Wearable IoT Devices for Health Monitoring

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Abstract

Advances in wearable electronics pave the way for a new class of devices that combine sensing, processing, and communication. These devices enable a wide range of applications including health monitoring, activity tracking, and human-computer interaction. However, three key challenges prevent the widespread use of wearable devices. First, users stop using these devices quickly due to frequent charging requirements. Second, existing wearable devices are bulky and uncomfortable since they are designed using rigid materials. Third, the value of wearable devices has not been demonstrated yet by high-impact applications. This paper presents a set of potential solutions to these three challenges. More specifically, we start with a runtime optimization technique that can enable recharge-free operation. Then, we discuss the design of physically flexible and stretchable devices, which are comfortable to wear. Finally, we review high-impact wearable applications ranging from health monitoring to human-computer interaction.

1 Introduction

The Annual World Report on Disability reveals that 15% of the world's population lives with a disability, while 110 to 190 million people face significant difficulties in functioning [31]. Diagnosis, treatment, and rehabilitation of this population depends on the behavior observed in a clinical environment. After the patient leaves the clinic, there is no standard approach to continuously monitor the patient and report potential problems [7]. Moreover, frequent visits to a clinic can be challenging for patients with movement disorders, while self-recording is inconvenient and unreliable. The quality of life of this population can be improved significantly with the help of *wearable internet-of-things (IoT) devices* that combine sensing, processing and wireless communication capabilities within a small form-factor.

Wearable IoT devices offer an attractive solution for continuous health monitoring and augmenting clinical treatment. Sensor data can be processed both locally and at a gateway by mobile health applications to enable remote diagnostics [4,7]. Wearable devices are ideal for health monitoring since they can enable monitoring users in a free-living home environment. As a result of this capability, health professionals can evaluate the progression of symptoms over time. Despite recent promising results, the widespread use of wearable devices is hindered by three key challenges. According to user surveys, many people stop using wearable devices due to frequent charging requirements, which is imposed by limited battery capacity [12, 21]. Therefore, there is a strong need for techniques that can harvest energy and manage it optimally at runtime. These techniques can minimize, or ideally, completely eliminate battery charging requirements. Another source of user irritation is the size and shape of current wearable devices. Many patients report that they feel uncomfortable and awkward wearing physically perceptible devices, such as headsets [21]. Hence, there is a need for replacing conventional devices made by rigid materials with physically flexible and stretchable alternatives. Finally, the adoption of new devices can be enabled only by high-impact and practical applications that demonstrate their value. There is a wide range of wearable health and activity monitoring solutions. However, their clinical relevance and contributions to users' quality of life (QoL) are yet to be proven [7]. To address these three challenges, we discuss respective solutions in the following areas:

1. Energy-neutral operation through optimal energy harvesting and management,
2. Wearable IoT devices using Flexible Hybrid Electronics (FHE),
3. New wearable applications enabled by integrated sensing, processing, and communication.

The rest of this paper summarizes our contributions in these areas. Section 2 details our work on energy-neutral operation of wearable devices. Then, Section 3 presents the proposed wearable health monitoring ecosystem. Section 4 discusses high-impact application areas enabled by wearable devices, while Section 5 summarizes our conclusions and future directions.

2 Energy-Neutral Operation

Frequent recharging requirement is cumbersome for users. This burden is aggravated for patients who suffer from functional disabilities [7]. Therefore, extending the lifetime of wearable IoT devices is critical to make them user-friendly. Since the overall device weight and wearable form-factor severely limit the battery size, we must leverage ambient energy resources. To this end, recent research has focused on developing energy harvesting solutions, using ambient light [22], body heat [9] and body motion [10] to extend the operating time of wearable devices. Moreover, the harvested energy must be utilized optimally to maximize the amount of time the device stays powered (i.e., the active time) and its utility (e.g., the amount of processed data). Therefore, there is also a need for runtime energy management techniques that can channel the harvested energy to power the IoT device and recharge the battery in the background. In this way, we can achieve *energy-neutral* operation while maximizing the utility of the device.

Flexible photovoltaic (PV)-cell modeling: Flexible PV-cells offer great potential for energy harvesting in wearable applications. First, they can adapt to the shape of the clothing and body, unlike rigid materials. Second, their energy harvesting potential (100 mW/cm^2) is significantly larger compared to piezoelectric (0.73 mW/cm^2) and thermo-electric generators (0.76 mW/cm^2). However, flexible PV cells can experience various levels of bending depending on their placement on the body. The degree of bending (i.e., the radius of curvature), in turn, affects the amount of energy that is harvested. For instance, our experiments on a commercial PV cell show that the maximum power point varies by as much as 56% with bending of 50 degrees [22]. Therefore, we first model the energy harvested by flexible PV cells while considering their amount of bending. More specifically, the proposed model calculates the radiation received by a PV cell as a function of its radius of curvature, the intensity of radiation, and the angle of incidence of the light. It is able to predict the harvested power with a 4.8% error when compared to experimental results obtained with a commercial PV cell. Consequently, this model enables the designers of wearable systems to predict how much energy can be harvested at a given time and location. Hence, it helps to obtain the energy budget available for wearable devices. Furthermore, this model is also used by a maximum power point tracking (MPPT) algorithm at runtime to maximize the energy harvested from the PV cell. Our experiments show that this algorithm increases the harvested energy by up to 25% when compared to a baseline approach that does not take bending into account.

Near-optimal energy allocation algorithm: Scarce energy must be utilized optimally at runtime to ensure that the wearable device stays operational. Therefore, many recent approaches have focused on developing algorithms to allocate the harvested energy over a period of time, such that the device does not experience any downtime [2, 13]. To enable energy-neutral operation, we propose a dynamic programming algorithm that optimally allocates the harvested energy while maximizing user utility [2]. The proposed algorithm takes as input

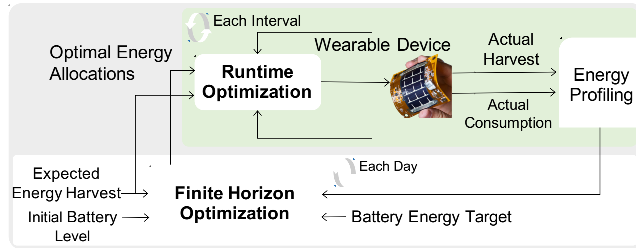

Figure 1: Overview of the energy allocation algorithm

the expected energy harvest over a finite horizon, the initial level of battery energy and a target battery level, as shown in Figure 1. Then, we derive a closed form solution using dynamic programming to determine the energy allocation for each period in the finite horizon. This step is performed at the beginning of the horizon and takes a constant amount of time to execute. While this solution is optimal as long as the actual energy harvest energy matches the expected value, there may be variations in the harvested energy. Therefore, the second step of the algorithm performs reallocation of the energy at runtime to compensate for these variations. We keep track of the actual energy harvested in each period and change the allocations in the future intervals based on the deviations from the expected harvest. Our experimental evaluations using real solar radiation data show that the algorithm is able to achieve results that are within 3% of the optimal solution computed offline.

3 Wearable IoT Devices using FHE

Existing wearable devices are largely limited to wristbands and watches since rigid materials are uncomfortable to wear. Moreover, many patients feel awkward when they wear physically distinctive devices, such as headsets [12, 21]. In contrast, flexible and stretchable electronics enable lighter, thinner, and low-cost solutions that conform to the body [5]. Thus, they offer attractive wearable solutions like electronic shirts, ties, and jackets. However, their performance is still orders of magnitude lower compared to state-of-the-art CMOS technology. FHE overcomes these limitations by combining the performance advantages of rigid integrated circuits and form factor advantages of printed electronics [3, 14]. As a result of these advantages, FHE has attracted significant attention in recent years [8, 28, 30].

A number of studies have proposed wearable devices designed with FHE technology [25, 27]. For example, Rose et al. propose an adhesive sensor patch for monitoring electrolytes in human sweat [27]. This device integrates a radio-frequency identification (RFID) chip on a flexible substrate, where the RFID chip is used to both power and sense the sweat data. The sensor data is then transmitted to a smartphone for further processing. Similarly, Polkis et al. propose a wearable ECG monitor using the FHE technology [25]. The device

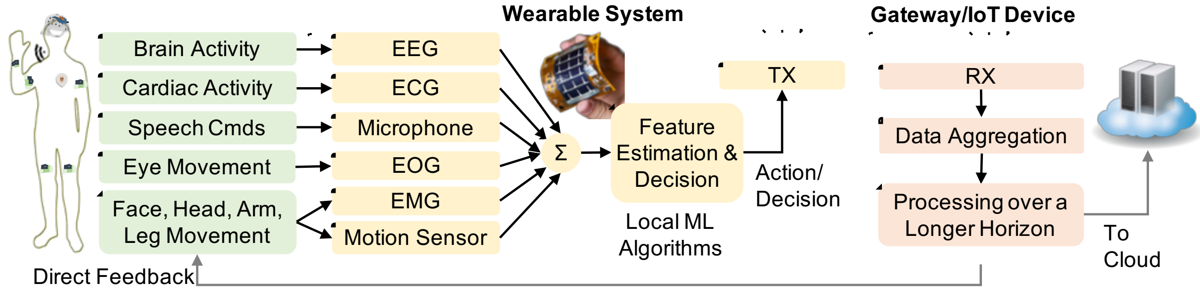

Figure 2: Overview of the wearable ecosystem

includes a microcontroller, ECG electrodes, and signal conditioning circuitry for ECG monitoring. The device continuously acquires data and transmits it to a host.

We envision that wearable devices form a central component of future health monitoring ecosystems, as shown in Figure 2. On-body sensors are used to capture a variety of physiological signals, speech commands, and user movements. For example, electroencephalogram (EEG) and electromyography (EMG) signals can be monitored together with human motion to detect the human intent [16, 20]. The sensor data is processed in real-time by one or a network of wearable devices for health monitoring or human activity recognition. Data is processed locally using resource-constraint machine learning algorithms to avoid transmitting raw sensor data over a network. Local operation not only reduces the wireless communication power, but also improves privacy [7]. We prototyped one specific instance of the envisioned wearable device as shown inside Figure 2. Our wearable device prototype integrates a TI CC2650 MCU, Invensense MPU-9250 motion sensor and other components mounted on a flexible substrate [8]. Since energy-neutral operation is one of the primary goals, we use a flexible PV cell and energy harvesting circuitry to harvest energy from ambient light. The device also supports Bluetooth low energy and Zigbee communication protocols to connect to a gateway [29].

In the envisioned system, the wearable device connects to a gateway, such as a smartphone or local router, as shown in Figure 2. The gateway receives the actions or decisions of the machine learning algorithms on the wearable device. It is responsible for aggregating data from multiple devices and processing the aggregated data for a longer duration, such as a week. The longer horizon allows analyzing trends and periodic patterns that repeat daily or weekly. Finally, the gateway is connected to the cloud, where the health professionals can access and evaluate the user data.

4 Target Application Areas

Widespread adoption of wearable devices depends critically on new applications that can impact the QoL of users. Thus, a significant amount of recent research has focused on developing health and activity monitoring applications using wearable devices. One of the most popular applications is physiological monitoring and wellness [18]. These applications use activity trackers for amateur users [6] as well as professional athletes [17]. The activity trackers measure quantities such as speed, distance, and cadence of the user. These quantities are then used to evaluate metrics related to body posture evaluation and muscle fatigue. These metrics, as well as the collected data, are shared with the user for feedback and gamification purposes. The feedback is useful in demonstrating specific steps while doing an activity of interest. Furthermore, gamification helps in building a sense of competition among the user community and encourages users to be more active [33].

Vital sign monitoring is another significant application area of wearables. Vital signs such as body temperature, pulse rate, respiration rate, blood pressure, blood sugar, and sweat rate are helpful in monitoring or detecting medical issues [15]. Since wearables are portable, convenient, and non-invasive, vital signs can be measured either in a hospital or at home. Furthermore, wearables can enable continuous monitoring of vital signs. The real-time monitoring helps keep patients safe and provides a closer link between clinician and patient allowing for more personalized and timely health care. For instance, smart bandage is an emerging application in the vital sign monitoring field [19]. A smart bandage contains sensors, a drug carrier, and a microprocessor. It detects early signs of wound infection using metrics such as pH, bleeding condition, and pressure. If an infection is detected, it injects an appropriate dosage of drugs to the patient.

Another high-impact application of wearable technology is increasing the QoL of individuals who suffer from limited mobility, either due to age or movement disorders. Examples include fall detection applications for elderly, tremor and freezing of gait detection for people with Parkinson's Disease, and accurate assessment/treatment for post-trauma and post-surgery movement capabilities [24, 26]. In addition to these, human activity recognition (HAR) has also received significant research attention in the context of movement disorders since it allows doctors to understand the activity patterns of patients [4]. HAR tries to identify the various activities in daily life such as sitting, standing, and walking. Due to its numerous applications, we implemented HAR on our wearable device [1]. We employed a textile-based stretch sensor along with our prototype to identify common activities, such as, *sit, stand, lie down, walk, jump*, and transitions among them. To enable this application, we collected data from 9 users and implemented a neural network classifier. Our experiments show that the classifier achieves an accuracy of 97% for all the activities.

Wearable devices are also used for human-computer interaction applications. These applications use gesture recognition to enable interaction medical devices, assistive devices, and games [11, 32]. Due to the high-impact of these applications, we implemented gesture recognition on our wearable device [23]. Using the accelerometer data on our device, we trained a neural network to recognize gestures such as *up, down, left* and *right*. These gestures can be used to control an electric wheelchair or other assistive devices.

In summary, applications reviewed in this section have the potential to increase the adoption rates of wearable devices by improving the quality of life of the users.

5 Conclusion

Wearable devices have the potential to change the landscape of health and activity monitoring. This paper presented the key challenges that hinder the widespread adoption of wearable devices and proposed solutions to address them. To this end, we presented an algorithm to enable recharge-free operation of wearable devices. Then, we used flexible hybrid electronics technology to develop a wearable device for health monitoring. Finally, we presented high-impact target applications that can enable widespread adoption of wearable devices.

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