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Design Issues of Portable, Low-Power & High-Performance ECG Measuring System

Jyoti Bali, Anilkumar Nandi

Abstract -There is lot of need and demand for portable medical equipments consuming ultra low-power and operating with higher speeds. Medical equipments need to work with higher speeds in order to process digital processing algorithms and consume lowest possible power in order to extend battery life. This paper is to discuss about the various issues in designing the portable, low-power and high-performance Electrocardiogram (ECG) measuring system. The individual blocks of ECG measuring system are namely modules for Power/battery Management, Control/data processing, Sensor interface, Amplification, Analog-to-digital conversion (ADC), User interface/display and Wireless connectivity. The objectives of design for incorporating features of smaller size, improved battery life, lower cost and faster response has to be implemented across each of the modules chosen for building the system. and the designer faces the challenge of extracting a very small ECG signal of amplitude 1 mV present along with large high frequency noise of the order of around 300mV. Here we discuss the issues in the choice of an ultra-low-power MSP430 family microcontroller from Texas Instruments in order to do acquisition, processing and analysis of the ECG signal. Here we even address the issues related to adoption of standard techniques for estimation and measurement of power in the chosen microcontrollers for the intended application.

Index Terms: **Analog to Digital Conversion, Analog front end, Control/data processing, Electrocardiogram (ECG), Sensor interface, Mixed Signal Processor (MSP), Power/battery management, Wireless connectivity.**

I. INTRODUCTION

Healthcare industry is one of the prominent areas where a lot of research activities are taken up. In Indian scenario, there are various reasons for increase in the demand for medical electronics like increased number of people suffering due to malnutrition, lifestyle diseases, rising costs of healthcare facilities. Also the initiation of government bodies through rural healthcare initiatives, need for requirement of portability in medical devices and increased awareness about healthcare among people has also added to this demand. Even the parameters like higher efficiency and high-precision with a fast response are considered to be intrinsic features of any modern medical equipment. Electrocardiogram (ECG) equipment has become important diagnostic equipment used by doctors nowadays. Application of the technological developments happening in chip design has made possible the development of portable and lower power consuming ECG devices. As a result of awareness of preventive health care, common people can have provision of getting ECG reports with much ease at a cheaper price and consult doctors to know about their health status. Hence we have undertaken the study of design issues in developing a low-power, high-performance, portable ECG measuring device.

II. DESIGN ISSUES AND PROPOSED PLAN

The important function of an ECG machine is waveform display either through LCD screen or printer and also heart rate indication. The additional features can be provision of patient record storage through convenient media using wireless/wired transfer. The captured and digitized ECG signal can be displayed and analyzed for further signal processing. The five common system blocks used in building the ECG system are Power battery Management module, Control data processing, sensor interface, amplification, analog-to-digital conversion, user interface display and wireless connectivity [1]. The design goals have to be set for extended battery life, high precision, small size and fast response which are driven by the system specifications of each of the equipments. There are a lot of latest developments in the field of chip design and communication leading to the selection of ideal circuit elements and also the use of suitable low power modes of control modules. Additional requirements include need for more memory to allow for profiling, cabled or wireless interfaces for data upload or for access to the sensor. Hence to build such medical systems with these added features and without increasing power consumption is a big challenge. The block diagram shown in Fig 1.0 shows the key functional blocks of the ECG measurement system.

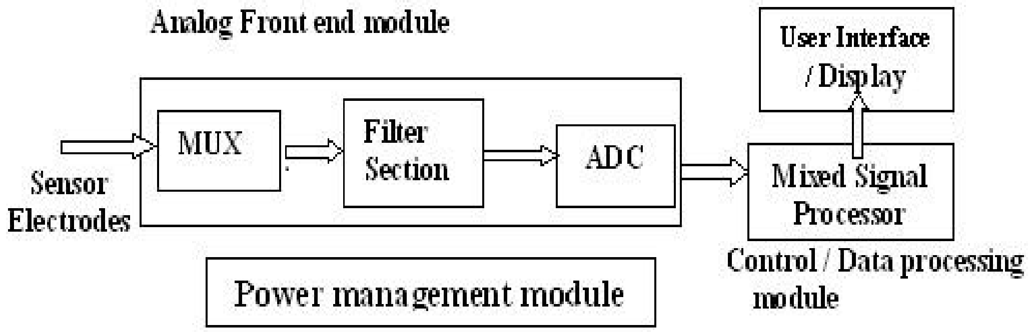

Fig 1 Functional Block diagram to ECG system ***(Courtesy: Texas instruments ti.com)***

Under Power/battery Management module, concern here is to select devices and their configuration for consuming the least possible power without staking its performance. All the core components must meet tight power requirements in terms of low operating voltage, low operating current, low standby current, small size, on /off power management, low noise and a fast response. Advanced low-power controllers from MSP430 family microcontrollers can be used to match this requirement [2]. ECG is an AC signal having amplitude of 1 mV peak to peak and frequency range of operation from 0.05Hz to 100Hz. It may stretch even to a maximum of 1 KHz. It is present along with a external high frequency noise of the order of 300mV. Muscle noise has the same bandwidth as that of ECG signal and hence it is difficult to separate it. Ag/AgCl (Silver-Silver chloride) is the commonly used electrode in ECG system to tap the signal from human body.

The Analog signal chain for the ECG data acquisition system is built using instrumentation amplifiers, filters and Analog to Digital Converters. Instrumentation Amplifier needs to have stability in low gain, high common-mode rejection, low input bias current, good output swing, very low offset and drift connectivity etc. The signal can later be filtered to avoid high frequency noise, amplified and digitized using A/D converter to record it on a battery powered memory. Thus selected A/D converter should have high resolution and a reasonable conversion time. A specially designed digital-filter block can be used to fix up the frequency range of operation of the ECG system. High-speed analog multiplexers can be used to acquire data from channels connected to different electrodes. By choosing a high resolution ADC of the order of 20 bits, further component reduction can be achieved in turn to build portable ECG equipment. The processing of ECG signal is difficult as we need to work with very small voltages of mV range. Use of a single, mixed-signal controller from MSP430 family as a complete analog front-end with integrated hardware and software can also be considered to achieve increased system accuracy and reduced overall power consumption[2]. Even by adopting System On chip (SOC) design we can further reduce system cost effectively. Thus we can employ these features in order to run the system from a single battery for a good number of days.

III. ISSUES IN USAGE OF MSP430 MICROCONTROLLER

Nextly, the selection of appropriate controller to process and analyse the acquired ECG signal has to be done. One of the low power optimized controller from MSP430 family can be used for this purpose as they are known for their very efficient low-power modes of operation and proved efficient in ultra-low power applications. Our objective is to keep the microcontroller in active mode whenever the ECG signal is available through analog front end and make it switch to low power modes when it is idle and has no signal to process. The MSP430 has one active mode and five programmable low-power modes of operation driven by different clock sources. One of them is a 32.768 KHz watch crystal oscillator consuming very low-power and low-frequency. Second one is the internal Digitally Controlled Oscillator (DCO) which is meant for low power consumption, low cost and also better speedy response. One distinct characteristic of the internal DCO is that it uses the clock source which stabilizes in less than 1 micro sec. The basic clock module of MSP430 also provides the clock signals like Auxiliary clock (ACLK) sourced from a 32768-Hz watch crystal, Main clock (MCLK) for CPU, Sub-Main clock (SMCLK) for peripheral modules. The clock generator of MSP430 microcontroller devices have a multiplexer, a divider and clock polarity selector in order to select the appropriate clock sources based on the operating mode of the controller[2].

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By using interrupts, the microcontroller unit can be woken up from any of the five low-power modes. Thus it can service the interrupt request and go back to the low-power mode after returning from the interrupt program. The six operating modes of microcontroller are named as 1) Active mode 2) Low-power mode 0 (LPM0) 3) Low-power mode 1 (LPM1) 4) Low-power mode2 (LPM2) 5) Low-power mode3 (LPM3) 6) Low-power mode 4 (LPM4) and can be configured by software [3].

We can always activate and deactivate the required clock sources for managing power in these operating modes. If the MSP430 controller starts up in Active mode with the CPU, all clocks and enabled modules being active, it consumes an average current of 300uA at a supply voltage of 3V. But we can always reduce the current up to 200uA, by operating the controller at its minimum allowed supply voltage i.e 1.8V. Thus it leads to saving of power and thus adding to battery life. One of the important low power modes is the LPM3, as only one clock ACLK is active there. This mode is used in conditions when a peripheral wakes up regularly to execute a predefined program before returning to sleep mode. Later DCO can be started, which otherwise takes more time to start from LPM0 mode [3]. Here we need to stress on the choice of appropriate low power modes of operation for the ECG measuring system [7].

Brown out Reset (BOR) protection feature available with MSP microcontroller proves to be very beneficial in the real time system design as the Brown Out Reset circuitry detects dip in supply voltage and initiates a Power On Reset (POR) signal to reset the controller to avoid any malfunction in the system. The MSP430's BOR circuit is a low power consuming circuit and is enabled even during low power modes of operation. This feature helps in enhancing the performance of system by avoiding the problems caused due to lower supply voltage.

In MSP430 family controller there is provision for connecting Intelligent Peripherals which can be handled using all instructions. They can be activated or deactivated based on the requirement at appropriate timings thus saving power as well increasing system performance. Here the electrodes used for tapping ECG signal from human body can be used in the system with intelligent peripheral.[2]

Watchdog timer (WDT) module available on MSP430xx series chip can restart the controller in case of any software problems causing infinite looping. In such cases in order to restore the normalcy of operation, the system is reset as soon as the selected time interval of WDT expires. If the watchdog function is undesired for an application, the WDT module can be programmed as an interval timer to generate interrupts at selected time intervals [3].

The MSP430 family supports three types of serial communication protocols namely Universal Serial Interface (USI), Universal Serial Communication Interface (USCI), Universal Synchronous/Asynchronous Receiver/Transmitter (USART). USI peripheral supports synchronous communication, such as Serial Peripheral Interface Bus (SPI) or Inter-Integrated Circuit Bus (I^2C). For the ECG measurement system we can make use of USI communication peripheral with its interrupt support for capturing the data from the ECG electrodes through the analog front end system [2,3]. Because of interrupt support provided by USI peripheral we can reduce the software complexity involved during the serial communication and thus improving the low-power capabilities of ECG system under study. The option of reducing the size of ECG measurement system by increasing portability through the wireless communication protocols can also be considered. Even the factor of advanced technologies used in chip manufacturing has made microcontrollers reduce in size in turn reducing power consumption. Thus MSP430 microcontrollers are available only in Surface Mount Device packages (SMD).

IV. ISSUES IN BUILDING ANALOG FRONT END MODULE

There are various means of building Analog Front end module for implementing the design of ECG measurement system. One option can be to use a single-converter 16-bit, analogue-to-digital conversion module, SD16A implemented in the MSP430x20x3 series. It consists of one sigma-delta analogue-to-digital converter and an internal voltage reference. It has eight fully differential multiplexed analogue input channels, of which three are internal which can be connected to AgCl electrodes used for capturing ECG signal. Other option is to use ADS1298 IC from Texas Instruments which is a perfect setup as 12 lead ECG analog front end as it provides eight channels of PGA plus separate 24-bit delta-sigma ADCs, a Wilson center terminal, the augmented Goldberger terminals and their amplifiers. Thus the advantage of using ADS1298 is that it reduces component count and power consumption by up to 95 percent as compared to the analog front end circuit built using discrete components. It provides very good power efficiency of 1 mW/channel, highest levels of diagnostic accuracy and low noise. Hence

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the IC ADS1298 is being popularly used for patient monitoring systems, portable and high-end electrocardiogram (ECG) and electroencephalogram (EEG)[1,2].

V. DESIGN OF SOFTWARE FOR ECG MEASUREMENT SYSTEM

Here we aim to make use of the architectural and algorithmic techniques for ensuring high performance and low power operation of ECG measuring system. We need software algorithms which help in filtering of ECG after digitization. The chosen microcontroller needs to be efficient enough to implement the complex signal processing algorithms aiming at good accuracy, reproducibility and efficient information. The system needs to be rigorously tested against standard measuring devices and validated by experts. Algorithm design for the system has to be done with care in order to interpret the information on the ECG signal which is captured using analog front end [7]. The values of each parameter P, Q, R, S, T as well the time intervals between each parameter as shown in **fig.2.0** has to be recorded accurately for a specified duration on a storage media[9]. We need to fix up the time duration in which we can measure the parameters P, Q, R, S, T for ECG waveform and then calculate the heart rate accurately and predict the heart related ailments as per the template parameters stored in database. The controller in the ECG system stays in sleep mode or the low power mode till an ECG signal is made available to it through interrupt. Microcontroller needs to wake itself up in order to take the ECG signal from analog front end and start processing as per the algorithm requirements. Once the MSP430 microcontroller completes the processing of ECG information and sends it to memory and display device, it can again go back to low power mode. This technique helps in making use of processor time very efficiently as well conserve battery power.[8]

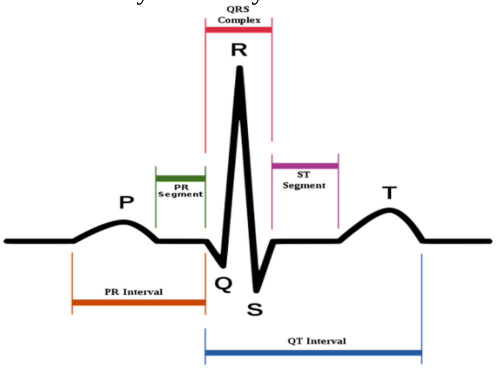

Fig 2 An Ideal ECG Waveform

VI. POWER ESTIMATION FOR MSP430 MICROCONTROLLER

While doing power estimation in case of battery operated systems, the parameter considered is the energy required to execute a given set of tasks. Even based on the varying load, different power reduction methods are adopted during the microcontrollers design. Here some of such methods for experimental measurement of energy consumption in MSP430 microcontroller are considered and thus can conclude regarding techniques related to minimization of energy consumption. Also the time interval between battery changes for the electronic device is an important parameter [6]. Here the need is to make use of all those provisions available with MSP430 in order to maximize the battery life like use of power down modes, intelligent peripherals etc.
For MSP430 device, being a CMOS processor its power requirement P can be evaluated by the formula

$$P = C_e V^2_{cc} f + I_L V_{cc} \qquad \text{- Eqn. 1.0}$$

Where Ce is the effective switching capacitance, a constant, V_{cc} denotes supply voltage, I_L is leakage current and f is clock frequency [6]. The frequency of operation decides the number of clock pulses needed for any specified task execution by the microcontroller and it is also constant. In that case the only way by which microcontroller power can be reduced is by decreasing the supply voltage V_{cc} up to the value while guaranteeing proper processor operation, without compromising on system deadlines [4]. This method is known as Dynamic Voltage Scaling.
The Dynamic Voltage Scaling (DVS) method is used many a times with a simplified processor power requirements model and evaluated [5,9]. But practically, analyzing a power requirement of microcontroller working on real time proves to be very complex as we need to consider the influence of all devices and functional blocks like clock generator, internal memory, peripherals etc. Our objective here should be to find an optimal method for

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microcontroller frequency and supply voltage scheduling in order to meet specified performance requirements of the system along with minimal energy consumption.

VII. POWER MEASUREMENT FOR MSP430 MICROCONTROLLER

For the ECG system under consideration, it needs to acquire the signal whenever it is available by interrupting the controller. Hence we need to keep the controller active only during the time required for acquiring and processing the same. The microcontroller can be made to stay in low power mode all the other time [4]. The power characteristics of a specific device should be known in order to plan for optimum voltage, current and clock frequency in turn the execution time. We can experiment to measure the power requirements of MSP430 controller in run mode while it is involved in processing of ECG signal and in idle state while it does not have any ECG signal available to it. In run mode, the High Frequency (HF) oscillator can be turned on to generate the clock signal for CPU core and (Digitally Controlled Oscillator) DCO and Low Frequency (LF) oscillators can be turned off by setting CPU clock divider set to 1:1 ratio. All other on-chip peripheral modules should be switched off. Supply voltage has to be changed for microcontroller unit (MCU) in the range from 1.8 V to 3.6 V. [4] The CPU can now execute the algorithm written for ECG signal processing [2,3]. The practical setup for measurement of voltage, current and clock frequency can be very well implemented on NI ELVIS II hardware from National Instruments. This NI ELVIS II (National Instruments Electronics Laboratory Virtual Instrumentation System) hardware is very powerful housing a data acquisition system and instrumentation system used for real time capturing of signals and measuring with great accuracy. As it can be directly accessed through Lab VIEW software, we can even use the graphical language based visual development environment for creating powerful control and signal processing algorithms. Voltage measurement can be done across the shunt resistor connected in series with supply voltage of MCU, whereas average current consumption of MCU for one cycle of ECG signal can be measured by using Digital multimeter present in NI ELVIS II. There is also the provision to make use of timers/counters available with NI ELVIS II to measure the clock frequency accurately [4].

The power curves measured in run condition can be studied and compared with theoretical assumption given by formula in Equation 1.0. We can study graphs of power dependency of MSP430 microcontroller on the clock frequency and also supply voltage. For the idle state measurement the CPU clock (MCLK) can be switched off in the clock selectors block keeping HF oscillator still running. In order to further save energy, the HF oscillator can be switched off as the CPU is idle. But MCU takes a very long time to wake up from that state and switch to servicing of interrupts. To avoid this problem, initially the MSP430 and other subsystems can be clocked using the DCO (Digitally Controlled Oscillator) which has a very short starting delay of the order 6 µs. Power characteristics of the CPU in run state with DCO clock source can be studied. MCU power requirements of MCU while using clock sources DCO and HF oscillator can be recorded separately and compared later by estimating power consumed in both cases. In order to have an efficient wake up algorithm, as soon as the MCU wakes up, both HF and DCO oscillators can be restarted. After elapse of 6 µs time, CPU can run the program using DCO clock source. This is the advantage of using DCO as it requires only a short interval of 6 µs time. Once the HF oscillator stabilizes, clock source can be changed to HF oscillator and DCO can be stopped. We need to look at the disadvantage of using DCO clock as it uses RC type oscillator having poor stability in case of temperature and MCU supply voltage changes. Even the power requirement of DCO clocked CPU is nearly twice as that of HF oscillator clocked CPU [4].

VIII. ISSUES INVOLVED IN SELECTING OPTIMUM CLOCK FREQUENCY

For the ECG measuring system, in order to have a fixed set of tasks to be executed by MCU, the specific number of CPU clock pulses is required. As the energy consumed in one clock period is a constant for a fixed supply voltage, the total energy for the complete execution of task is not determined by the CPU clock frequency. Higher the clock frequency used by the MCU, the higher is the supply voltage required and vice versa. MSP430 can be operated with supply voltage in the range 1.8 to 3.6 V. For each clock frequency, the required minimum supply voltage can be noted from the MSP430 datasheet [6]. Even we can always estimate the worst case processor load by experimenting with different clock frequencies as well and then identify the clock frequency required to execute all tasks meeting their deadlines. If the clock frequency is known, supply voltage can be set to minimal possible value in order to achieve maximal energy conservation. We can also do the selection of the optimum clock frequency required for running the algorithm written for ECG signal processing by switching for each of the frequencies in

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turn and analyzing the performance of algorithm in each case. This can be implemented using the programmable frequency divider of MSP430 clock generator. Each clock frequency has to be set by all possible combinations of crystal oscillator frequency and clock divider ratio and then microcontroller power consumption can be measured for each case. The data collected through the experimentation results can very well be used to have the tradeoff in selecting the optimum supply voltage and the clock frequency of operation.

The total energy consumption in MCU for extraction and processing of one cycle of ECG signal can be measured in idle, low power and active modes to be later compared with theoretical curves. Dynamic voltage scaling [DVS] method is well applicable on MSP430 microcontroller. For application of the DVS method with dynamic task planning, we need to use DC/DC converter for required variation in supply voltage [6, 9]. Overview of experimental techniques discussed in this paper can be implemented using simple software loops, without any operating system. We can further focus to the power requirements of microcontroller running ECG algorithms in Real time operating system (RTOS) environment. The goal of our work can be to find rules for optimal task planning for energy conservation by choosing optimal supply voltage and clock frequency.

IX. SUMMARY

With the given constraints of large population of India residing in the villages and doctors living in urban areas, the challenge for designers is to make the healthcare delivery accessible and affordable. Our work in this direction for suggesting an efficient design of ECG measurement system with low-power, low-cost and high-performance features can help in overcoming this challenge.

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AUTHOR BIOGRAPHY

Mrs.Jyoti Bali has completed her B.E in Electronics & Communication from Karnataka University, Dharwad, M.Tech in Digital Electronics from Visvesvaraya Technological University (VTU), Belgaum in Karnataka. She is presently pursuing her PhD under VTU in the area of low power strategies used in building Medical instrumentation systems. Her area of interest also include Real time system design, Mechatronics System design, Fuzzy logic based systems. She is working as Asst. Professor in the department of Automation & Robotics at B.V Bhoomaraddi College of Engg. & Tech. Hubli, Karnataka, an autonomous college under VTU and has put in 14 years of teaching in the area of Mechatronics Control systems.
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Dr. Anilkumar Nandi has completed his Ph.D. (Electrical and Electronics Engineering) in the domain of VLSI Architectures and Embedded Systems under VTU Belgaum. He has done his M.Tech in Microelectronics and VLSI Design from Indian Institute of Technology, Kharagpur and B.E. in Electronics and communication Engineering from Karnataka University, Dharwad. He is working as Professor of Electronics and Communication Engineering at B.V.Bhoomaraddi College of Engineering and Technology, HUBLI for last 23 years contributing towards the education and research activity in the field of VLSI / Embedded Systems and Micro Electro Mechanical Systems (MEMS). He has been the resource person for many of the workshops and conferences. He has published till now, 6 Research papers in journals and 35 papers in National and International Conferences .He has been the member of Indian Society of Technical Education (ISTE), Semiconductor Society of India, Systems Society of India, International society IACSIT and Teacher Member of Indian Academy of Sciences, Bangalore