Integration of Low-power ASIC and MEMS Sensors for Monitoring Gastrointestinal Tract using a Wireless Capsule System

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Abstract—This paper presents a wireless capsule microsystem to detect and monitor pH, pressure, and temperature of the gastrointestinal (GI) tract in real-time. This research contributes to the integration of sensors (microfabricated capacitive pH, capacitive pressure, and resistive temperature sensors), frequency modulation and pulse-width modulation based interface IC circuits, microcontroller, and transceiver with meandered conformal antenna for the development of a capsule system. The challenges associated with the system miniaturization, higher sensitivity and resolution of sensors, and lower power consumption of interface circuits are addressed. The layout, PCB design, and packaging of a miniaturized wireless capsule, having a diameter of 13 mm and length of 28 mm, have successfully been implemented. A data receiver and recorder system is also designed to receive physiological data from the wireless capsule and to send it to a computer for real-time display and recording. Experiments are performed in vitro using a stomach model and minced pork as tissue simulating material. The real-time measurements also validate the suitability of sensors, interface circuits, and meandered antenna for wireless capsule applications.

Index Terms—Wireless Capsule, Microsystem, Application specific integrated circuit (ASIC), Frequency modulation based interface circuit, Pulse-width modulation based interface circuit, Capacitive pH sensor, meandered conformal antenna.

I. INTRODUCTION

A wireless capsule system is used for real-time and continuous measurement of physiological parameters in the gastrointestinal (GI) tract to replace the traditional endoscope system [1]–[12]. The traditional endoscopy method, which involves inserting an endoscope to the GI tract, is uncomfortable and time-consuming for patients [13], [14]. This method can not measure physiological parameters of the small intestine [10], [13]. A wireless capsule system overcomes these limitations and provides more in-depth analyses of physiological parameters and motility of the GI tract [1], [3], [4], [10], [13]–[17]. A wireless capsule contains several sensors with interface integrated circuits (IC) to detect physiological parameters, a digital microcontroller to manage and process all data from sensors, and a transceiver system with antenna for wireless communication. The pH, pressure, and temperature are the essential physiological parameters to detect dysfunctions of the GI tract [13].

Early attempts were to monitor motility of the GI tract as pressure change and to measure body core temperature [18]–[22]. An oscillator circuit is used as an interface circuit for pressure or temperature sensor to obtain frequency variations for changes in physiological parameters as well as to transmit the data using low frequencies. Those systems were bulky due to large electronic components and large sensor systems. A prototype named IDEAS, which is 55 mm in length and 16 mm in diameter, is designed to measure pH, temperature, conductivity, and dissolved oxygen concentration in the GI tract and to transmit data at 38.242 MHz frequency [1], [2]. A wireless capsule system named as lab-in-a-pill (LIAP) has a dimension of 36 mm in length and 12 mm in diameter [9]. It consists of pH and temperature sensors, interface circuits, controller circuit, and transmitter to measure and transmit pH and temperature signals of the GI tract. The data is transmitted using a loop antenna. For both IDEAS and LIAP systems, voltage amplifier based interface circuits are used to achieve lower power consumption. These circuits are affected by flicker and thermal noises and minimize the sensor readout range and resolution of these circuits. Commercial products from Given Imaging, Bravo pH system, and Smart Pill are also available [8], [23]. Recently, a wireless capsule system, having a dimension of 26 mm in length and 11 mm in diameter, can measure pH, pressure, and temperature of the GI tract [10]. Wheatstone bridge based interface circuits are utilized to convert sensing signals into measurable quantities of voltages. Though these circuits consumes lower power, they are affected by noises and provide lower sensitivity and resolution. The data is transmitted using a cylindrical helix antenna which occupies large space inside the capsule. A flexible gastric battery or a wireless power link is also adopted to replace traditional bulky battery to reduce the size of the wireless capsule [24], [25]. Overall, capsule miniaturization, power consumption, sensitivity and resolution of sensors, wireless communication, and miniaturized antenna are key challenges for the development of a wireless capsule system.

In this paper, a wireless capsule system with a data receiver and recorder system is developed to measure pH,
pressure, and temperature. The wireless capsule contains a microfabricated pH, pressure, and temperature sensors to detect and convert physiological signals in the GI tract to electrical quantities with interface IC circuits. The microfabricated capacitive pH sensor is employed to measure high acidic pH levels in the stomach. A frequency modulation (FM) and a pulse-width modulation (PWM) based interface IC circuits are designed and implemented to translate sensor changes in the GI tract into electrical quantities for the pH sensor and pressure sensor, respectively. A miniaturized meandered conformal antenna with omnidirectional radiation pattern and center frequency of 433 MHz is also integrated for the transmission of sensor data to an external receiver system. This antenna is wrapped around the inner cylindrical surface of the capsule to increase radiation efficiency and to provide extra space for sensors and circuits inside the capsule. A flexible printed circuit board (PCB) is fabricated on a biocompatible polyimide material [26], [27] which allows rolling the antenna as a cylindrical shape and to fold and fit remaining parts inside the capsule. The transmitted data from the wireless capsule is received for remote monitoring and recording with a data receiver system.

Most of the research works performed for the development of wireless capsule endoscopy are focused on system level design, with less emphasis on each system components to address challenges. It is important to focus on the design of sensors, interface circuits, and antenna, which are essential components for the implementation of wireless capsule, in order to tackle the challenges. This work contributes to the integration of the capacitive pH sensor, FM-based and PWM-based interface circuits, and the compact meandered conformal antenna to design and implement a wireless capsule system platform that forms a foundation for the embodiment of a multisensor microsystem. Along with these system components, system level design using those system components are also verified experimentally.

The components of the wireless capsule system are described in Section II. The layout of system components, printed circuit board (PCB) design, and packaging of the wireless capsule are described in Section III. The design of a receiver and data recorder system is presented in Section IV. The device is also experimented and evaluated in vitro to validate the design and implementation of the system. The experimental results are provided in Section V. Finally, Section VI presents a summary of this paper.

II. SYSTEM DESCRIPTION

The block diagram of the wireless capsule system is shown in Fig. 1. The system consists of two main sections. The first section is the wireless capsule, as presented in Fig. 1(a). The wireless capsule contains pH, pressure, and temperature sensors to detect and convert physiological signals in the GI tract to electrical quantities with interface IC circuits. The capacitive pH sensor [28], [29] with the frequency modulation (FM) based interface IC circuit [30] is used to translate capacitive changes due to pH changes into voltage changes. A capacitive pressure sensor with the pulse-width modulation (PWM) based interface circuit [31] is used to obtain pulse-width variation due to pressure changes. A resistive temperature sensor with a voltage divider circuit is used to convert resistance shifts due to temperature shifts into voltage shifts. The wireless capsule is powered by two batteries with commercial voltage regulator circuits for supply voltage of 1.8 V. The microcontroller processes all the sensor data and controls interface circuits, regulators, and a wireless transceiver circuit. The microcontroller controls a regulator connected with interface circuit to reduce power consumption. Sensor data is processed with a microcontroller and then transmitted using the wireless transceiver with a meandered conformal antenna [32].

The external data receiver and recorder systems is shown in Fig. 1(b). This receiver system consists of a microcontroller, a wireless transceiver with inverted-L antenna (ILA), a universal asynchronous receiver/transmitter (UART) to universal serial bus (USB) bridge, and a computer. The transmitted data from the wireless capsule is received using the transceiver and transmitted using a UART to a computer for remote monitoring and recording of data. A graphical user interface (GUI) developed using MATLAB software is used for visualization of physiological data in real-time.

A commercial microcontroller with transceiver circuit from Silicon Labs [33] is selected for the proposed wireless capsule system. The major blocks, which are utilized for the wireless capsule, are analogue-to-digital converter (ADC), programmable counter array (PCA), and wireless transceiver. The UART block of the microcontroller is used for the data receiver and recorder system to send the received data from wireless capsule to a computer. The baud rate of the UART is 115.2 kbps. The microcontroller also includes a
programmable precision internal oscillator as a system clock operating at 24.5 MHz frequency. The ADC uses an internal precision voltage reference of 1.68 V. A repeat count of 8, which increases the effective ADC resolution, is used to increase accuracy for pH and temperature measurements. The PCA, which is an enhanced 16-bit counter or timer triggered by both positive and negative edges of a PWM signal, is configured to capture values of the counter and type of transitions of a signal. From captured counter values for both transitions of a signal, the pulse-width of the PWM signal is calculated for pressure measurements. The transceiver, which is integrated with the microcontroller for wireless sensor data transmission, is configured for Gaussian frequency shift keying (GFSK) modulation and operating at 433.9 MHz of center frequency having 128 kbps data rate and 250 kHz channel spacing. This is sufficient for sensor data transmission in real-time. It is also possible to transmit multiple wireless capsule data using other transmission channels.

The power management system includes batteries, regulators, and algorithm to supply and control power to all circuits. The wireless capsule is powered by two silver oxide batteries (RENATA 370), each having 9.5 mm in diameter and 2.05 mm in height, nominal voltage of 1.55 V, and capacity of 40 mAh. Two regulators (Texas Instruments, TPS73118) are used to supply 1.8 V separately to the interface circuit and the microcontroller. The microcontroller is always powered by a regulator, while the regulator for the interface circuit is controlled by the microcontroller to reduce the power consumption. The power consumption of the microcontroller is also optimized using algorithm to control different blocks, such as the transceiver, ADC, PCA, and system clock.

A. Sensors

The pH, pressure, and temperature sensors are used to detect physiological signals inside the GI tract. The photograph of the sensors are depicted in Fig. 2. The dimension of the pH sensor is 10 mm x 10 mm. The dimension of the packaged pressure sensor is 3 mm x 3 mm. The diameter of the temperature sensor is 2.413 mm.

The digestive fluid in the stomach, also known as gastric acid, usually has a pH level between 1 and 2 [34]. The capacitive pH sensor, as shown in Fig. 2(a), is employed to measure strong acidic ranges of gastric acid [28], [29]. The pH sensor consists of interdigitated electrodes fabricated on a quartz substrate and passivated by silicon nitride layer using conventional microfabrication steps. Instead of measuring solid-solution interfacial potential, the changes of bulk solution capacitance, corresponding to pH levels, are measured using the sensor.

The pressure in the GI tract is necessary for clinical or physiological examinations. The normal pressure values in esophagus and stomach are slightly lower than atmospheric pressure of 101 kPa while the pressure in colon is slightly higher than atmospheric pressure [14], [35]. A capacitive pressure sensor from Microfab [36], as shown in Fig. 2(b), is utilized for the wireless capsule.

The temperature of the GI tract is measured using a discrete thermistor (192 series) from Honeywell [37], as shown in Fig. 2(c). The resistance of this thermistor is 100 KΩ at 25 °C with negative thermal coefficient.

B. Interface Circuits

The block diagram of interface circuits for pH, pressure, and temperature sensors are shown in Fig. 3. There are three separate interface circuits for each sensor. For pH sensor, the FM-based interface IC circuit [30] is used to convert capacitance changes from pH sensor into voltage changes. The FM interface circuit provides higher resolution and sensing for pH measurements [38]. The changes in capacitance due to pH levels are converted into frequency variations using a voltage-controlled oscillator (VCO) circuit. The control voltage ($V_{ctrl}$) and inductance ($L_0$) controls the nominal frequency of the VCO. A sine-to-square converter circuit converts frequency shifts from the VCO into time-period variations. The time-period changes are then converted to voltage changes using a frequency-to-voltage (FVC) circuit.
The FVC circuit consists of a logic controller circuit and a charge pump circuit. The logic controller circuit, that produces three control pulses ($S_1$, $S_2$, and $S_2$) to control the charge pump circuit, translates the time-period variation into pulse-width variations. An external delay control voltage ($V_{BD}$), a feedback voltage ($V_{FVC}$) from charge pump circuit, and charging current ($I_{ch}$) of the charge pump circuit provide controls to obtain voltage changes ($\Delta V_{pH}$) at the output of the charge pump circuit.

The capacitive pressure sensor is connected with the PWM-based interface IC circuit to translate capacittance changes from pressure variations into pulse-width or duty cycle changes variations of a square wave. The square wave clock from a ring oscillator drives both reference and sensing RC controlled pulse generators each containing a high-pass filter, a reference resistor ($R$), and a capacitor ($C_{ref}$ or $C_{pressure}$). The pressure sensor ($C_{pressure}$) is connected to the sensing RC circuit while a fixed capacitor ($C_{ref}$) is connected to the reference RC circuit. The voltages across the pressure sensor and the reference capacitor are compared with a set threshold voltage ($\alpha$) using a self-tuning inverter comparator circuit. The PWM signal having pulse-width dependent on the capacitance of the pressure sensor is obtained using an XOR gate. The circuit provides higher sensitivity and linearity with lower power consumption.

The interface circuit for resistive temperature sensor is the voltage divider circuit where the sensor is in series with a reference resistor to produce a varying output voltage with respect to sensor resistance changes due to temperature variations.

The interface circuits are fabricated in the UMC 0.18 µm process and packaged in a standard 48-pin QFN-package having dimensions of $7 \times 7$ mm$^2$. As shown in Fig. 4, there are two FM-based interface circuits and one PWM-based interface circuit. For the wireless capsule, one of the FM-based interface circuit is used for pH measurement and the other one is retained for future extension. The PWM-based interface circuit is used for pressure measurement. The active area of FM-based and PWM-based interface circuits are 0.18 mm$^2$ and 0.17 mm$^2$, respectively.

### C. Antenna and Propagation

The meandered conformal antenna [32], as shown in Fig. 5, is used for the wireless capsule to communicate with the external receiver system. The antenna that is fabricated on a flexible polyimide material having a length and width of 21 mm and 36.2 mm, is rolled up or wrapped inside the wireless capsule as a cylindrical shape having radius of 5.76 mm.

For measurements, the capsule containing the antenna is inserted in a plastic container filled with pork mince. The antenna operates at center frequency of 436 MHz with 124.4 MHz bandwidth (18.5% fractional bandwidth) without overlapping of segments, as shown in Fig. 6. For the first case of 25% overlapping (half of first and fourth segments are overlapped) while rolled up, as illustrated in Fig. 6(a), the radius of rolled up antenna becomes 4.45 mm. For the other case, the radius of the rolled up antenna, as illustrated in Fig. 6(b), becomes 3.12 mm due to 50% overlapping. The measured results of return loss, as shown in Fig. 6(c), does not exhibit significant changes in resonance frequency despite its lower gain. Therefore, the antenna is suitable for capsules having smaller radius.

![Die photograph for wireless capsule comprising both FM-based and PWM-based interface IC circuit.](image)

A low frequency transmission through skin layer is preferred due to higher efficiency [39], [40]. A band-pass filter type impedance matching circuit from Johanson Technology is used which operates in the range of 424 to 444 MHz frequencies [41]. For the external receiver system, the ILA antenna operates at 434 MHz center frequency with 5.1 MHz bandwidth (from 431.7 to 436.8 MHz) for voltage standing wave ratio (VSWR) less than 2. The distance between the external receiver system and the meandered antenna inside the wireless capsule traveling through the GI tract, as depicted in Fig. 7(a), varies significantly depending on body sizes. A significant portion of transmitted power is absorbed by the surrounding tissue. From Fig. 7(b), the in-body path loss, which is measured considering the stomach is full of lossy tissue medium, increases rapidly with the propagation distance. The experimental results shows path
loss of 17.24 dB for in-body propagation of 140 mm. The transmit power of 13 dBm is used for the wireless capsule system. The maximum communication distance between the wireless capsule and the transmitter is 15 cm. The required receiver sensitivity is -103 dBm. The antenna gain is roughly uniform in the azimuth plane and is slightly nonuniform in the elevation plane. The maximum measured far field antenna gain at 433 MHz frequency is -36.86 dBi.

III. WIRELESS CAPSULE DESIGN

The schematic of the wireless capsule is illustrated in Fig. 8. The cylindrical shaped capsule is 28 mm in outer length and 13 mm in outer diameter. Since, the thickness of the capsule body is 0.5 mm, the available inner length and diameter of the capsule for sensors, circuits and antenna are 27 mm and 12 mm, respectively. The top side of the capsule is partially opened for sensors to interact with the stomach fluids and other end of the capsule is closed. The PCB is fabricated on a flexible polyimide material to allow folding and fitting components inside the capsule. The batteries are placed in between sensors and interface circuit to utilize the empty space created due to the shape of the pH sensor. The space between sensors and batteries are sealed using Dow Corning sealant to protect the circuits inside the capsule from leaking of stomach fluids [42].

The flexible PCB contains sensors, circuits, and antenna, as presented in Fig. 9(a)-(b). The PCB is designed in two layers, where the top layer (Fig. 9(a)) contains most of the circuits, sensors, and an antenna and the bottom layer (Fig. 9(b)) contains battery connectors, a reed switch, and regulator circuits with input and output capacitors for noise reduction. The structure of the PCB allows to roll the antenna as a cylindrical shape and to fold and fit the remaining parts inside the capsule. Three components of wireless capsule body, as shown in Fig. 9(c), are fabricated using a 3D printer. The inner and outer diameter of the capsule is 12 mm and 13 mm, respectively and the thickness is 0.5 mm. The first cylindrical component holds the circuits and battery. The second component is used to separate circuits and sensors. A part of the PCB containing sensors are routed through a small opening in the middle of the component to position the sensors on the top side of capsule. The last component is positioned and sealed on top of the capsule to protect sensors as well as to allow contact with stomach fluids. The side view and top view of the packaged capsule is shown in Fig. 9(d)-(e). The outer diameter and length of the capsule is 13 mm and 28 mm, respectively. The partially opened top side of the capsule allows the stomach fluid to interact with sensors. The soldering parts of sensors are also sealed using Dow Corning sealant to avoid short-circuit due to stomach fluids [42].

The microcontroller is programmed to meet controlling, processing, and transmission requirements. The system flow chart for the wireless capsule is shown in Fig. 10. All modules used in the microcontroller are initialized when power is on. Then the sleep mode is enabled for a specific time by activating a low frequency clock instead of the system clock to reduce the power consumption of the
The physiological data, which is a slow varying signal, is collected in every 18 seconds. To measure and collect data, the interface circuit is enabled along with pH, pressure, and temperature settings. Using two separate interrupt service routines for the ADC and PCA, voltage values for temperature and pH levels as well as pulse-width of pulses for pressure levels are obtained. When data from all sensors are available, interface circuits are turned off to limit the power consumption of circuits and the transceiver is turned on for data transmission. After the data is transmitted, the transceiver operates as a receiver to acquire acknowledgment data from the external data receiver system. If the acknowledgment data is not received within a predefined time, the data is transmitted again. If the acknowledgment signal is received, the transceiver is disabled to decrease the power consumption. Then the microcontroller enters into the sleep mode for 18 seconds.

IV. RECEIVER DESIGN

The photograph of the receiver system is shown in Fig. 11. The system contains a microcontroller [33] and UART to USB bridge [43] from Silicon Labs, impedance matching circuit from Johanson Technology [41], and an ILA antenna.

The ILA antenna operates at 434 MHZ with 5.1 MHz bandwidth.

The microcontroller for data receiver system is programmed to communicate with the wireless capsule and a computer. The system flow chart for the receiver system is shown in Fig. 12. The required blocks, such as transceiver and UART are initialized at the beginning. Then the transceiver is turned on as a receiver mode for acquiring data from the wireless capsule. If data is received, the validity for the data packet configuration is checked to ensure that data is from the wireless capsule. If valid data is obtained, the transceiver operates as a transmitter to send acknowledgment data to the wireless capsule. Then the UART is enabled to transmit the data to a computer using a UART-to-USB bridge. After the transmission of acknowledgment data, the transceiver changes to receiver mode for acquiring next data from the wireless capsule. A MATLAB based GUI is developed to communicate with the receiver system and to display and record the data from wireless capsule in real-time.

V. EXPERIMENTAL RESULTS

The packaged wireless capsule prototype is experimentally evaluated through in vitro measurements of pH, pres-
sure, and temperature of pH buffer solutions. Sensor responses are experimentally obtained using the wireless capsule and then real-time measurements are performed to validate the feasibility of the system for wireless capsule applications.

A. Experimental Setup and Procedures

The performance of the wireless capsule is experimented and evaluated in vitro using a setup, as shown in Fig. 13(a), mimicking the stomach environment\(^1\). Figure 13(b) shows a stomach model which is fabricated using a 3D printer and placed inside a cylindrical shaped container. Minced pork is used as a tissue simulating material in between the stomach model and the container, as the electrical property of minced pork and stomach tissue at 433 MHz frequency is similar [44]–[46]. During the experiments, the stomach model is completely immersed in the minced pork. The wireless capsule is inserted in the stomach model for measurements.

\(^1\)Due to ethics difficulty, we experimented in vitro.

The pH solutions, made from standard buffer solutions by mixing deionized water, is used for pH measurements, and the temperature is applied using a hot plate. The pressure measurement is controlled and verified using a syringe pressure system with a precision positioner and a pressure gauge [31]. The pH and temperature levels of the solution is verified by a commercial pH glass-electrode (HQ40d, HACH) sensor. The temperature of the solution is also measured using a mercury based thermometer. The receiver circuit, containing the ILA antenna, is placed outside the container.

For the experiments, a set of circuit parameters for interface circuits shown in Fig. 3 are selected to convert sensor signals to measurable electrical quantities. For the pH sensor interface circuit, the LC-tank of the VCO circuit is set by \(L_0\) of 15 nH and \(V_{ctrl}\) of 1.0 V to convert the capacitance changes to frequency shifts. The \(I_{ch}\) of 41.7 A and \(V_{BD}\) of 1.3 V is used to convert the frequency shifts to voltage change. The \(V_{ctrl}\) of 1.0 V and \(V_{BD}\) of 1.3 V is generated using a voltage divider circuit from a 1.8 V supply. To produce \(I_{ch}\) of 41.7 A, \(R_{ch}\) of 10 k\(\Omega\) is used.

For temperature sensor interface circuit, a voltage divider circuit having 50 k\(\Omega\) of reference resistor is used. For the pressure sensor interface circuit, ring oscillator of the PWM-based interface circuit is operated at 12.5 kHz frequency, the RC circuit is set by \(R\) of 4 M\(\Omega\) and \(C_{ref}\) of 4.7 pF, and the comparator threshold is set by \(\alpha\) of 0.9.

B. Sensor Responses

The capacitance changes due to pH levels are converted to frequency changes and then into voltage changes with FM-based interface IC circuit. The ADC of the microcontroller converts the voltage levels into digital codes. The ADC output codes for pH levels ranging from 1.0 to 4.03 is shown in Fig. 14. The changes of ADC output codes are
1221 for pH 1.0 to 2.0, 701 for pH 2.0 to 3.0, and 186 for pH 3.0 to 4.0. There is a slight difference in ADC output codes between room temperature and body temperature. The difference is much smaller in high acidic levels than the output code variations due to pH change. Since the output of the ADC includes a repeat count of 8, the average resolutions of the pH sensor are 0.0066 for pH 1.0 to 2.0, 0.0114 for pH 2.0 to 3.0, and 0.0430 for pH 3.0 to 4.0.

For pressure sensor, the capacitance changes due to applied pressure is converted into pulse-width variations using the PWM-based interface circuit. The pulse-width of the PWM signal is calculated using PCA of the microcontroller by capturing counter values for both positive and negative edges of the PWM signal. The PCA output codes for pressure values ranging from 50 kPa to 200 kPa is shown in Fig. 15. The changes of PCA output codes are 143 for 101 kPa to 200 kPa, 18 for 80 kPa to 101 kPa and 12 for 50 kPa to 80 kPa. The average resolutions of the pressure sensor are 0.69 kPa for 101 kPa to 200 kPa, 1.17 kPa for 80 kPa to 101 kPa and 2.5 kPa for 50 kPa to 80 kPa.

The resistance changes due to temperature levels are converted into voltage changes using a voltage divider circuit which is translated into ADC output codes using the ADC of the microcontroller. The ADC output codes for temperature values ranging from 25 °C to 50 °C are shown in Fig. 16. The response from the temperature sensor exhibits linear characteristics for temperature values ranging from 25 °C to 50 °C. The difference of ADC output code for 25 °C and 50 °C is 2302, which provides the average resolution of 0.087 °C for the temperature sensor.

C. Real-time Measurements

For real-time measurements, the wireless capsule measures pH, pressure, and temperature values and transmits to the receiver system which is connected to a computer. A MATLAB based GUI is developed to communicate with the receiver system and to record and display the data from the wireless capsule in real-time. The acquired data is ADC and PCA output codes which are converted into pH, pressure, and temperature values using a third order fitted regression curve obtained from responses of sensors (Fig. 14, 15, and 16). A snapshot of the GUI for real-time display and record of received data from the wireless capsule is shown in Fig. 17.

The ADC and PCA output codes of measurements for pH, temperature, and pressure sensors, which are acquired in 18 seconds intervals for 3000 seconds, are shown in Fig. 18. In the first part, pH and temperature are varied and recorded for 1500 seconds. At the same time, the pH and temperature of the buffer solution are also verified using commercial pH and temperature meters. The pH values of 0.98, 1.12, 2.49, 3.23, and 3.78 are used by mixing deionized (DI) water with standard buffer solutions. The ADC output code due to pH changes is shown in Fig. 18(a). Since it takes some time to completely stabilize the pH of a medium, the ADC output response contains transient spikes at the same time of mixing DI water. The temperature is changed linearly in between 36 °C to 42 °C, as shown in Fig. 18(b). In the second part, the syringe pressure system with a pressure gauge is placed to verify the pressure and the opening of the stomach model is sealed to induce slightly higher and lower than atmospheric pressure of 101 kPa inside the stomach model. The PCA output code due to pressure change is shown in Fig. 18(c). Though the pressure is not varied from 0 to 1500 seconds, transient spikes are observed due to induced force from mixing DI water during pH measurements. The pressure values of 105, 110, 120, 95, 90, and 80 kPa are induced in this experiment for 1500 seconds to 3000 seconds. Sensor responses and real-time measurement results validate the potential of the
wireless capsule system for real-time monitoring and display of physiological parameters of GI tract.

The FM-based and PWM-based interface circuits consume 11.772 mW and 98 µW, respectively, from a 1.8 V power supply. The power consumption of the microcontroller is 1.08 µW in sleep mode and 7.38 mW in active mode from a 1.8 V supply. The power consumption of the transceiver is 32.4 mW in transmitter mode and 18 mW in receiver mode. The microcontroller stays in active mode for 1.3 milliseconds and in sleep mode for 18 seconds. The measurement time for the FM-based and PWM-based interface circuits are 40 and 80 microseconds, respectively. Since the power consumption of the transmitter is much higher, all sensor data is transmitted at the same time. The average power consumption is 207 µW including the power dissipation from the voltage divider circuit for temperature sensor and two regulators. The wireless capsule can function for 200 hours with two silver oxide button batteries.

Table I shows a comparison with the performance parameters of the wireless capsule system with previous capsule systems in the literature. The implemented capsule system integrates sensors with low power, low noise, and higher resolution interface IC circuits. Although the power consumption of FM-based interface circuit is higher than amplifier-based and Wheatstone bridge-based circuit, the lower measurement time effectively reduces the overall power consumption. A microfabricated capacitive pH sensor is utilized to measure high acidic pH levels which provides higher sensitivity, low noise, fast response, and consistent results. A meandered conformal antenna, which uses the whole cylindrical capsule surface, is integrated to achieve better radiation pattern and improved performance as well as to provide extra space for sensor and circuits. The dimensions of the system, which is comparable with [10], is smaller than other systems in the literature.

Fig. 18. Real-time measurement results of pH, temperature, and pressure sensors in 18 seconds intervals for 3000 seconds. (a) pH measurements. (b) Temperature measurements. (c) Pressure measurements.
TABLE I
PERFORMANCE COMPARISON OF WIRELESS CAPSULES USED FOR PHYSIOLOGICAL SIGNAL MONITORING.

<table>
<thead>
<tr>
<th>Capsule Name</th>
<th>Capsule Dimensions (H × D)</th>
<th>Sensors</th>
<th>Range (Resolution)</th>
<th>Interface Circuit Technique</th>
<th>Wireless Transmitter (Modulation)</th>
<th>Antenna Type</th>
<th>Power Source</th>
<th>Ref. (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gutnic</td>
<td>28 × 9 mm</td>
<td>pH</td>
<td>-</td>
<td>-</td>
<td>Loop antenna</td>
<td>Gold-Iron electrode battery</td>
<td>[18]</td>
<td>(1957)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITMS</td>
<td>22.6 × 10.7 mm</td>
<td>Temperature (Crystal)</td>
<td>32-44 °C (-)</td>
<td>Oscillator 262 kHz</td>
<td>kV</td>
<td>Nickel-Cadmium battery</td>
<td>[21]</td>
<td>(1988)</td>
</tr>
<tr>
<td>Rigel Research Ltd.</td>
<td>8.8 × 6 mm</td>
<td>Pressure (Inductive)</td>
<td>0-40 kPa (-)</td>
<td>Oscillator 250-570 kHz</td>
<td>Ferrite aerial</td>
<td>Mercury battery</td>
<td>[20]</td>
<td>(1997)</td>
</tr>
<tr>
<td>IDEAS (Prototype)</td>
<td>55 × 16 mm</td>
<td>pH (ISFET)</td>
<td>4-10 (0.64) 0-70 °C (0.4 °C) 0.05-10 mS/cm (0.02 mS/cm)</td>
<td>Voltage amplifier 38.342 MHz (FSK)</td>
<td>Cylindrical helix antenna</td>
<td>Silver oxide battery</td>
<td>[1], [2]</td>
<td>(2002)</td>
</tr>
<tr>
<td>Dissolved O₂ (Three Cell)</td>
<td>0.0-8.2 mg/L</td>
<td></td>
<td>(0.08 mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 × 19 mm</td>
<td>Pressure (Resistive)</td>
<td>0-60 kPa (-)</td>
<td>Wheatstone bridge 433.92 MHz (ASK)</td>
<td>Cylindrical helix antenna</td>
<td>Lithium battery</td>
<td>[16]</td>
<td>(2004)</td>
</tr>
<tr>
<td>Smart Pill™ (Commercial)</td>
<td>26 × 13 mm</td>
<td>pH</td>
<td>1-10 (0.1) 10-50 °C (0.25 °C)</td>
<td>Voltage amplifier 433.92 MHz (OOK)</td>
<td>Loop antenna</td>
<td>Silver oxide battery</td>
<td>[9]</td>
<td>(2006)</td>
</tr>
<tr>
<td>LIAP</td>
<td>36 × 12 mm</td>
<td>pH (ISFET)</td>
<td>1-14 (0.01) 95-120 kPa (0.01 kPa) 35-42 °C (0.01 °C)</td>
<td>Wheatstone bridge 433 MHz (FSK)</td>
<td>Cylindrical helix antenna</td>
<td>Silver oxide Battery</td>
<td>[10]</td>
<td>(2014)</td>
</tr>
<tr>
<td></td>
<td>26 × 11 mm</td>
<td>pH (ISFET)</td>
<td>0-10 (0.2) 70-150 kPa (0.5 kPa) 34-42 °C (0.2 °C)</td>
<td>Wheatstone bridge 433.92 MHz (FSK)</td>
<td>-</td>
<td>Silver oxide Battery</td>
<td>[12]</td>
<td>(2015)</td>
</tr>
<tr>
<td></td>
<td>22 × 11 mm</td>
<td>pH (ISFET)</td>
<td>0-4 (0.0066) 50-200 kPa (0.69 kPa) 25-50 °C (0.087 °C)</td>
<td>FM-VFC PWM Volt. divider 433 MHz (GFSK)</td>
<td>Meandered conformal antenna</td>
<td>Silver oxide battery</td>
<td>(2016)</td>
<td></td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

A complete wireless capsule system is designed and implemented to detect and monitor pH, pressure, and temperature of the GI tract in real-time. A microfabricated pH sensor is employed to measure high acidic pH levels ranging from pH 1.0 to 4.0. The pressure values from 50 kPa to 200 kPa are measured using the pressure sensor. The temperature values ranging from 25 °C to 50 °C are also measured. The FM-based and PWM-based sensor interface IC circuits are adopted to provide a low noise, low power, and high resolution alternative for interface circuit. The processed data from the microcontroller is transmitted using the wireless transceiver with a meandered conformal antenna. The integration of sensors, interface IC circuits, microcontroller, and transceiver circuit with meandered conformal antenna also form a basis for future multisensor microsystems. Components of the wireless capsule are packaged and sealed inside a cylindrical shaped capsule having length of 28 mm and diameter of 13 mm. The packaged wireless capsule is experimented in vitro and validated for real-time monitoring and display of physiological parameters of the GI tract. Future works will be emphasized on further miniaturization...
of both sensors and circuits, sensor diversity, including other functionalities, adopting energy harvesting techniques, and validating the system through human experiments and clinical trials.

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REFERENCES


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