Measurement Automation Monitoring, Jun. 2016, no. 06, vol. 62, ISSN 2450-2855

Tadeusz SONDEJ, Marcin MACIEJEWSKI
ELECTRONIC DEPARTMENT, MILITARY UNIVERSITY OF TECHNOLOGY THE JAROSLAW DABROWSKI
2 Gen. Sylvester Kaliski St., 00-908 Warsaw 49, Poland

A Low-Power Autonomous Sensor Module for Biomedical Applications

Abstract

The paper presents the construction of an energy-efficient, stand-alone measurement module, designed for use in biomedical applications. The paper discusses the use of an algorithm implementing the acquisition and processing of data, whose main objective was to minimize energy consumption. For the construction of the measuring module, there are used a microcontroller with Cortex-M4F core and two external digital sensor systems: (1) analog-front-end circuit, designed to measure the ECG signal, and (2) a 3-axis system of an integrated accelerometer, gyroscope and magnetometer, made in MEMS technology. In order to minimize the energy consumption, the solutions proposed include dynamic frequency management, the introduction of sleep modes, and the use of selected hardware features of the microcontroller. The proposed techniques and algorithms are implemented to measure the ECG signal at a sampling rate of 250 Hz. Experimental studies of the sensor module constructed were carried out. As a result of the energy saving techniques used, the working time of the device was extended by more than 6 times.

Keywords: low-power, sensor, ECG, biomedical application.

1. Introduction

In the past few years, we can see significant progress in the development of autonomous measuring systems intended for biomedical applications, particularly in telemedicine. The reason for this is the increasing interest in remote monitoring of the patient's health and activity. Acceptance of personal telemedicine devices by the users, and thus their further development, depends largely on the convenience of their use. This in turn mainly depends on the size and weight of the device, which is mainly due to the size of the battery. The size of the battery depends on the power consumption by the device.

There are several approaches to the issue of reducing power consumption in stand-alone measurement modules. It is proposed, among other things, to use specialised ASIC systems [1], implement hardware processors in FPGA structures [2], use dual-core systems [3] or combine a simple microcontroller and a programmable device with hardware-based data processing [4]. However, such solutions are expensive and inflexible. Solutions in which the CPU unit is an energy-efficient microcontroller (MCU) are used much more often. External sensors or sensor circuits are usually connected to the MCU [5]. Low power consumption of this type of sensor is achieved through the use of appropriate hardware and software techniques. Such solutions are presented in this paper. A stand-alone microprocessor system was designed and constructed, based on an energy-efficient microcontroller with Cortex-M4F core. As the sensor, an accelerometer designed to measure physical activity and a dedicated analog-front-end (AFE) circuit designed to measure the ECG signal were used. By using special control techniques and data acquisition, there were achieved the ability of real time data processing and low power consumption.

2. Power saving techniques in embedded systems

The current drawn by the stand-alone measurement module depends largely on the used MCU and its configuration. The selected devices should be characterized by: low power consumption in active mode and sleep modes, high efficiency (allowing to minimize the activity time needed to realize a given task) and a short wake-up time.

Given the above assumptions, a good solution is to use a microcontroller with Cortex-M4 core. These microcontrollers are characterized by high efficiency and low power consumption. The use of other microcontrollers, for example, MSP430 family, ATxmega, PIC24, could also be taken into account. However, we should remember, that not only the current consumption per MHz is important, but also the architecture of the microcontroller and the available modes of power management. Most of the algorithms, e.g. for data processing, will be performed much faster in a 32-bit MCU (Cortex-M4) than in a 16-bit (MSP430, PIC24) or 8-bit one (ATxmega). For this reason, a microcontroller with Cortex-M4F core was used in the design of the sensor. Devices available on the market were analyzed in regard to power consumption and energy saving techniques. A comparison of the devices taken into account is shown in Tab. 1.

Tab. 1. Summary of energy-efficient microcontrollers with Cortex-M4 core

MCU	SAM4L	EFM32WG	STM32F411
CPU	Cortex–M4	Cortex–M4F	Cortex–M4F
Max frequency	42 MHz	48 MHz	100 MHz
Active current	100 µA/MHz	225 µA/MHz	100 µA/MHz
Sleep current	62.46 µA	65 µA/MHz	32 µA/MHz
Deep - sleep current	1.5 µA	0.95 µA	42 µA
Wakeup time	1.5 µs	2 µs	21 µs

The microcontrollers described are suitable for use in the construction of hardware-software systems for saving energy. They have an expanded clock signal distribution system that can be reconfigured during the operation of the system. This allows selecting the optimum clock signals for the individual microcontroller blocks and for dynamic frequency scaling. An additional reduction in power consumption is provided by integrated voltage regulators, the configuration of which can dynamically change depending on the required efficiency. An important feature of the proposed systems are numerous reduced power consumption modes, and a short wake-up time from sleep. The deeper the sleep, the more functional blocks of the microcontroller are powered off. This translates to lower power consumption but a longer time required to return to the active state. From the standpoint of power consumption and external dimensions of the device, a suitable selection of the sensors is also important. Energy-efficient MEMS sensors, dedicated circuits (AFE) or passive sensors are used most often.

3. Sensor design

The sensor module presented in the paper is made based on the STM32F411 microcontroller. This MCU has a high performance and memory resources, while maintaining low power consumption. Besides functionalities typical for low-power MCUs, the system has an ART block (Adaptive Real Time Accelerator), containing prefetch buffers and a cache. In addition, the microcontroller includes the BAM (Batch Acquisition Mode) [6], which makes it possible to read data by DMA (Direct Memory Access) when the core remains in sleep mode. For the construction of the sensor module, an energy-saving 9-DoF (Degree of Freedom) position sensor type LSM9DS0 as well as an AFE circuit type ADS1293, designed to measure the ECG signal, were used. Both systems were connected to the MCU via the SPI (Serial Peripheral Interface). The SPI was used to shorten the time needed to read data to the maximum. In addition, the module sensor board has a memory card, power supply and the necessary connectors. The block diagram of the sensor is shown in Fig. 1. Firmware is written in MDK ARM integrated development environment from Keil (version: 5.04, optimization level: 2). The data processing algorithms used mainly CMSIS-DSP library (from ARM), that is optimized for speed (e.g. selected fragments written in assembler).

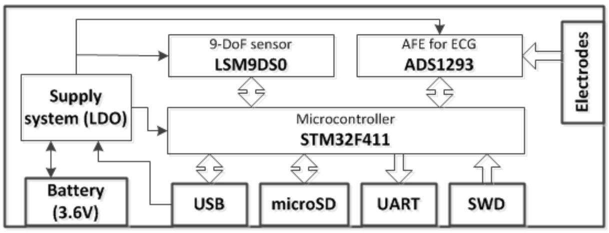

Fig. 1. Block diagram of the sensor module

The software module was prepared using the spatial and dynamic power scaling. MCU clock system can be divided into low (a) and high (b) frequency domains. The first domain works continuously with a constant frequency and is used by the real-time clock (RTC) and blocks generating periodic interrupts. The high frequency domain is reconfigured during the operation of the module. This way, the optimum ratio of static and dynamic power is achieved during data acquisition and processing. A configuration diagram of the clock system is shown in Fig. 2.

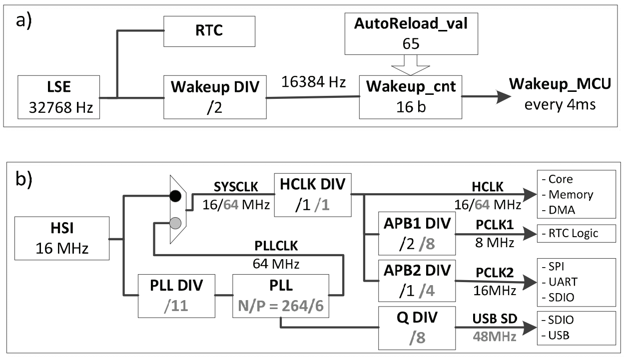

Fig. 2. Block diagram of the clock signal generation and distribution system
a) for the low-frequency domain b) for the high-frequency domain

Settings for acquisition are marked in black, settings for data processing are in grey. In addition, the microcontroller software (firmware) uses two MCU sleep modes. A simplified block diagram depicting the operation of the system is shown in Fig. 3.

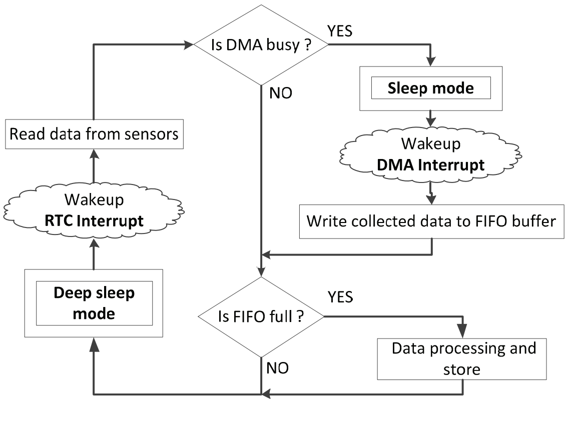

Fig. 3. A simplified block diagram of the sensor module's algorithm

Most of the time, the MCU is in sleep state with an active RTC. This clock, with a frequency of 250 Hz, generates an interrupt, which occurs during the reading of data from the AFE in BAM mode. Data from 9-DoF sensor are read every fifth interrupt (50 Hz). Clocking frequency for the core and the majority of peripheral devices is 16 MHz. Both the microSD card and USB interface are disabled. In addition, each time before the system switches to the sleep mode, most pins are reconfigured to "analog in" mode, guaranteeing the lowest power consumption. After filling the FIFO buffers (containing subsequent samples of the measured signals), a reconfiguration of system clocks and a longer activity of the MCU occur. During this time, the procedures of processing data and saving them on the microSD card are implemented. In this state, the MCU core is clocked at 64 MHz. This value allows keeping a constant clocking frequency for peripheral devices after changing prescaler settings. There is also a maximum frequency at which a single wait state for access to memory is required. During signal processing, samples are still read with a constant frequency, but the MCU is not in the sleep mode.

The implemented method of processing data included digital filtering of signals from the position sensor and the ECG and determining the position of the QRS complexes of the ECG signal, using the Pan-Tompkins method [7]. The method was slightly modified (in IIR filters matter) and added a maximum search for the determination of R-wave.

4. Measurement setup

Several tests were conducted in order to determine the power consumption by the module. The first of these was to determine the current drawn during specific states of activity. The program was then subjected to modifications, so that the states of the two pins (PD5 and PD4) changed in specific parts of the algorithm. Using an oscilloscope connected to these pins, durations of individual states of activity were specified. A block diagram of the measurement system used to carry out these tests is shown in Fig. 4.

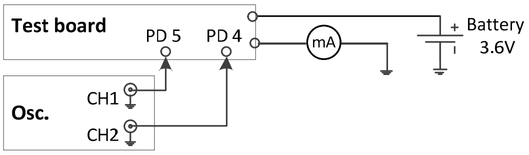

Fig. 4. Block diagram of the measuring system used during the measurement of current and times of activity

The waveform of the current drawn by the system during sampling was also determined. For this purpose, a measuring resistor was connected in the place of the previously used milliammeter, to which an oscilloscope was connected. A block diagram of the system used in this part of the tests is shown in Fig. 5.

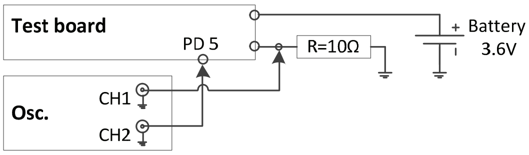

Fig. 5. Block diagram of the measuring circuit for determining the current waveform

The last of these tests was to determine the operating time using battery power. This time was determined for power supply using a Li-Po battery with 250 mAh and nominal voltage of 3.6 V. The point of battery charge was determined by the MCU by comparing the battery voltage with the threshold value of 2.9 V. The operating time was calculated based on the number of samples saved on a memory card. The study was performed for the system working according to the described algorithm and without using the MCU sleep modes and frequency management.

5. Results

Based on the results of measurements described above and assuming that the data processing procedure was started when the buffers held 500 samples, the duration of a single measurement cycle was determined. It is defined as the period between successive procedures for processing the data from the position sensor. The share of individual states of activity in the test cycle was also determined, which in combination with the measured current values allowed determining the values of power and energy. The results are presented in Tab. 2.

Tab. 2. The results of calculations of average current, power and energy consumed by the measurement module

	Time	U	I	E	P
	s	V	mA	mJ	mW
Processing and Store	0.662	3.6	12.920	30.768	46.512
Sampling	9.409	3.6	1.867	63.236	6.721
Complete cycle	10.070	3.6	2.593	94.004	9.335

The above results show that the average current drawn by the circuit during sampling has a value of 1.87 mA. The analysis of the voltage on the measuring resistor with a resistance of 10 Ω shows that this value is primarily related to the current consumed in the sleep mode, amounting to 1.64 mA. The recorded waveform is depicted in Fig. 6.

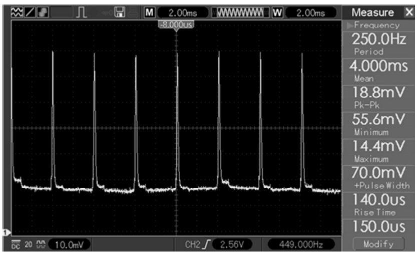

Fig. 6. Waveform showing power consumption during data acquisition

The result of the last test, the purpose of which was to determine the maximum operating time of the sensor module, is shown in Tab. 3.

Tab. 3. Results of the measurement of run time of the tested module

	Run time
Proposed algorithm	78 h 32 min
Fixed frequency, unimplemented sleep modes	12 h 45 min

The use of the proposed algorithms and power saving techniques allowed increasing the operating time by more than 6-fold.

6. Conclusions

The study shows, that the average current consumed by the measurement module is only 2.6 mA. This translates into more than three days of continuous operation of the system supplied by a small Li-Po battery with a capacity of 250 mAh and nominal voltage of 3.6 V. These results support the conclusion that the systems and software proposed in the paper can be successfully used in stand-alone measurement modules which require the implementation of DSP operations.

The proposed power saving techniques associated with dynamic scaling of power and the use of sleep modes make it possible to achieve a more than 6-fold reduction in power consumption compared to non-optimized software. This result confirms that it is possible and efficient to use the techniques described at sampling frequencies, also up to 250 Hz. Theoretically, a similar benefit could be obtained even at higher frequencies. The limiting factor seems to be the time needed to process the data, because its increasing share reduces the period during which the sampling mode with switching to the sleep mode takes place.

The energy absorbed by the system in the process of data acquisition using the procedure of switching the microcontroller to sleep mode is more than twice the energy consumed during data processing. The reason for this is the relatively high current consumption in sleep mode associated with the need to supply uninterrupted power to the sensors. As is apparent from the waveform, even at a relatively high sampling frequency of 250 Hz, the microcontroller is in sleep mode for most of the time. Therefore, the reduction of current consumed in this mode could significantly reduce overall power consumption.

This work has been supported by the Military University of Technology, Warsaw, Poland, as a part of the project PBS918.

7. References

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Received: 16.03.2016 Paper reviewed Accepted: 02.05.2016

Tadeusz SONDEJ, PhD

He received the MSc degree in electronic engineering and the PhD degree in applied sciences from the Military University of Technology (MUT), Warsaw, Poland, in 1997 and 2003 respectively. Since 1998, he has been with the MUT, where he has been working on design and programming of embedded systems. His current interests are in the field of design, optimization and programming of System-on-Chip based digital systems, especially for biomedical applications.

e-mail: tadeusz.sondej@wat.edu.pl

Marcin MACIEJEWSKI, MSc

He is a PhD student in the Institute of Optoelectronics at the Military University of Technology (MUT). He received his BSc and MSc degrees in electronics and telecommunications from MUT in 2014 and 2015, respectively. His main scientific interests are measurement and analysis of biometric signals, and energy-efficient microprocessor systems.

e-mail: marcin.maciejewski@wat.edu.pl