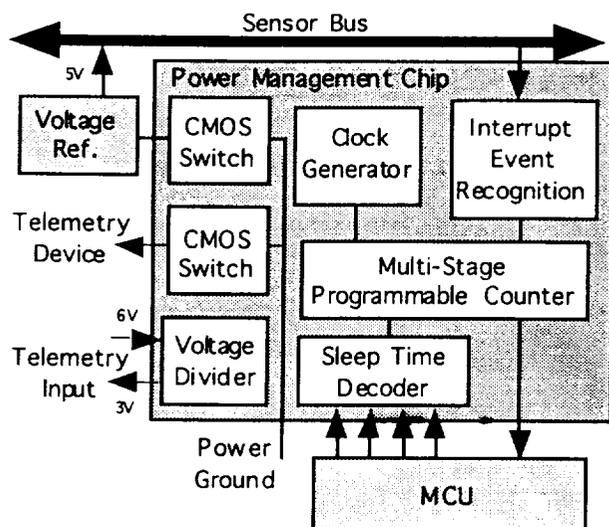

Figure 6: Block diagram of the power management chip and its connections to the system.

EXTERNAL I/O

The system offers both a hardwired external port and a wireless link. Included in the eight-line hardwired bus are power and ground, two lines for asynchronous serial RS-232 communications, and four advanced feature selects (e.g., programming toggles). For normal data transfer operations this bus can be reduced to four lines. The 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. The transmitter is active only in battery powered operation where its 3V supply can be tapped off the center contact of thetwo series 3V batteries. 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 precededby 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-moduleby 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.

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 it and should permit repair or replacementof 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. Figure 7 shows a microinstrumentation cluster populating the 65mm x 35mm PCB which provides access to all system components during testing. This "card-like" packaging structure with two coin cell batteries attached below the board is placed into the cavity of an anodized aluminum outer case. The case has an external volume of approximately 25cc and provides battery access from the back. An O-ring, seated between the PCB and the outer case, seals the system components from the external environment while providing access to the humidity and pressure transducers. The transmitter's loop antenna is wrapped into a groove on the perimeter of the case.
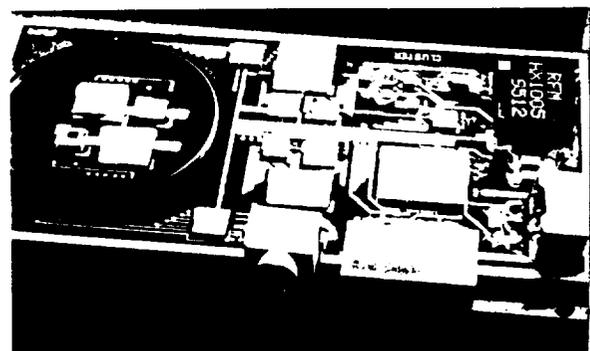

Figure 7: Complete microinstrumentation system mounted on the printed circuit board version of the system packaging.

An additional package that has been developed to further reduce the system volume is shown in Figure 8 and consists of several micromachined silicon platforms connected by gold-plated silicon ribbon cables [9]. The platforms include sites fora
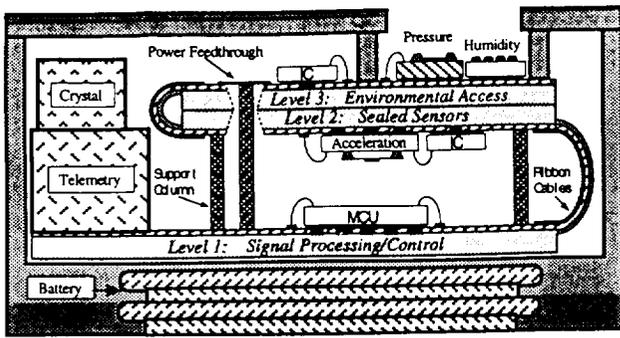
Figure 8: Three-level folding-platform packaging using micromachined silicon platforms and ribbon cables.

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 transmitter and 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 9 shows a prototype platform assembly before it is folded into a 5cc wristwatch-size cavity.
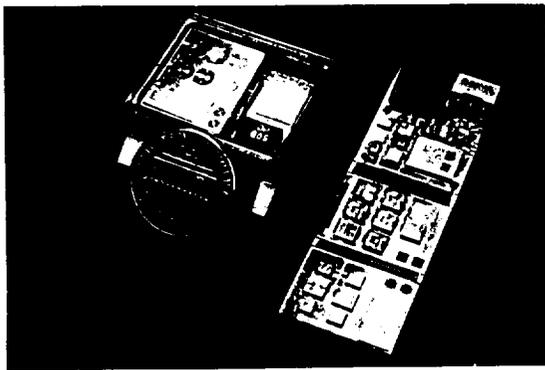

Figure 9: Prototype microinstrumentation system using a silicon micromachined platform assembly.

CONCLUSIONS

A generic structure for a multi-element sensing system has been developed and applied to a specific microinstrumentation system for environmental monitoring. Transducers for pressure, humidity, temperature, and acceleration are present in this system along with a microcontroller for in-module sensor calibration, digital compensation, and system control. A

standardized intramodule sensor bus is used along with interface/readout circuitry that links the transducers to the embedded microcontroller. A custom circuit provides additional power management control permitting the system to operate up to 330 days at 400μW (average) from a 6V battery supply while communicating with a remote host through a wireless transmitter that provides a range greater than 100 ft. Both printed circuit board and micromachined silicon platform structures have been developed for system packaging.

ACKNOWLEDGMENT

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