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Wireless Ultra-Low Power Smart Data Acquisition System for Pressure Sensing in Medical Application

K. Arshak and E. Jafer

Abstract - The development of a wireless sensor micro-systems containing all the components of data acquisition system, such as sensors, signal-conditioning circuits, analog-digital converter, embedded microcontroller (MCU), and RF communication modules has become now the focus of attention in many biomedical applications.

This paper discusses innovation circuits and system techniques for building advanced smart medical devices (SMD). Low power consumption and high reliability are among the main criteria that must be given priority when designing such wirelessly powered Microsystems. Different capacitive readout circuits used for pressure sensing will be described. An example for a low power wireless system developed for multi-sensors monitoring will be presented.

I. INTRODUCTION

The need for patient remote monitoring is vital to measure some biological signals. Any mobile medical system should consist of three main modules, these are: non-invasive technique to measure biological signals without doctor interfere, wireless system for transmitting data captured, and a user interface software to enable data acquisition. Pressure sensor can be used in a wide range of medical invasive measuring, some of these are:

- Blood pressure
- Respiration rate
- Gastrointestinal (GI) activity

This paper will concentrate on different aspects of designing smart wireless sensing systems that can be used for monitoring the GI activity.

A. Smart wireless interfacing

Figure 1 illustrates the most straightforward method in capturing data and transmitting it to the monitoring site. A sensor is placed in a process environment to provide relevant information, with the sole intention of being able to control the process as accurately as desired. The sensor is coupled to a sequence of stages, which each play their proper role in signal handling and conditioning. The first part is the analogue sensor interface circuit, which must be well adapted to the sensor and often requires careful design, in order not to jeopardize the usually small sensor output signals. Its role is to amplify the minute signals from the sensors up to acceptable levels for further treatment. In modern systems, an analogue-to-digital (A/D) conversion is carried out as soon as possible, to take advantage of the many possibilities that are offered these days by the ever-increasing mathematical and decisive power of digital electronics.

The transmitter stage is an important stage in remotely placed systems, since this stage will send the information over a longer distance to a matched receiver unit. This transmission can be carried out by a wireless system, which is most desirable in applications where monitoring has to occur in closed environments (e.g. vessels, but also in biomedical applications). After decoding the received signal, the data handling and storage unit will usually decide on the relevance of the signals, will store eventual interesting data, and will provide useful or important information to the outside, for example on a display, as shown in the Figure 1. The intention of the complete system is to give the operators a better control over the process they are responsible for. The displayed data, which should be corresponding to the sensor's output, is used as a decisive element to take the required measures for action and control of the process. Often, the control or action is taken on a fully automated base.

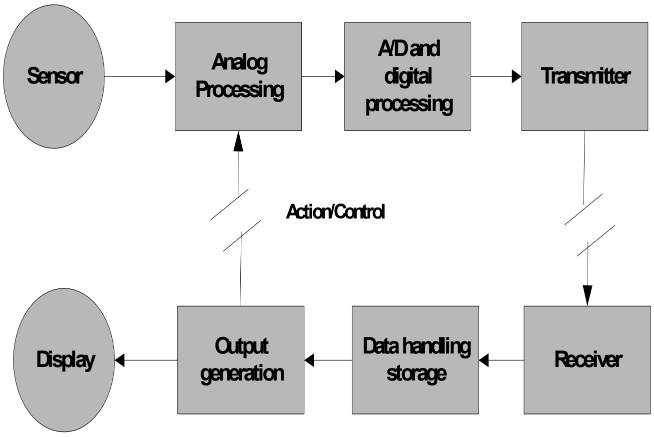

Fig. 1. The most general representation of sensing system and its use.

One of the most common problems that affects the system above is the stability of the sensor with time and that the interface circuits are able to follow the sensor signals at all times. No matter how desirable this situation is, in real life most sensors cannot fulfill this requirement. In particular, in long-term applications, sensor drift is a known problem.

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In many cases, the drift can become so important that the amplifier, which is coupled to the sensor, will not be able to follow the signal and will turn into saturation, with of course signal loss as a major consequence.

To tackle the problem of the lack of long-term stability of the sensing front-ends, the only way out is to provide a bi-directional communication link, instead of a single direction link as depicted in figure 1. Figure 2 illustrates the idea. The data transmission system has now been expanded with a second transmission stage, which allows one to communicate data to the device. By doing so, not only will the mere data captured by the sensors be transmitted, but also one can ask the device to go into a self-interrogating mode to verify the status of all the individual building blocks. After transmission of these data, the remote controlling station can adapt the settings of, for example, the offset of the amplifier, to cope for unwanted drift, or to re-program the built-in compression algorithms etc. The addition of such bi-directional communication has proven to be very advantageous, especially in novel applications, where the end user may not have had any experience with the possibility of measuring on such remote sites.

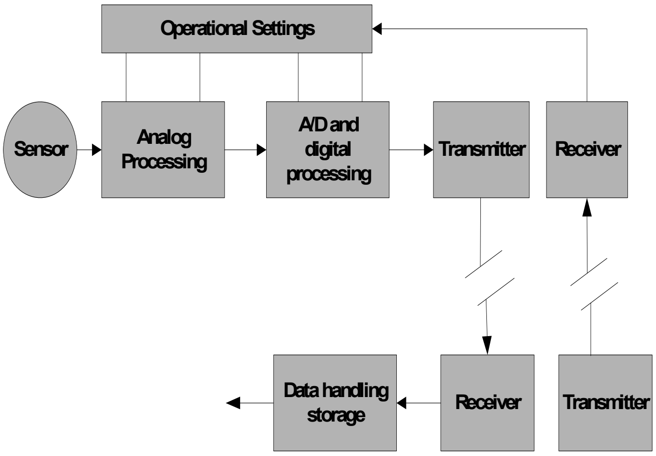

Fig. 2. Sensing system with reprogrammable operational setting points.

The paper is organized as follows: Basic types of telemetry systems are described in the next section. In section III, some of the main and recent capacitive analog circuitries are studied. Then, the fabrication process of biomedical compatible pressure sensors is given in section IV. Finally, an example of smart wireless system for multi-sensor monitoring developed by our research group has been presented.

II. TELEMETRY SYSTEMS

Wireless data gathering systems have the potential to restructure the instrumentation used in a variety of industries, including security, health care, and transportation. Looking at wireless sensing technology, both active and passive telemetry are used. Active telemetry systems provide relatively long-range bidirectional sensor data transfer [1], but with increased size and decreased life when internal batteries are used. Passive telemetry significantly reduces transmission distances but allows the implementation of battery-free devices with indefinite lifetimes [2,3]. In the following sections, some basic aspects about the two telemetry systems are given:

A. Passive Telemetry System

Wireless passive telemetry systems based on the integration of MEMs and RF backscatter modulation has been realized for implantable pressure monitoring [4,5]. The block diagram of the passive telemetry system is depicted in Figure. 3. It consists of an external control unit (the base unit) and an implantable transponder. Wireless communication can then be established between the two units, based on an absorption modulation mechanism.

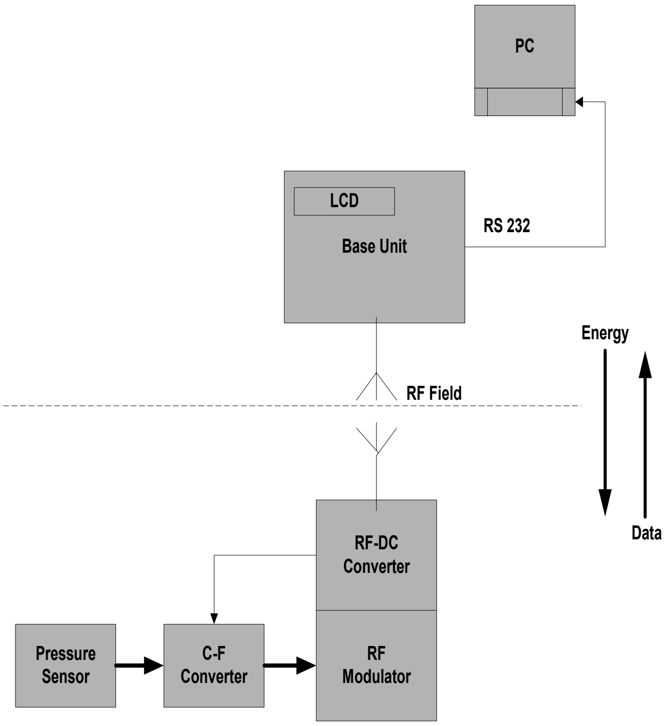

Fig. 3. Passive system comprised of a base and transponder unit.

The capacitance to frequency converter unit (C-F) will convert the signal read by the pressure sensor to a frequency tone to be transmitted later on through the RF-link to the base station. The transponder receives power and external control data through an RF field, while it can transmit data by modulating the absorption rate. The base unit, on the other hand, demodulates the transmitted data and processes it though (MCU) to convert the signal into a digital bit stream. The resulting data can then be sent to a

PC through a serial output or alternatively be displayed on an LCD on the base unit.

The performance of the RF-DC converter considered being crucial for the overall implant system performance. In this unit, received RF energy will be rectified and regulated to power the implant.

A typical RF-DC circuit is shown in Figure.4. A start up circuit is used to provide the bandgap reference with the rectified voltage on power up. Then the circuit will be switched to the regulated voltage when the latter reaches a sufficient level. The start up circuit compares V_{rec} and the high-regulated voltage and feeds the larger to the bandgap reference.
Low drop-out (LDO) linear regulators [6] are used for high and low voltage regulations. A step up switched capacitor circuit has been used to provide the 3.3V LDO with voltage since it leads to a better power efficiency. Temperature does not vary substantially, but the rectified voltage shows a strong ripple because a small tank capacitor must be used for at the input for size considerations.

It can be noticed that the above circuit is suitable for minimizing power consumption and can be further improved in the future.

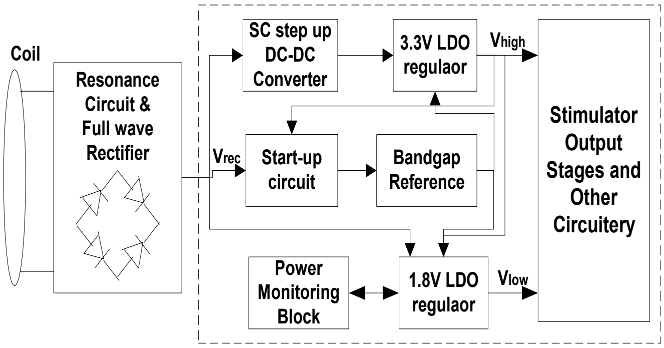

Fig. 4. Block diagram of the power recovery circuit.

B. Active Telemetry System

Power supply is needed internally for such system, which provides a long distance range for bi-directional sensor data flow. Because these portable systems will be battery powered, one of their key constraints is the overall power consumption, which must be minimized without scarifying performance.

Capacitive sensors have no intrinsic power dissipation and thus they considered being an attractive option for low power circuit techniques while offering high sensitivity and self-test capabilities [7,8]. The analog interface circuitries and development of the pressure capacitive sensors will be the issues of the coming sections.

The need for a generic system capable of reading out multiple sensors has widely increased. Furthermore, a generic interface circuit should provide standard communication link to the main system controller, support sensor self-test and self-calibration, support multi-ranging within a single sensor, dissipate low power, and occupy very small size.

One of the common wireless multi-sensors system architecture is shown in Figure 5. The system here 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 such as the Field Programmable Gate Array (FPGA) [9].

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 [10], including the lntramodule Multielement Microsensor (IM^2) bus that was specifically designed to complement the system architecture shown in Figure.5. Key requirements for a sensor bus in modular low power multi-sensor systems include a physical bus, which minimizes hardware overhead, and supports power management features such as interrupt generation and multiple power supply signals.

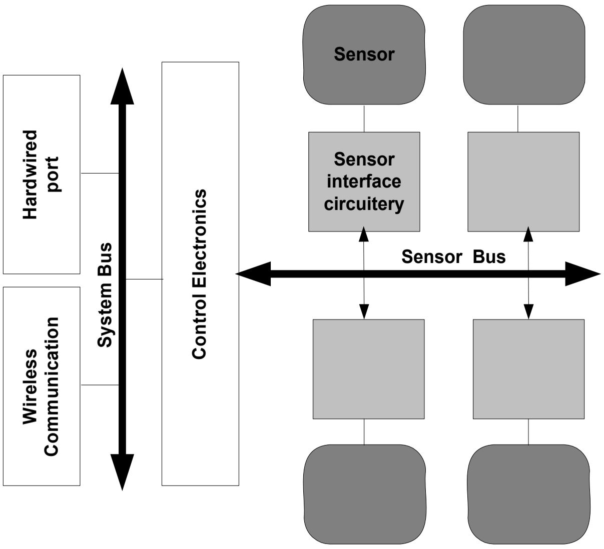

Fig. 5. Block diagram of a wireless modular sensor system.

C. Use of FPGA in wireless systems

FPGA have become a dominant technology for first-stage intermediate frequency (IF) in a variety of wideband wireless applications [11]. This is especially true in markets where “reprogrammability” and time-to-market concerns outweigh the costs benefits associated with application-specific integrated circuits (ASICs) in mass production. Table 1 compares between wireless smart systems based on the use of FPGA as a control unit and those use a microcontroller.

TABLE I
WIRELESS SYSTEMS COMPARISON USING FPGA AND MICROCONTROLLERS

FPGA	Microcontroller
Permits design upgrades with no hardware replacement.	Hardware is fixed and can't be upgraded.
Provides a good platform for a later on ASIC design.	ASIC is not possible.
Support a wide range of Digital Signal processing (DSP) operations.	Not efficient for implementing a complicated DSP.
Power consumption and chip size are still considerable.	Some processors now a day can be found with a very small size and low power.

III. CAPACITIVE READOUT CIRCUITS

Most developed pressure sensors have capacitive properties since they are highly sensitive. In general, two main approaches have been followed to design a capacitive readout circuitry. The measured output parameter will determine the approach type to be either capacitance-to-frequency (C-F) or capacitance-to-voltage (C-V). Types of circuits in each approach will be presented briefly as follows:

A. Capacitance to Frequency conversion

Switched-capacitor (SC) front-end (FE) is a good selection for the miniaturized capacitive readout circuits since the gain of this circuit is less sensitive to variations in input parasitic capacitance. A basic switched-capacitor relaxation oscillator used as capacitance transducer as shown in Figure 6 [12].

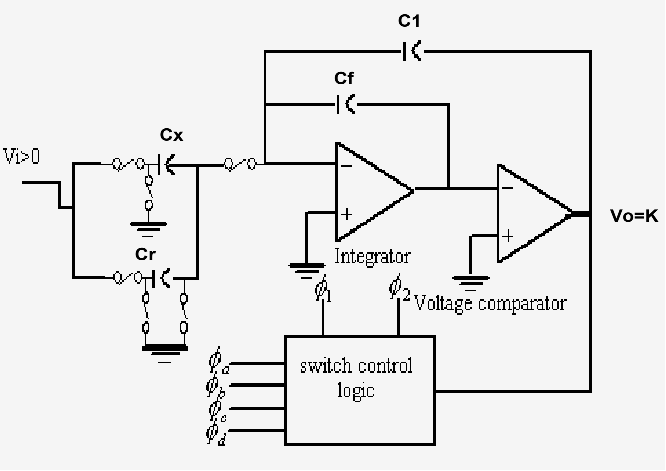

Fig. 6. Capacitive interface based on SC relaxation oscillator.

In this circuit, C_x denotes an unknown capacitance (capacitive sensor), C_r is the known reference capacitance and C_f is a non-critical value integration capacitance. The circuit consists of a standard switched-capacitor integrator, a voltage comparator (Schmitt trigger), and switch control logic. The MOS switches are controlled by a two-phase clock, Φ_1 and Φ_2 and switch control logic with logic signals Φ_a, Φ_b, Φ_c, and Φ_d as given by the following equation:

$$\Phi_A = \Phi_2,\ \Phi_B = \Phi_1,\ \Phi_C = \overline{K}\,\Phi_1,\ \Phi_D = \overline{K}\,\Phi_2 \qquad (1)$$

The oscillation frequency is expressed as:

$$f \cong f_c \frac{(C_r - C_x)C_x}{2C_1 C_r} \qquad (2)$$

Where f_c is the clock frequency.

The above-mentioned circuit is sensitive to the offset voltage of the op-amp and to the clock feedthrough of the clock signals through the gate-source and gate drains parasitic capacitors of the MOS.

B. Capacitance to Voltage conversion

This type of capacitive interface circuitry is widely preferred in telemetry systems because of the frequency drift that occurs with the first type. SC circuits proved to be a good option when low power performance is required. A simple SC based C-V capacitive readout is shown in Figure.7.

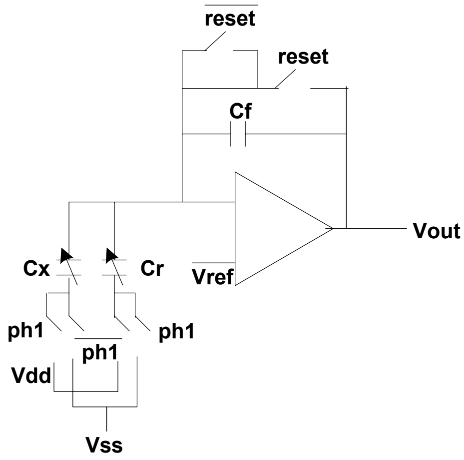

Fig. 7. SC capacitive readout circuit.

Cx is the sensor capacitor, and Cr is the reference capacitor. Both ph1 and ph2 are two non-overlapping clock signals. During ph1, the reset switch of the charge integrator is closed and Cs is charged through the charge integrator output to Cx (Vref-Vdd), and Cref is charged to Cr (Vref-Vss). Once ph1 goes low, charge stored in Cx changes to Cx (Vref-Vss) and that in Cr changes to Cr (Vref-Vdd). The net change in charge is (Cx-Cr)(Vdd-Vss). This change of charge is transferred to feedback capacitor Cf. The magnitude of the output voltage will be equal to:

$$Vout = Vref + (Vdd - Vss)(Cx - Cr)/Cf \quad (3)$$

The performance of the above design can be further improved by adding a second stage to form a two-stage Delta-sigma (ΣΔ) modulator as shown in Figure 8. The feedback capacitor Cfb has been introduced to increase the charge transfer efficiency. Consequently the modulator exhibits a large sensitivity to drift and noise of the voltage sources.

In [13] another capacitive signal conditioning circuitry based on the principle of capacitance-frequency-voltage conversion has been developed. Here the sensor C_x and the reference C_r capacitances are converted first to a frequency tones Fx and Fr respectively using a low power CMOS timer IC's and then to a voltage values using a (Phase locked loop) PLL as presented by Figure 9. An analog switch, which is controlled by a processor unit, is used to output the measured sensor voltage value with respect to the reference voltage.

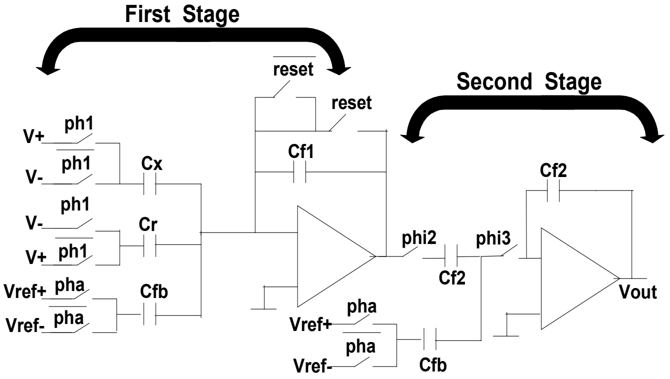

Fig. 8. Two stage ΣΔ modulator with sensor and reference connected to first stage.

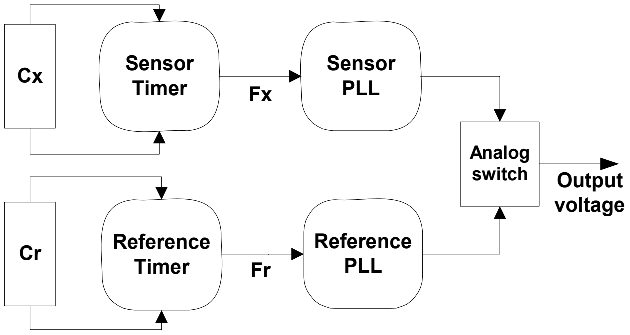

Fig. 9. Block diagram of the PLL capacitive interface.

The above design can be suitable for building a low power prototype if suitable units have been selected but it is not efficient an ASIC system. The main reason behind that is the non-linearity of the PLL unit, which has negative impact on system performance. It is found experimentally that the PLL design is sufficient for the pressure sensors range developed as will be explained in the following section.

IV. PRESSURE SENSOR DEVELOPMENT

In this study, capacitive sensors were fabricated using interdigitated electrodes as they contain no moving parts, require one less process step than a sandwich structure and detects pressure/strain changes through the deformation of the dielectric layer [14]. Furthermore, the interdigitated arrangement is popular with designers as altering the length of the electrodes can easily change the structures capacitance. DuPont 4929 silver conductive paste was used to form the electrodes which were printed onto alumina and Melinex® substrates using a DEK RS 1202 automatic screen-printer. After printing the substrate were allowed to cure at 120 °C for 30 minutes. A Thelco Model 6 oven was used for this purpose.

The dielectric layer consists of a polymer thick film paste, prepared using polyvinylidene fluoride (PVDF) as the functional material. This was combined with 7 wt.% binder and 0.1 wt.% surfactant. Typically, commercial powders have a particle size of 30 μm or more and so mechanical milling is necessary to reduce this to between 0.5 μm and 5μm for the functional material and 0.2 μm and 2 μm for the binder. The binder used in this study is ethyl cellulose and lecithin was added to act as the surfactant. Finally, the solvent, Terpinol-α was used to form a paste of suitable consistency. Three layers of PVDF paste were deposited over the electrodes and then placed in the oven for curing.

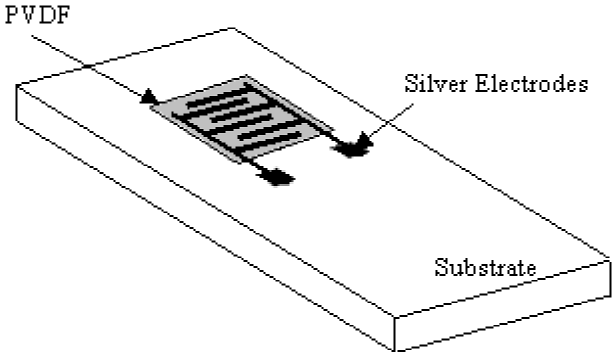

Fig. 10. Shows the structure of the interdigitated device.

A. Sensor Testing Mechanisms

After fabrication, the sensors on alumina substrates were placed in a cantilever beam arrangement so that the change in capacitance with applied strain could be measured. The experimental arrangement is shown in Figure 11. It can be seen from equation 4 that with knowledge of the beam geometry and displacement, the strain on the sensor can be calculated:

$$\varepsilon = \frac{3xyh}{2L^3} \ , \quad (4)$$

where ε is the strain, x is the distance from the centre of the beam to the point where the load is applied, y is the displacement of the beam and L is the distance from the clamped end to the point where the load is applied. By measuring the change in capacitance, ΔC and the applied strain, the gauge factor (GF) can be calculated from equation 5, where C is base line capacitance. The change in capacitance was measured using a HP 4192A LF Impedance Analyser.

$$GF = \frac{\Delta C / C}{\varepsilon} \qquad (5)$$

To assess the suitability of the PVDF device for pressure sensing applications, sensors on flexible substrates were connected to the developed interface circuit and subjected to pressure in the range of 0 to 12 kPa. A flexible substrate was chosen, as there is a potential for these devices to be applied to irregularly shaped objects. The applied pressure causes a deformation of the dielectric layer, which leads to a change in the sensor capacitance.

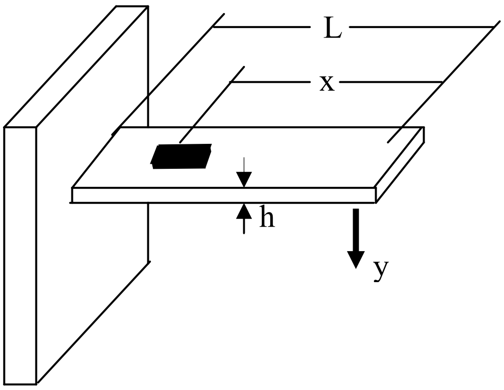

Fig.11. The cantilever beam arrangement

B. Testing the Strain Gauge Properties

The PVDF sensors were mounted in the strain gauge test rig, and the strain was increased from 0 to 500 μstrain. Previous results for a sandwich capacitor based on PVDF showed a gauge factor of 3.5 and linearity error of 5 %. In this study, a gauge factor of 6.2 was measured, which is higher than that measured for the sandwich structure. The sensors response showed a linearity error of 6 %, as shown in Figure 12.

V. DEVELOPMENT OF MULTI-SENSOR WIRELESS SYSTEM (ACTIVE TELEMETERY EXAMPLE)

An overview of the developed system main units is shown in Figure 13. The mote is configured to be for either resistive or capacitive measurements [15]. The output samples from the signal conditioning circuit will be processed and buffered by a microcontroller till the transmitter becomes ready. The data will be sent to the Base Station over 433 MHz channel using FSK modulation type. The mote also has the ability to power off the appropriate conditioning interfaces if they are not being used between the sampling times of the two analog signals to save power.

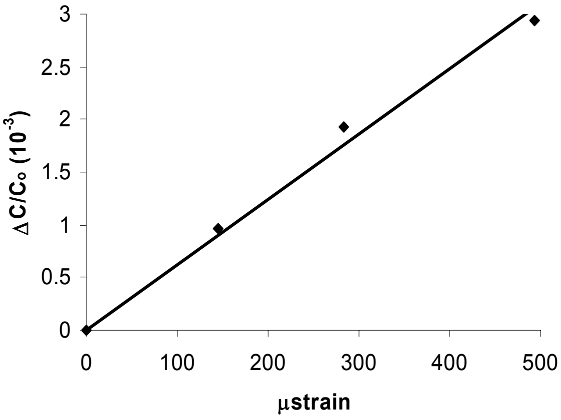

Fig. 12. Linearity of the PVDF sensor

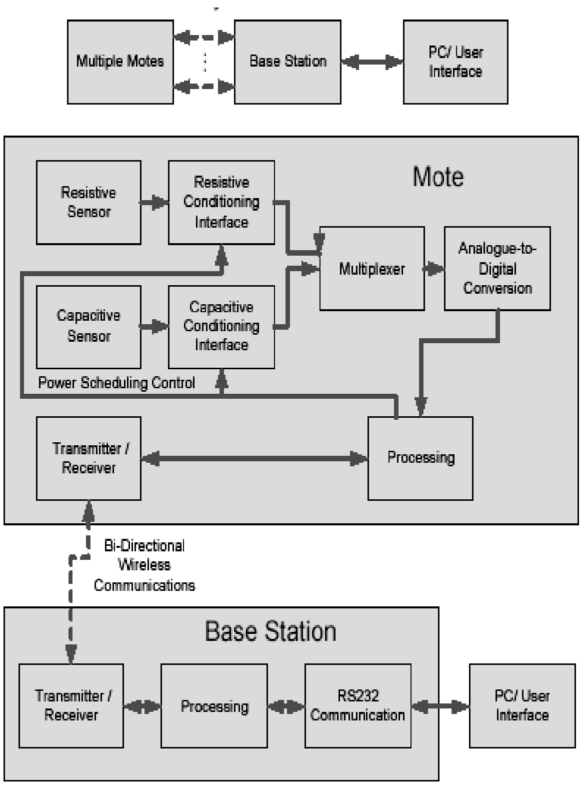

Fig. 12. System overview

The base station is able to communicate with multiple motes. This can be accomplished by using a form of time-division multiplexing, where the base station coordinates for each mote to start transmission. The data received from all motes at the base station are then sent to a PC via RS232 serial communication.

In the following sections, a brief description of both capacitive and resistive analog interface circuitries employed in the system is given. More attention will be given to the techniques used to reduce overall power consumption.

A. Capacitive and Resistive interface circuitries

The capacitive readout circuit is based on Capacitance-to-Voltage conversion based on the use of the PLL unit as mentioned in section III. It is desired that the circuit can measure sensor of range between 0 to 40 pF. A PVDF developed pressure sensor and a commercial temperature sensor have been used for the capacitive and resistive interface circuitries respectively.

Anderson Loop [15] circuit topology has been selected for the resistive interface since it has a linear performance. The circuit has been designed to be configurable and able to read from sensors with different ranges.

B. Power management

The first Power scheduling has been designed carefully to control the different parts of the system since it is required to reduce power consumption on the mote side as much as possible. Figure 14 shows the power flow mechanism controlled mainly by the processor unit. The transceiver and MCU have a "sleep" mode that can be controlled by the embedded software.

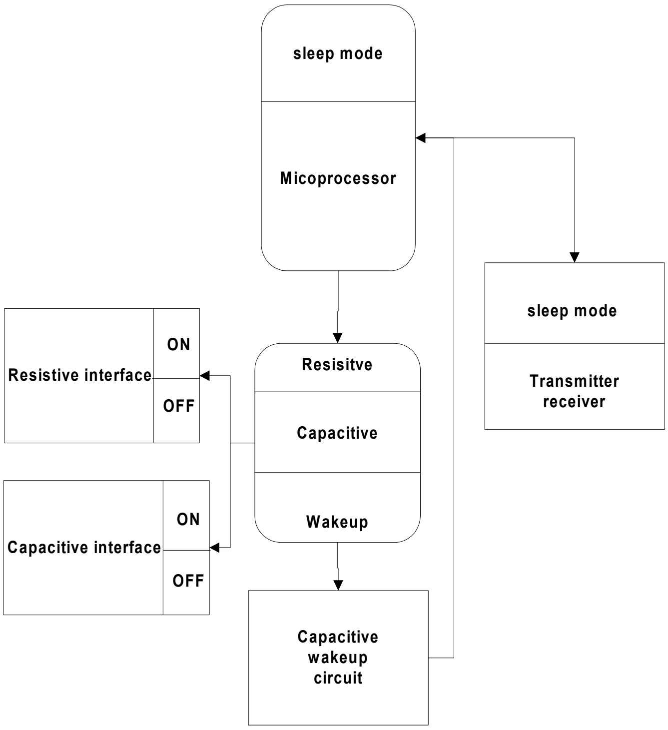

Fig.14. Power control of the mote system

As shown above, the sensor signal conditioning circuits can be switched either on or off by the control signals of the processor unit. A CMOS analog switch is used for this purpose. Table 2 clarifies the power scheduling options for the sensor interface circuits. In order to preserve the power, certain modules within the mote system are powered off when they are not in use.

TABLE 2. POWER SCEDUALING OF SENSOR INTERFACES

MCU	Resistive	Capacitive	Wakeup
Wakeup	ON	OFF	OFF
Wakeup	OFF	ON	OFF
Sleep	OFF	OFF	ON

A wakeup circuit has been introduced in the system to get further reduction in the power consumption. The idea came from the work done in [16] where a miniaturized low power wireless system has been described for remote environmental monitoring. The operation of the wakeup circuit is to put the MCU in sleep mode when the input signal is not changing. When the signal starts to give a significant change, an interrupt is generated that wakes up the MCU and it will start sampling again. The circuit is designed as shown in Figure 15.

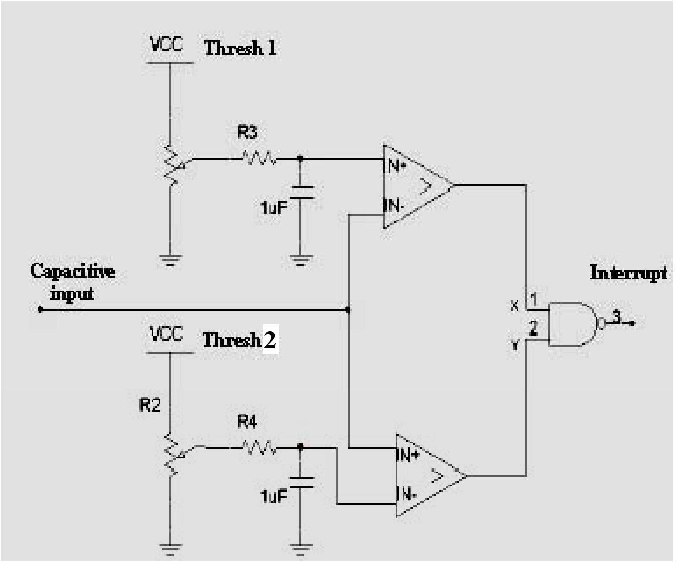

Fig.15. Circuit diagram of the wakeup circuit

The design is based on the principle of window detector, where two digitally controlled potentiometers are used to set the upper and lower trip points of the two comparators. At the beginning of operation, the MCU decides when the capacitive samples are not changing, then it will set the upper and lower limits of the window and powers up the wakeup circuit. The MCU will be in sleep mode when the sensor goes outside the limit. Than an interrupt signal will be generated to wakeup the MCU that will power down the wakeup circuit to save power.

The above design draws bout 700µA and a NAND gate that outputs zero when the sensor is within the window range will generate the interrupt signal. If the sensor goes above the upper-trip or below the lower trip, the desired output is high, that will interrupt the MCU from the sleep mode.

It has been noticed that wakeup circuit is not suited for the resistive interface where a higher power is needed to keep the circuit operating constantly. The wakeup circuit must be on when the processor unit is in sleep mode.

VI. CONCLUSION

In this paper, the issue of building a smart low power wireless system has been considered. The focus of the paper was mainly on pressure sensing and the capacitive interface circuitries.

Passive telemetry systems are more efficient in term of power consumption but it only suits applications with a very short-range. On the other hand, active telemetry system can provide a long-range of bi-directional communications. According to this, active type requires more power to function properly but the level of consumption can be controlled with well-designed system power management.

It can be concluded that C-F interface circuitry is more suitable for passive telemetry systems where the transmission will not be affected much by any frequency drift. For the active telemetry systems C-V based interface circuitry is a good option to get a good and stable performance. The ΣΔ SC circuit type proved to have a high sensitivity to noise and drift and it can be incorporated within the ADC of the data acquisition system. Although the SC is designed for high-speed operation but there are a lot of special techniques that can be employed to reduce the supply of power. This should be done without affecting the ON resistance of the MOS switches.

As a case study, a multi-sensor wireless system has been presented as an example of development a smart active telemetry system. Two mechanisms have been adopted to reduce further the overall power consumption. These are power scheduling and wakeup circuit for the capacitive interface. The first one is implemented fully by the MCU in order to switch on/off all the system units. A wakeup circuit has been designed to interrupt the MCU when it is in the sleep mode and the capacitive samples are changing significantly. It was found that such design is more suited for the capacitive interface than the resistive one where the circuit consumes much less power even if it is kept working continuously.

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