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Wearable Electronics: A Circuitry Perspective

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Abstract. With the advancement of flexible electronics and low-power circuit design, wearable sensing systems have emerged as a interdisciplinary research area within electronic and computer engineering. These kind of systems can support continual identification with non-disruptive, precise sensing of the physical signs of person with pliable, various type sensor arrays. Viewed from the perspective of the systems engineering approach, this paper classifies wearable device architectures into three mutually supportive electrical paths: the analog signal chain, the digital signal chain, and the energy self-sufficiency chain. At the signal chain level, it focuses on analog front-end design for flexible electrochemical, strain sensor, high-input-impedance Transimpedance Amplification design, differential anti-interference design, analog-to-digital conversion design to ensure that the signal-to-noise ratio and low-drift performance of the microampere-level signal are very high. In the digital chain the study is on the signal processing and information transmitting using an embedded MCU unit. Adaptive filtering, dynamic gain adjustment, and event-driven communication have achieved real-time, low-power data management: The energy chain combines biofuel cell (BFC) and power management unit (PMU), it's proposing the hybrid power chain, which would be combining NFC and the energy scheduling algorithm for autonomous power. Looking at it from the system level, it is hard to say that wearable electronics' core competitiveness comes from better analog, digital, but more likely the synergy between them: This provides a solution for field-effect transistors (FETs) and self-powered smart health trackers. It establishes a scalable implementation approach suitable for both low-power signal processing and energy-autonomous circuits.

Keywords: wearable electronics, low-power circuit design, energy-autonomous systems

1. Introduction

In recent years, due to the rapid development of health management and smart electronics, wearable sensing system has become an important research direction of electronics and computer engineering [1]. The main goal of these kinds of systems is achieving continuous, no-obvious, multiple aspects human physical signals monitoring, supporting practical applications like chronic disease treatment, athlete's quality assessment, human-computer interface and so on [2].

As is evident from Figure 1, for wearable system to be realized, there exist three interdependent technological chains – Signal chain, Data chain, and Energy chain [3]. The Signal Chain centers around analog circuitry, including interfaces and the front-end amplification for electro-chemical,

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capacitive, resistive, etc. sensors. Data chain involves analog-to-digital conversion, digital signal processing and wireless transmission, while the energy chain focuses on energy harvesting, scheduling and management to power the autonomous system. The balance of these three circuit pathways is what will decide if a wearable system is able to properly sense and track the real world environment, all day long with pinpoint accuracy.

In the wearable systems, there are innovations on the flexible materials and processes which made the bases of miniaturization and low power consumption for the next electronic systems [4]. While it is true that the more mature silicon based device fabrication process makes integration of large or performant sensors possible, the rigidity of the silicon device makes it less conformable to nature. Thus, there are more flexible materials like PDMS and Polyimide (PI) being used. At the same time, microfluidic technology has been introduced into sweat analysis platform to quantitatively collect and divert body fluid samples. Controlling the surface wettability and channel architecture and the microfluidic board can guide sweat for a straight path to the electrochem detection spots, so signals are more constant and repeatable [1].

However, as detectors move from single electrolyte to many like glucose, lactate, uric acid and hormones the variety and complexity of signals makes it difficult for amplification and filtering circuits to handle dynamic range, noise as well as power consumption at the same time. Analog circuits need exact matching for high-impedance power sources and microampere current signals and should avoid trouble caused by movement and temperature changes. After analog-to-digital conversion,digital circuits do other important things—data compression, filtering, self-tuning, and wireless transmission—that take "embedded intelligence" to have hardware and software working together all through the system. Especially when there's less energy, we need to think carefully about when to use the system and data and how much power to use to get the best results from every little joule [5].

Under such premises, it turns out that the energy chain is key, and it affects whether a device is actually usable. Traditional Lithium Batteries have stable power but their size, lack of flexibility, inability to charge over a long time, are problems for long term wear. Thus, biofuel cell-based self-power system has become a research hotspot in recent years. Metabolism byproducts like lactate and glucose can provide power to current that medicine uses on electrode to make circuit works fast. This technology uses enzyme-accelerated reaction to provide power through electrode. It has been combined with near-field communication (NFC) and Bluetooth Low Energy (BLE), which provides fully wireless, bidirectional energy and data links. At the same time designing energy saving circuit and power scheduling algorithm is required to make system work autonomously.

From the system's perspective, the actual value of wearable sensors isn't these tiny sensing articles, it is the work done by bringing microfluidics, biointerfaces, analog circuits, digital algorithms, and power systems together [4]. It can be said that material and process set the limit, while circuit and system design sets the performance limit. This paper designs the analog front ends for system signals sequencing, designs the digital chains of embedded processing and wireless transmission, and realizes the power management systems of energy-autonomous engineering. Through system level and electrical mechanism analysis, in order to summarize the development process which wearable sensing system has gone through from the circuit level all the way to the system level and give some design ideas to the researchers working on high integration as well as self-powering smart health electronics [5]:

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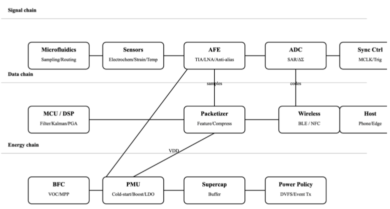

Figure 1. System-level block diagram of a wearable electronics platform showing the signal, data, and energy chains

2. Analog front-end and signal chain optimization

The signal acquisition stage in wearable sensing system starts at the part that is tightest with the human body—from the physical-electrical changing of the sensing units and physiological signals [6]: No matter whether it is electrolyte concentration detection, metabolite detection, or other physical quantity detection like temperature, strain, and flow rate, all information will first convert to recognizable voltage or current signal of electronic circuit: Human signal source is usually a high-impedance, low-amplitude, and large environmental noise signal. The front-end part needs to be designed sensitively, quietly, and power-saving, but not too sensitive. It should be designed carefully.

In sweat detection systems, there is a complete electrochemical sensor, which has a working electrode, a reference electrode and also a counter electrode [7]. Electrode surfaces are generally made of precious materials like gold, platinum or other ion concentration-sensitive membranes, as well as enzyme or ion selective membrane materials. These are functionalized materials [8]. As for PAR, when we test things like lactic acid and glucose, some enzymes can cause something similar on metal, with electrons moving at a charge and the shifting charge is related to the amount, but those kinds of signals are usually in the microamps or lower range and come with tons of noise. High-input-impedance transimpedance amplifier (TIA) [8] is used in the first part of the signal chain to get steady numbers on bendy, stretchy electrodes.

TIA design needs to consider signal bandwidth and controlling input bias current at the same time. The amplifiers can use a low-bandwidth amplifier with a high gain for the physiological signals that have a slower dynamic, like lactate, potassium, and glucose in sweat. Multimodal platforms like the ones that combined electrochemical and strain sensing module uses programmable gain amplifier(PGAs), so that they can make changes in the gain at any time and also match the signals coming into it on different channels dynamically. Flexible integrated circuits usually use operational amplifier arrays and low-noise metal-oxide-semiconductor field effect transistor (MOSFET) structures to keep signals intact even when consuming very little energy [9].

Input protection and noise suppression are equally indispensable at the interface between electrodes and amplifiers. The front end of the analog is always in a human environment with a lot of electromagnetic interference. The analog front end needs to have an input network with electrostatic discharge protection and low-pass filtering to filter out high-frequency noise and protect against sudden changes in electrode potential that could damage the equipment [10]. But some system is also using pseudo-differential readout to reduce the common-mode interference at the front-end physical layer, coupled with shielding and reduced by the wiring length of the parasitic capacitance effect.

After signal conditioning the system needs to do channel specific filtering and offset correction. Sweat signal's characteristic of slow-changing and low-frequency, so common front-end filtering

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structure will be combined with high-pass capacitive-coupling and low-pass RC filtering to remove the baseline drift and motions-artifacts [7]. Temperature and strain usually use the Wheatstone bridge layout, and we can get very precise results if we use the trimming resistor or differential amplification. In the phase response of each front-end filter has to be calibrated thoroughly when the channels are being sampled simultaneously so as to avoid the distortions caused by the timing delays [11].

Analog-to-digital converter (ADC) is the main bridge of the analog world to the digital world, hence, the performance of ADC determines the entire signal's quality of the system. Since sweat signal amplitude is typically in the millivolt range, a $\Delta-\Sigma$ or successive approximation ADCs with high resolution and low input noise [1] is required: In low-power applications, the structure is simple and fast conversion speed make the SAR ADCs more suitable for real-time monitoring. The sampling-holding circuit and the ADC's front-end reference voltage stability determin the linearity and quantization errors when the system does continuous sample. In order to conserve power, there are some use a time-division multiplexing architecture.

As for the realization of flexible integrated circuits, usually the analog front end is realized at the same time as the metal interconnection layer on the flexible substrate. The metal layer is formed through thin-film deposition and lithography processes. It's in charge of signal transmission and providing a low resistance path to the electrode bias and amp power supply. And at the system packaging level, using polyimide C for electrical insulation, as a sweat resistant, robust and long-time stability can be achieved. Flexibility and chemical inertness make this layer a barrier between sweat and electrolytes, thereby preventing sweat from causing changes in bias current or input resistance.

In short, the analog front end is like the human nerve node nearest to the whole body within the entire wearable electronic system [12]; The synergistic operation of multiple circuit layers such as high input impedance, low noise amplifier, differential noise rejection, high precision ADC makes sure the output data is stable and repeatable even if the physical body is complicated, have different movement.

3. Digital signal processing and edge computing architecture

In wearable sensing systems, once the analog signals are converted from analog-to-digital format, they enter into the digital realm, and thus the physical information is represented as information [13]. Digital pathway takes on vital work, handling data and managing it, working on things as they happen and fixing errors, also passing along messages. It is determined by it to a large extent the response speed, accuracy, and energy efficiency of the sensing system [14];

In multi-channel integrated wearable platform, the most difficult for data path is the parallel sample and the channel multiplexing [15]. Since flexible sensors usually integrate many kinds of simple array sensor (such as electrochemical sensors, temperature sensors, strain sensors), so it needs to use time division multiplexing or spatial division multiplexing to obtain data at once. For time division multiplexing structures, it uses high-speed multiplexed analog switches, and in a single sampling cycle, it sequentially connects each channel input. So it lets us use one ADC for digitizing more than one signal, shrinks the chip's size and power but maintains the accuracy [16]. In the structure with more nodes such as the multi-node FISA (flexible integrated sensor array), a distributed analog-to-digital converter (ADC) architecture is employed. Use multiple ADC circuits to sense different types of area, so as to get rid of signal collision and sequential delay: The basic principle of this architecture is keeping clock synchronization and channel calibration so that we can spatially register and join digital analysis for many dimensions of physiology.

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Data is processed by MCU or SOC after being acquired, there is filtering and pre-processing work [17]: Since there is often low-frequency drift and temporary noise due to sweat, electrode contact, and action, the system must filter and rectify clean signals in the digital world. The usual technique is to use an IIR filter for the baseline drift and an FIR filter for the high-pass components with a fixed delay. The signals may be non-stationary body fluid conductivity, dynamic body moving strain, it will use Kalman filter and adaptive weighting algorithms to perform real-time noise and signal state modeling. The hardware version of such algorithm usually uses embedded digital signal processing chip, which uses lookup table and fixed number to reduce power cost while keep doing efficient real-time execution in low-bandwith data stream.

The second layer of logic comes after the data filter and involves dynamic gain and automatic calibration mechanism [18]. The output of continuous monitoring is that the response curves of the electrochemical sensor can also drift because of changes in the concentration and skin surface temperature of the sweat. To guarantee outputs are stable, the system uses closed-loop calibration in the digital domain: it takes samples of reference channels or temperature-compensation units right now, and then it changes the gain and bias of the front-end amplifier. The embedded controller turns the analog gain by the digital potentiometer or ADC output. Calibration of cross-domain multimodal signal is used in similar way. Like setting multivariate models with ion concentration and temperature, the digital system changes detection coefficients live and fast according to real-time stuff, so it can keep its measure right in the tricky parts of our bodies.

Under the upper structure of the digital pathway, the communication module is responsible for two duties: information output and the system's energy handling. Bluetooth Low-Energy (BLE) and NFC are the two main wireless transmission solutions [19]. BLE offers more distance and stability; thus, it can be used for continuous streaming of real time data. The NFC module is a kind of ultra-low power consumption device with battery-free feature, it can do two-way energy and data exchange by using short-range field coupling. To achieve a balance between communication efficiency and energy autonomy, the device commonly carries out power domain partitioning at the micro-controller level: once detection channels are stable, the BLE module goes into sleep mode and only retains clock function and interrupt observing. When there are breakages, threshold change and other irregular samples, the system quickly wakes the communication module for synchronization. Event-driven communication has greatly decreased power usage; it makes devices last much longer [14].

It's not like the making of wireless data transmission is all about the communication protocol but also about the improvement of both hardware and algorithm. To stop energy consumption from getting too high because of lots of information, systems make things smaller and find important parts close by [16]; A usual strategy uses embedded codes to work out important looks (things like signal summits, full quantities, or frequency lists), just sends back the squished numbers or looks figures through radio waves instead of big packages. Some will use edge computing architecture which does partial signal analysis on device and sends resulting decision to the terminal [19]. This design philosophy changes from passive sensing of wearable devices to active analysis, saves energy but improves the system response speed a lot.

And also it is very crucial regarding the materials' time and power [15]. For multithreaded task scheduling, MCUs use DMA method to do parallel data collection and file storage, so they don't keep interrupting the CPU often and get better at it. Clock management part changes the speed and power depending on the different situation. And it keeps ultra-low power consumption when nothing is happening but it can jump super fast to working super well when there's sudden loads of data. In this DVFS (Dynamic Vo3/Frequency Scaling) method which is used on low power devices, such as

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cell phone and wearable, it try to find the best dynamic balance between power usage and performance.

Digital systems don't just take in analog signals anymore—via smart scheduling, on-the-go tweaking, energy savvy, they turn into the spinal cords of the whole wearable electronics system. In order to bridge the analog and logic worlds they achieve the most representative cross-layer optimization between electronics and computer: Engineering, coordinated circuit and algorithm & communication protocols [13].

4. Energy autonomy and power management systems

In wearable electronic systems, energy supply and management are very important parts of making them work well in real life. In contrast to traditional wearable that uses batteries that need to be replaced or charged from time to time, the next wearable will aim to become power independent—energy self-sustains from body fluids, environment, or wireless—ensures constant functions [14].

Right now, lactate biofuel cells (BFC) seem to be one of the best ideas [13]. These systems use lactate found in sweat as fuel and carry out redox reactions between electrodes powered with enzyme to make very tiny amounts of electricity through low-energy circuit. BFCs bring some clear pros in terms of being eco-friendly and flexible: with constant sweat production happening during exercise time, this gives a steady source of fuel so they can keep working all by themselves without needing help from outside sources. BFCs can be combined with electrodes and microfluidic channel freely, which can be achieved to have space co-existence together with get signals and power generation [17]:

However, the BFC output power is low, and it changes a lot, so the PMUs that manage the system need to be good, because PMUs use boost, voltage regulating and energy storing modules to change the unclear electrochemical power into stable DC power and provide power for the sensor and communication modules [20]. Some use little supercapacitors or energy buffer components to even out the power surge due to a sudden load change [21]; Other study uses wireless NFC to assist external energy Coupling so as to enhance the device endurance.

Energy autonomy and power management transcend mere power supply concerns, forming the core logic throughout system design [22]. Merges energy collection, power transfer and job scheduling into the future wearable will realize continuous functions, which give more reliable and independent system for medical observation and human-machine co-operation.

5. Conclusion

This paper analyzes in a systematic way the core architecture of wearable sensing system from perspective of electronic and computer engineering, where the interaction of three parts is focused, i.e., analog front end, digital signal chain and energy autonomy in system design: The research shows that the core idea of wearable sensors is to get accurate information and intelligent processing of multidimensional physiological, while the engineering difficulty lies in the circuit stability integration of low-power communication and energy closed-loop system [1].

With integrating high-input-impedance readout circuits, embedded digital filtering algorithm and low-power wireless modules, the device delivers continuous and accurate data with complex dynamic bodily fluids. At the same time, the combination of biofuel cells and power management modules gives us a source of energy that is sustainable and ensures that it runs for a very long time without needing another power source [13]. Currently, this system-level synergy between energy

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management and information processing is driving the evolution of wearable devices from simple health sensors to intelligent health platforms.

Looking forward to the future, the further application of artificial intelligence and configurable circuits will lead to wearable system having better adaptability and learning capability [17]. Coupled with standardized interfaces and secure communication protocols, wearable devices appear to be essential infrastructure for personalized medicine and man-machine collaboration, which will greatly promote in-depth development in smart health and digital physiology research [22].

References

[1] A. J. Bandodkar et al., "Flexible wearable chemical sensors, " Nature Reviews Materials, vol. 5, pp. 539–556, 2020.

[2] J. A. Rogers et al., "Stretchable electronics for skin-mounted biointegrated devices, " PNAS, vol. 111, no. 47, pp. 17019–17024, 2014.

[3] D. Qin, Y. Xia, and G. M. Whitesides, "Soft lithography for micro- and nanoscale patterning, " Nature Protocols, vol. 5, no. 3, pp. 491–502, 2010.

[4] H. Y. Y. Nyein et al., "A wearable microfluidic sensing patch for dynamic sweat secretion analysis, " ACS Sensors, vol. 3, no. 5, pp. 944–952, 2018.

[5] R. Ghaffari et al., "State of sweat: Emerging wearable systems for real-time, noninvasive sweat analysis, " ACS Sensors, vol. 6, no. 4, pp. 922–940, 2021.

[6] M. A. Iqbal, H. A. Khan, and S. H. Khan and "Advances in healthcare wearable device" npj Flexible Electronics 5 (2021), 9.

[7] A. J. Bandodkar et al., Battery-free, skin-interfaced microfluidic/electronic systems for simultaneous electrochemical and colorimetric analysis of sweat. ScienceAdvances, vol.5, eaav3294, 2019.

[8] Y. Yu, H. Y. Y. Nyein, and W. Gao, "Flexible electrochemical bioelectronics: "Rise of in situ bioanalysis, "Advanced materials, VOL.32, No.19, 2020.02.083.

[9] T. Someya et al., "Skin electronics by ultrathin organic semiconductors, " Science, vol. 354, pp. 1191–1194, 2016.

[10] M. N. Szentirmay and C. R. Martin, "Ion-exchange selectivity of Nafion films used in electrochemical sensors, " Analytical Chemistry, vol. 56, no. 10, pp. 1898–1902, 1984.

[11] D.-H. Kim, R. Ghaffari, N. Lu, and J. A. Rogers, "Flexible and stretchable electronics for biointegrated devices, " Annu. Rev. Biomed. Eng., vol. 14, pp. 113–128, 2012.

[12] L. B. Baker et al. "A skin-interfaced microfluidic platform with real-time monitoring of sweat rate and total sweat loss, " Science Advances, Vol. 6, eabe3929, 2020.

[13] Y. Liang, R. Zhao, and L. Li, "Lactate biofuel cells: Recent advances and applications: Advanced Energy Materials, Vol.10, 2001786, 2020.

[14] Y. Song et al., "Wireless battery-free wearable sweat sensor powered by human motion, " Science Advances vol. 6, eaay9842, 2020.

[15] Z. Advanced Energy Harvesters and Energy Storage For Wearable And Implantable Medical Devices by Gao et al., Appearing in Advanced Materials, 2024.

[16] C. Dagdeviren et al., "Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm, " PNAS, vol. 111, pp. 1927–1932, 2014.

[17] J. Shen, X. Wang, and Y. Liu. Hybrid energy harvesters for wearable and implantable devices.n Nano Energy, vol. 87; 106146; 2021.

[18] S. I. Self-powered wearable electronics by energy extraction from human motions, Park et al. Nature Communications. 10(5748).

[19] W. Ehrfeld and H. Lehr, "Deep X-ray lithography for microfabrication, " Radiation Physics and Chemistry, vol. 45, pp. 349–365, 1995.

[20] C.-T. Huang et al., Stretchable power sources for biointegrated electronics, Advanced Energy Material, vol.9, 1900300, 2019.

[21] S. Xu, Y. Zhang, and L. Jia, "Soft microfluidic assemblies for energy-autonomous wearable systems" Advanced Functional Materials, vol 33, 2305442, 2023.

[22] H. Lee et al. Wearable / disposable sweat based glucose monitoring device with in - situ transdermal drug delivery. Science Advances, vol. 3, e1601314 2017.