Low Power Embedded Control Design

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ABSTRACT

This paper describes laboratory design exercises to introduce the added constraints of low power consumption to microcontroller design. Many new hand-held, portable, and remote instruments must operate several years on small, commercially available batteries. This means reducing the average consumption to less than 100 microamps. In addition, the system hardware and software architecture must be interrupt-driven. Also, reduced noise margins, varying supply voltage, increased power supply impedance, burst-mode analog signal conditioning, and serial communications all present unique problems to the designer.

Most modern high performance microcontrollers and microcomputers include software selectable modes of power reduction. This is often done by manipulating the on-board oscillator and providing an external wake-up interrupt. These modes can be used to reduce the typical 10-100 milliamp current consumption down three orders of magnitude. Also, recent high efficiency power supply regulators now include very low dropout voltage, low quiescent currents, power shut down control, and large input voltage range. A wide variety of these regulators are available in both linear and switch-mode. Some provide extra features such as low battery voltage detector and indication.

Some new high precision analog to digital converters require low power supply current during normal operation, and can be shut down to consume extremely low power when not in use. They require a minimum amount of setup time and are easily interfaced to the microcontroller via fast standard serial data communication. Internal auto-calibration permits full offset and span correction by the microcontroller. Additional features may include multiple channels, differential inputs, noise rejection, reduced parts count, and medium speed conversions.

These emerging technologies are incorporated in laboratory design exercises, and presented as part of an intermediate level microprocessor course in the Electrical Engineering Technology program at Penn State Erie.

INTRODUCTION

Contemporary microcontroller texts cover basic architecture and simple interface circuit design. [1-4] They primarily concentrate on functionality contained within the microcontrollers themselves, and do not get into circuit electrical details. This paper presents supplementary lessons and labs that delve more deeply into electrical considerations, especially the constraint of low power consumption.

Figure 1 shows an example of a microcontroller application for a remote turbine flow meter. The turbine produces an electrical pulse on every revolution; the higher the flow rate, the more pulses are produced every minute. The concept block diagram shows the sensory information, along with operator and computer interfaces of the flow meter control.

The actual flow rate varies depending upon the temperature and pressure inside the pipe, and these must be compensated for in order to determine a standardized flow rate under normal conditions. Also, since such flow meters are installed in remote locations, no commercial power is available, and it is expensive to maintain a local electrical generator such as a solar cell. Batteries are the preferred means of supplying power.

BATTERY POWER SUPPLY

There are several battery related design questions that should be considered. [5-6] What kind of battery, what battery technology should be used for the application (heavy duty, alkaline, lithium, nickel cadmium)? How much energy is available from the battery? How does the battery perform throughout its entire operating temperature range? What is the expected battery life for various load levels, load profiles, and load conditions (magnitudes and durations, constant resistance or current or power)?

Figure 2 shows average battery life as a function of load current for a Lithium D-cell. For high current applications of 10 milliamps or greater, the life expectancy is on the order of a few days. For low current applications of less than 100 microamps, the life can be as high as 10 years, and is limited mostly by expected shelf life and leakage current. The longest rated life is on the order of 10 years, but they may last longer at a lower voltage. Although alkaline batteries are only rated for up to one year life, test data has shown them to provide adequate service for over 5 years. Heavy duty and nickel cadmium batteries are not suitable for very low current, long life applications.

SYSTEM DESIGN

As usual, a primary design consideration is complete functionality at the lowest possible cost. This includes both the initial product cost of the circuit and batteries, as well as the life cycle maintenance cost of replacing the batteries. The design challenge in this case is to design a system, including both hardware and software, that consumes the least possible power without sacrificing performance. The designer must become aware of the available technology, and be able to assemble that technology into a working system.

The designer moves from the context block diagram to the general functional block diagram like the one shown in Figure 3. This presents the concept design showing the internal control functionality, and allows the designer to layout the system in such a way as to reduce power consumption. The turbine flow sensor produces several pulses per minute. The temperature and pressure are read at each turbine pulse, and the normalized flow rate is computed, and the accumulated volume is calculated and stored in memory. Several times per year, an operator may interrogate the system using the panel switches and alpha-numeric display, or may initiate automatic data transfer via the computer data link. A periodic clock signal accumulates time, and permits calculation of flow rate.

Figure 4 shows a simplified timing diagram, illustrating the asynchronous nature of the input signals. At each different event, the microcontroller has something different to do, and uses a unique collection of circuit hardware components.

For instance, every half second the accumulated time is increased and stored in memory, and nothing else happens. At another instance, at every flow sensor turbine pulse, the temperature and pressure must be read, the volume change is calculated and stored in memory. At a third instance, when an operator interrogates the system, the display shows time, temperature, pressure, flow rate, and volume. If desired, the information can also be transmitted via the computer data link. In between these events, the microcontroller could be in idle mode since it has no work to do.

DETAILED DESIGN

Various approaches are used to minimize power consumption. One simple method is to externally switch the power off to a section of the circuit that is not being used. [7] Another method is to slow down the clock of a circuit that must be used a large percentage of the time. [8] The main power converter is used continuously, and therefore a special component must be chosen which requires a minimum of standby current. [9-10] Also, digital signals can be capacitively coupled to eliminate steady state current flow. Finally, some components incorporate a power down mode, wherein the component power consumption is reduced internally by means of an applied logic signal. [7,11] The software is organized around event interrupts rather than polling to allow the microcontroller to be shut down between events to conserve power. [12-14]

The same power saving technique cannot be used universally throughout the entire system. Components are used at different intervals and for different lengths of time, and they have different inherent capabilities to reduce power. For instance, in the flow meter controller design, the clock runs continuously, so it is run at a low frequency to minimize power consumption. The main power converter also runs continuously, so a device was chosen which required the lowest possible standby current. The flow sensor turbine input must be monitored continuously, so it is capacitively coupled to eliminate steady state current flow while passing the pulse to the microcontroller.

SYSTEM OPERATION

The main power converter supplies power to the wakeup clock, the microcontroller, and the input switch buffers at all times. The microcontroller is in the shutdown mode, waiting for an interrupt from either the wakeup clock, the turbine flow sensor, the operator panel switches, or the data link. The interrupt wakes up the microcontroller, which then polls the devices to determine the cause of the interrupt. If it was from the wakeup clock, the time is accumulated and stored, and the microcontroller is shut down.

If it was from the turbine flow sensor, then the analog to digital converter, multiplexer, and channel amplifiers are powered up by means of an auxiliary power converter. This converter is controlled by a logic signal from the microcontroller. Once the amplifiers reach equilibrium, the temperature and pressure are read, the normalized volume and flow rate are computed, and stored in memory, and mirrored in EEPROM in case of power loss. The EEPROM retains data with power removed, and power is only applied while data is either being written or read. Then the microcontroller is shut down.

If the interrupt was from the operator panel, the analog circuit components are again powered up and the signals are read for display. Because of ambient temperature extremes, the LCD display requires a bipolar power supply. This must be shut down to conserve power, even though LCD are notoriously low power consumers. If the data link caused the interrupt, the information is transmitted over the link in batch mode. The microcontroller is then shut down.

Figure 5 shows a comparison of current consumption by section, giving the battery current that would be required if the circuit was continuously powered, versus the minimal battery current that is actually necessary to provide full functionality. If the circuit was designed for continuous operation, the circuit would draw a total of 25 milliamps and the battery would only last 23 days. By considering low power consumption in the design, the circuit will draw a total of 0.11 milliamps and the battery could last over 10 years.

CIRCUIT DETAILS

Figure 6 shows the external low frequency wakeup clock. By operating at 32.768 Khz, the circuit draws only 0.06 milliamps average (0.01 milliamp for the oscillator and 0.05 for the microcontroller in power down mode), compared to 5.00 milliamps for the microcontroller operating in idle mode using internal timers. The crystal maintains frequency and time accuracy of greater than 0.2%. The output interrupts the microcontroller every half second.

Figure 7 shows a comparison of the functionality, as well as typical and worst case operating current for the microcontroller running in normal mode, idle mode, and power down mode. This microcontroller, in addition to having versatile power saving modes, contains many integrated functions especially optimized for control applications. Variations of the basic microcontroller are available from many manufacturers, and are widely used for embedded controls.

Figure 8 shows the primary switch-mode power converter, that raises the nominal 3.6 VDC battery voltage to 5.0 VDC. It requires minimal quiescent current, and delivers full output voltage at a battery supply voltage as low as 1.8 VDC. It has a low saturation voltage of less than 170 mVDC at up to 1 amp load current. It is available in small outline or dual inline integrated circuit packages.

Figure 9 shows the switch input circuits. These capacitively coupled signals draw less than 0.1 microamp average, compared to 20 microamps for comparable directly coupled circuits.

Figure 10 shows the secondary linear power converter. It is used as an external switch to control power delivered to the analog circuits, display circuits, and serial data link circuits. It has the advantage of low dropout voltage of 220 mVDC. While in use, it draws minimal standby current of 11 microamp, and it draws less than 1 microamp in shutdown mode.

CONCLUSION

These lessons and lab experiments give the student a new insight into real-world design. As more electronic equipment is used in portable or remote environments, it is necessary to design under the added constraint of low power consumption. The problems presented in these labs and lessons have the added excitement to the student in that they reflect current problems actually being solved today in industry with modern technology. They realize that it is not only necessary to provide full functionality, but it must usually also be done under other constraints such as low cost and low power consumption.

ACKNOWLEDGEMENTS

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BIOGRAPHICAL

RONALD KRAHE is Assistant Professor of Engineering at Penn State Erie, Behrend College, teaching since 1989. He graduated from Case Western Reserve university in 1969 with a BS in Electrical Engineering and received an MS in Engineering from Gannon University in 1991. From 1969 to 1989 he designed industrial and military instrumentation and control systems, specializing in embedded controls and interface.

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FIGURES

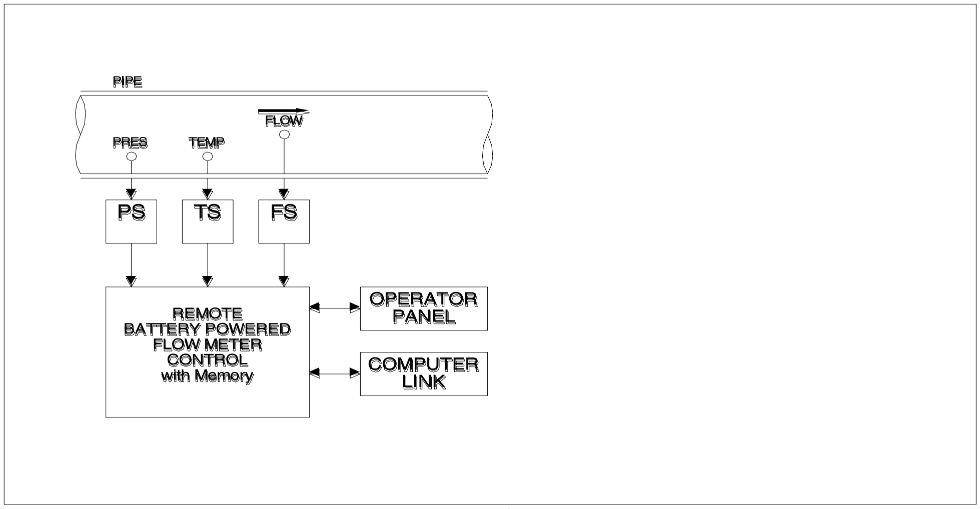

Figure 1. Remote Battery Powered Flow Meter Control Context Block Diagram

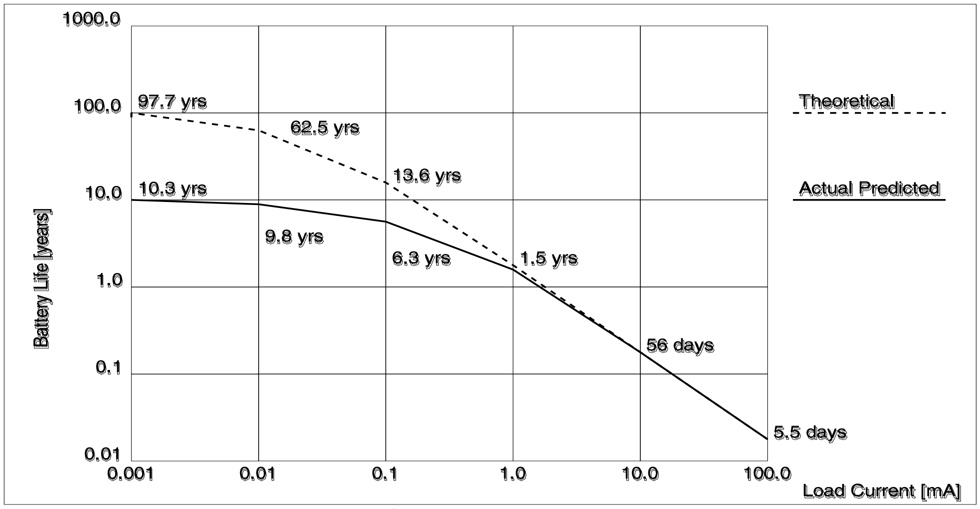

Figure 2. Battery Life Versus Load Current
Lithium D-cell

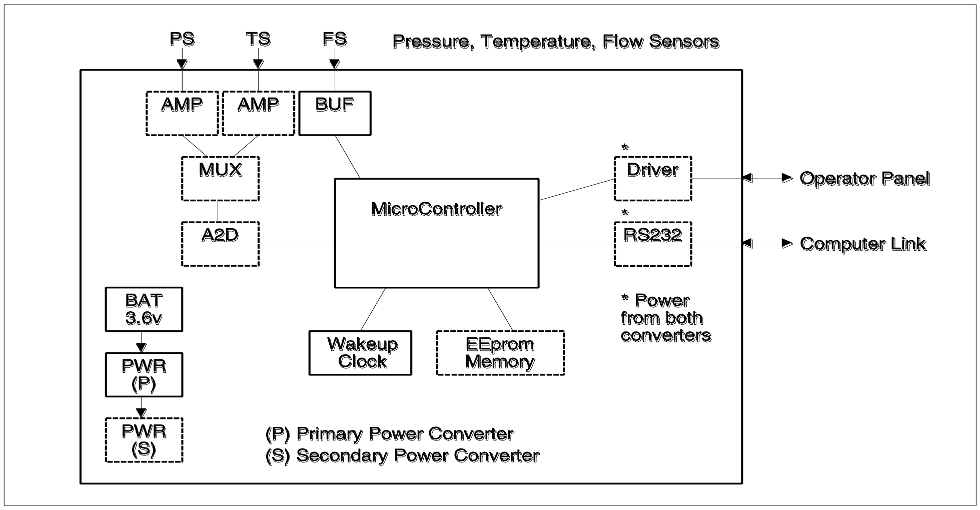

Figure 3. Concept Design
General Functional Block Diagram

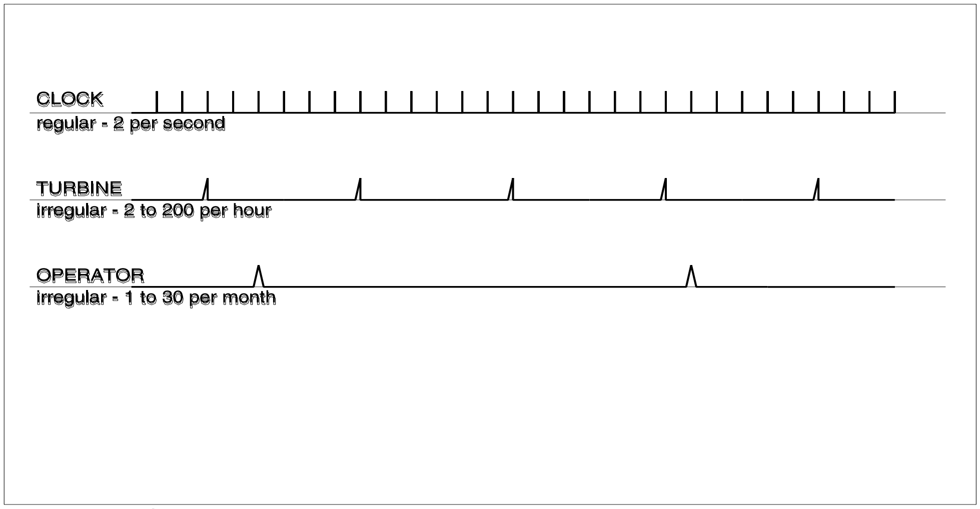

Figure 4. Simplified Timing Diagram
Asynchronous Signals

Components & Circuits	Continuous [mA]	Intermittent [uA]	Percent
Primary Power Converter	0.060	60.00	100.00
Wakeup Clock	0.008	8.00	100.00
Input Switch Buffers	0.020	1.00	5.00
Microcontroller	15.000	40.00	0.27
Secondary Power Converter	0.011	0.01	0.09
Display and Driver	2.000	0.40	0.02
RS232	0.310	0.02	0.01
Amps, Mux, A2D	4.500	0.50	0.01
EEprom Memory	3.100	0.60	0.02
TOTAL CURRENT	25.009	110.5	0.44
Expected Battery Life	< 23 days	> 10 yrs	160:1

Figure 5. Comparison of Current Consumption
Continuous versus Intermittent Operation

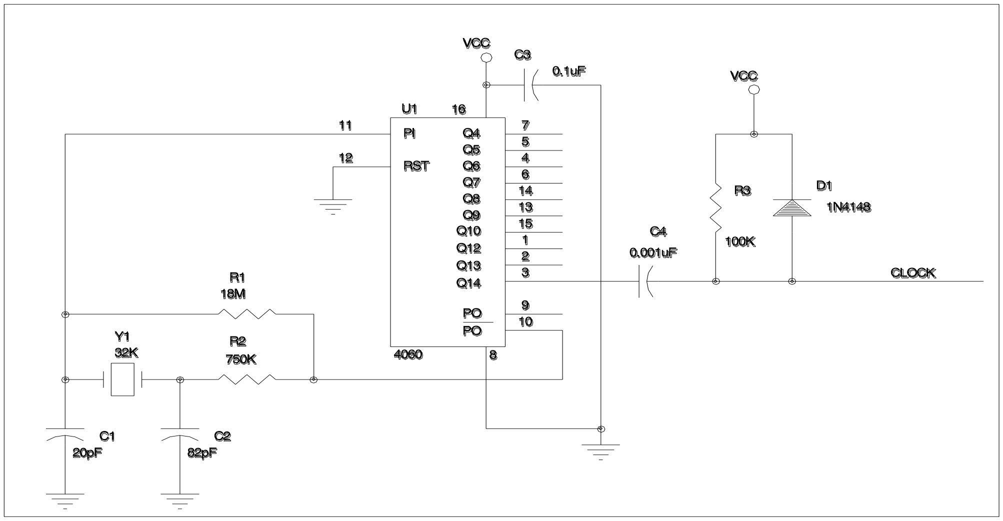

Figure 6. Wakeup Clock Schematic

MODES	FUNCTIONALITY	CURRENT	POWER RATIO
NORMAL MODE	CPU running, instructions executing, all functions operational.	32.00 mA	640 X
IDLE MODE	CPU asleep, on-chip peripherals active (timers, serial, etc.).	5.00 mA	100 X
POWER DOWN MODE	Oscillator stopped, all functions are asleep, RAM memory is retained.	0.05 mA	1 X

Figure 7. Comparison of Microcontroller Power Modes

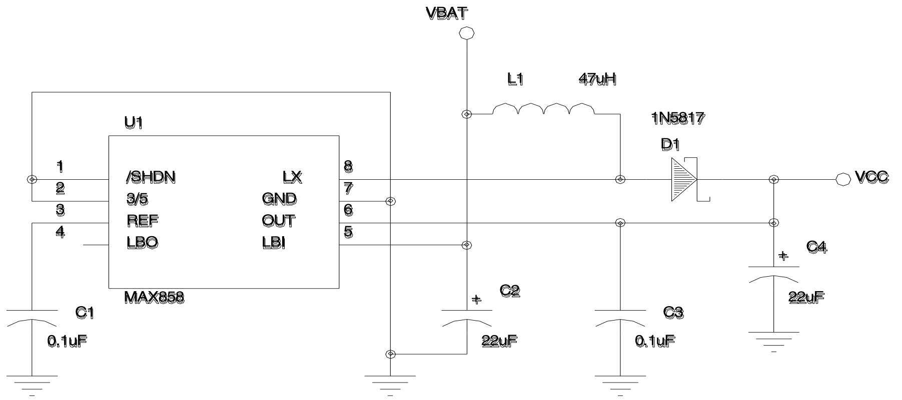

Figure 8. Primary Switch Mode Power Converter

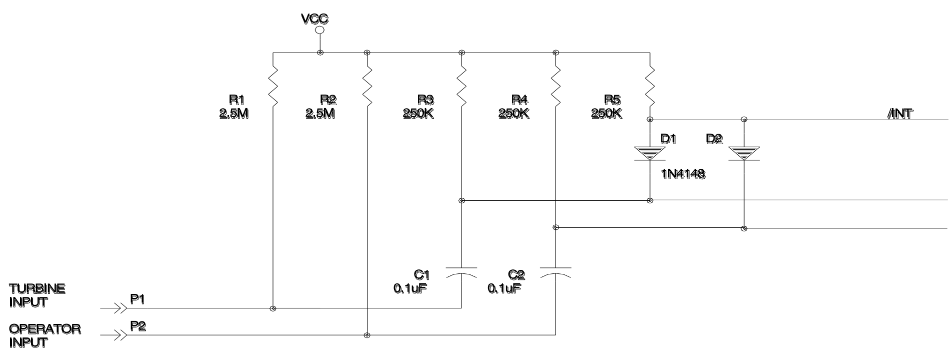

Figure 9. Switch Input Buffer

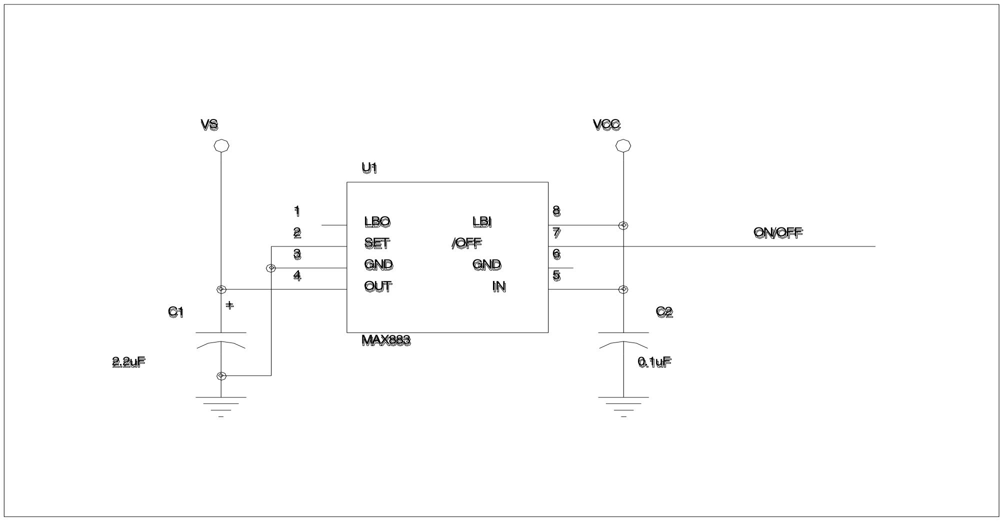

Figure 10. Secondary Linear Power Converter