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Energy trade-offs in the IBM Wristwatch computer

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Abstract

We recently demonstrated a high function wrist watch computer prototype that runs the Linux operating system and also X11 graphics libraries. In this paper we describe the unique energy related challenges and tradeoffs we encountered while building this watch. We show that the usage duty factor for the device heavily dictates which of the powers, active power or sleep power, needs to be minimized more aggressively in order to achieve the longest perceived battery life. We also describe the energy issues that percolate through several layers of software all the way from device usage scenarios, applications, user interfaces, system level software to device drivers. All of these need to be systematically addressed to achieve the battery life dictated by the hardware components and the capacity of the battery in the device.

1 Introduction

We built the high function IBM wrist watch computer prototype to study several areas of mobile computing such as user interfaces [1], high resolution displays [2], system software, wireless communication, security, and interaction patterns between various pervasive devices. We view this watch as a wearable computing platform rather than a special purpose device. Therefore our goals differ quite significantly from those posed to the designer of a traditional wrist watch with just time keeping functions.

We chose a watch form factor (Figure 1) because watches are easily accessible and get misplaced less often than PDAs and cell phones since they are worn, not carried. It is also commonly believed that many people glance at their watches up to forty times a day and this we think is a good reason to put some additional useful information, such as upcoming appointments on the watch face. The watch is also an ideal device for conveying information alerts to the user, since it is instantly viewable.

The watch form factor also takes many of the packaging, user interface, and power problems to the extreme which appealed to several of us.

Figure 1. Wrist watch prototypes

Our watch has a touch sensitive screen and a roller wheel for user interaction. The main card has an ARM 7 based Cirrus EP 7211 processor, 8MB of Flash memory and 8MB of DRAM, and serial, IrDA, and expansion interfaces. We have two monochrome displays, a 96x120 reflective LCD and a 640x480 Organic LED (OLED) display [2]. Bluetooth™ functionality is provided by an auxiliary card that connects to the main card in some watches. The watch is powered by a rechargeable Lithium polymer batter with 60mAh capacity at a nominal voltage of 3.7V. Figure 2 shows the hardware block diagram.

We chose the Linux operating system for our watch because of the availability of source code and a wide variety of software tools, and programmer familiarity. Third party software developers are less likely to be interested in learning new APIs unless the platform is already widely deployed. For the same reason we chose the X11 graphics library instead of defining a new library.

People are often impressed by the amount of function we have managed to fit into such a small package. However, a question that often gets asked is how long the batteries last. Obviously the battery life on a watch like ours will not compare favorably with conventional watches that have limited functionality. Notwithstanding, battery life is an important aspect that we paid attention to, and is at the heart of many trade-offs in the design of the entire system [3]. In the rest of this paper, we discuss the trade-offs we made and the motivations behind these

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trade-offs.

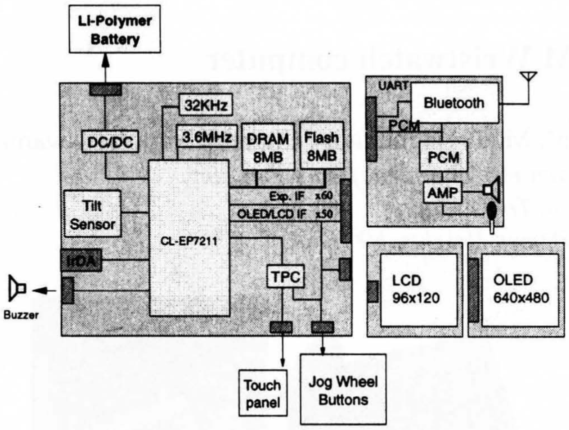

Figure 2. Hardware block diagram

1.1 The Energy Challenge

The holy grail, energy wise, in the design of mobile devices is to enable them to be self sustaining [4]. Calculators powered by solar cells and self-winding mechanical watches are examples of devices that have attained this goal.

Though the energy challenge is often interpreted as making the device run as long as possible and be as energy efficient as possible, a more pragmatic viewpoint is whether battery life can exceed some acceptance thresholds. Under normal usage patterns, cell phone batteries last about a week which appears to be an acceptable threshold. An analogy can be drawn from automobiles. Both car buyers and manufacturers do not agonize excessively and solely over gas mileage and pay attention to form and function because most people don't need to refuel on each trip, and when they do, it is fairly easy to refuel. The device is likely to get used if it provides services to the user that outweigh the difficulty for caring for it. So we have the dual challenge of providing useful function while minimizing the effort of caring for it.

Devices that are unable to attain the goal of self sustenance often use primary cells and attempt to make the replacement of the batteries easy and less frequent. If the energy requirement is such that the user will need to replace the battery too often, rechargeable batteries have to be employed to minimize user aggravation and to protect the environment. However, while rechargeable batteries can be charged a several hundred times, they generally hold four to five times less energy than non-rechargeable ones for comparable size and weight [5]. Devices that operate on rechargeable batteries must also attempt to reduce the time taken to charge up the battery.

If the recharging can be serendipitous, i.e., combined with some other benefit that is delivered to the user, such as receiving information from the Internet, the user may not perceive recharging as an inconvenience.

1.2 Challenges in a wrist watch form factor

In addition to the general energy challenge faced by other wearable computing devices, there are several additional challenges imposed by the choice of a wrist watch form factor.

The simplest way to increase the battery life is to use a larger capacity battery which will be larger and heavier, but the size and weight requirements on a wrist watch place an upper bound on the capacity of the battery that can be used to power it. With the best available rechargeable Lithium polymer batteries today, the maximum capacity of a battery measuring 3cm x 2cm x 0.5cm, that can be fit into a regular size watch, is about 200 mAh.

Second, replacing batteries on a watch is generally difficult due to the small size of the watch and the need to make the watch water resistant. As per our discussions with people who repair watches, a significant number of customer complaints directly result from users trying to replace the batteries without the right tools. Traditional watch manufacturers attempt to make the battery last so long that the user is more inclined to buy a new watch when it is time to replace the battery.

The third problem relates to user perception. Users are not accustomed to having to recharge wrist watches, but may be willing to recharge other devices such as cell phones and PDAs. It is important to make the user perceive a high function wrist watch as being similar to these other devices rather than traditional wrist watches.

As mentioned earlier, an advantage of the wrist watch is that it is instantly viewable. A constraint that arises from this aspect is that the watch should preferably have some useful information on its display at all times. While saving energy by turning off the display is an option on many devices, doing so on a watch may take a significant advantage away unless it can be done so cleverly that the display is always on when the user is looking at the watch.

In the following sections we describe the energy related tradeoffs associated to the device usage model, the hardware, system level software and application level software. We end with some suggestions for further improvement of battery life.

2 Device usage model

Wearable computing devices are generally in one of two modes, sleeping or active. The device is in the active state typically when the device is doing something for the user; e.g., performing some computation, obtaining and

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displaying data etc. The rest of the time, the device sleeps. It transitions to the active mode in response to some action by the user or the environment. Depending on how long the device takes to come out of the sleep mode, there may also be states in between these two extremes, such as an idle mode where the device responds more quickly to the user than if it were in the sleep mode.

As a gross approximation one may characterize the device using two power metrics: The power consumed in the active mode (P_{active}) and the power consumed in the sleep mode (P_{sleep}). One can also approximate the actual usage of the device using a single metric: the usage duty factor (D) which is the fraction of the time the device spends in the active mode.

Informal surveys reveal that owners of Palm Pilots™ use them about ten times a day for about 30 seconds at a time. This adds up to about 5 minutes per day or a duty factor of about 0.0035. Users of the ParcTAB [6] reported that their device was on for less than 100 seconds at a time. With today's hardware, the device can periodically go into a sleep mode, unbeknownst to the user, even when the user is actively interacting because of the reaction time of the human user and further reduce the actual duty factor. The exceptions to low duty factors tend to be devices that perform active functions even when the user is not consciously and actively using the device. An example of such a device is an MP3 player watch where the user only needs to initiate the play function and cause the watch to actively run and play the music requested.

Observations of the usage patterns of wristwatches suggest that the amount of time the user actually spends interacting with the advanced features on a digital watch is generally an insignificant fraction of the total time. This is true for many high function wrist watches as well. Calculators probably have an even smaller duty factor.

Based on these metrics, the average power consumed by the device is given by P_{sleep} (1-D) + P_{active}D. If we further define the ratio of active power to sleep power as the power factor ratio: PFR = P_{active}/P_{sleep}, then the total power consumed by the device is P_{sleep} (1-D) + PFR * P_{sleep} D = P_{sleep} (1-D + PFR*D).

The PFR for our watch ranges from around 30 to 100 as seen from table in section 3. In comparison, PFR for a PalmPilot™ ranges from 60 to 280 [7], the Psion Series 5™ PDA ranges from 70 to 240 [8], and the Compaq Itsy ranges from 30 to 90 [9,10].

The battery life can be approximated as Battery Capacity (mWh) / Average power consumed. This is an approximation since battery capacity is not really a constant but is a function of the precise wave form of the load as opposed to just the average [5,11]. Nevertheless, it is useful to examine the effects of the different parameters on the battery life.

Figure 3 below shows the interplay between the usage duty factor and the predicted battery life for the watch for different power factor ratios. The duty factor is shown on a logarithmic scale. The battery life is normalized to one when the device is in the sleep mode all of the time. Once the hardware is built, the PFR is fixed, and the predominant way of extending the battery life is to minimize the actual duty factor.

Ideally, both the minimum sleep current and the maximum current consumption must both be minimized. But which is more important depends on the duty factor.

At the frequently encountered low duty factors, it is very important to focus on minimizing the sleep power because reducing the PFR has less perceivable impact on relative battery life because we are at the left end of the curves in Figure 3. On the other hand, if the duty factor is much higher, say two hours a day, then we operate in the middle of the graph and it is important make the PFR smaller by reducing the active current consumption very aggressively.

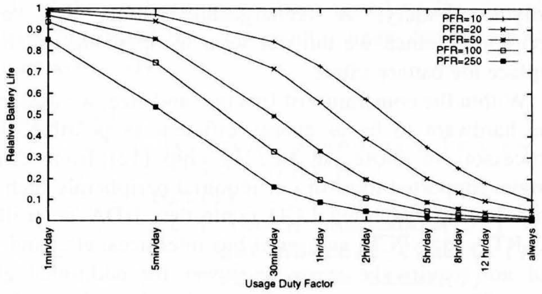

Figure 3. Relative battery life versus duty factor

3 Hardware level energy trade-offs

The upper and lower bounds on the battery life for a device are determined by hardware. The maximum battery life depends on the minimum sleep current that can be achieved. Similarly, the minimum battery life is dictated by the maximum current consumption when all hardware components are turned on.

We attempted to keep the energy requirement as low as possible by choosing energy efficient components whenever possible. However, energy efficiency often comes with less function, e.g., task specific hardware can generally operate at a lower energy cost compared to a programmable processor, and smaller memories consume less power to refresh than larger ones. Compared to other wrist watches our design trades off energy efficiency for greater function, as is evident from the 32-bit processor and large amount of memory we incorporated.

Fitting all of the components onto a small board, measuring 27.5 mm x 35.3 mm, was very challenging.

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