Concepts and developments of an wearable system – an IoT approach

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***Abstract*—This paper presents the concepts and the development process of a new and innovative wearable system able both to track the position and to analyze the movements of the head. This wearable system was developed as a main platform for a large class of applications in fields like: biomedical, medical, entertainment, military, automotive, consumer field etc. In the proposed system, the head position and movements are acquired in non-contact mode and by using some smart clothes that embed several capacitive sensors in the collar. The entire system was developed to be ultralow power and easy cloud-connected.**

I. INTRODUCTION

Nowadays, the wearable systems start to play an increasing and a very important role in the development of a large number of applications. These types of systems are designed to include: **a)** different kinds of sensors (specific to each particular application) and, **b)** sometimes, even actuators that provide feedback to the wearer, **c)** processors and **d)** transmission modules. Their ultimate design is intended to provide final users with small, independent, low-power, wearable and unobtrusive solutions for continuous all-day and in any-place monitoring and forecast systems.

The health monitoring applications are an essential field in which the wearable sensors systems received lots of attention both from the research and the industry communities. The applicability of these systems starts with the infants [1], [2] and ends up with the elderly people [2], [3]. For instance, the fall detection wearable systems [2], [3], [4] are used especially by the elderly people, at least, for two reasons: first, to mitigate the effects of the falls and, second, to significantly reduce the medical care costs associated with these falls [3]. A possible solution for this kind of systems was to place the sensors inside a wrist device (e.g. a smartwatch). However, some studies have already proved [4] that the hand wrist placement generates poorly results due to frequent random movements of the hand. Beside the above particular applications, there are, also, other very specialized classes of wearable systems designed to monitor, to detect and to assess: (1) the epilepsy seizures [5], [6], or (2) the health state of a joint, following a musculoskeletal injury; in this last case, for example, the technical solution includes the airborne measurement of joint acoustic emissions [7].

The wearable monitoring systems are dedicated not only for sick people or people with different types on injuries. Providing accurate information on people's activities and behaviors (i.e., human activity recognition) is an important function of wearable devices, with a large class of applications [8], [9], [10]: coaching (e.g. fitness), performance improvements (e.g. tennis or sky), entertainment, continuous supervising of soldiers on the field, monitoring people in critical environments etc.

The main purpose of the current paper is to present the design details, the key technologies and the practical implementation methods used in the developing of a smart clothing system. The wearable system was conceived as an open platform, able to further sustain a large class of future applications, concept similar with [11].

The smart clothing system was designed as an IoT device. This one uses the device-to-gateway communication in order to connect to an Internet cloud service to further exchange data. A personal computer or a smartphone acts, in this case, as the middleware for the interaction between the Internet (the cloud application [12], [13]) and the “things” (the wearable device – the smart clothing). To build the system with these constructive landmarks, a number of standards must be respected.

Our smart clothing system includes a number of capacitive sensors and it monitors both the head position and the head movements. The head monitoring system has a large number of applications, like: analyzing the head tremor of people with neurological disorders [14], [15], augmented reality system (the synthetic imagery is mapped from the world coordinate system to the helmet coordinate system) - with lots of applications in the fields of military, biomedical and entertainment industries [16], [17], the hand free navigable menu etc. In the hands-free navigable menu applications, the head rotation is processed together with other supplemental information, namely, the eyes gestures [18].

This paper is organized as follows. In the second section, the selection method for the best capacitive sensors is presented. In Section 3, the hardware part of the system is detailed. Section 4 is devoted to the software component, and the last section draws the main conclusions.

We thank to Texas Instruments™ (TI) Company for its IoT development boards and CC2650STK wireless Sensors Tags donation, used in the development of this system.

II. THE CAPACITIVE SENSORS

The working principle of the capacitive sensing solutions is based on the interaction between the electric field lines, generated by the capacitive sensor, and the objects from its proximity.

Right now, there are two main types of the capacitive sensing solutions. The first approach take into consideration a switched-capacitance architecture. The system works by sampling a reference source on the sensing element and, then, by quantizing the charge stored in it [19]. These types of circuits are known under the generic name of capacitance-to-digital converters (CDC). On the market, there are several semiconductor companies that produce capacitive sensor circuits with such a working principle. These circuits are well suited for our application – low power consumption, small size and they are endowed with the ability to interface with a SoC through a SPI bus or I2C bus. For example, Analog Devices™ has the AD714x, AD715x, and AD774x families, Texas Instrument™ is producing the FDC1004 circuit and Silicon Labs™ has the TouchXpress™ capacitive controllers' family.

Unlike the approach described above, the second method uses an oscillator. This one has a frequency given by a circuit with fixed inductance, fixed capacitance, and to which a conductive sensor plate (e.g. cupper – the sensing part of the sensor) is connected. The two fixed characteristics of the circuit set the main oscillation frequency of the sensor. When a conducting object (e.g., a finger or the neck – as in our case) changes its position or moves near the plate, the mutual capacitance modifies the oscillator frequency. By measuring the oscillation frequency, the equivalent capacitance can be determined. The most well-known LC-based capacitive sensors circuits are built by Texas Instruments and include only the FDC2x1x family.

III. THE HARDWARE ARHITECTURE

The simplified design of the smart clothing system is presented in **Fig. 1**. The core of the proposed wearable system is based on the SimpleLink CC2650 wireless System-on-Chip (SoC). This SoC is centered on two ARM processors: **(1)** the Cortex-M3 (CM3) and **(2)** the Cortex-M0 (CM0). The CM3 processor handles mainly: **(a)** the user application layer and **(b)** the Bluetooth low energy (BLE) protocol stack. The CM0 processor controls the autonomous 2.4 GHz RF transceiver radio core and it handles: **(a)** parts of the *link layer* for the BLE RF module, and **(b)** all the low-level radio control and processing functions, associated with the BLE *physical layer*. Moreover, the CC2650 SoC has an ultra-low-power ***Sensor controller engine*** (SCE). The SCE is typically used to interface with external sensors circuits. It works independently of the system's CM0 and CM3 processors and its main function is to wake up the CM3 CPU whenever it has new data.

The head position and movement were acquired using the multi-channel (4), noise and EMI-resistant, high-resolution (28 bits), LC-based capacitive sensors circuit FDC2214. The FDC2214 is connected at the CC2650 SoC through the I2C bus and a GPIO line. The GPIO line, that has a 2 µA consumption, is used to place the circuit in shutdown mode.

Other hardware components used in the developing process were: CC2650STK and SensorTag Debugger DevPack.

IV. THE SOFTWARE COMPONENT

The developed application is sustained by the TI-RTOS. Using the TI-RTOS, the power manager component manages the system (mainly, the CM0 and CM3 processors), keeping it into the lowest possible power mode whenever it is possible.

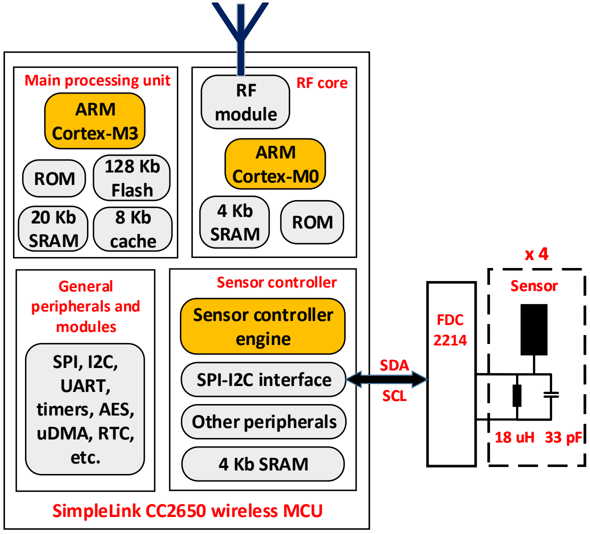


Figure 1. Simplified block diagram of the smart clothing system

There are three different implemented software components and all have to work together in order to sustain the functions of the wearable system.

The ***first component*** is primary responsible with the control and data exchange functions of the RF core, see **Fig. 1**. To do these, a new custom Generic Attributes (GATT) service and four new characteristics, associated with it, were implemented. This service is one associated with the FDC2214 capacitive sensors circuit and has a 128-bit universally unique identifier UUID address of F0001130-0451-4000-B000-000000000000. The first characteristic is used to decide which input capacitive channels should be activated. Writing 0x00 not only will disable all channels for the FDC2214 circuit, but, also, will put this circuit in the shutdown mode. The second characteristic allows the setting of the sensor measurement period – in our case the chosen resolution was 10 ms. Given this value, the FDC2214 circuit starts to perform measurements and the results are stored in the data characteristics. There are two data characteristics. The first data characteristic stores the data channels 0 and 1 of the FDC2214, while the second one stores data channels 2 and 3. Data from each channel consist of four bytes, encoded as unsigned integer. Each data characteristics has reading (for infrequent measurements) and notification function implemented. The wearable system can be configured to send notification to each pair of channels (channels 0 and 1 and/or channels 2 and 3). In addition, the GATT server (the wearable device), also, contains other several BLE services: Generic Access Service (UUID: 0x1800), Generic Attribute Service (UUID: 0x1801) and Device Information Service (UUID: 0x180A) that conform with the official BLE Special Interest Group profiles.

The ***second software component*** is running on SCE. The SCE was configured to be in standby mode. It wakes up when a real-time clock (RTC) triggers an execution code. The wake up period is equal with the one configured in the second characteristic of the new implemented BLE service. When activated, the capacitive sensing acquisition process starts; later, when the acquisition process is finished, a one-shot timer triggers an event handler code (EHC) and, in the end, the SCE is set to the standby mode. In the EHC, the capacitive value(s) from all active channels are taken and an alert signal is used both to wake up the system's CM3 from standby and to start the data exchange process. Finally, the SCE goes to standby, up to the moment when the RTC restarts, once again, all the process.

The ***third software component*** works as a glue layer between the ***first*** and ***second*** software components. It runs on the system core (CM3) and manages: a) the RF driver (the link between RF core and the BLE protocol stack), b) the BLE protocol stack from the link layer up to the user application and c) the Sensor Controller Interface driver (the link between the second software component and the user application).

V. RESULTS

In what follows we are going to detail and to analyze, first, each of the capacity-measuring methods, previously presented. Then, based on the obtained results, we will decide which approach is more valuable to our application.

The electrical properties of the biological tissues are given by a large number of factors [20], [21], [22]: water content (can vary with the time of day or other external factors like temperature) and the ions that are suspended in it, the gradient of water content related with the depth from the skin surface, the physical structure of the tissues, the polarization of the cell membranes (which act as barriers to the flow of ions), ionic diffusion through the cellular membrane and the polarization of water molecules.

In this section of the paper only the static characteristics of two capacitive sensing solutions are obtained and presented. Due to the complexity of the biological tissues and, more, in order to be as realistic as possible, the sensing element was chosen to be the right hand of a subject. The hand was moved on the vertical direction over the center of the sensor. The distance from the hand to the sensors was measured with a rule. The hand was held in a static position with a support.

Fig. 2(a) presents three sets of measurements (indicated by solid circles marks) and their average (squared marks), for the FDC1004 capacitive sensing circuit, in the static case and for displacements up to 5 cm. The detail **(b)** is from displacements of the sensed object up to 12 mm. The details of the sensor characteristic, presented in **Fig. 2(b)**, could be taken - for our particular application - as a complete description of sensor characteristics; our choice is mainly justified by the actual working active range of the sensors placed in the subject's shirt collar. The sensing surface, connected to the channel 0 of the FDC1004, had 2 cm wide and 1.5 cm high and it was completely protected from interferences through a shield. The shield had the same geometric characteristics as the sensing surface. Similar sets of measurements, acquired for the second capacitive sensing approach, are shown in **Fig. 3(a)** and **(b)**. The actual sensor size area was 3 cm^2. The conductive sensor plate was made of cupper and it had the same geometrical dimensions like in the previous case, but this time, no shield structure was used.

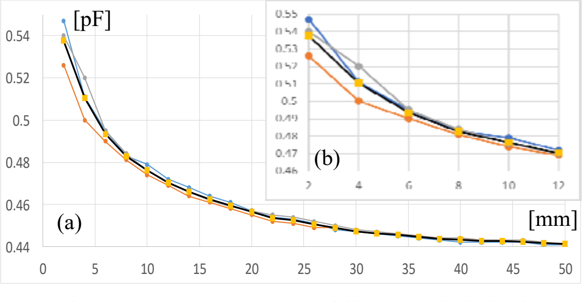


Figure 2. FDC1004 circuit for capacitive sensing solution: (a) static measurements (full range) with the hand as sensed object, (b) capacitive sensor response for the distance to the object in the range of [2, 12] mm

In order to better support the decision process with regard to which could be the best capacitive sensing solution, for our special application, out of the two presented above, a further step was carried out. Namely, the sensors sensitivities and the end point linearity error were computed. Both parameters were estimated by using only the detail part of the sensors characteristics, on the average characteristic.

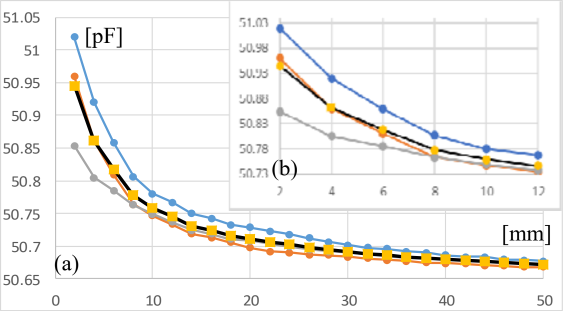


Figure 3. The relationship between the physical input and output for the FDC2214 resonant capacitive sensing solution: (a) three static measurements sets and the average and (b) a detail view for hand displacements up to 1.2 cm

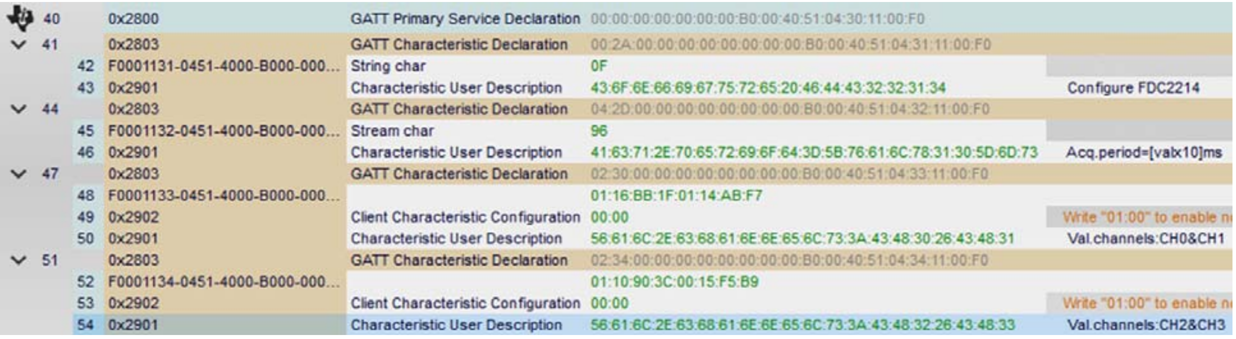
The sensitivity of a sensor indicates how much the sensor's output changes when the input changes – being, thus, given by the slope of the output average characteristic curve **Fig. 2(b)** and **Fig. 3(b)**. The non-linearity describes the worst possible deviation of the actual characteristic curve from an ideal straight line. There are different methods proposed in the literature that could be used to determine this ideal straight line [23]. The most used methods are [23]: best fit straight line (BSFL) and least squares BSFL. In this paper, the first method was employed in order to compute the end point linearity parameter.

TABLE I. COMPARISON OF THE TWO CAPACITIVE SENSING SOLUTIONS

	Sensitivity [pF/cm]	**Non-linearity [%]**
FDC1004 solution	**0.006733**	**25.84**
FDC2214 solution	**0.019867**	**20.81**

Finally, based on the outcomes given in Table 1, we concluded that the best solution for our application was the LC-based capacitive sensors approach.

Another aspect that proved to be of interest for our analysis was also the fact that a major limiting factor, largely accepted in the capacitive sensing applications, is the noise susceptibility of the sensors. From this point of view, we highlight that one of the main advantages of the FDC2214 resides especially in its innovative EMI resistant architecture. Due to the narrow-band of the LC-based capacitive sensors, this solution offers a high rejection of both noise and interferences. Exactly this advantage was another envisaged criterion that led us to the final decision: the FDC2214 is the best sensing solution for us.



40	0x2800	GATT Primary Service Declaration	00:00:00:00:00:00:00:B0:00:40:51:04:30:11:00:F0	
41	0x2803	GATT Characteristic Declaration	00:2A:00:00:00:00:00:00:00:00:B0:00:40:51:04:31:11:00:F0	
42	F0001131-0451-4000-B000-000...	String char	0F	
43	0x2901	Characteristic User Description	43:6F:6E:66:69:67:75:72:65:20:46:44:43:32:32:31:34	Configure FDC2214
44	0x2803	GATT Characteristic Declaration	04:2D:00:00:00:00:00:00:00:00:B0:00:40:51:04:32:11:00:F0	
45	F0001132-0451-4000-B000-000...	Stream char	96	
46	0x2901	Characteristic User Description	41:63:71:2E:70:65:72:69:6F:64:3D:5B:76:61:6C:78:31:30:5D:6D:73	Acq.period=[valx10]ms
47	0x2803	GATT Characteristic Declaration	02:30:00:00:00:00:00:00:00:00:B0:00:40:51:04:33:11:00:F0	
48	F0001133-0451-4000-B000-000...		01:16:BB:1F:01:14:AB:F7	
49	0x2902	Client Characteristic Configuration	00:00	Write "01:00" to enable n
50	0x2901	Characteristic User Description	56:61:6C:2E:63:68:61:6E:6E:65:6C:73:3A:43:48:30:26:43:48:31	Val.channels:CH0&CH1
51	0x2803	GATT Characteristic Declaration	02:34:00:00:00:00:00:00:00:00:B0:00:40:51:04:34:11:00:F0	
52	F0001134-0451-4000-B000-000...		01:10:90:3C:00:15:F5:B9	
53	0x2902	Client Characteristic Configuration	00:00	Write "01:00" to enable n
54	0x2901	Characteristic User Description	56:61:6C:2E:63:68:61:6E:6E:65:6C:73:3A:43:48:32:26:43:48:33	Val.channels:CH2&CH3

Figure 4. The implemented GATT service and the asociated characteristics

The new implemented service, characteristics and all attributes are presented in **Fig. 4.** The figure was obtained using a standard air sniffer BLE Device monitor application developed by Texas Instruments Company.

VI. CONCLUSIONS

Unlike other wearable systems proposed in the literature [1], [2], [15], our wearable system was developed as a main IoT configurable platform for a large class of applications. This system is only the first low-power component (powered by a CR2032 coin cell battery) of a chain that relies on the device-to-gateway communication concept in order to connect to an Internet cloud service. As a result, the wearable system obeys all requirements of the Bluetooth low energy standard version 4.2.

The new introduced system design has another major advantage. Knowing that the CC2650STK development platform embeds 10 low-power MEMS sensors (accelerometer, gyroscope, magnetometer, microphone etc.), other hot new applications, such as human activity recognition, health monitoring systems or fall detection, can be easily implemented.

In conclusion, the new presented system comes with the following advantages: low power, high sensitivity, high noise immunity, small size, high versatility and, more, it is an IoT device (this allows that a large existing expertize and services to be easily used and integrated in the final product).

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