TurboCap: A Batteryless, Supercapacitor-based Power Supply for Mini-FDPM

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Abstract— This paper describes TurboCap, a batteryless, supercapacitor-based power supply subsystem for a handheld, laser-based breast cancer detector named the Mini-FDPM. Supercapacitors have high power density and are a better match with the power usage pattern than batteries. However, the multi-voltage requirement poses a new problem on the selection of supercapacitor topology for conversion efficiency and for form-factor minimization. Experimental results show that our design can efficiently power the Mini-FDPM system for energy-efficient, untethered operation in a compact size while supporting fast recharge.

I. INTRODUCTION

The Mini-FDPM [1] is a handheld, non-invasive breast cancer detector based on the principle of frequency domain photon migration. It performs broadband modulation (10 MHz to 1 GHz) on near-infrared laser light (in 600 to 1000 nm wavelengths) as carriers, shines it into the subject's breast tissue, and measures the (modulation) phase and amplitude of the backscattered light. Postprocessing extracts the scattering and absorption coefficients, which are content indicators of the tissue composition.

While successful at miniaturizing a refrigerator-sized instrument downto a handheld device, the Mini-FDPM is still relying on a wired power source, making it cumbersome to operate. A portable power source is required, and the designer is faced with the choice between batteries and supercapacitors.

Batteries have high energy density but low power density, while supercapacitors have high power density but low energy density. In this application, a complete sweep of all frequencies and wavelengths takes less than one second, and usually a few dozen locations are marked and measured. The instrument may be recharged in a cradle, but the charging time should be short to enable either repeated measurement or serving more patients. The power consumption is dominated by the broadband signal generator and the laser drivers. Moreover, these subsystems require different voltages, which can significantly impact the efficiency of the conversion circuitry if not carefully designed. To address this problem, we study the discharge patterns of the subsystems of the Mini-FDPM instrument and select the appropriate supercapacitor topology and regulator circuitry to maximize the conversion efficiency. Experimental results show that this approach leads to high conversion efficiency and effective operation.

This paper is organized as follows. Section II provides a background on the Mini-FDPM system and a comparison of power issues, including batteries, supercapacitors, and regulators. Section III discusses design principles related to
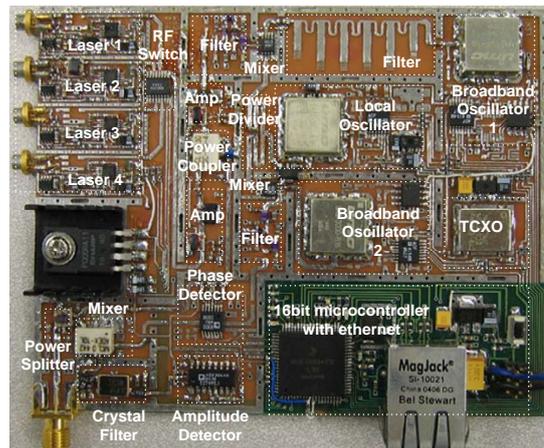
Fig. 1. The Heterodyne Mini-FDPM.
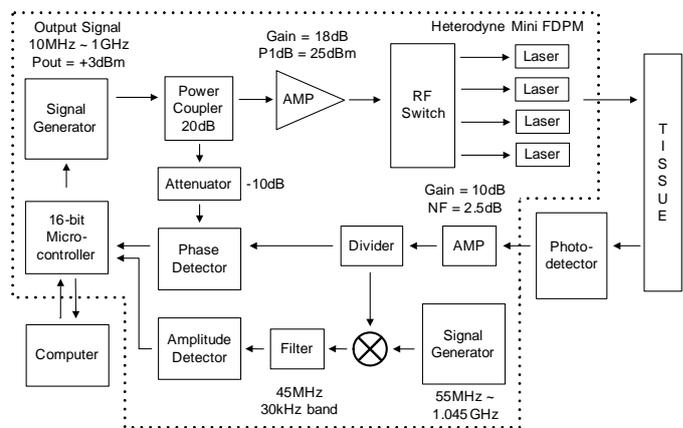
Fig. 2. Block diagram of the Heterodyne Mini-FDPM

supercapacitor-based power supplies. Section IV describes our hardware design, which entails sizing each supercapacitor to match the power consumption, duration of discharge, and recharge time of each subsystem. Section V presents our evaluation results.

II. BACKGROUND

Before we address design details of our power supply, we first provide a specification of our target system. Also, we review the principles of operation for supercapacitors and regulators, which are the main two components of our power supply design.

A. Mini-FDPM

A photo of the Heterodyne-FDPM is shown in Fig. 1. As shown in Fig. 2, the Mini-FDPM consists of three subsystems: Digital, RF, and VCOs. The digital subsystem consumes about 110 mA at 3.0 V. It controls all other subsystems and communicates with a host computer via Ethernet. The RF subsystem includes a set of laser diodes, frequency synthesizers, power amplifiers, attenuators, mixers, and phase/amplitude comparators. This subsystem is the most power-hungry and consumes about 800mA at 5V. The VCO (voltage-controlled oscillator) subsystem has two VCOs and consumes about 80mA at 12V. Because the last two subsystems are highly sensitive to power noise, we must supply very clean power. Voltage outputs directly from switching regulators may not be used to power these two subsystems. The measurement time, which includes sweeping up to 400 RF frequencies in the 10MHz–1GHz spectrum for four lasers sequentially, takes just a few seconds. However, one-minute lifetime is preferable, because users may want to take multiple measurements at the same time, or there may be power leakage while in standby mode. In addition, very short charging time is desirable for the Mini-FDPM. Although there are no hard timing constraints, in certain clinical settings, multiple patients may need to be measured consecutively. Since the users are medical professionals rather than electrical engineers, making these devices as maintenance-free as possible also means they should not have to replace batteries or any components that may suffer from non-wear-and-tear degradation.

B. Supercapacitor

Supercapacitors have high power density and low energy density compared to batteries. They have been used in conjunction with batteries to compensate for batteries' low power density for applications that occasionally consume very high current. Recently, designers have been trying to use supercapacitors as a primary power source to take advantage of its fast charging feature. For example, using very high current (tens of amperes), it takes just a few seconds to fully charge a 2.7V, 100F supercapacitor (equivalent to 364.5J) [2]. This is a major advantage, considering that it usually takes a few hours to fully charge batteries, mainly because batteries cannot be charged with such a high current (should be less than 1C) and need long Constant-Voltage charging mode. Fig. 3 shows charging and discharging profiles of a 50F, 2.7V supercapacitor. We can observe that the terminal voltage increases almost linearly with time. If we double the charging current, then the charging time will be cut almost in half. Also, supercapacitors do not suffer from battery effects such as memory effect and aging effect, which require periodic change of a battery. Another merit of supercapacitors is easy lifetime estimation. The terminal voltage is an exact indicator of the remaining energy, which is not the case with batteries. However, supercapacitors also have drawbacks. First of all, they are bulky compared to batteries, so it will increase the volume of devices. In addition, as show in Fig. 3(b), a supercapacitor's output voltage drops very fast and behaves differently from batteries. Over 70~80% of the lifetime, the batteries' output voltage stays around 3.6V for Lithium-Polymer). With all these considerations, we believe
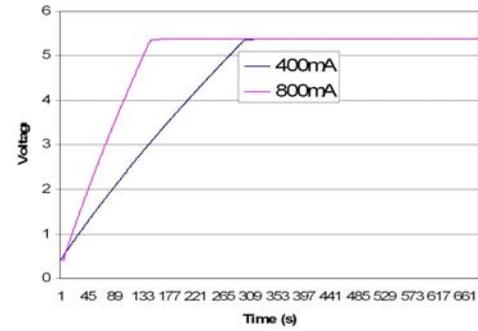
(a)
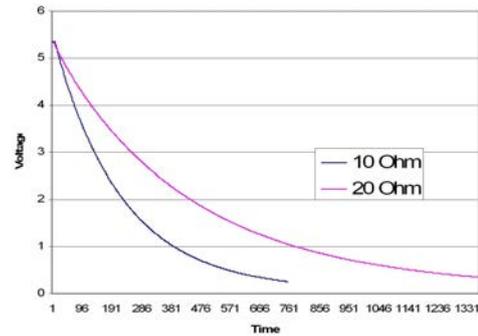
(b)

Fig. 3. Supercapacitor's (a) charging and (b) discharging profiles with different charging currents and discharging loads: two 50F, 2.7V supercapacitors in series

supercapacitors to be a good choice for certain applications that require very short charging time and do not require very long operation lifetime, as is the case with the Mini-FDPM.

Voltage regulators are used to fill out the gap between the output voltage of a power source and the input voltage of a system and to supply stable power regardless of the power source's voltage drop over time. Switching regulators are commonly used in portable electronic devices owing to their high conversion efficiency. However, the output voltage is too noisy to power noise-vulnerable components such as RF or sensors. Linear regulators output clean and stable power, but they suffer from heat, low conversion efficiency, and voltage drop.

There are three different types of switching regulators: Buck, Boost, and Buck-Boost. A buck regulator should take higher voltage than its output voltage, or else it cannot output proper voltage. Buck regulators may not work very well with supercapacitors, because supercapacitors' output voltage drops. A boost regulator takes a lower voltage than its output voltage. This regulator goes better with supercapacitors, because it can still operate even though supercapacitors' output voltage drops fast. A buck-boost regulator works like a buck regulator when the supply voltage is higher than its output voltage and like a boost regulator in the opposite case.

III. Design Issues

In this section, we discuss design issues related to supercapacitor-based power supplies. We first address those on conventional power supply subsystems for portable, mostly battery-powered systems. Next, we show new design challenges imposed by adapting supercapacitors as a primary power source.

A. Battery-based Power Supplies

Most of current power supply subsystems of portable electronic devices follow a system architecture shown in Fig. 4(a). It consists of a battery pack, a set of voltage regulators, and battery charging circuitry. To design a power supply for a certain portable device is all about 1) choosing the proper voltage regulators, 2) determining the terminal voltage and capacity of the battery pack, according to expected lifetime and voltage/current requirements of each subsystem.

1) Choice of voltage regulators: When choosing a voltage regulator for each subsystem, we should consider its *conversion efficiency* over the input voltage range, as well as the output voltage and current consumption level of the subsystem. The choice must be first made in a way to maximize the conversion efficiency under given output voltage and current consumption level.

2) Choice of the battery pack: The output voltage of the battery pack must be chosen by considering the requirements of the subsystems. When each of multiple subsystems requires a different supply voltage and current, a separate regulator is needed for each subsystem. This greatly complicates the choice of the battery pack, because the battery pack's output voltage where the conversion efficiency of one regulator is maximized does not necessarily result in maximum conversion efficiency for all other regulators. Also, each regulator has a different input voltage range. Therefore, the battery pack's output voltage should be chosen between the minimum and maximum input voltages of the regulators such that the overall conversion efficiency is maximized.

The capacity of the battery pack can be determined by considering the conversion efficiency and battery efficiency as well as the expected lifetime and power consumption of the subsystems. Note that the sum of power consumption of all regulators is always higher than that of all subsystems, because the conversion efficiency is less 100%. In addition, considering the battery efficiency, the capacity required to achieve a given lifetime is greater than just the sum of energy consumption by all regulators.

B. Supercapacitor-based Power Supply

The supercapacitor-based approach imposes many new challenges, because the characteristics of supercapacitors are very different from those of batteries. In this subsection, we discuss new challenges for designing supercapacitor-based power supplies: the overall system architecture, the voltage regulators, and the terminal voltage and capacity of supercapacitors.

1) System Architecture: The most obvious system architecture for supercapacitor-based power supply is the one shown in Fig. 4(b). In this architecture, the battery pack is just replaced with an equivalent supercapacitor pack. This architecture can
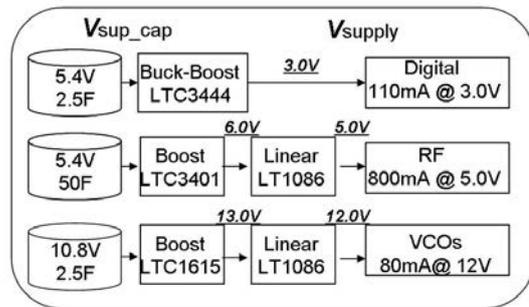
Fig. 5. Block Diagram of Supercapacitor-based Power Supply

take advantage of good features of supercapacitors such as fast charging time and high power density, as described in the previous section, but choosing the output voltage of the supercapacitor pack still remains a problem.

We propose a system architecture as depicted in Fig. 4(c). In this architecture, each regulator has its own supercapacitor pack whose terminal voltage is optimally chosen to maximize the corresponding regulator's conversion efficiency. Also, each supercapacitor's capacity is determined individually based on the expected lifetime when used in conjunction with the regulator. With this architecture, we can achieve overall higher power efficiency, save power, and reduce the capacity of supercapacitors, size, and cost. The charging circuitry is more complicated, because each capacitor needs a different capacity and voltage to finish the charging at the same time. As the life time of the system is limited by the shortest lifetime of all subsystems, the recharging time will be lower bounded by the longest one.

2) Choice of Voltage Regulators: The cutoff voltage of a regulator imposes a limit on the supercapacitor's efficiency, since efficiency is measured by the output voltage of a supercapacitor, rather than the output of the regulator.

The choice among buck, boost, and buck-boost types depends on the input voltage of a subsystem. Buck regulators may be efficient on their own, but they are not efficient when used in conjunction with a supercapacitor, because the buck regulator needs to be supplied a higher voltage than its output. Once the output voltage of the supercapacitor drops below the output voltage plus threshold, the supercapacitor's remaining energy becomes unusable, even if it is a nontrivial amount. This translates into low supercapacitor efficiency. Therefore, for the supercapacitor-based power supply, boost or buck-boost regulators are more suitable.

3) Choice of supercapacitors: The output voltage of the supercapacitor pack is important, because it directly affects the regulator efficiency. The easiest way is to choose one as close to the output voltage of the regulator as possible. For example, if we have a boost regulator that outputs 6V and 2.7V supercapacitors, then 5.4V is the optimal choice, which can be achieved by connecting two 2.7V supercapacitors in series.

IV. Hardware Design

We implement TurboCap, a batteryless, supercapacitor-based power supply using COTS components as shown in
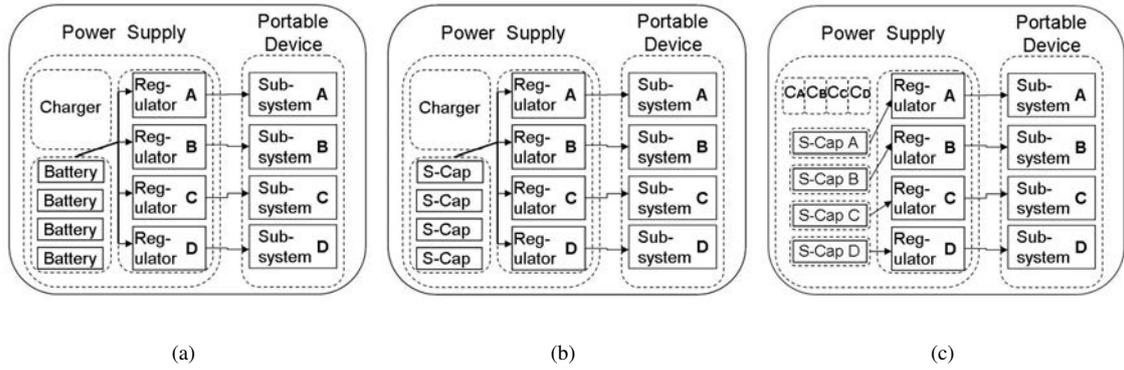
Fig. 4. Three candidate rechargeable power supply architectures: (a) batteries composed in series, but with separate regulators for each required voltage; (b) same as (a) except with supercapacitors; (c) separate supercapacitors for different require voltages.
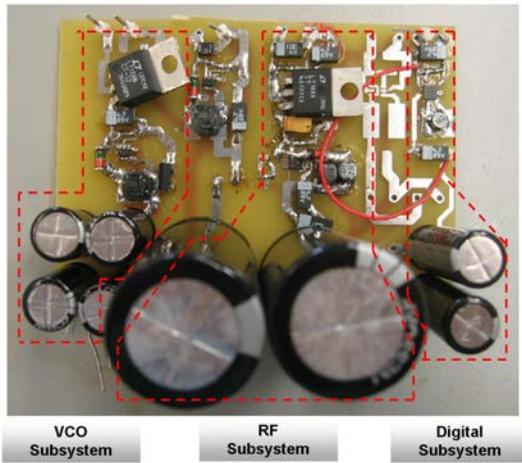
Fig. 6. Photo of Supercapacitor-based Power Supply

Fig. 5 and Fig. 6. We carefully consider all the design issues discussed in the previous section to achieve high power efficiency and expected lifetime. In this section, we detail our design choices of voltage regulators and supercapacitors with justifications. Note that we used 2.7V supercapacitor of various capacities.

A. Digital Subsystem

The Mini-FDPM's digital subsystem consumes 110mA at 3.0V. For this subsystem, we can consider three different ways to implement its power supply: 1) buck-boost regulator with 5.4V supercapacitors, 2) buck regulator with 5.4V supercapacitors, 3) boost regulator with 2.7V supercapacitors. In the first scheme, when V_{sup_cap} is higher than 3.0V, the regulator works as a buck regulator and when V_{sup_cap} is lower than 3.0V, it works as a boost regulator. Therefore, we can achieve higher supercapacitor efficiency than the two other schemes. We use the LTC3444 [3] buck-boost regulator whose input voltage range is from 2.6V to 5.5V. Fig. 7(a) shows that the conversion efficiency of this regular is about 90% over supercapacitor's output voltage range. We also have to determine the capacity of the supercapacitors. According to the Fig. 7(b), only when the output voltage of the supercapacitors is at least 2.6V, the

regulator outputs stable 3.0V. When V_{sup_cap} reaches 2.6V, the remaining energy becomes useless. Therefore, the energy required to achieve the expected lifetime is

$$\frac{1}{2}C(5.4V)^2 - \frac{1}{2}C(2.6V)^2 = 11.2C \text{ Joules} \qquad (1)$$

According to Fig. 7(c), the average switching current between 2.6V and 5.4V is about 102mA, and the average voltage is therefore $(2.6V + 5.4V)/2 = 4$V. Also, our expected lifetime is 60 seconds. So,

$$11.2C = 4V \times 0.102A \times 60\text{secs}$$
$$= 24.48\text{Joules.} \qquad (2)$$

Therefore, the capacity is about 2.2F. Because a 2.2V supercapacitor is not available on the market, we use two 5F, 2.7V supercapacitors [4] (connected in series), whose capacity is 2.5F and output voltage is 5.4V.

B. RF Subsystem

The RF subsystem of the Mini-FDPM consumes 800mA at 5V. Also, this power should be very clean. To implement this power supply, we use one boost regulator (LTC3401 [5]) and one linear regulator (LTC1068 [6]). The boost regulator first boosts the output voltage of the supercapacitors to 6.0V, and the linear regulator regulates it to less noisy 5.0V. Fig. 8(a) shows the conversion efficiency of this multi-stage regulator. The conversion efficiency is about 70% when the input voltage is from 5.4V to 4V, at which the regulator outputs the required voltage (5V). The efficiency is much less than that of the digital subsystem, because we use a linear regulator instead of a switching regulator in this design. To achieve high conversion efficiency of LTC3401, we choose 5.4V at the output voltage of supercapacitors, which is as close as possible to the regulator's output voltage (6V) using the available supercapacitors. By the same way to calculate the capacity described in the previous subsection, we choose 50F.

$$\frac{1}{2}C(5.4V)^2 - \frac{1}{2}C(4V)^2$$
$$= \frac{(5.4+4)V}{2} \times 0.982A \times 60\text{secs,} \qquad (3)$$
$$C = \text{about 42 F}$$
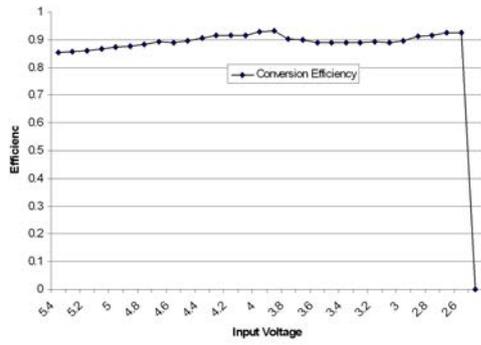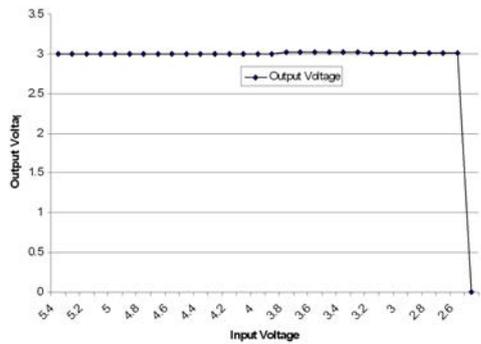
(a) Conversion Efficiency
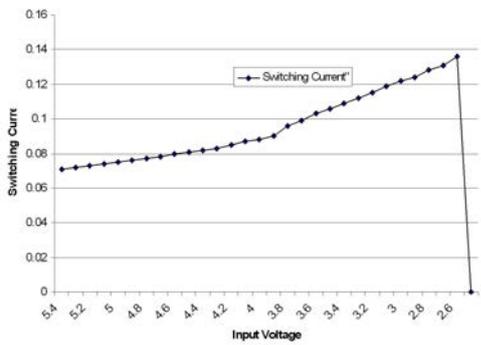
(a) Conversion Efficiency
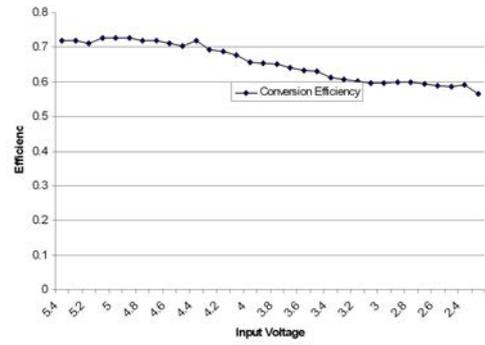
(b) Output Voltage

(b) Output Voltage
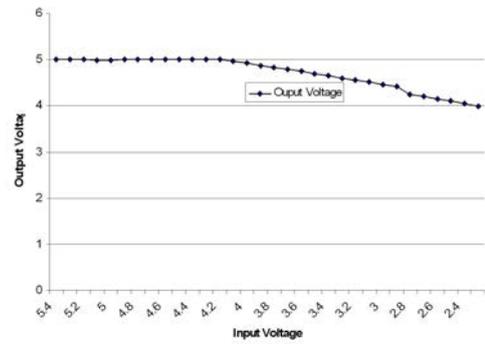
(c) Switching Current
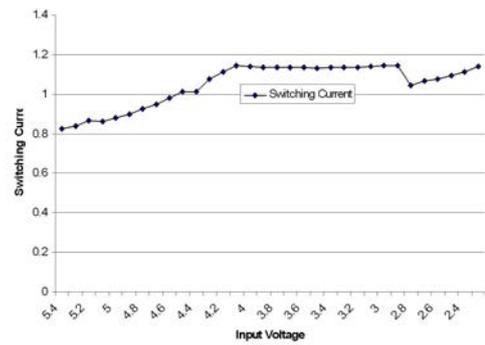
(c) Switching Current

Fig. 7. Measured Conversion Efficiency, Output Voltage, and Switching Current vs. Input Voltage (LTC3444)

Fig. 8. Measured Conversion Efficiency, Output Voltage, and Switching Current vs. Input Voltage (LTC3401 + LT1068)

(a) Conversion Efficiency

(b) Output Voltage

(c) Switching Current

Fig. 9. Measured Conversion Efficiency, Output Voltage, and Switching Current vs. Input Voltage (LTC1615 + LT1068)

We use two 100F, 2.7V supercapacitors [2](connected in series), whose capacity is 50F and output voltage is 5.4V.

C. VCO Subsystem

The VCO subsystem of the Mini-FDPM consumes 80mA at 12V. As this is an analog component, the power should also be very clean. To implement this power supply, we use one boost regulator (LTC3401 [5]) and one linear regulator (LTC1615 [7]). The boost regulator first boosts to 13.0V, and the linear regulator regulates it downto 12.0V. Fig. 9(a) shows that the conversion efficiency is about 70% (input voltage is from 10.4V to 7.1V where the output voltage is 12V). To achieve high conversion efficiency of LT1615, we choose the output voltage of supercapacitors as close to 13V as possible (should not be higher than 13V, because we use a boost regulator). By the same way we calculated the capacity described in the previous subsection, we choose 2.5F.

$$\frac{1}{2}C(10.8V)^2 - \frac{1}{2}C(7.1V)^2$$

$$= \frac{(10.8V + 7.1V)}{2} \times 0.127A \times 60secs, \tag{4}$$

$$C = about\ 2.3F \tag{5}$$

We use four 10F, 2.7V supercapacitors [8] (connected in series), whose capacity is 2.5F and output voltage is 10.8V.

D. Charger

We use an adjustable linear regulator (LT1068) and adjustable 1.2A current limiter (ST890) to implement a supercapacitor charger. In our power supply, there are three different supercapacitor packs: a) 5.4V, 2.5F, b)5.4V, 50F, c)10.8V, 2.5F. Therefore, we need to design three separate chargers that have different voltage and current limits. Because the supercapacitor pack for the RF subsystem is the largest, the overall charging time is upper-bounded by that of the RF subsystem. For this RF subsystem, we set the voltage limit to 5.4V and current limit 1.2V. The expected charging time is

$$\frac{\text{Total energy charged}}{\text{Avg. voltage} \times \text{Charging Current}}$$

$$= \frac{\frac{1}{2} \times 50F \times 5.4^2V}{2.7V \times 1.2A}$$

$$= 225\ \text{seconds.}$$

However, the actual charging time will be less than 225 seconds, because in most of cases, there is a certain amount of energy remaining. We use 5.4V, 300mA and 10.8V, 600mA for the digital subsystem and VCO subsystem, respectively.

V. EVALUATION

In this section, we evaluate our TurboCap design. We first verify that our power supply works as we design in terms of operating lifetime and charging time. Also, we supply power to the Mini-FDPM using this power supply and collect optical properties of an arm to show that our power supply does compromise data integrity.
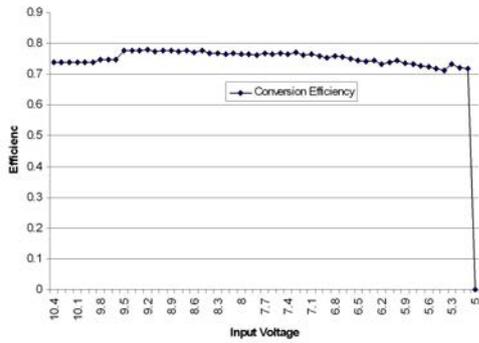
(a) Digital Subsystem
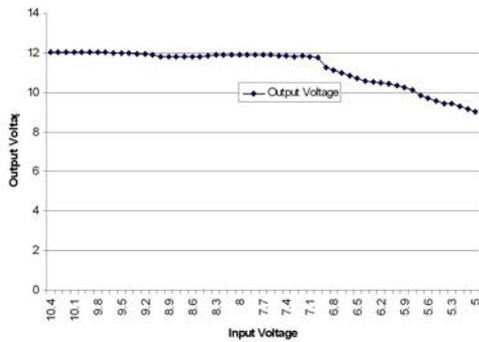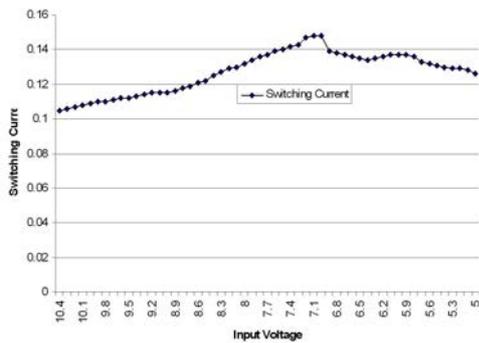
(b) RF Subsystem

(c) VCO Subsystem

Fig. 10. Charging and Discharging Profile of (a) Digital Subsystem, (b) RF Subsystem, and (c) VCO Subsystem

A. Operating Lifetime

Fig. 10 shows operating lifetime of each subsystem. We connect the Mini-FDPM to the power supply and measure V_{sup_cap} and V_{Supply} using National Instrument's PCI-6230 Data Acquisition System. The digital subsystem, RF subsystem, and VCO subsystem last for 72, 60.5, and 62 seconds. Therefore, the overall lifetime of this system is 60.5 seconds. This meets our design specification of one-minute lifetime. In Figs. 10(b) and 10(c), we can observe that the output voltages are fluctuating as the supercapacitors discharge. However, these variations are all less than 0.3V, which is small enough that it will not cause any malfunction of the Mini-FDPM system.

B. Charging Time

Fig. 10 also shows the charging time of each subsystem. It takes 70.5, 153, and 67 seconds to charge the supercapacitor packs of the Digital, RF, and VCO subsystems, respectively. Note that in these experiments, we charged the supercapacitors using less than 1.2 Amperes, because our current limit IC (ST890) has a maximum output current of 1.2A. However, considering that the rated current level of supercapacitors is on the order of tens of amperes, we can reduce the charging time by up to tens of seconds if necessary. In this case, we may need a new current limiter with a higher capacity.

C. Data Integrity Test

We power the Mini-FDPM using our TurboCap system and measure the optical properties of an arm. Fig. 11 shows our experimental setup and measured data. TurboCap successfully provides power to the Mini-FDPM and operates stably during the entire lifetime. Also, the measured data are as good as when we use a digital power supply connected to the Mini-FDPM via wires.

VI. CONCLUSION AND FUTURE WORK

In this paper, we report our experience in designing Turbo-Cap, a batteryless, supercapacitor-based power supply for a portable medical device, the Mini-FDPM. The supercapacitor-based design imposes many new challenges on choosing the voltage regulators, and the capacities and output voltages of the supercapacitor packs. TurboCap successfully provides power to the target application for the target duration, and we verify that it does not compromise the integrity of data collected by the noise-sensitive analog subsystems.

Our future work includes further integration of the Mini-FDPM and supercapacitor-based power supply. Also, we plan to re-design the charger to increase charging current and further decrease charging time.

ACKNOWLEDGMENTS
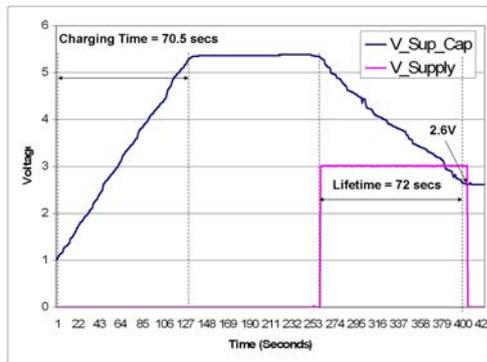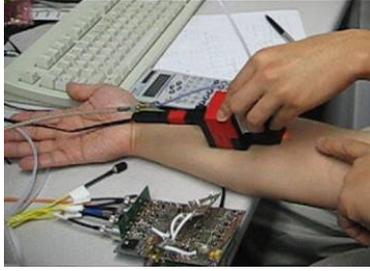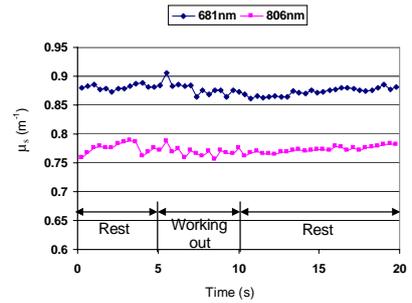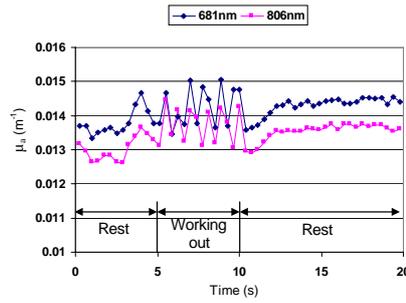
(a) Setup   (b) Measured Data

Fig. 11. FDPM powered by supercapacitor-based power supply measures optical properties of an arm

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