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# Remotely programmable architecture of a multi-purpose physiological recorder

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ABSTRACT

Wearable recording devices are widely used in home care monitoring or follow-up of high-risk or chronic patients. This paper presents a flexible architecture of multi-purpose physiological signal recorder. The recorder supports wired and wireless body sensor networks and features remote programmability of a wide-range of hardware settings, data processing and reporting options and dynamic linking of libraries. The recorder is based on a three-layer architecture including data acquisition, processing and communication modules. The design is not dedicated to a particular purpose, and thus any remote diagnosis based on variety of spontaneous physiological signals (e.g. ECG, EMG) may be performed. The configuration of all three layers is independently controlled by the software and thus allows for real-time reconfiguration of sensors, processing level and report content.



## 1. Introduction

Building an intelligent environment for aging well is presently one of the most challenging topics of information technology. Due to the acuteness of cardiovascular diseases, remote surveillance systems usually dedicated to heart diagnostic, benefit from wearable computers and wireless digital communication [1,2]. The remote health sensing, often put forward in context of cardiovascular off-hospital patients [3–5], has actually a much larger impact on the quality of life [6,7]. It concerns seamless monitoring of large variety of vital or motion signs from sportsmen, elderly people, or members of military or civil services exposed to danger. The design of wearable recorders minimizes their influence to the everyday subject activity. In the same time the embedded processing and reporting procedures simulate the continuous assistance of medical experts. The health surveillance services are supplied by digital communication networks of conventional star-shaped topology and worldwide range. Such networks are managed by their multi-user central servers and consist of multiple remote clients being personal wearable recorders of different kinds. In cardiovascular monitoring, two approaches to the automatic signal interpretation are represented in systems marketed today. One assumes the transmission of the raw signal to the interpretation center (e.g., CardioNet [8], Spacelabs [9], and Cardiobeat CT2014 [10]) while in the other signal processing is fully embedded in the remote device (e.g., Welch Allyn Micropaq [11], GE Healthcare SEER Light [12], and QRS Diagnostic Biolog [13]). Unfortunately, the first method requires a seamless availability of wireless data carrier and significantly raises telecommunication service expenses. The second method, however, suffers from the reliability of the diagnostic outcome depending on a compromise between computing power and energy savings.

Our approach consists in a versatile design of wearable recorder dedicated to wide range measurements of biosignals and accompanying signals [14]. To this point it supports three sources of input data: analog electrical signals, switches and auxiliary sensor data streams. The processing layer includes several universal data processing procedures and simple ECG-specific routines (e.g. QRS detector). These routines are configurable in processing chains and controlled by own calculation parameters. Moreover, the libraries of supplementary procedures may be uploaded and dynamically linked to the on-board processing. Finally, the reporting module is configured accordingly to the output of data acquisition and processing modules. The reporting supports a continuous streaming of raw data, schedule- or request depending transmission of parameters or signal strips and asynchronous reporting of recorder-detected events. In comparison to other proposed solutions described later, our concept shows the following points of novelty: frequentative remote adjustment and customization of the recorder without the personal contact with the patient, reconfigurability and extensibility of supported sensor set and on-board hardware resources and dynamic configuration of biosignal interpretation software (i.e. partial replacement of interpretive software without interrupting the ongoing data processing).

This paper is organized as follows: Section 2 provides a review of related works, Section 3 focuses on details of the recorder's architecture, Section 4 presents a limited-scale prototype recorder

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and the usage case study and Section 5 provides discussion and comments on results.

## 2. Related works

Our proposal of a wearable, programmable multi-purpose biosignal recording and processing device falls in the halfway between intelligent sensors and experimental computer-based recording systems. Selected most relevant achievements in these domains are presented below. We also present a single paper describing a prototype engineered independently in parallel to our work, and now being a closest reference to our achievement.

### 2.1. Intelligent sensors for biosignals

Common features of intelligent sensors are: wireless data communication, low energy consumption and programmability of basic hardware characteristics. An ultra-low power front-end amplifier dedicated to biosignal recordings was proposed by Tseng [15]. The applied 0.18 µm CMOS technology allowed to achieve the SNR value of over 54 dB at a supply voltage of 0.4 V (0.09 µW). The architecture consists of two blocks: a chopper-stabilized instrumental amplifier with common mode interference cancellation and a programmable gain amplifier (0–30 dB in frequency bands 0.5–100 or 10–400 Hz). A year later, Morrison [16] proposed a single-chip biosignal monitoring system with wireless programmability and telemetry interface suitable for various electrophysiological recordings (ECG, BCI, EMG etc.). Its diagram consists of a four-channel low-noise front-end, 8-bit ADC, MICS/ISM transmitter and infrared (935 nm) programming input (gain/bandwidth and transmission channel selection). The prototype is realized in 0.13 µm CMOS technology, weights 0.6 g and consumes 1.07 mW from a 1.2 V supply. The gain can be programmed between 43 and 80 dB with corresponding bandwidth of 230–2000 Hz. Similar solution, proposed by Teng [17] used configurable CMOS integrated circuit front-end for the recording of a wide range of biopotentials. A prototype offers a single-differential or double-differential recording channel topology, with continuously adjustable gain in a range of 37 to 66 dB with a bandwidth of 2.8 kHz. The chip is manufactured in 0.35 µm CMOS technology and needs between 110 and 324 µW for operation, excluding the transmission and storage. Finally, in 2014 Bailey [18] proposed a miniature multi-purpose biosignal data sensor and recorder (2.3 g). The recorder has programmable parameters (sampling frequency, sensitivity) in order to adapt to wide range of biosignal types (ECG, EEG, EMG, EOG). Its 8GB flash memory allows for storage of weeks of such signals in raw format. The recent paper by Wang et al. [19] also presents a general-purpose low noise, low current biopotential amplifier with configurable bandwidth and gain. This paper also includes a comparative analysis of performance of several recently proposed front-ends.

All designs in this category assume the cooperation within a measurement system supervised by a computer responsible for signal processing and storage.

### 2.2. Computer based biosignal recording systems

Various experimental biosignal measurement systems were proposed for laboratory setups for human and animals. These systems usually employ a standardized analog front-end and a set of interpretation procedures implemented in a high level programming language for easy adaptation. The example of such system was proposed by Peterek [20] with use of a general-purpose biosignal front-end g.Bsamp from Gugger and acquisition mode-dependent analysis software in Matlab. It provides a processing chain with configurable parameters for ECG, EEG and PPG signals. Another experimental measuring system for acquisition, processing and evaluation of ECG signal, blood and perfusion pressure dedicated to recording from animals in experimental setups [21]. The analog front-end consists of specialized instrumental amplifiers with adjustable gain, and the signal is sampled with 12-bit ADC at a rate of 1 kHz per channel. Digital data stream is transmitted to a host computer via USB cable and then processed with LabView- or Matlab-based custom-developed software. Recently, Chmelar et al. [22] proposed an experimental device for recording biological signals, such as electrocardiogram (ECG) and photoplethysmogram (PPG), and their use in a new non-invasive method of blood pressure measurement without a cuff. It consists of specialized signal-related inputs, ADC with processing unit and a storage (SD card) and transmission (USB) module. The processor runs dedicated software analyzing the pulse wave delay and calculates the blood pressure.

A wireless data logger with EMG, ECG, and accelerometer transducers for field measurements of biosignals was proposed by Yung-Ping [23]. A four-channel 16-bit signal is acquired at 1 kHz and saved in microSD card, or sent via ZigBee wireless interface (a range up to 100 m with 11dBi/9dBi directional antennas). The device weights 102 g, and requires 430 mW at full power (6 h with two batteries of 860 mAh). A development of Intelligent Electrode and Active Cable concept [24] led to proposing of a biosignal recording system suitable for ECG, EMG, EOG, and EEG measurement [25]. The system includes a custom-designed digital controller to support alternately the network management and biosignal measurements. A mixed-signal system-on-chip with analog front-end (45–63 dB, 0.5–1000 Hz), 8-bit ADC and digital core was made in 0.18 µm CMOS technology and consumes 20 µW from a 1.2 V supply. A separate low-energy Bluetooth chip was applied for wireless digital communication with signal storage equipment. Miniaturization of recording systems also allows for an unprecedented configurability for matrix recording. A leading example here is a multichannel system consisting of an analog front-end, ADC and digital signal processing unit and a wireless transmitter designed to high-density recordings of brain signals (up to 400 channels) [26]. The prototype was fabricated in 0.65 µm CMOS technology and a single amplifier of 2.5 µV noise and 10 kHz bandwidth consumes 17.2 µW from a 1 V supply. The provided classification of recording systems as: (a) analog recording, (b) spike detection, and (c) using a digital-signal processor (DSP) for feature extraction and/or clustering was also adopted in present studies. Such classification applies also to other biosignals, however more sophisticated algorithms are usually applied, depending on expected diagnostic parameters.

### 2.3. Integrated acquisition and processing approach

An interesting ECG-dedicated mixed signal system architecture was presented in a paper by Kim et al. [27]. The system design focuses on low power consumption, but it also provides high degree of configurability thanks to a custom digital signal processor. It is capable to perform ECG-specific operations like motion artifacts removal, heart beats detection, classification and arrhythmia detection based on general signal processing procedures (e.g. Least Mean Square, Recursive Least Squares, Principal Component Analysis and Continuous Wavelet Transform). The design also includes several smart ideas like electrode-tissue impedance monitoring, adaptive sampling, program memory loop buffer and low energy Bluetooth transmission with AES encoding. The prototype was built in a wrist-mounted housing and with power consumption of 32 µW (at 1.2 V) it allows for long time continuous monitoring in various scenarios including life record, emotion monitoring and fitness. However, advanced ECG interpretation was not possible to implement there due to limited computational power.