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A Modular Sensor Microsystem Utilizing a Universal Interface Circuit

A. Mason[1], N. Yazdi [2], J. Zhang [1], and Z. Sainudeen [2]

[1] Michigan State University, Dept. of Electrical and Computer Engineering, East Lansing, MI 48824

[2] Formerly with: Arizona State University, Dept. of Electrical Engineering, Tempe, AZ 85287
Currently with: Corning IntelliSense, 36 Jonspin Rd., Wilmington, MA 01887

ABSTRACT

The performance features of MEMS transducers allow the development of a new class of small, low-power sensor microsystems which utilize a suite of sensors to support a wide range of applications. This paper presents a system-level framework for constructing such microsystems where system modularity for application adaptability is a primary design consideration. System architecture, communication protocols, modular packaging, and interface electronics are discussed in general terms, and an implementation of these concepts is presented. Key requirements for microsystem modularity, such as a communication bus and a universal microsensor interface circuit which support plug-n-play operation for online reconfiguration, are developed and presented in this paper.

1. INTRODUCTION

Recent advances in the integration of solid-state devices on a chip continue to drive the on-going revolution in computing and communications. Today monolithic memories capable of storing over one billion bits and microprocessors operating in excess of 1000 MIPS are a reality. Nevertheless, in numerous applications including industrial automation, condition-based monitoring, health care, defense systems and consumer products, microelectronics are required to interface to a non-electronic world [1]. While MEMS technology has enabled fabrication of miniature, low-cost, lightweight, and low-power microsensors, *sensor microsystems* fulfill the application domain needs by combining microsensors and integrated circuits to deliver useful information to the user or host system. To enable the widespread availability of sensor microsystem components, which will allow them to be developed for applications outside of the niche markets they currently inhabit, modular microsystem frameworks are necessary. Most of the microsystem efforts published over the past decade have focused on smart sensor nodes with fixed capabilities and system architectures that require significant communication and signal processing capability within each sensor node [2,3]. These approaches are not appropriate for systems that support a network of microsystems, each of which contains a modular, adaptive, network of sensor nodes. This paper reports a new generation of a multi-node microsystem that is based on a previous wireless multi-element microinstrument for environmental monitoring [4]. The new microsystem provides improved modularity and application adaptability through enhanced architecture and communication protocols and a more flexible sensor interface circuit.

Each component of this sensor microsystem is an autonomous module, and the task of each component is defined by the modular architecture shown in Fig. 1. Standard interfaces are used to accommodate various modules. Thus, each microsystem can be built to suit a specific application. One of the distinct features of this sensor microsystem is support of self-configuring interchange of component modules that is referred to as "plug-n-play". In order to implement the plug-n-play feature, each module must be capable of communicating with and being programmed by the microsystem central control electronics. A universal interface circuit has been developed to provide a critical link for communication and intelligent interaction between the sensors and the central processor. The interface chip contains all necessary reference, readout, control, and communication circuitry to interface a range of capacitive, resistive, voltage, or digital output devices to system control electronics. The following sections discuss the microsystem architecture and a sensor communication bus, plug-n-play support and a modular packaging concept, and the universal interface circuit.

2. MICROSYSTEM MODULARITY

2.1 System Architecture

The architecture shown in Fig. 1 is optimized for sensor microsystems in the regime of applications which require a multi-parameter network of sensors operating with low-power within a physically small system. It also provides a highly modular framework with components that can be easily interchanged to meet a wide range of application-specific demands. The central control electronics manages microsystem operation, perform sensor signal processing including calibration and compensation, interface to front-end sensors and external systems, and implement system-level power management. These functions can be implemented using a commercial low power microcontroller, typically with 8b or 16b processor. A low power DSP could be used in application with high signal processing demands. The system bus allows a widely distributed network of microsystems to be implemented via wireless or hardwired interfaces. It also provides a standard interface to

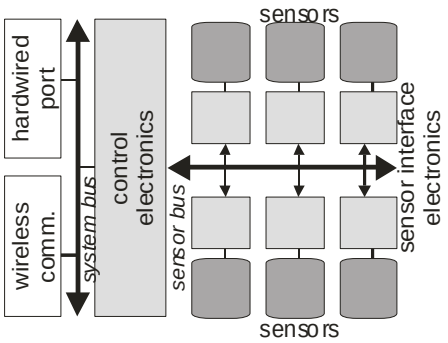

Fig. 1. Block diagram of a modular sensor microsystem.

application-specific components, such as a satellite communication link. The sensor bus provides a standard for intramodule communication to link the network of sensor (or actuator) nodes to the microsystem controller. It includes capabilities for power management and plug-n-play that can optionally be implemented in a microsystem with some software and hardware overhead. Each sensor module must be capable of interfacing to the sensor bus to receive commands from the control electronics, upload sensor parameters, and deliver sensor data to the microsystem controller. A generic interface chip, which would be included within each sensor module to allow a variety of transducers to be connected to the sensor bus, is cost effective, very useful in this architecture and simplifies the construction of microsystems for many applications.

2.2 Sensor Bus for Network Communication

A variety of sensors busses have been used to interface sensors with microcontrollers, including the IEEE P1451.2 standard. Several sensor busses are discussed and compared in [5], including the Intramodule Multielement Microsensor (IM^2) bus which was specifically designed to complement the microsystem architecture shown in Fig. 1. Key requirements for a sensor bus in modular low-power multi-sensor microsystems include a physical bus which allows plug-n-play configuration, minimizes hardware overhead, and supports power management features such as interrupt generation and multiple power supply signals. The sensor bus protocols are required to support a network of programmable front-end sensors that can upload configuration data which is vital to support plug-n-play modularity of the microsystem. These features are available in the IM^2 bus that has been implemented in the interface circuit discussed below.

2.3 Plug-n-Play Operation

Plug-n-play operation can decrease the complexity of setting up a sensor network and has often been employed at the system level to connect several microsystems. This concept can be extended to provide modularity *within* microsystems and allow the individual sensors in each microsystem to be added/removed as applications demand. However, implementing plug-n-play within a microsystem introduces a different set of requirements due to the power limitations and minimal processing capability of each sensor node.

Within a multi-sensor microsystem, the plug-n-play feature enables addition or removal of a sensor module during a system power-down and automatic reconfiguring of the system at power-up, where changes to sensor front-end are recognized and sensor parameters are uploaded from the new sensor modules. Plug-n-play is highly effective and significantly reduces the development complexity of sensor microsystem, since it allows the microsystem components to be developed individually and automatically configured for application-specific use. This feature is implemented by: control software which manages data exchange with new nodes; control hardware which implements sensor bus protocols to identify changes in the front-end network; protocols which allow the sensor bus to be polled or interrupted for new devices; and sensor interface electronics which can set interrupts for new device and upload node parameters to the microsystem controller. Thus, it is a feature that impacts the design of many microsystem components.

2.4 Packaging

Modularity must be maintained in the system packaging in order to receive the full benefit of modular architecture and communication protocols. In a sensor-based microsystem, the compact package must provide structural support and overall protection from the environment while exposing selective sensors to the parameters being measured. Figure 2 shows a packaging concept which achieves these goals. The high density package employs three distinct planes for the battery pack, control electronics, and sensor modules, organized to accommodate physically taller components like a wireless transceiver. The control electronics module and the sensor modules are individually hybrid packaged multi-chip modules containing ICs, surface mount passive components, and high density connectors integrated into the package substrates. As shown in Fig. 2, a typical sensor module consists of transducer and interface circuit chips and a memory chip to implement plug-n-play operation. This scheme allows compact microsystem construction with easy access to exchange the modular sensor nodes. Furthermore, it allows needs such as environmental access to be addressed individually, independent from neighboring modules.

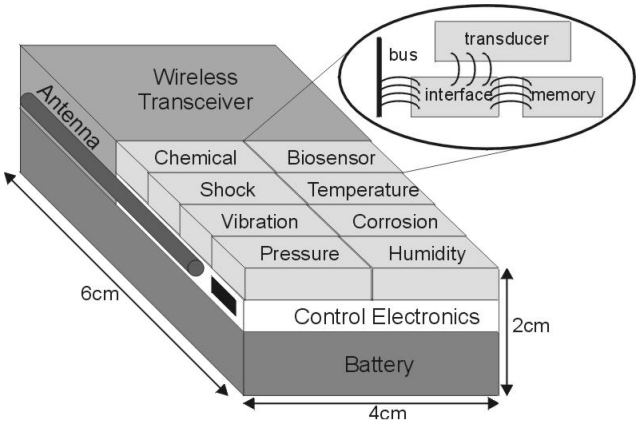

Fig. 2: A compact modular microsystem packaging scheme showing sensor module components and microsystem module arrangement.

3. SENSOR INTERFACE

3.1 Circuit Overview

The Universal Microsensor Interface (UMSI) circuit has been developed to support the features discussed above and link a network of low-level signal output transducers to microsystem control electronics. Based on past developments of sensor interface electronics [6-8], the UMSI chip (Fig. 3) includes digital communication interfaces and analog sensor readout interfaces combined on a highly programmable, all-inclusive circuit.

3.2 Digital Interface

The digital I/O blocks of the UMSI chip include a multi-node sensor bus interface to a microcontroller that is fully hardware compatible with the IEEE P1451.2 standard, a Serial Peripheral Interface (SPI) with a 4b chip select for communication with optional external components, a bi-directional 8b digital I/O port,

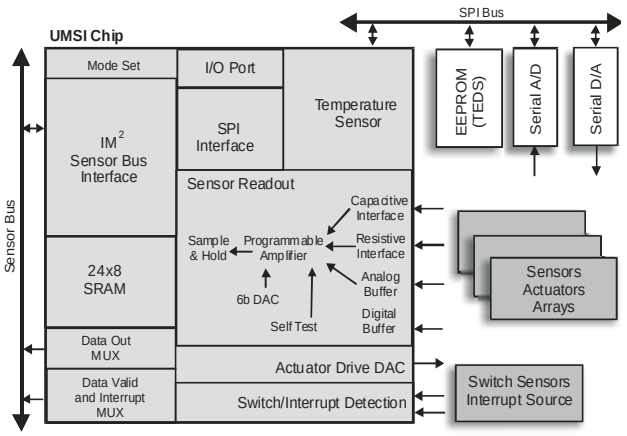

Fig. 3. Block diagram of the UMSI chip.

and an 8-input switch-detection interrupt generation circuit. The circuit implements several addressing modes including single node, 4b or 8b node address, and broadcast. The chip address can be hard-coded via wire bonds or downloaded from external memory through the SPI interface. The UMSI chip may be setup by the host with configuration data that is stored in on-chip RAM. It supports the Transducer Electronic Data Sheet (TEDS) feature of the IEEE P1451.2 standard via an external EEPROM which is accessed through the SPI interface to enable plug-n-play operation and the upload of sensor parameters (e.g., gain/offset values and calibration coefficients).

3.3 Analog Interface

The analog blocks, as shown in Fig. 4 include a switched capacitor circuit with programmable on-chip reference element for capacitive sensor readout, a resistive input readout amplifier configurable for single input or two-input bridge (with on-chip reference resistor) operation, and a voltage buffer/attenuator amplifier. Each of these three readout blocks is connected to a second-stage programmable gain amplifier and a third-stage sample and hold circuit. The chip also includes a 6b DAC for programmable reference voltage at the gain stage, an internal 1.5V reference, and a 6b DAC for actuator control and readout self test. Details of the programmability of the circuit are shown in Table 1. The analog block utilizes multiple power supplies to minimize power consumption by activating only the circuitry needed for a given application. The highly programmable circuits are controlled by data downloaded through the sensor bus and stored in an on-chip 24-byte SRAM.

Through an 8-to-4 analog signal router, the chip can interface with up to 8 sensors that are capacitive and/or resistive and/or voltage-output. A 5b sensor mode register in SRAM determines the type of sensor and which channel is selected. The capacitive readout circuit uses a switched-capacitor charge integrator at the front-end to generate an output voltage proportional to the difference between an off-chip capacitive sensor and an on-chip programmable reference capacitor. The resistive sensor readout interfaces with a resistive sensor half or full bridge, and provides an output corresponding to the bridge resistor change. The voltage-output readout provides control over the signal range/sensitivity by attenuating the input voltage and feeding it to the programmable gain amplifier stage. Three outputs of these readout circuits go into a 4-to-1 multiplexer with a self-test signal. One of them is selected and amplified by the gain stage with programmable sensitivity. Finally, the output of the gain stage is stored on a capacitor in the sample and hold stage.

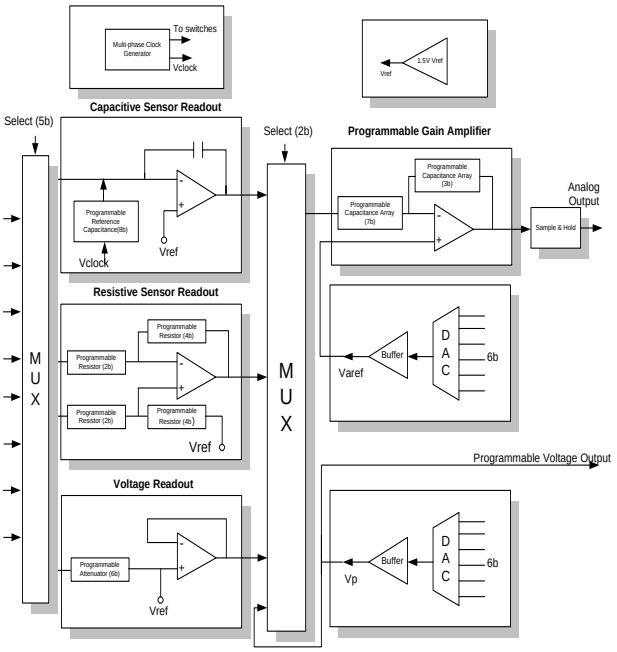

Fig. 4. Block diagram of the analog interface.

Table 1. Programmable features of the UMSI chip.

Features of the UMSI	**Signals/Bits**
Bus Address Modes	single, multi, broadcast
Chip (bus node) ID	4b or 8b
Chip ID Setting	hardwired or external memory
On-chip RAM	24x8b
Bi-directional Digital I/O	8b
SPI Bus Interface	4b chip select
Digital Switch Detection/Interrupt	8b
Analog Inputs	8-to-4 signal router
Analog Output	6b DAC
Gain Amp: gain control	8b (range: 0.03-31.75V/V)
Gain Amp: ref. Voltage control	6b DAC
Gain Amp: self-test input	6b DAC
Capacitive Amp: offset control	8b, 50 fF – 6.4 pF
Resistive Amp: reference	6b, 3.75 kΩ – 30 kΩ
Resistive Amp: feedback	6b, 3.75 kΩ – 30 kΩ
Voltage Buffer: attenuator	6b, (range: 0.125 – 0.875V/V)
Resolution (Capacitive)	0.5mV/fF at gain = 1
Resolution (Resistive)	0.44mV/Ω at gain = 1
Power Dissipation	20 uW to 13.5mW
Temperature Sensor Control	12b

3.4 Results

The chip, shown in Fig. 5, has been realized in the AMI 0.5µm CMOS process with a 5 mm^2 die size. Test results show the chip to be functional, well matched to simulations, and within design specifications. To test the sensor bus communication functions, data was sent from a microcontroller to the UMSI chip and read back out by the controller. Fig. 6 shows the output of the UMSI chip for write and read memory commands. Fig. 7 is the sample-and-hold output response to a low-frequency large-signal sinusoidal input when the gain stage is programmed to 0.8 V/V.

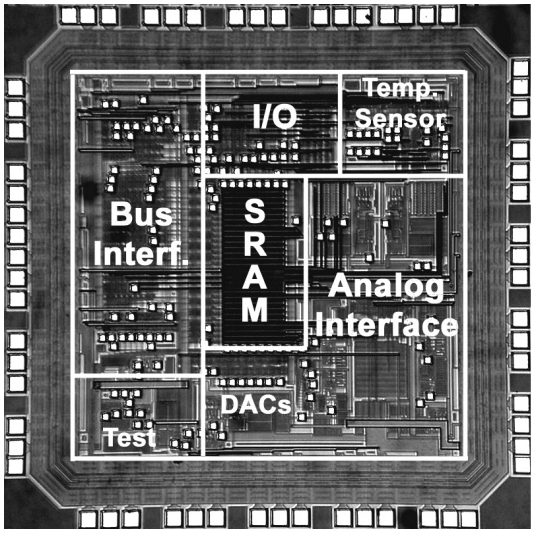

Fig. 5. Die photograph of UMSI chip.

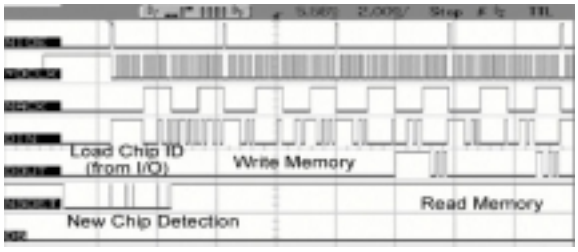

Fig. 6. UMSI output for write and read commands.

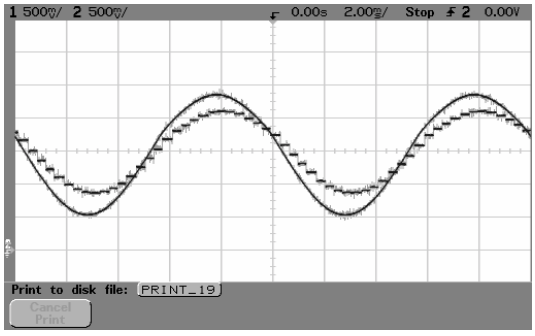

Fig. 7. The analog sample and hold output with a sinusoidal input and the gain stage programmed to 0.8 V/V.

4. CONCLUSIONS

In this paper a system-level framework for a highly modular and application-adaptable sensor microsystem was presented. Furthermore the system architecture, communication protocol, modular packaging, and interface electronics are discussed in general terms, and an implementation of these concepts is presented. A Universal Micro-Sensor Interface (UMSI) circuit developed for the microsystem implementation was also presented. The UMSI chip contains several programmable analog readout circuits capable of interfacing with a variety of sensors. The integrated digital I/O blocks include a multi-node sensor bus interface, which is compatible with IEEE P1451.2 standard, a Serial Peripheral Interface with a 4b chip select for communication with optional external components, a bi-directional 8b digital I/O port, and an 8-input switch detection interrupt generation circuit. The circuit is fabricated in a foundry 3M 2P 0.5µm CMOS process. The die occupies 2.22mm x 2.22mm and draws 6.7 µA to 4 mA, (depending on configuration) from a 3V supply. Preliminary test results show the chip to be functional within design specifications.

5. ACKNOWLEDGMENTS

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