A SMART SENSING MICROSYSTEM WITH A CAPACITIVE SENSOR INTERFACE

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ABSTRACT

This paper describes a smart microsystem that utilizes a generic interface circuit capable of interfacing with a large variety of capacitive sensors. This wireless microsystem includes a microcontroller for signal processing, sensors that measure temperature, pressure, humidity, and acceleration, and a 315MHz transmitter for data output. An interface chip handles communication between the microcontroller and the sensors over a standard sensor bus and provides readout circuitry for the capacitive transducers. This interface circuit is highly programmable, can interface with up to six external sensors, supports sensor self-test, and includes three programmable internal reference capacitors in the range of 0.2-12pF and a temperature sensor. The chip dissipates less than 2.2mW from a single 5V supply and can resolve input capacitance variation better than 1fF.

1. INTRODUCTION

Recent advances in the development of integrated sensors and actuators have made realization of smart microsystems combining a large mix of microsensors, microactuators and signal processing circuitry possible and is going to have a significant impact on a variety of applications such as industrial process automation, health care, automotive industry, consumer electronics, and environmental monitoring [1]. Capacitive microsensors are very attractive for these microsystems due to their low power, high sensitivity, and self-test capabilities [2]. By integrating the intelligence of a microcontroller with these microsensors, measurements can be made with more accuracy and reliability, and signal processing can take place in-module. The critical link between the transducer and the microcontroller is provided by the interface circuit, which must be capable of reading out capacitive microsensors with a wide range of base capacitance and sensitivity. Hence, there is an increasing need for a low power generic interface for capacitive sensors in smart microsystems. Although there have been numerous readout circuits introduced for capacitive sensors [3-4], to date a generic interface is not reported. Such an interface circuit should be able to read out various capacitive microsensors with a wide range of base capacitance and sensitivity, handle communication with the main controller in the microsystem, support self-test and self-calibration, support multi-ranging for a single sensor, dissipate low power, not require external components and take small area. This paper presents a sensing microsystem utilizing such a capacitive interface circuit.

The following sections will focus on the components of the microsystem, including the interface chip and its functions. First the microsystem itself and its embedded sensors are described. Then, the standard sensor bus is briefly discussed followed by a description of the interface chip. Finally, measurement and test results are presented.

2. SYSTEM CONFIGURATION

The sensing microsystem integrates sensors for measuring a variety of environmental parameters, including barometric pressure, humidity, and acceleration, as shown in Fig. 1 [2]. The heart of the microsystem is a microcontroller unit (MCU) that provides the system intelligence and allows for data storage as well as software routines for each sensor to perform in-module sensor calibration, digital compensation, and self-test. The MCU communicates with the front-end transducers via a nine-line intramodule sensor bus and the sensor interface chip. The interface chip is a critical component of this overall system because it allows a standard microcontroller to communicate and collect data from a variety of sensors. Once sensor data has been collected and calibrated in-module it can be stored or sent out through either a hardwired serial I/O port or an on-board 315MHz wireless transmitter [2].
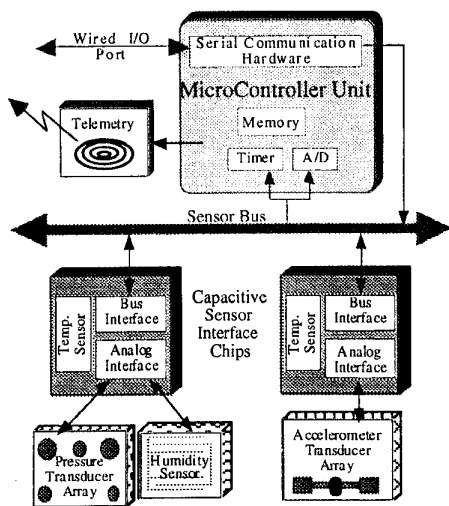
Fig. 1: Block diagram of a multi-parameter microsensing system.

The microsystem accommodates temperature, pressure, humidity, and acceleration sensors for environmental monitoring application. The temperature sensor is an oscillator with temperature-dependent frequency that has been integrated on the interface chips while the other devices are capacitive transducers formed on individual micromachined dies. For barometric pressure, a multi-element, thin-diaphragm pressure transducer [5] is used. While one sensor element measures pressure over the entire measurement range, the other elements measure segments of that range with a much greater resolution of 25mTorr from 600 to 800Torr. Figure 2 shows a photograph of the multi-element pressure sensor [5]. The base capacitance of the elements varies from 6 to 10pF, and each element has a full scale capacitance variation of about 1.5pF. Humidity is measured by a high aspect ratio inter-digitated hygrometer operating over 30 to 90%RH. This capacitive transducer has a base capacitance of about 12pF and full scale capacitance variation of 250fF. The sensor is fabricated using 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 quad crab-leg structure. The sensor has a base capacitance of about 0.8pF and sensitivity of 40fF/g over the range -2 to 2g. As it can be observed the base capacitance and sensitivity of the sensors vary over a wide range. The sensor interface chip has to measure the capacitance change of all of these sensors, and generate a voltage signal that can be transmitted to the MCU over the standard sensor bus. In the following, we
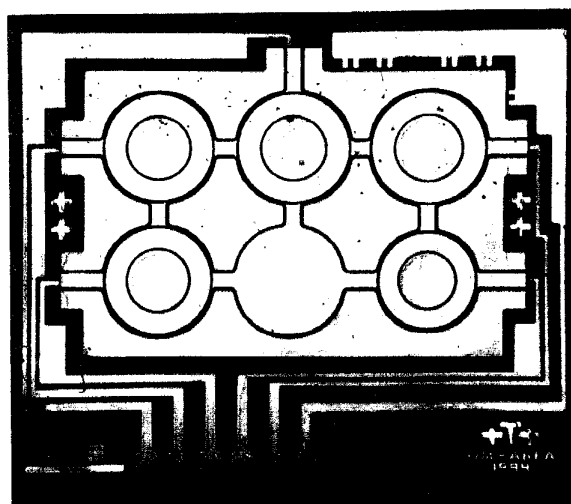

Fig. 2: Photograph of the multi-element pressure sensor[5]

will describe the standard sensor bus and the interface chip which provides the link between the MCU and the sensors.

3. STANDARD SENSOR BUS

In integrated microsystems it is desirable to interface with multiple sensors while using a minimum number of interconnects, yet provide a full range of functionality. For that purpose a standard sensor bus has been developed [2]. The sensor bus consists of nine lines as shown in Fig. 3, three for power, two handshaking lines used with a clock and serial data line for synchronous serial communication, a data output line and a data valid/interrupt signal. The three power leads are the system supply, VDD, ground reference, GND, and switched reference voltage, VR, which provides a separate power line for devices that can be turned off during a low-power sleep mode. For synchronous communication to front-end devices, chip enable, CE, and data strobe, STR, provide the handshaking used with a programmable frequency clock, CLK, and serial data line, CIN. The last two signals of the sensor bus are for data output, DO, which can be an analog level, frequency encoded or serial bit stream; and data valid, DV, which signals the MCU when valid data is present on the DO line. DV is also used as an interrupt from the front-end devices that can initiate an event triggered sensor readout.

The serial data format, shown in Fig. 3, includes a 4-bit chip address followed by a 5-bit sensor/actuator address, 3 command bits and up to 12 bits 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. The 3-bit command contains a read/write bit and
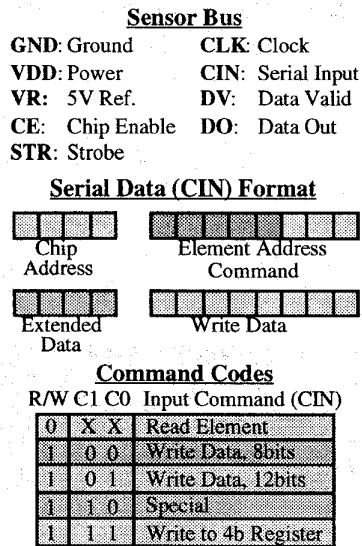
Sensor Bus

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

Fig. 3: Sensor bus signal lines, serial data format and command codes.

two bits to choose from four possible write instructions for a total of five command options.

4. INTERFACE CHIP

Figure 4 shows the block diagram of the interface chip. This circuit utilizes a low noise front-end charge integrator to read out the difference between a sense capacitance and a reference capacitor [4]. Communication with the MCU is performed over the sensor bus and is handled by the bus interface unit. Serial data transmitted over the bus is received, decoded and applied as control lines to other circuit blocks as illustrated in Fig. 4. The input multiplexer enables the chip to interface with up to six sensors. Furthermore, the chip can be digitally programmed to operate with one of three external/internal reference capacitors. The on-chip reference capacitors are laser trimmable in a range of 0.2pF to 12pF. Programmability of reference capacitors allows the chip to interface with various capacitive sensors with a wide range of base capacitance, and also provides offset control.

The chip analog signal path consists of an input multiplexer, the input charge integrator, a switched-capacitor gain stage, an output sample/hold circuit and an output multiplexer. The gain stage can be programmed on-line to any of its three gain settings. These gains can be used both for input sensors with different sensitivities and for multi-ranging of a single sensor, and are predetermined by laser trimming of on-chip capacitors. The overall readout sensitivity can be varied over a wide
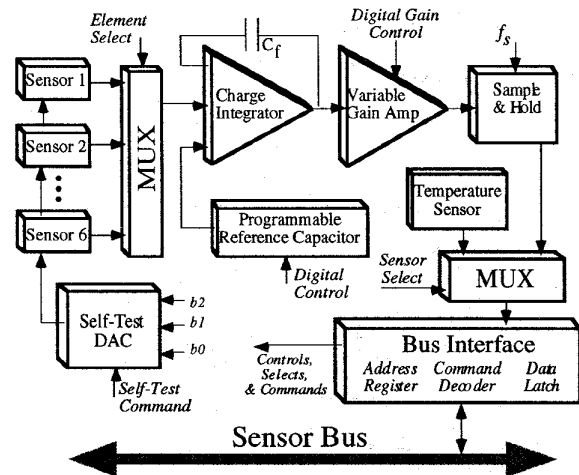

Fig. 4: Diagram of the capacitive sensor interface chip showing the major circuit blocks.

range of 0.15 mV/fF to 47.8 mV/fF using both digital programming and laser trimming, which translates to an effective gain variation of 1 to 312. The output multiplexer provides access to the sensor bus for both the capacitive readout circuitry and the on-chip temperature sensor. The interface chip additionally supports self-test and self-calibration. A 3-bit on-chip DAC can be utilized to generate a variable amplitude two-phase clock for driving the sense and reference capacitors in each input charge integration cycle. The self-test DAC consists of three switched current mirrors driving an on-chip poly resistor. The DAC output changes the amplitude of the clock when a control line is set. The variable amplitude clock can apply a varying electrostatic force to the sensor for self-test and self-calibration.

5. TEST RESULTS

The chip has been fabricated using a standard 3μm, single metal, double poly p-well CMOS process. Figure 5 shows a photograph of the chip, which measures 3.2mm x 3.2mm and dissipates less than 2.2mW from a single 5V supply. About 85% of the power dissipation is due to quiescent current of five OpAmps integrated on the chip. Table 1 summarizes the chip specifications. Test results have shown full circuit functionality with a resolution of input capacitance variation better than 1fF. Although sized dummy switches with their specific clock phases are used in the switched-capacitor circuit to compensate clock-feedthrough, the resolution is still limited by the clock switching noise rather than KT/C and folded flicker noise. Figure 6 shows the output of the charge integrator as the input sense capacitance is varied.

The microsystem has been implemented with an interface chip dedicated to the multi-element pressure sensor and humidity sensor, and another interface chip dedicated to the accelerometer. The system has been utilized successfully to measure the ambient pressure.

6. CONCLUSIONS

In this paper a smart microsystem with a generic interface circuit for capacitive sensors is presented. The readout chip can interface with a large variety of capacitive sensors, is highly programmable, supports communication over a standard sensor bus with a microcontroller, and supports self-test. The interface chip dissipates less than 2.2mW from a single 5V supply voltage and can resolve an input capacitance variation better than 1fF.

ACKNOWLEDGMENT

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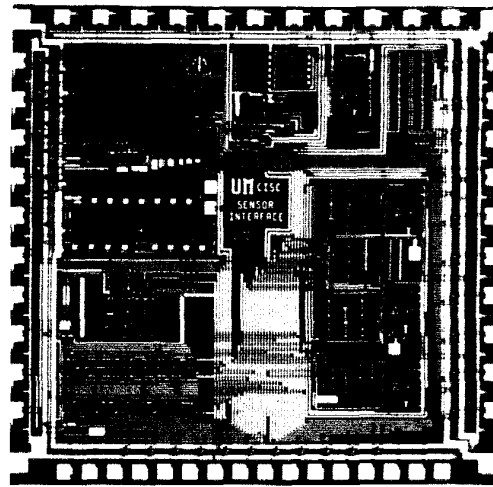*Sensor and Actuator Workshop*, Hilton Head, June 1994, pp. 160-163.

Fig. 5: Photograph of the capacitive interface chip.

Table 1: Summary of the interface chip specifications.

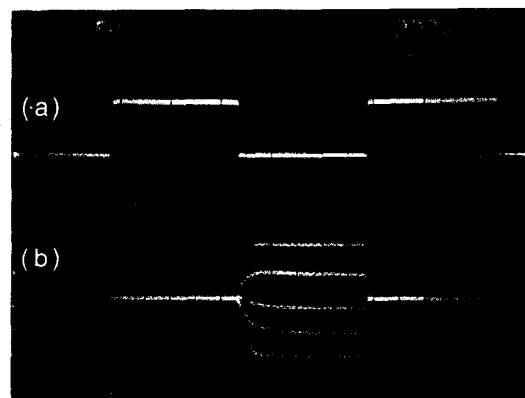| Number of sensing channels	6 Capacitive + Temperature
Reference capacitor channels	3 internal/external, Internal capacitor programmable 0.2pF-12pF
Chip address	4 bits
Sensitivity 1 [mV/fF]	0.15-14.7
Sensitivity 2 [mV/fF]	0.15-33.1
Sensitivity 3 [mV/fF]	0.31-47.8
Resolution	< 1fF input capacitance
DAC	3 bits for self-testing
Supply	Single 5V
Power dissipation	< 2.2 mW

Fig. 6: a) Reset control of the input charge integrator; b) Output of the charge integrator as the input capacitance changes.