# Energy Minimization and Reliability for Wearable Medical Applications

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## Abstract

*Wearable medical systems, which are used for medical monitoring, assessment, and/or treatment have the essential requirements to be low energy consuming and reliable. They must be energy efficient, so that battery size is minimal, to ensure that the systems are convenient to use. Also, they must be highly reliable, because they are being developed for critical medical applications.*

*In this paper we examine the critical requirement of energy minimization, specifically for wearable medical systems. We present an overview of the general power management schemes, along with more specific approaches tailored to wearable systems. We specifically highlight two medical wearable systems, RFAB and CustoMed, being developed by our group. Finally, we discuss the relationship between reliability and power management, and how this impacts the critical medical systems we are examining.*

## 1. Introduction

Wearable medical systems are composed of sensors, actuators, and computation and communication units that are used for medical monitoring, assessment, and/or drug or other treatment administration. These systems have the following the important requirements. First, they must meet their functional requirement. Second, they must be convenient to use, or wearable. Finally, they much be highly reliable, because they are developed for critical applications. In this paper we address broadly the last two requirements.

We present an overview of different power management approaches, including dynamic voltage scaling, battery energy optimization techniques, and system-wide energy management techniques that can be applied to wearable medical systems. Then we address, more specifically, the requirements of wearable medical systems. In particular, we highlight the RFAB and CustoMed systems. In the area of wearable medical systems, and more generally wearable systems, we take a look at specific approaches that tackle the important energy minimization goal that these systems strive for. Finally, we discuss the relationship between system reliability and energy minimization.

## 2. Energy Management Techniques

### 2.1 The Problem of Energy Management

Energy minimization is a critical requirement for medical systems, and for wearable computing in general. Given a required system lifetime, a more energy efficient approach will decrease the size of the battery required to ensure the proper lifetime of the system and/or minimize time between recharges. Additionally, cooling and packaging costs can be minimized, if heat dissipation can be controlled.

Advancements in battery technology are being far outpaced by the evolution of IC technology, however. As a result system level solutions, which reduce the burden on batteries by intelligently scheduling the execution of tasks, are able to bridge the gap and meet the growing energy requirements of embedded systems.

### 2.2 Dynamic Voltage Scaling (DVS)

In this section we provide an overview of three main approaches to energy management, dynamic voltage scaling, system-wide energy minimization, battery energy optimization.

#### 2.2.1 DVS Power Model

The majority of the previous work assumes that the switching, or dynamic, power dominates the power consumption of the processor. Switching power per cycles is given by the following formula,

$$P = C_{eff} \cdot V_{dd}^2 \cdot f$$

where $C_{eff}$ is the effective switching capacitance, $V_{dd}$ is the supplied voltage, and $f$ is the frequency [14]. Consequently, energy expended is given by the following formula,

$$E = C_{eff} \cdot V_{dd}^2 \cdot c$$

where $c$ represents the number of cycles executed with the supplied voltage [14]. In general, there is a linearly proportional relationship between frequency and voltage.

Dynamic voltage scaling takes advantage of the quadratic relationship between voltage and energy to reduce energy consumption. Dynamic voltage scaling algorithms aim to decrease the applied voltage up to a point so that deadlines are still met. This is referred to as just-in-time execution. Scheduling algorithms are critical to ensure just-in-time execution of tasks, so that power consumption can be minimized, without adversely affecting performance.

The general problem requires, the assignment of real-time tasks to resources and the assignment of voltage and frequency setting over a period of time, with the goal of minimizing the energy consumption.

There can be many variations to this problem, as we discuss below.

### 2.2.2 Uniprocessors vs. Multiprocessors

A large portion of the research in power scheduling algorithms has focused on uniprocessors. The scheduling and assignment of tasks onto multiprocessors generally has been solved utilizing heuristics that have a two-phase approach. They assign jobs to the resources, and then they allocate the voltages for the processors, assuming the job assignment was determined in the first phase [32][56].

Yu and Prasanna [53] examine the two problems of assignment of jobs to resources and the determining of the voltage levels in a joint manner. They formulate the problem as an integer linear program (ILP), and they utilize a linear relaxation heuristic (LP-relaxation) to solve the problem.

### 2.2.3 Online vs. Offline and Discrete vs. Continuous Voltage Settings

Yao et al in [54] present an optimal static algorithm for dynamic voltage scaling, assuming continuous voltage values were available.

Algorithms that assume continuous voltage values set the voltage of the system to any voltage value. Many current processors, however, such as the Tansmeta Crusoe processor [49], do not support continuous voltage values. Instead they have a discrete set of acceptable voltage values.

Kwon et al [29] developed an optimal algorithm for static voltage scaling given discrete voltage values. Static, or offline, algorithms are aware of all of the tasks that are to be executed. They present a feasible scheduling of tasks onto a single processor and present an optimal voltage selection for energy minimization. One limiting assumption made is the fact that all tasks are assumed to have equal uniform load capacitance. Later they present a modified version of the algorithm to consider non-uniform load. Another interesting method has been proposed by [59] in which not only they consider discrete voltage values but also consider dynamic workload. Their method relies on integration of a DVS scheduler and a feedback controller within the EDF (earliest deadline first) scheduling algorithm.

In reality, most environments do not lend themselves to predicting tasks that will be executed in the future. Especially, when the future is the entire lifetime of a system. Hence online algorithms are required for real world low power system execution. Yao et al in their paper [53] also formally presented an online dynamic voltage scaling algorithm. The online algorithm is based on an average rate execution of tasks. The average rate algorithm determines the density at each time unit and dynamically sets the processor speed accordingly. The algorithm, however, similarly depends on the availability of continuous voltage values.

There do exist other online dynamic voltage scaling algorithms [3][[45], but they too do not consider the cases where there are only discrete voltages available.

### 2.2.4 With and without Dynamic Power Management

Energy minimization techniques can be classified in two broad groups. The first, called dynamic power management, aims to shutdown processors when they are idle. The second, dynamic voltage scaling, dynamically varies the voltage supplied to the processor, to provide just in time execution of tasks. Benini et al provide a survey of the paper in these areas [3][4]. Irani et al combine the two methods, DPM and DVS, for systems with DVS and multiple power modes [17].

### 2.2.5 Leakage Current Changes Everything

As feature sizes decreases, the effect of static or leakage power will because increasingly important. Until recently, dynamic power was a must more considerable component of the power consumption, and hence most approaches ignored the effect of leakage power. Slowly, it is becoming foolish to ignore this component, which is posed to match the dynamic power component. [28].

Jejurikar et al provide a scheduling approach for dynamic voltage scaling, while considering the effect of leakage power. [23]. They also extend this work to consider fixed priority scheduling while still considering the effects of leakage power [24]. Huang et al. approach the problem of intra-program scheduling while considering leakage power in [16].

#### 2.2.6 Sub-threshold Voltage

Most techniques take a look at varying the voltage from $V_{dd}$ to about half of that. Research is underway to extend the range, including all the way down to the sub-threshold voltage range. Zhai et al take a look at the energy efficiency of this approach in [54]. They demonstrate the energy efficiency of using sub-threshold values for specific applications, but show that deep sub-threshold operation is never energy-efficient. More detailsed look at subthreshold voltage usage is done by [39][50][51].

### 2.3 System-Wide Techniques

In addition to DVS techniques that consider only the processor, researcher have taken a look at system-wide approaches to energy management. This approach can be very robust, since local optimizations at the processor may not produce the best overall optimization.

Choi et al present a dynamic voltage scaling approach that considers all of the system components, including idle and fixed system components in addition to active components whose energy consumption can be varied by using a dynamic voltage scaling scheme. [11] Jejurikar et al in [25] examine system-wide energy minimization, while considering leakage power in [25].

### 2.4 Battery Optimization Techniques

Minimizing power consumption is not necessarily directly related to the decreasing the battery requirement. Battery characteristics make this relationship much more complicated. There have been proposed task scheduling approaches that consider battery energy dissipation characteristics while task scheduling [32][41][61][62]. More recently, Rao et al examined the question of when to optimize the battery lifetime versus when to consider only energy optimization. One conclusion they mad is that the fine-grained task scheduling does not always produce gains in battery lifetime [42].

Specifically for wearable medical systems, Martin et al have taken a look at battery properties in a real wearable computing systems, with their wearable ECG monitoring deice. [33][34][35].

## 3. Wearable Medical Systems

### 3.1 RFAB and CustoMed

An example of wearable medical system is the RFAB projects created at UCLA [21][22][14]. The underlying feature of these systems is the ability to reconfigure the devices to ensure reliability of the system, given the wear and tear of daily life. The RFAB architecture consists of several computational resources along with physiological sensor and actuators. All the computation and reconfigurability is embedded into these low-profile processing elements. The target medical application of RFAB is fatal heart detection. Increasing system lifetime as a function of power consumption is an effective ways to increase the reliability of such systems. Power saving techniques can be applied in different levels starting from efficient algorithms to low-power electrical components. RFAB utilizes wired communication through wires woven into fabric.

Another proposed architecture for wearable medical systems is called CustoMed [20]. The basic idea behind CustoMed is having wireless enabled distributed sensing and computational components named “MedNode” are placed all aver the body. While having wireless communication offers more design and application freedom, the issue of power consumption and reliability grasps new challenges. Wireless communication is one of the major sources of power consumption in this system.

### 3.2 Wearable Computing and its Approach to Energy Minimization

Wearable computing shares common requirements with technology for medical applications. The technology is placed close to the body and therefore it must be comfortable. Thus the battery usage reduction for minimizing the size of the battery is an important constraint.

General wearable systems share many requirements with systems tailored to medical applications. The main difference is the degree to which the requirements are flexible. For medical applications, the wearable systems must be very wearable because it tends to be used by unwilling patients who much wear the technology for long periods of time. Second, the reliability of the medical application is critical to the patient's health.

There are many groups working in area of the wearable computing including. A number of them have taken a look at power minimization and battery usage minimizations for wearable systems. An overview of general system issues facing wearable computing can be found in [47].

Dorsey and Siewiorek have taken a look at online power level monitoring in wearable systems, so that the power available can be treated as a resource to allocate [12]. Bharatula et al have developed an energy efficient circuitry for a wearable device. Through a real-life office worker scenario testing they have demonstrated the large energy reduction can be achieved with their system [38].

Wearable systems groups are also taking a look at obtaining energy from sources other than batteries. These techniques are referred to as energy harvesting, energy scavenging, or parasitic energy harvesting. Energy harvesting is also being studied in the related area of sensor networks [26], for source such as solar and vibration energy.

More specifically for wearable computing, attempts have been made to capture the kinetic energy produced humans to power their systems, at least partly. A general overview can be found for some of these projects in [1]. Buren et al attempt to scavenge energy from human kinetic energy [6][7]. MIT's Media lab is using of piezoelectric materials to convert mechanical energy, from pressure, force or vibration, into electrical energy. They have accomplished "parasitic power harvesting" using piezoelectric shoe inserts [37][40][44][48].

## 4. Power Aware Reliability

Although slack time in real-time systems can be eliminated, by using dynamic voltage scaling techniques, transient faults (for example soft errors caused by single event upset) are directly dependent on the operating frequency and supply voltage. Recent studies show that voltage scaling techniques can reduce the reliability of a computer system dramatically. As more mission critical application like medical or space applications benefit from low power embedded systems, their reliability raises a big challenge in both research and industry.

As a source of transient faults, single event upset (SEU) refers to faults caused by particles hitting the surface of a digital circuit. Since critical charge required to keep the system resilient from SEU is proportional to supply voltage, DVS approaches decrease supply voltages greatly increase error rate [5] [43][46].

In [49] the tradeoff between power reduction and error rate was investigated and furthermore [58] proposes a methodology for dynamic energy management under reliability constraints. In their approach, dynamic recovery recuperates the reliability loss due to energy management. The main idea is to use the slack time both for voltage scaling and for recovery. A novel approach for SEU-aware DVS in real-time systems has been proposed in [13] where they show how to benefits from information redundancy to correct the possible soft errors in the system and therefore spend less time for recovery. Furthermore, this additional time saved from avoiding unnecessary recovery, the slack time available and can be used to reduce energy consumption.

## 5. Conclusion

In this paper, we presented an overview of different power management techniques that can be very useful in tackling the power management issues facing wearable medical systems. In such systems, reliability also plays an important role, especially since its relationship with power management can be so closely tied.

We specifically highlighted the prototype wearable medical systems being developed by our group, how energy and reliability issues are being addressed by the wearable computing community in general.

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