Real-Time ECG Analysis Using a TI TMSC54x Digital Signal Processing Chip

S Mohammad, Z Lim, Y Lin, A Sani, K Zanjani, M Paracha, J Jenkins

University of Michigan, Ann Arbor, USA

Abstract

Real-time template-based correlation was implemented on the Texas Instruments TMSC5402 Digital Signal Processing (DSP) chip to allow for the detection of abnormal QRS-complexes in electrocardiographic signals. Several novel techniques were used to achieve real-time implementation of correlation algorithms, as well as development of an automatic template generation module.

The main goal was the successful development of an algorithm to rapidly and efficiently detect irregular QRS complexes. This is implemented by software embedded in a DSP chip using limited memory resources. Once the algorithm produces a favorable correlation of a normal QRS, the timer is reset (and alarm deactivated, if active) indicating a normal passage. Values of the timer and correlation threshold are also displayed on an oscilloscope to allow for visual inspection of the system while executing.

This paper describes an academic undergraduate semester-long project in the implementation of an arrhythmia (abnormal beat) detector accomplished via a standard DSP chip. The bulk of the project consisted of software design, which was kept modular to facilitate the visualization of project flow and modification of individual software components.

The system can easily be implemented on a small DSP, Field Programmable Gate Array (FPGA), or an Application Specific Integrated Circuit (ASIC). The device can be bundled with a micro hard-drive to record ECG signals over a lengthy period of time in minimal space.

1. Introduction

Electrocardiography is a method to record the electrical activity of the heart. It is used to measure the rate and regularity of heartbeats. ECG analysis can also indicate the size and function of the heart chambers, any damage to the heart, and the effects of drugs. By examining the ECG signal, we can tell whether a ventricular depolarization results in a heartbeat that is normal.

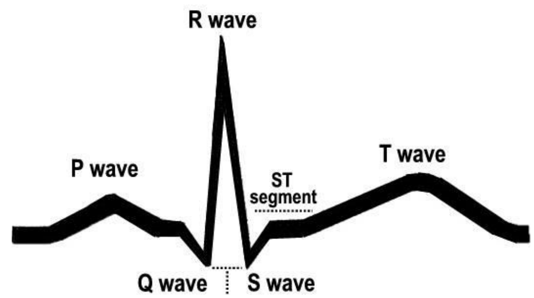

Figure 1. Schematic ECG signal showing the characteristic waveforms, intervals, and segments.

The ECG signal consists of P, Q, R, S and T waves as shown in Figure 1. The first upward deflection in the ECG signal is the P wave which is formed when atrial depolarization occurs in the two upper chambers of the heart, causing the atria to contract to pump blood to the ventricle. The next waveform is the QRS complex which reflects ventricular depolarization causing the ventricles (the two lower chambers of the heart) to contract and pump blood systemically to the remainder of the body. The next slightly elevated section is the T wave that reflects the repolarization or resting period of the ventricles. The QRS complex is the most easily detected waveform of the ECG and its analysis is a classic method for determining the electrophysiologic state of the heart. Our method of reducing filtering (preprocessing), detection (triggering) and QRS waveform analysis (correlation) to a small off-the-shelf integrated chip (IC) may find use in small implantable or subcutaneous medical devices.

Intraventricular electrograms analyzed in this study were recorded from right ventricular apex (1-500 Hz) during clinical cardiac electrophysiology studies of patients undergoing clinical evaluation and treatment. Written informed consent was obtained from each patient. Episodes included monomorphic VT and VF having a duration of ≥ 9 seconds and were recorded from bipolar and unipolar electrodes located in the right ventricular apex. Intraventricular electrograms were recorded continuously on FM magnetic tape at a tape speed of 3.75 in (9.5 cm)/sec 9bandwidth of 0-500 Hz) (Hewlett-Packard® Model 3968A, San Diego, CA, USA) after signal amplification and filtering at 1-500 Hz. Amplifier gain and filter settings were held constant during the entire recording procedure, and all electrogram amplitudes were computed using a 1-mV calibration signal entered as a reference at the time of recording. Each recording was assigned a case number and catalogued for subsequent off-line retrieval (Ann Arbor Electrogram Libraries, Ann Arbor, MI, USA).

A normal ECG signal is shown in Figure 2. A stream of irregular QRS complexes is considered an abnormal rhythm, or arrhythmia. Abnormalities, such as ventricular fibrillation can be easily visually distinguished from normal heartbeats as shown in Figure 3. Automation of detection schemes is standard practice in all computer-based electrocardiographic systems.

Figure 2. ECG tracing of a normal heart rhythm.

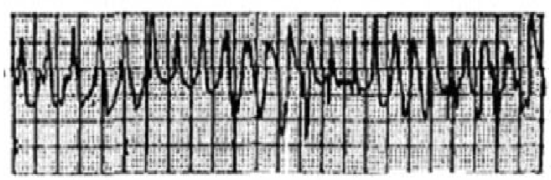

Figure 3. Ventricular Fibrillation

We were given approximately eight weeks to design, implement and to present the results for this project.

2. Methods and Materials

The complete demonstration system consisted of the Texas Instruments (Dallas, TX) DSP evaluation board (EVM), a host computer, TEAC (Montebello, CA) DAT tape recorder for ECG playback, an oscilloscope to monitor outputs, and accompanying visual and audio warning systems. The main goal of the project was the successful development of an algorithm to efficiently detect irregular QRS-complexes and its implementation on a standard off-the-shelf DSP chip using limited memory resources.

Upon successful completion of the original algorithm design, code was generated using native C for the TI DSPC54x family. To test and validate the design, human ECG recordings from clinical electrophysiology studies were used from patients who underwent provocative studies. These recordings are housed in the Medical Computing Laboratory, Department of Electrical Engineering and Computer Science at the University of Michigan and sets of them are licensed to many pacemaker companies [1]. The tapes contain both regular and irregular patterns for identification by the system. During a period of 15 seconds of normal rhythm, the system generated a reference template. SNR for the template was increased by 4 dB by averaging 16 normal beats that were automatically triggered and captured by the system.

The ECG system is comprised of the following components: (wiring diagram specified in Figure 4):

-Texas Instruments TITMS320C5402 Digital Signal Processing DSK

-1GHz Dell Pentium PC, Windows 98

-TEAC Digital Tape Recorder (DAT) Model # RD-130TE DAT Data Recorder (See Figure 2.2.)

-Hewlett Packard Arbitrary Waveform Generator Model # 33120 A

-Tektronix Oscilloscope, Model #TDS 410A

-Mono Transistor Buzzer Driver (self-assembled)

The system setup is detailed in the following figure:

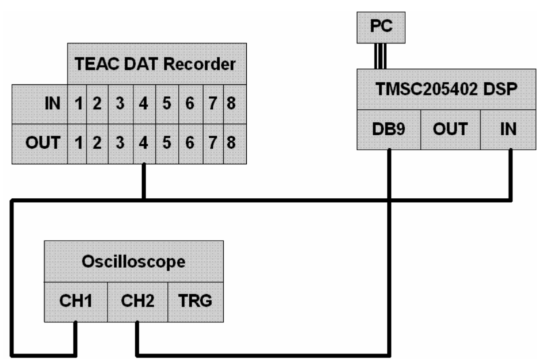

Figure 4. Device Wiring Diagram for Real-time ECG Analysis

The TMS320C5402 DSP is based on an enhanced Harvard architecture, with separate program and data memories. The program was loaded onto off-chip, single access memory (SARAM). Data including variables and buffers were loaded onto on-chip, dual-access memory (DARAM).

The coder-decoder (CODEC) built on this particular model is capable of sampling up to 16KHz with 16 bit quantization. For this particular application, the sampling rate was set to 2KHz to easily coincide with data that was previously captured and downsampled to 1KHz.

Code Composer Studio software, an integrated design environment by TI, was used to program the DSP chip.

The TEAC Digital Tape Recorder (Figure 5) was used to feed ECG signals into the DSP, in real-time. The data recorded on the tape were originally sampled at 12 KHz.

Figure 5. TEAC Digital Tape Recorder

The Tektronix Oscilloscope provided a real-time display of the ECG signals along with visual inspection of whether particular heartbeats were normal or abnormal. Thus the system was evaluated on real-time data with oversight of each incoming beat.

3. System Overview

The project was divided into three parts in which work was divided between team members. Regular meetings were held and progress reports were given to insure each member understood each project component. Therefore, all individuals were competent in all aspects of the project in case a member became unavailable.

The three major components implemented on the DSP chip included the following:

1. Filtering
2. Auto-template
3. CWA (Correlation Analysis)

3.1. Filtering

Both research and FDAtool in MATLAB were used to analyze different filters to discover the one that best suited our purpose. A good filter was required to clean up the input signal, isolate the section of interest (the QRS complex of the ECG signal) and minimally distort the ECG signal.

3.2. Auto-template

An auto-template module was designed in order to store a representative normal QRS complex. This template was used as a reference for comparison with the incoming ECG signal in order to determine whether the incoming heartbeat was normal or abnormal. C and Assembly code were written to perform this task. The program first analyzed the initial heartbeats input into the DSP and determined the maximum amplitude of those beats. Then, this maximum value was multiplied by a fraction to obtain a triggering threshold. According to this threshold value, the program formed a normal template by ensemble averaging. The template formation was completely automated.

3.3. Correlation Waveform Analysis

The CWA module performed real-time correlation, comparing heartbeats to the template. The first step in correlation waveform analysis was to correlate the template with itself to determine a maximum correlation value for a normal beat. A correlation threshold was derived from this maximum value and was used subsequently for continuous discrimination of normals from abnormals. This correlation threshold value was the minimum value for a signal to be considered normal. The incoming signal was stored in a circular buffer and correlated with the samples in the auto-template. The program then checked whether the correlation was normal or abnormal.

4. Conclusions

The oscillographic display demonstrates the capability of the system to discriminate normal from abnormal beats in real time fashion with the incoming beats shown on the top trace of the screen and the real time output depicted on the lower trace. (See Figure 6.)

The system can easily be implemented on a small DSP, FPGA, or an ASIC. The device can be bundled with a micro hard-drive to record ECG signals over a lengthy period of time in minimal space.

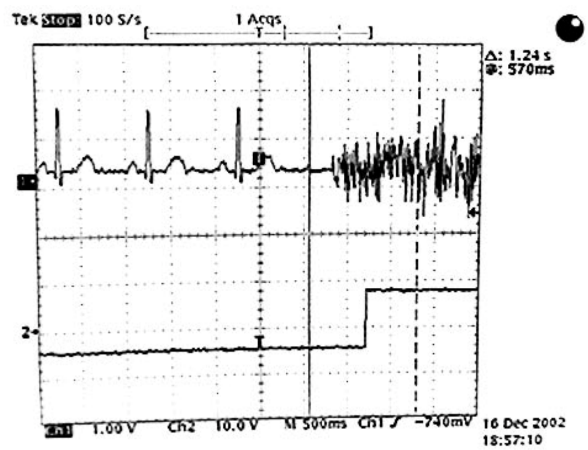

Figure 6. Oscillographic display of the DSP chip beat classifier

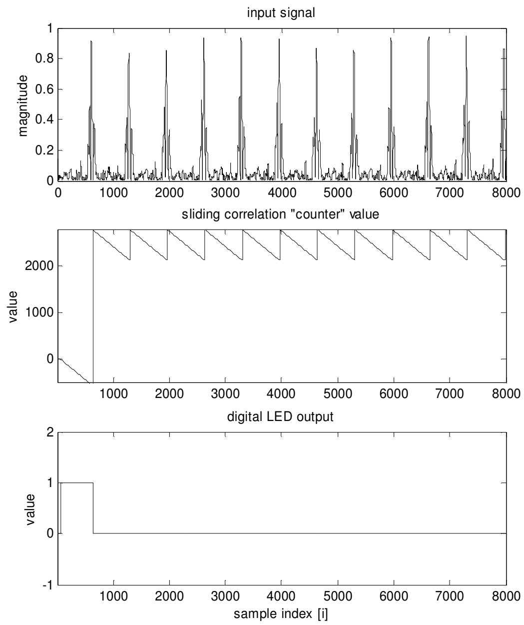

Figure 7. A run of the simulation on known good beats. The initial beat is flagged as bad because, according to the system's logic, a good beat has not yet been seen by the system. Once the first good beat is seen by the system, the counter is set to 2800. Once the good flag is asserted, the LED output is set to high. The LED remains low as long as the grace counter does not expire.

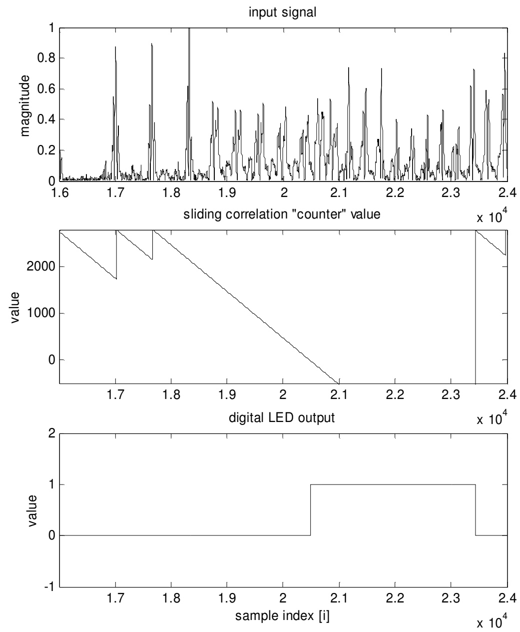

Figure8. Demonstration of the system processing on a signal with mixed good and bad beats. It can be seen that as the counter falls below 0, the LED is asserted high, indicating that the heart has not produced a good beat within the last 1.4ms (2800 samples). Once the results were verified, the algorithm was implemented on the DSP.

Acknowledgements

Dr. Kurt Metzger (Associate Research Scientist, University of Michigan, Dept. of Electrical Engineering and Computer Science).

Jared Goulart (BS Electrical Engineering '03, University of Michigan, MCL Staff) for Data Recoding, and Systems Support.

References

[1] Ann Arbor Electrogram Libraries, Ann Arbor MI, USA. http://www.electrogram.com

[2] Chiang CJ, Jenkins JM, DiCarlo LA. Digital signal processing chip implementation for detection and analysis of intracardiac electrograms. PACE, Vol 17, august 1994:1373-1379.

Address for correspondence.
Professor Janice M Jenkins
Dept. of Electrical Engineering and Computer Science,
and Dept. of Biomedical Engineering
University of Michigan
Ann Arbor MI 48109-2122
jenkins@umich.edu