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Integrating mems sensors in wearable biomedical devices: challenges and opportunities in embedded systems

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Abstract.

Wearable biomedical devices, aided by the advancements in Micro-Electro-Mechanical Systems (MEMS) sensors, are creating new opportunities in personalized healthcare. These nano-sensors have the potential to measure physiological, bio-chemical and kinetic parameters, and are contributing to transforming health monitoring by elaborating continuous non-invasive monitoring. This paper addresses the multilevel interplay of MEMS in current wearable biomedical mechatronic architectures, with a specific focus on the MEMS embedding into system on chip and embedded system architectures. MEMS accelerometers, gyroscopes, pressure sensors, and biosensors are indispensable to contemporary equipment for cardiac activity, respiration, glucose, hydration and neurological signal monitoring. In spite of their revolutionary capabilities, MEMS sensors cannot be directly incorporated into wearable embedded systems due to a number of issues. These issues involve signal noise and drift, power consumption, sensor calibration, miniaturization, biocompatibility, and robust real-time data communication under resource-constrained platforms. The embedded system designer also needs to meet strict low power requirements but yet provide fast sampling rates and edge computing features. In addition, the interconnection of different sensory systems, the intricate algorithms for sensor fusion and the security of personal health information via secure systems are important issues. On other hand, this fusion creates unprecedented opportunities as well. Innovations in low-power microcontrollers, ultra-low-power wireless communication protocols (e.g., BLE, NB-IoT), and smart data processing techniques like TinyML enable context-aware, adaptive, and autonomous healthmonitoring systems. Such systems are particularly useful in the handling of chronic diseases, such as diabetes, epilepsy, and cardiovascular diseases. Moreover, the integrated microfabrication, provided by MEMS technology, combined with soft electronics and flexible substrates, offers an emerging direction toward next-generation biomedical wearables that are stretchable, skin-like, and noninvasive. This paper presents a comprehensive survey on the landscape of MEMS sensor integration into embedded systems for wearable healthcare, covering the latest advances in the area and the recent progress as well as open issues. It also takes a future-oriented view on how AI-based sensor data processing, energy harvesting methods and cybersecurity architectures can be employed to mitigate existing shortcomings. The proposed work contributes to the advancement of more reliable, scalable, and user-centric biomedical wearables that support quality of life and shift patient care paradigms.

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1. INTRODUCTION

Wearable biomedical devices are commonly available, providing non-intrusive means for monitoring multiple health parameters. MEMS sensors are the key component of these devices that offer the required sensitivity and miniaturization for proper monitoring. The inclusion of these sensors in embedded systems offers opportunities for innovation but also challenges that have to be overcome in order to achieve maximum performance and user experience.

The convergence of Biomedical Engineering (BE) and embedded systems, we are witnessing a dramatic change of the healthcare industry with the advent of the wearable biomedical devices.

These devices have proven to be particularly important to drive non-invasive, continuous and real time monitoring, providing people and professionals the capability to observe physiological parameters in a way that has never been possible (Kim et al., 2019). The global market for wearable medical devices is estimated to exceed \$60 billion by 2027, indicating that there is increasing interest from consumers in personalized health, management of chronic disease, and fitness tracking (Nan et al., 2022).

Central to these wearable systems are our old friends, Micro-Electro-Mechanical Systems (MEMS) sensors: little devices that mix mechanical and electrical components on a microscopic scale.

MEMS sensors have transformed wearable devices with the ability to sense humans in multi-modal sensing modes such as motion sensing, pressure sensing (flex/press), temperature sensing, chemical/biological sensing etc., within miniaturized, low power footprint (Ghasemi et al., 2020).

For example, wrist-worn fitness trackers and fall-detection devices integrate MEMS-based accelerometers and gyroscopes, while MEMS pressure sensors are found in smart insoles and respiration monitoring systems (Dahiya et al., 2019).

MEMS sensors and its integration with embedded computing platforms are important parts of the wearable biomedical devices functioning. Embedded systems dedicated-to-purpose computerized devices with real-time processing capability,

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often power optimized constitute the computing core of these systems, being in charge of collecting the data, extracting features, processing it, sending information wirelessly, and allowing users to have a look at current and past recordings (Fischer et al., 2016).

However, such integration is not at all straightforward and contains numerous difficulties. Designers need to manage conflicting requirements in size reduction, battery life, sensor accuracy, and processing power, all within tight constraints dictated by medical-grade needs and user comfort.

In the face of these challenges, the convergence of MEMS technology with embedded system design provides transformative potential for applications in biomedicine.

However, with advances in material science, low power design, as well as machine learning techniques targeted at edge computing (TinyML), the subsequent era of wearables is expected to offer smarter, more adaptive, and patient centered solutions (Zhang et al., 2021).

These advances are especially encouraging in the context of chronic diseases, i.e., diabetes, cardiovascular, and neural diseases, in which a continuous monitoring may substantially improve the precision of diagnosis and the timing of intervention (Gao et al., 2016).

In addition, the advent of flexible and stretchable electronics extends the MEMS-integrated wearables platform through the development of skin-like systems which can be formfitting and conformal, biocompatible, and nontethered. These advances lead to the era that seamless integration of human physiology and digital diagnostics comes from hospital-based interventions to daily personal life (Kim et al., 2019).

In this framework, the paper offers an insight into the key challenges and opportunities in the integration of MEMS sensors in wearable biomedical applications, and it specifically addresses the embedded architecture, energy management, signal processing, and future technology trends.

By drawing together the information available in various engineering, medical, and computer science disciplines, the presented study aims at providing a holistic approach that may assist the community of researchers, developers, and clinicians in developing the next generation of wearable

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biomedical systems.

2. MEMS Sensors in Biomedical Wearable Devices

MEMS based sensors, such as accelerometers, gyroscopes, pressure sensors, and bio-sensors, play an essential part of wearables devices to acquire data on heart rate, respiration, and glucose levels. The small and the low power consumption of these sensors fit well the requirements of continuous surveillance systems. For example, MEMS accelerometers are highly used in fall detection system and activity monitoring -since, motion and orientation changes are detectable by them (Ghasemi et al., 2020).

3. Challenges in Integration

Challenges in Integration are:

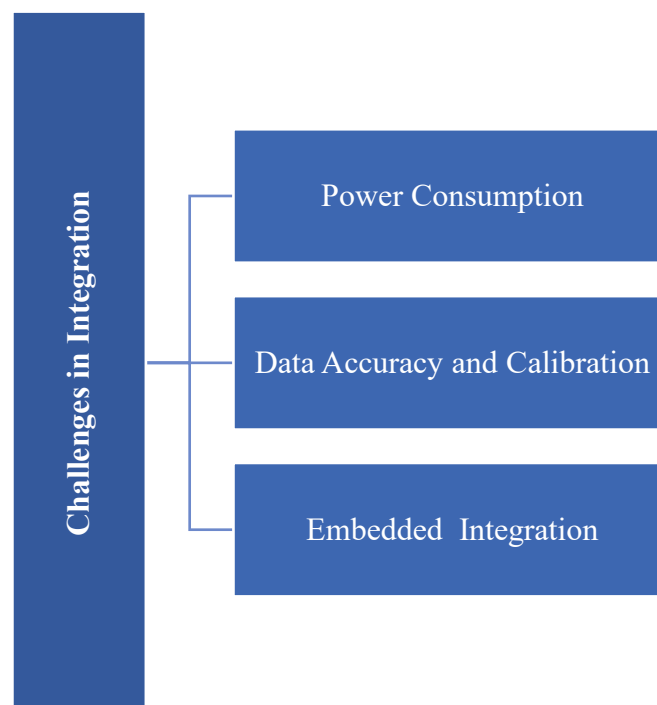


Figure 1

Challenges in Integration

Source: prepared by author

3.1. Power Consumption

One of the major issues with MEMS sensors integration on wearable devices is power consumption. However, the

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extraction of consecutive data, as well, causes fast battery drain, that may not make the device very usable. Approaches such as duty cycling, energy harvesting and low-power electronics are being investigated to address this limitation (Dahiya et al., 2019).

3.2. Data Accuracy and Calibration

Reliable health monitoring cannot be achieved without accuracy of the data. Since MEMS sensors are sensitive to noise and drift, data quality may be compromised. By periodically calibrating and using advanced signal processing algorithms, stability can be maintained over time (Ghasemi et al., 2020).

3.3. Embedded Integration

Together, MEMS sensors and embedded systems need to be designed by taking into account both hardware and software compatibility. These challenges involve providing end-to-end latency of real-time data processing, handling resource-constrained computation capability, and ensuring system stability. Developments in system-on-chip (SoC) solutions and modular design strategies are enabling increasingly full-body integrated solutions (Fischer et al., 2016).

4. Opportunity for Embedded with 2 to 4 years experience:

4.1. Advanced Data Processing

MEMS sensors paired with embedded systems provide new levels of processing such as real-time analytics and machine learning. Such functions enable advanced health tracking and predictive diagnosis, expanding the application scenarios of wearables (Zhang et al., 2021).

4.2. Personalized Healthcare

Wearable gadgets could be tailor-made through such embedded systems for personalized health applications. Using data obtained from MEMS sensors, devices may deliver personalized feedback and recommendations – which is expected to increase patient engagement and outcomes (Ghasemi et al., 2020).

4.3. Scalability and cost-effectiveness

Steps forward in fabrication and standardisation are enabling the scale of production needed for wearable devices. This scalability, and the decreasing cost of MEMS sensors, drive down the barriers to entry for wearable health technology to a wider set of individuals (Fischer et al.).

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Figure 2

MEMS Wearable Integration

Source: prepared by author

5. CONCLUSION

The penetration of MEMS (Micro-Electro-Mechanical Systems) sensors into wearable biomedical devices represents a disruptive extension that can completely redefine what is known about and how health is monitored and managed. Through the real-time, non-obtrusive, and in-context data acquisition, these technologies have greatly improved the possibilities of personalized health-care and of early disease detection. Embedded system, serving as the computation and control center, allows MEMS devices to operate as smart and standalone systems that performing sophisticated signal processing, user interaction, and wireless communication in limited resources.

Yet, even with these developments, many obstacles remain that need to be overcome in order to deliver the full potential of MEMS-integrated wearable devices for biomedical applications in practice. Among them, power efficiency is a major challenge: a lot of wearable devices are restricted by low battery capacity, which restricts long-term seamless use, especially for patients who need uninterrupted measurements.

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Advances in low-power microcontroller units (MCUs), energy harvesting and power management algorithms are key to addressing this impediment. As well, sensor reliability is still a major concern MEMS sensors are generally prone to noise, thermal drift and mechanical fatigue, which may result in physiological measurements that become less accurate and consistent over time.

A second key challenge is to obtain robust sensor-embedded system integration while minimizing the impact on device size, usability and performance. The close integration of MEMS sensors and embedded processors requires novel co-design approaches that ensure efficient computations, signal integrity and fast response. Compatibility with additional parts including wireless modules, memory, and energy management circuits increases complexity even more. Embedded AI (e.g., TinyML) has become a promising direction for on-device processing of sensor data with efficient, compressed models and reduced demand on continuous cloud communication.

Peace of mind and information security are also especially important in healthcare and biomedical use cases. Wearables enabled with MEMS frequently capture sensitive information in health care, hence they are potentially vulnerable to security breaches. Trusted embedded system architectures, edge encryption, and trusted execution are key to preserving data integrity and user confidence. Compliance to regulations (e.g., HIPAA, GDPR) shall also be taken into account at early stages in the development of these kinds of devices, to ensure they are compliant with healthcare standards worldwide.

For opportunity, MEMS sensor integration is enabling new research and clinical directions. For instance, multimodal sensing wearable systems (e.g., ECG, PPG, motion, sweat composition, temperature sensor combined) allow to populate rich datasets that capture the entire health status of a patient. Such systems are especially useful for long-term condition monitoring, elderly care, rehabilitation and the like where subtle changes in the physiological behaviour can provide early alerting cues.

Furthermore, the progress of flexible electronics and nanomaterials is also adding to new landscape of MEMS sensor utilization from conventional rigid wearables. Clothing-

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borne, skin-applied and even subdermal devices are increasingly becoming practicable for a nonspecialist. These developments not only improve comfort and compliance but also improve the signal quality by ensuring the continued contact with the biological surfaces.

With the development toward smarter, connected and more ubiquitous devices worn at the body, the use of MEMS sensors and embedded processing will evolve. The coming future will be about personalized, predictive and preventive care using omnipresent, data driven wearables. But interdisciplinary cooperation between (bio)medical engineers, embedded system designers, data scientists, the medical community, and the policy makers is needed to overcome current bottlenecks and scale innovations in a safe and ethically responsible way.

In summary, despite significant engineering and practical roadblocks, integration of MEMS sensors in wearable biomedical devices offers unprecedented opportunities with the potential to greatly impact healthcare today. The converged power of MEMS technology and embedded devices has the potential to re-shape healthcare delivery from reactive treatment to proactive health management, from clinic-driven to distributed wellness ecosystems. At the same time, research needs as we proceed ahead, are not necessarily to look for advancements and innovations only, but also how technologies may become accessible, equitable and sustainable in bringing these beneficial solutions at scale.

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