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Design and Development of Intelligent Electrodes for Future Digital Health Monitoring: A Review

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Abstract. Electrodes are sensors used in electrocardiography (ECG) monitoring system to diagnose heart diseases. Over the years, diverse types of electrodes have been designed and developed to improve ECG monitoring system. However, more recently, with the technological advances and capabilities from the Internet of Things (IoT), cloud computing and data analytics in personalized healthcare, researchers are attempting to design and develop more effective as well as flexible ECG devices by using intelligent electrodes. This paper reviews previous works on electrodes used in electrocardiography (ECG) monitoring devices to identify the key ftures for designing and developing intelligent electrodes in digital health monitoring devices.

1. Introduction

Traditionally, patients with cardiovascular diseases are required to monitor their heart conditions on a continuously basis. The diagnosis and measurement of the patients' vital signs need to be performed in controlled environment such as at the medical centers or hospitals. This clinic-centric approach requires patients to regularly visit the medical centers and hospitals. This traditional approach however can be very costly, tiring and time consuming for the patients. More recently, the Internet of Things (IoT) and supporting technologies such as cloud computing and big data analytics are helping to shift the clinic-centric approach towards the person-centric model or personalized healthcare [1]–[3].

The adoption of IoT, cloud computing and big data analytics in the healthcare industry is not only changing its landscape but also enables a new way of organizing the delivering of health care and health related services in the industry. For instance, with IoT, it is now possible to provide high quality personalized health to all individuals anytime, anywhere and when needed. More specifically, the IoT supported personalized healthcare allows health care and health related services to be delivered to an individual based on his or her unique biological, behavioral, cultural, and social characteristics [4]–[6].

As one of the major innovations in digital technology, the IoT is also increasingly changing the way in which the medical centers and hospitals in the health care sector operate. Since its introduction and adoption in the health care sector, this digital technology has been able to provide various medical and health care applications to the medical centers and hospitals. Among the essential medical applications provided by IoT include; remote health monitoring and delivery, chronic diseases and post-surgery care, fitness programs, elderly care, compliance with treatment as well as medication at home [7].

In addition, the IoT as interconnected technology enables medical devices such as ECG, sensors, diagnostic and imaging devices to be connected to each other as well as between doctors and their patients. These networks of IoT-based devices have helped to not only improve the detection, prevention and treatment of diseases but also reduce medical costs, increase the quality of life and enhance the experience of the patients that use these medical devices [8]–[10].

The major innovations in digital technologies have also made it possible to design and improve the capabilities of existing medical devices such as ECG devices and their essential components. More specifically, the improvement in the contemporary ECG devices has mainly resulted from the adoption of the advances and capabilities found in the IoT and supporting technologies such as cloud computing and big data analytics. However, the literature reveals not only little research but also limited information on the development of intelligent electrodes used in contemporary ECG devices. This paper reviews previous works on ECG devices to identify the key features that useful for designing and developing intelligent electrodes for digital health monitoring.

2. Limitations of Electrodes in Conventional ECG Devices

Electrocardiography (ECG) monitoring system devices are used to obtain information about the electrical activity of the human heart as well as to detect cardiovascular diseases. The electrical activity is recorded by placing the electrodes or sensors in the ECG device on the body surface of the patient.

Regarding the electrodes, the literature indicates that over the years, diverse types of electrodes have been developed and used in electrocardiography monitoring system devices. Each different type of electrode has its own advantages and disadvantages. For instance, according to [11], the traditional wet silver chloride electrode used for accumulating ECG signal from the human body requires not only certain amount of preparations but also needs the expertise of an expert to attach the electrode with wet gel [12]. The wet gel has disadvantages such as irritation, allergic reactions, inflammation, bacteria growth and undergoes dehydration that can reduce the recorded ECG signal quality [13]–[19]. Moreover, the wet electrodes cannot be used for longer period and they must also be replaced on a regular basis.

Besides the wet electrode, the dry electrode was also introduced to collect ECG signal. Like the wet electrode, the dry electrode also has disadvantages such as it often becomes stiff and it can also cause skin irritation to the patients as well. Apart from the wet and dry electrodes, the textile electrode was proposed. However, the textile electrode has a major disadvantage of requiring high pressure for good skin and electrode contact. The other disadvantage is that the textile electrode is most often embedded inside chest strap or wristband and as such it can cause not only discomfort but also constraint among the wearers [20].

In addition to the disadvantages of the conventional electrodes, the study by [21] indicated that there are also other problems linked to portable ECG monitoring devices. Among these problems included; too many cables are required to connect the electrodes with the portable device, overall cost of the ECG device has increased, patients are found to be uncomfortable during long-term monitoring as well as difficulty in acquiring high quality ECG signal because the signal is sensitive and can be affected by noises.

The more recent study by [22] reviewed past research on conventional ECG devices and also identified several issues and problems associated to these devices. Apart from recognizing the various disadvantages of traditional electrode in the conventional ECG devices, the study also verified the following issues and problems related to these devices; the present of artifacts in ECG signals, the adoption of different performance measurement criteria, the complexity of signal analysis algorithm, the impact of electrical entities on the ECG wave morphology and the difficulties in the analysis of the P-wave and the T-wave. Figure 1 and Figure 2 illustrate the conventional electrode.

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Figure 1. The wet electrode for ECG by Philips [23].

Figure 2. The wet electrode for ECG by Ambu [24].

3. Intelligent Electrode and its Key Features

Given the various disadvantages, problems and issues related to the conventional electrodes, more recently, researchers have attempted to introduce more effective wearable ECG monitoring system devices that use intelligent electrode and active cable. The intelligent electrode was developed by using the advances and capabilities found in digital technologies such as IoT, cloud computing and big data analytics.

Regarding the intelligent electrode (also known as smart or intelligent sensor), the literature provides several definitions. For instance, according to [25], there are three different definitions of smart and intelligent sensor. The first definition viewed the smart sensor as the combination of a sensor, an analog interface circuit, an analog to digital converter (ADC) and a bus interface in one casing. The intelligent sensor in the second definition basically considered the sensor as having at least one or more intelligent functions. The third definition however combined the terms smart and intelligent into one single entity. In the third definition, the sensing, interfacing, signal processing, and intelligence functions of the smart sensor are placed in a single chip. The sensor is considered intelligent due to the presence of microcontroller or microprocessor although this alone may not be sufficient. The integrated smart sensor should also contain wireless communication and power management. Examples of the intelligence functions include; self-testing, self-identification, self-validation, self-checking, self-diagnosis, self-calibration, self-compensation and self-adaptation. More specifically, the previous study by [26] stated that intelligent sensor has additional functionality provided by the integration of microprocessors, microcontrollers or application specific integrated circuits (ASICS) with the sensing element itself.

Intelligent electrode can be created by embedding a system-on-chip (SoC) in each electrode to acquire high quality bio-signal [1], [21]. This is possible because the tasks of amplification, filtering, quantization, buffering and transmission of bio-signals are carried out directly on each electrode. The intelligent electrodes can communicate with each other by a serial communication link. This link which is known as the active cable connects all the intelligent electrodes together. The noise interference during ECG signal acquisition can be reduced because the analog and digital conversions happened on the electrodes rather than inside the portable device. The bio-signals are converted into the digital format and grouped in a single intelligent electrode. Then, the grouped data are transmitted wirelessly to the cloud services by using mobile devices for processing and analysis.

The research by [27] proposed a bio-signal acquisition system for both EMG and ECG that comprised intelligent electrode and data acquisition host. The system is small, light and low-cost. It specifically uses the ZigBee based communication as well as perform on-line parameter adjustment. The intelligent electrode consisted of two components that include the ZigBee module and the programmable system on chip (PSoC) chip. It also introduced additional features such as In System Serial Programming (ISSP), I2C connectivity, battery charging, and indicator LEDs. However, this system has limitations such as the software used is not user intuitive and that the prototype which is implemented on the printed circuit board (PCB) has no wearable value.

In another study, [28] developed the intelligent electrode that included low power reconfigurable application-specific integrated circuit (ASIC) and micro spike array to acquire ECG signal. The intelligent electrode developed in the study can be configured as the main electrode or sensing electrode. The main electrode gives reference signal for analog to digital conversion on the sensing electrode. It controlled and acquired ECG signal from each sensing electrodes available in the system. It also provided interface for the Bluetooth module. For the sensing electrode, it performed ECG signal conditioning and signal digitization. The active cable involved five flexible metal strips that have high conductivity and able to minimize the number of connecting cables.

The other study by [29] presented a wearable healthcare monitoring system that consisted of self-organized intelligent electrode which can be used for multiple measurements in various devices such as EEG, ECG and EMG. The intelligent electrode used in this study involved the analog front-end (AFE), successive approximation analog-to-digital converter (SARADC), active cable and digital controller. The digital controller enables the intelligent electrode to be configured to main electrode or sensing electrode.

The study by [30] specifically attempted to design intelligent electrode for personal ECG monitoring device. In this study, the intelligent electrode included configurable ASIC and micro spike array. The intelligent electrode in the study was built up with both field programmable analog array (FPAA) as well as field programmable gate array (FPGA) chips.

Importantly, a review of the previous research on the wearable ECG devices with intelligent electrode suggests several important benefits [31]. Firstly, the wearable device can sense a variety of bio-signals such as electrocardiogram (ECG), electromyogram (EMG), electrooculogram (EOG) and electroencephalogram (EEG) through the intelligent electrode. Secondly, user comfort can be improvised because the numbers of connecting cables are reduced by connecting all the electrodes with a single active cable. Thirdly, the device has serial communication protocol to set up body area network (BAN) with the group of intelligent electrodes. Finally, the intelligent electrode can provide user comfort because it is thin and flexible resulted from inkjet printing and hybrid integration technologies.

4. Design and Development of Intelligent Electrode

The design and development of intelligent electrode for future digital heath monitoring devices are vital for delivering quality health care and health related services. However, the development of these intelligent devices will not only take time and concentration but also requires the adoption of the capabilities from digital technologies such as IoT, cloud computing and big data analytics. When joined together, these technologies can integrate both the virtual and physical aspects of health monitoring and delivery. Furthermore, they are able to reduce the healthcare infrastructure cost, provide more scalability for storing vast amount of medical data as well as accessible to patients 24/7 [10].

According to [31], the ideal wearable sensing devices such as ECG devices should be ultra-thin and light, flexible, ultra-low power consumption, easy to apply and has multi sensing functions. These devices should also be energy efficient and be able to detect diverse bio-signals wirelessly. More significantly, they need to have an intelligent sensor that can determine accurately as well as independently the value of physical, biological and chemical measurements.

The research by [26], [32] proposed the development of an intelligent sensor by using a system that consists of the following three major components; hardware, software and smart sensor micro system. The following section explains briefly the three major components of the intelligent electrode and their relationships.

4.1. Hardware

The first important component of the system involves the hardware. According to the study by [26], the general hardware structure of the intelligent sensor has seven parts: (1) the sensor element that detects movement, language, light, heat, moisture, sound and transform any of them into digital data that can be mined for insights; (2) the amplifier that receives the input and helps to boost low signal levels; (3) the analogue processing has anti-aliasing filters for the conversion stage; (4) the data conversion links to the analogue-to-digital converter (ADC); (5) the digital processing software that processes sensor compensation or pattern recognition methods; (6) the data communication enables the passing, receiving data and controlling signals to the sensor bus; and (7) the control processor acts as the brain of the system and connects to the other elements. Figure 3 presents the general hardware structure of an intelligent sensor.

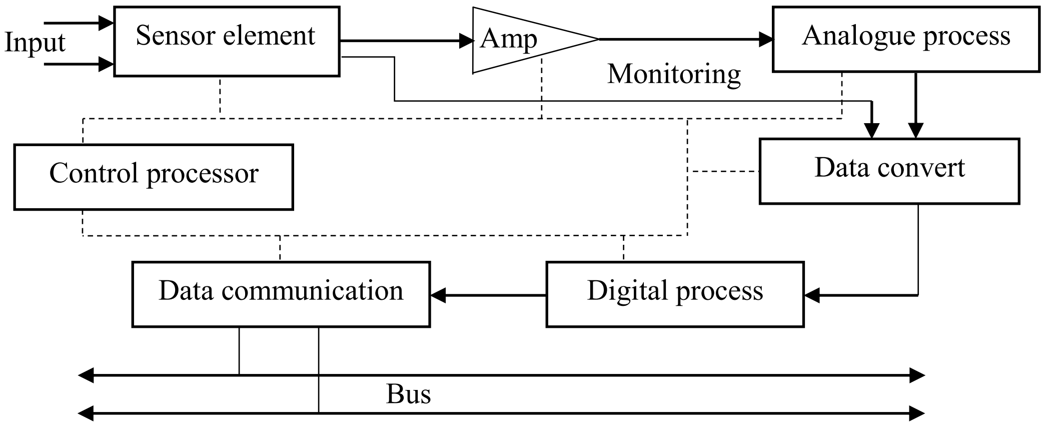

Figure 3. The general hardware structure of an intelligent sensor [26].

4.2. Software

The software is the second important component of the intelligent electrode system. The software applications enable the sensor to perform myriads tasks individually and collectively. For instance, the research by [26] indicated that the intelligent sensor should be able to evaluate the sensor signal originating from the sensing element by integrating the software with the hardware. The software applications should perform the task of evaluation that includes the ability to identify fault conditions, undertake error detection, and perform self-test or self-calibration.

4.3. Smart Sensor Microsystem

When combined, the hardware and software create a micro system for the intelligent electrode. According to [32] the smart sensor microsystem for the IoT can be realized by integrating the four essential functions which are; sensing and actuation, processing and control, power sourcing and management as well as communication. It is also important to identify and understand the application-dependent factors for each of the functions. Size, lifetime and physical interface are the application-dependent for the microsystem. For the sensing and actuation, the application-dependent are the physical parameters to sense, minimum detection limit, dynamic range, bandwidth, and sensing duty cycles. The communication function involves application-dependent such as the communication medium, distance, symmetry, protocol, data rate, and communication duty cycle. Figure 4 shows the structure of the smart sensor microsystem.

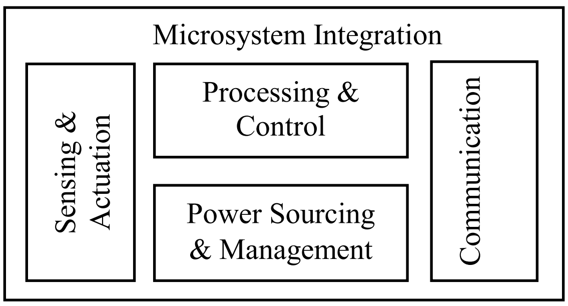

Figure 4. Smart sensor microsystem [32].

5. Conclusion

This paper reviews previous research on ECG devices and highlights how digital technologies such as IoT, cloud computing and big data analytics can help in the design and development of intelligent electrode for future digital health monitoring devices. Based on the review, the paper identified not only limitations of conventional electrodes but also emphasized on the benefits of using intelligent electrodes. In addition, the paper evaluates past studies on intelligent electrodes to determine the various key aspects of intelligent electrodes as well as to propose the system for designing and developing intelligent electrode that can be used in future digital monitoring health monitoring devices.

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