The architecture of an innovative smart T-shirt based on the Internet of Medical Things paradigm

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***Abstract*—This paper deals with a description of an innovative Internet of Medical Things (IoMT) system for implementing personalized health services. The proposed IoMT system has the following advantages respect to the state-of-the-art systems available in literature: (i) it fuses the data provided by several sensors, inertial measurement unit, the bio-impedance and electrocardiogram, (ii) it uses Compressed Sensing (CS) of data prior to transmission, and (iii) it adopts distributed artificial intelligence at the edge for anomaly detection. A description of the specific features and requirements of the wearable device that will be embedded on a smart T-shirt is reported. According to the delineated requirements, an architecture for the wearable device is proposed. Finally the contribution of Artificial Intelligence in the proposed IoMT system is discussed, aiming at identifying anomalies and supporting the process of decision making in the early diagnosis of diseases both at individuals level (local knowledge) or groups of individuals level (global knowledge).**

***Index Terms*—Internet of Medical Things, wearable device, telemedicine, distributed measurement.**

I. Introduction

Advanced wearable health systems are one of the most promising platforms for implementing personalized healthcare and health services [1], because they allow the monitoring of the vital parameters of a single person during her/his daily activities. In [2], wearable devices are defined as "Devices that can be worn or mated with human skin to continuously and closely monitor individual's activities, without interrupting or limiting the user's motions". Nowadays, these wearable devices have been integrated with the telemedicine and telehealth systems, by adopting the Internet of Things (IoT) paradigm [3]. The IoT paradigm consists of interconnecting several devices via Internet, allowing the remote managing and monitoring of physical quantities of the "Things" where the devices are embedded [4]. In case of wearable health devices, the "Things" are the human bodies, and the physical quantities to be monitored concern vital parameters, such as heart rate, respiration rate, skin temperature, and human motion information, such as daily distance walked and fall detection [5]. In this specific application field, the IoT paradigm is commonly called Internet of Medical Things (IoMT) [6]. An IoMT system has to combine both the reliability and safety of traditional medical devices and dynamicity, genericity and scalability capabilities of traditional IoT systems [6]. As reported in [1], research and development on IoMT systems based on wearable health devices was motivated by the need of responding to the following healthcare challenges: (i) the reduction of the healthcare costs while maintaining the high quality of the provided services, and (ii) the shifting of the healthcare expenditure from treatment to prevention through wellness programs. According to the above mentioned challenges, in literature, several kinds of wearable devices for implementing IoMT systems have been adopted [5]: (i) smart clothes, where the sensors and the electronic circuitries are integrated into textiles, (ii) smartwatches, (iii) smart glasses, and (iv) smart gloves [7]. The most promising wearable devices are the smart clothes because they provide more reliable and repeatable measurements than the other ones. For example, in [8], the authors propose an IoMT system called "Maglietta Interattiva Computerizzata" (MagIC). The MagIC system consists of: (i) a vest with embedded one electrocardiogram (ECG) lead sensor, a piezoresistive plethysmography sensor, and a data acquisition board with a Bluetooth transceiver, (ii) a local monitoring station that acquires the data provided by the data acquisition board, shows them to the user, and re-transmits them to a Server via Internet, (iii) the Server, which stores the received data in a database and sends an e-mail to the cardiologists with the recorded ECG and respiration rate signals. The main limitations of the MagIC system are: (i) the sensors embedded on the vest do not allow the monitoring of the user activities, (ii) the movement artifacts affecting the ECG signal are not automatically compensated, (iii) the recorded data are sent to the cardiologists every time the user is starting a data acquisition, (iv) the detection of cardiovascular diseases is directly performed by the cardiologists, and (v) the one-lead ECG sensor can be used for the detection of arrhythmic events, uniquely. Another IoMT system for cardio–surveillance, based on wearable devices embedded on a T-shirt is proposed in [9]. The cardio surveillance T-shirt embeds: (i) a five-lead

ECG sensor, (ii) a microcontroller with the Bluetooth Low Energy (BLE) interface, and (iii) an Electrically Erasable Programmable Read-Only Memory (EEPROM) that contains the microcontroller firmware. The microcontroller acquires the data provided by the ECG sensor and stores them on a buffer. When the buffer is full, the recorded samples are sent to the smartphone via BLE interface. The acquired ECG signals are processed by the smartphone application processor for obtaining QRS and T-wave information. The acquired samples and the obtained information are transmitted by the smartphone to a healthcare centre through Internet connection. This IoMT system has the following limitations: (i) the user activities are not monitored and the artifacts on the acquired ECG signals due to the user movements cannot be compensated, (ii) the system does not detect automatically cardiovascular diseases, and (iii) the recorded data are directly transmitted from the smartphone to the server without performing compression procedures for reducing their amount. Other IoMT systems based on textile wearable devices are described in [1]. In order to improve the reliability and usability of all these systems, the following research challenges need to be addressed: (i) the development of IoMT systems which fuse the data provided by several sensors (e.g. inertial measurement unit, bio-impedance sensor, ECG sensor) with the aim of improving the accuracy of the acquired measurements (e.g. the automatic compensation of artifacts on the ECG signals due to the user movements), (ii) the implementation of compression algorithms that reduce the amount of the data transmitted to the server, (iii) the implementation of Decision Support Systems (DSSs), which process the data provided by the sensors, detect and classify anomalies, and provide alerts, (iv) the minimization of the energy consumption of the wearable device for increasing its battery lifetime, (v) the implementation of high conductivity textile materials that are washable, and (vi) the minimization of the device dimensions for improving the comfort of the wearable system.

In this paper, an innovative IoMT system based on a wearable device embedded on a T-shirt, which aims to address the above mentioned challenges, is presented. The research activity presented in this paper is part of the project titled Ambient-intelligent Tele-monitoring and Telemetry for Incepting & Catering over hUman Sustainability, ATTICUS, supported by the Italian Ministry of Education and Research. In particular, the proposed IoMT system overcomes the lack of existing systems reported in literature, by: (i) allowing the acquisition of data from several sensors which enables the implementation of data fusion algorithms at the wearable device level, (ii) compressing data by means of CS without degrading the measurement accuracy, (iii) implementing an distributed artificial intelligence system. After the introduction, the paper is organized as follows. Section II describes the proposed IoMT system. A discussion about the key features of the IoMT system and the high-level system requirements are reported in Section III. The general architecture of the smart T-shirt, which implements the physical layer of the IoMT system is presented in Section IV. Furthermore, in Section V the architecture of the distributed artificial intelligence (AI) system is shortly described. The last section concludes the paper.

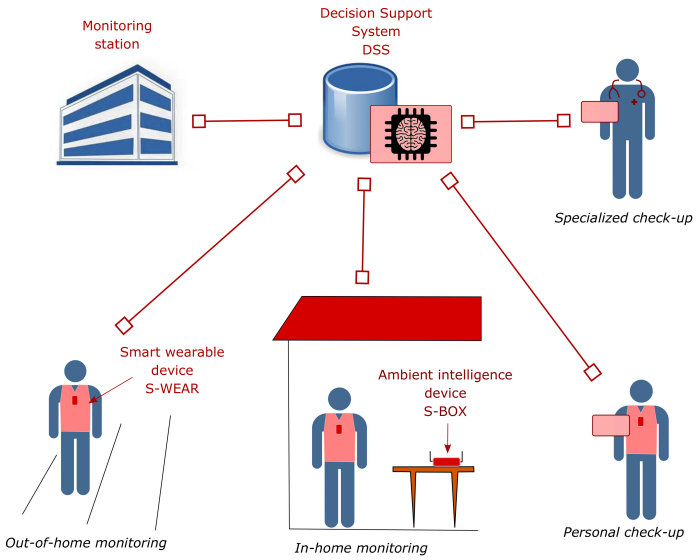

Fig. 1. The architecture of the ATTICUS system.

II. The Proposed IoMT System

The general architecture of the ATTICUS system is depicted in Fig. 1. It consists of: (i) a smart wearable device (S-WEAR), (ii) an ambient intelligence device (S-BOX), (iii) a Decision Support System (DSS), and (iv) a monitoring station.

The S-WEAR is a smart T-shirt that embeds sensors for: (i) ECG monitoring, (ii) respiration rate measurement, (iii) galvanic skin response estimation, (iv) skin temperature measurements, and (v) activity classification and monitoring. Furthermore, it consists of a microcontroller that: (i) acquires the measurements provided by the sensors, (ii) stores them in a SD memory card, and (iii) sends them to the S-BOX via a BLE interface or to the Server via a Wireless Wide Area Network (WWAN) interface (e.g. NarrowBand-IoT NB-IoT, Sigfox, and Long Range LoRa interface). The S-BOX is a domestic station which communicates with the S-WEAR via a BLE interface and is connected to the Decision Support System via Internet. The S-BOX has to: (i) acquire the measurements provided by the S-WEAR via BLE communication, (ii) store them on a memory for a reasonably long period of time (i.e. more than one month), (iii) perform the integration of the information provided by the S-WEAR by applying data fusion algorithms [11], (iv) perform predictive analysis to detect anomalies on the acquired signals in near real-time mode, and (v) notify alerts and provide the real-time tracking of the signals related to the detected anomaly to the DSS via Internet. Furthermore, the data stored on the S-BOX can be sent to the operating unit on request even in absence of critical situations, for the historical analysis of the monitored parameters. The S-BOX is supplied by the electrical grid and is connected to Internet via Wi-Fi or Ethernet interface. The DSS is a centralized system that: (i) receives the alerts

notified by the S-BOX and the signals related to the detected anomalies, (ii) predicts emergency situations, automatically, and (iii) sends the information related to the emergency alerts to the monitoring station. The DSS periodically sends a request of transmission of the acquired data to the S-BOX. The S-BOX transmits the acquired data including the information related to specific emergency alerts by applying a filtering better explained in Section V. The monitoring station: (i) is connected via Internet to the DSS, (ii) receives from the DSS the alert messages related to each user, (iii) shows the received information to the specialized user through an user interface implemented on a hand-held device or a personal computer, and (iv) provides facilities to the specialized user for activating specific intervention through the user interface. Each user will be able to receive from the DSS some integrated information related to his/her activities and the physiological parameters. The integrated information will be visualized on the user own personal computer or handheld device through an user friendly interface. Furthermore, the user will be able to contact and to be contacted from the specialized person for sending or receiving specific personal messages.

According to the above presented architecture, several application scenarios for the proposed ATTICUS system can be foreseen: (i) in-home monitoring, (ii) out-of-home monitoring, (iii) personal check-up, and (iv) specialized check-up. In case of in-home monitoring scenario, the S-WEAR measures the vital parameters of the person, traces his/her position, by means of indoor localization techniques, and posture (lying down, standing, walking). The measurement data are sent in real time to the S-BOX device for storage and preliminary analysis. This analysis is based on the detection of the vital parameters and on the behaviors of the monitored user (local knowledge). The S-BOX verifies the presence of any anomalies in real-time and it communicates to the DSS if there is a warning situation. The DSS, using a wider knowledge, based on the characteristics of all monitored users (global knowledge), confirms, (i.e., it alerts the monitoring station's personnel), or it ignores the alert. In case of out-of-home monitoring scenario, the S-WEAR measures the vital parameters of the person, and it traces the position through the embedded Global Navigation Satellite System (GNSS) receiver. The measurement data is stored locally and it is sent to the Server through the WWAN interface. The S-BOX acquires the data stored on the Server and analyzes them with the aim of identifying any anomalous situations. When an anomaly is detected, an alert is sent to the DSS. In case of personal check-up scenario, using a user friendly interface implemented on the user's personal computer or handheld device, the user can query both the data stored on the S-BOX or on the Server to check the status of the parameters and their time pattern. It is also possible to enrich the monitored data with additional data related to the user's health status, such as laboratory analysis, in order to populate a medical electronic record. In case of specialized check-up scenario, a medical practitioner or healthcare worker can query the monitoring station's database to verify the status of the monitored individual's parameters and possible alert events.

From the aforementioned scenarios, it is easy to deduce that ATTICUS has significant benefits in managing patients by monitoring their medical conditions. For example, by studying and constantly monitoring the ECG, it will be possible to get a general view of a person's heart condition based on historical and statistical trends that can also be cross-lined with lifestyle. At the same time, these data provide the predictive algorithms of ATTICUS with a basis for suggesting lifestyle changes that are viable and contiguous with the vital and operational parameters of the monitored subject. Finally, localization and inertial moves are particularly helpful in tracking older people, allowing the localization of the user on a map and the identification of critical events such as falls. ATTICUS is therefore intended as an instrument to break down the barriers that naturally arise among institutions capable of controlling patients or individuals with disabilities, using a modular, intelligent, non-invasive and inclusive mechanism that allows continuous monitoring and a possible rescue action in the shortest time and with the least amount of resources.

III. The IoMT System Requirements

As reported in the introduction, the ATTICUS system has to overcome the limitations of the IoMT systems already available in literature. In summary, the system has to guarantee: (i) a high accuracy of the measurements related to the monitored physiological and non-physiological parameters, (ii) a high comfort of the S-WEAR, which will be washable and with low dimensions, (iii) a low energy consumption of the S-WEAR, (iv) a low amount of data stored at the S-WEAR, S-BOX and Server levels, (v) a high compression of the transmitted data, while guaranteeing high accuracy of the measurements, and (vi) a low time delay in the detection and transmission of the alerts to the DSS and the monitoring station. In order to achieve the above mentioned high-level requirements, in the following, for the S-WEAR, the main specific features are delineated.

A. S-WEAR

The S-WEAR has to provide: (i) from one up to twelve leads ECG measurements, (ii) measurements related to the user activities (i.e. step counting, fall detection, user orientation, user position), (iii) skin temperature measurements, (iv) bio-impedance measurements for estimating the galvanic skin response, (v) respiration rate measurements, and (vi) heart rate measurements. All those measurements have to be stored on the local SD card and sent to the S-BOX via BLE or to the Server via WWAN interface. In order to reduce the amount of transmitted data and then the energy consumption of the S-WEAR device during the data transmission steps, data compression algorithms have to be implemented on board. These compression algorithms should operate, directly, on the sensor raw data and have to guarantee the accuracy on the reconstructed signals for reducing the information losses. Furthermore, the data processing and transmission delay time has to be as low as possible with the aim of guarantee early warnings. For each type of measurand, in Table I, the

TABLE I
THE MAIN REQUIREMENTS OF THE S-WEAR DEVICE.

Measurand	**Max. sampling frequency** [Hz]	**Number of sensors**	**Sensor technology**
ECG - Heart rate	500	from 1 lead up to 12 leads	ADCs
Step counting	1	1	IMU + magnetometer
Fall	by interrupt	1	
Orientation	100	1	
Position	1	1	GNSS
Skin temperature	1	2	Thermistor
Galvanic skin response	1	1	Bio-impedance
Respiration rate	1	1	Bio-impedance inductive piezoresistive

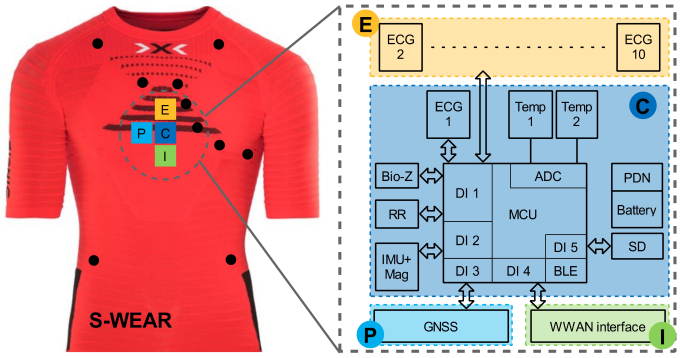

Fig. 2. The architecture of the proposed S-WEAR device.

main requirements of the S-WEAR device, are reported in terms of: (i) maximum sampling frequency, and (ii) number of sensors. Furthermore, for each measurand, an example of sensor technology is reported. From this table, it is possible to note that the higher sampling frequency is for the acquisition of the ECG signals, 500 Hz. For this reason, due to the big amount of acquired data for long time period, a data compression is required for the ECG data. The step counting, fall detection and orientation measurements can be obtained from three sensors, the Inertial Measurement Unit (IMU) that contains a 3-axis accelerometer and gyroscope, and the 3-axis magnetometer. The position measurements are acquired from a GNSS receiver and the two skin temperature measurements from two thermistors. The galvanic skin response is obtained from the bio-impedance sensor. For the respiration rate, three different sensor technologies can be adopted: (i) bio-impedance sensors, (ii) inductive sensors, and (iii) piezoresistive sensors. From the mechanical point of view, the S-WEAR should be comfortable and washable. An example of smart T-shirt that will be used for the implementation of the S-WEAR is reported in [13]. All the electronic parts contained in the T-shirt has to be removable, and the T-shirt washable. Furthermore, the electrodes integrated into the T-shirt for ECG and impedance measurements have to be created through a specific carbon-based membrane and fixed through a heat-seal technique. The T-shirt has to get in contact with the skin, for reducing potential signal distortions on the bio-impedance and ECG signals caused by movement artifacts.

IV. THE GENERAL ARCHITECTURE OF THE S-WEAR

In order to comply with the features and the requirements described in Section III, in this section the architecture of the S-WEAR device is proposed (see Fig. 2). It consists of five modules: (i) the smart T-shirt, which embeds all the electrodes used for acquiring the ECG signals, the bio-impedance (Bio-Z) measurements and the two skin temperatures, (ii) the core module (C), (iii) the extended ECG module (E), (iv) the position measurement module (P), and (v) the Internet interface module (I). The core module (C) consists of: (i) a microcontroller unit (MCU) with the BLE transceiver integrated on chip, (ii) two skin temperature sensors (Temp 1 and Temp 2), (iii) one-lead ECG sensor (ECG 1), (iv) one Bio-Z sensor, (v) a respiration rate (RR) sensor, (vi) an IMU and a 3-axis magnetometer (IMU+Mag), (v) an SD memory card, and (vi) the battery and the power distribution network (PDN), which provides the correct voltage supply to all the modules. The ECG 1, RR, and Bio-Z, will communicate with the MCU on the same digital interface (DI 1), such as Inter Integrated Circuit (I2C) or Serial Peripheral Interface (SPI). The IMU+Mag sensor and the SD memory card will communicate with the MCU through the DI 2 and DI 5, respectively. The two temperature sensors will be connected directly to two analog inputs of the Analog-to-Digital Converter (ADC) embedded on the MCU. According to the chosen architecture, the core module is able to comply with the following features: (i) heart rate measurements, (ii) respiration rate measurements, (iii) galvanic skin response estimation, (iv) step counting, (v) user orientation, (vi) fall detection, (vii) temperature measurements, (viii) local storage of the data on the SD memory card, and (ix) the transmission of the data to the S-BOX via the BLE interface. The E module extends the capabilities in terms of ECG monitoring of the C module, by providing up to nine additional ECG channels. By considering all the channels, it is possible to implement a 12-lead ECG monitoring system, which can be adopted for the identification and the localization of infarction or others cardiac anomalies [14]. The E module communicates with the MCU via the DI 1. Due to the fact that the amount of ECG data increases, in that case, the MCU performs a compression algorithm on the acquired signals before to store them on the SD card and to send them to the S-BOX. The P module is adopted when it is necessary to track

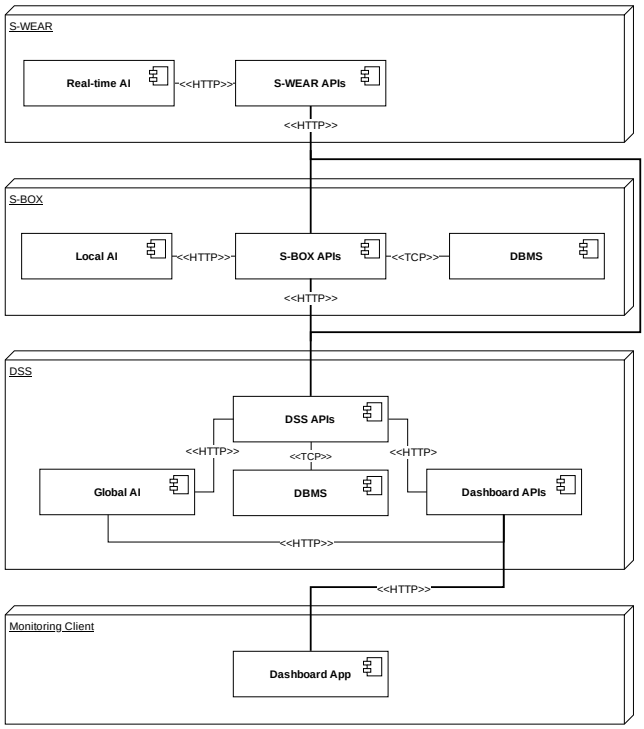

Fig. 3. The deployment diagram of ATTICUS