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A precision ECG signal generator providing full Lead II QRS amplitude variability and an accurate timing profile

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***Abstract*—This paper reports the design and development of a precision ECG signal generator intended for use in test and calibration of electrocardiographic equipment, ECG signal processing systems and as a cardiac teaching tool. It generates a Lead II signal which maintains the timing and profile characteristics of a Lead II electrocardiograph signal across a range of heart rates between 45 and 185 bpm in 1 bpm steps. The QRS amplitude can be adjusted in 1 µV increments from 100 µV to 10 mV. The up-slope of the QRS can be set between 15 ms and 45 ms with 1 ms resolution. The P and T wave amplitudes can be adjusted as a 1-100% scaling of the QRS complex amplitude with a 1% resolution. A color LCD with touch screen capability provides the user with facilities for inputting parameters, viewing the output wave parameters and a graphical representation of the resulting output waveform. The signal generator outputs a precision differential signal via a digital to analogue stage which has been designed using low noise techniques to produce accurate signals at the lower end of the QRS amplitude range.**

I. INTRODUCTION

EINTHOVEN'S first recording of the electrocardiogram (ECG) in 1904 began the process that would see the ECG become one of the most valuable diagnostic tools in medicine. In an age when complex imaging techniques such as coronary angiography are being used in the diagnosis and treatment of coronary ailments, the ECG still forms a frontline tool in coronary care. Therefore preservation of recorded ECG waveform morphology in its passage through recording equipment is vital.

The growth and availability of ECG recording equipment has continued to increase rapidly. Development of portable and compact 3 and 12 lead recording systems by manufacturers has seen the introduction of computerized equipment which provides modern graphical user interfaces (GUI's) and output platforms. ECG recording has been extended into the local surgery, sports medicine and applied to portable ECG telemetry. Given the dependence on ECG signal recording for the treatment of cardiac patients and the current global economic climate the necessity to evaluate, fault find and re-calibrate existing ECG instruments is as prevalent today as ever. Many industry standard signal sources or designs published in the literature offer all 12 lead ECG test signals as part of a patient simulator. By and large these signal generators do not offer a full QRS amplitude range with P and T waves scaled below 100 µV [1], [2]. Other designs do not recreate the timing of the ECG accurately and are based on models that merely estimate component durations [3]. This design offers precision across the full amplitude range with P and T waves with as little as 1 µV amplitude that adhere to legitimate timing parameters.

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II. BACKGROUND

A. Previous Design

This work is a continuation of a previous design suggested by Burke and Nasor [4]. This complete redesign was required to update the user interface for the system, increase the bit resolution of the resulting ECG signal and also correct the accuracy of the output signal at the lower end of the output amplitude range by redesigning the digital to analogue conversion (DAC) stage of the generator.

B. Component Durations

The timing of each component of the ECG signal is governed using a series of duration equations suggested by Burke and Nasor [5]. The components as defined in Fig. 1 are a standard method of segmenting the ECG lead II signal. The duration equations were derived by applying a wavelet transform method to identify the onset, peak, termination and duration of each of the individual components of the ECG. Second order equations with square root of the cardiac cycle time TR-R of the form $AT^{1/2}_{R\text{-}R} + BT_{R\text{-}R} + C$ were fitted to the data to charaterize its timing variation.

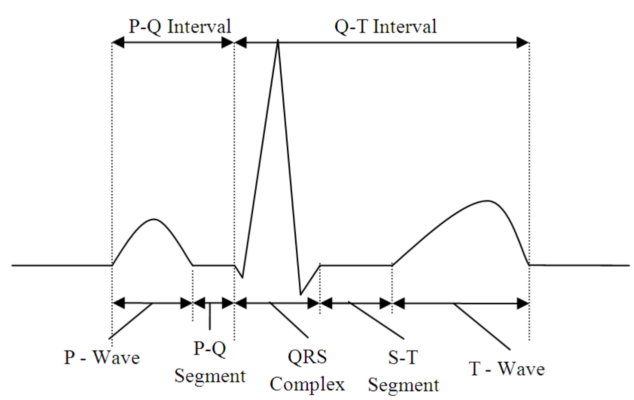

Fig. 1 A typical ECG Lead II with timing of components shown.

A set of equations for combined male and female subjects are:

$$T_{P-Wave} = 0.37T_{TR-R}^{1/2} - 0.22T_{R-R} - 0.06 \quad \text{s} \qquad (1)$$

$$T_{P-QSeg} = 0.33T_{TR-R}^{1/2} - 0.18T_{R-R} - 0.08 \quad \text{s} \qquad (2)$$

$$T_{P-QInt} = 0.69T_{TR-R}^{1/2} - 0.39T_{R-R} - 0.14 \quad \text{s} \qquad (3)$$

$$T_{QRS} = 0.25T_{TR-R}^{1/2} - 0.16T_{R-R} - 0.02 \quad \text{s} \qquad (4)$$

$$T_{Q-TInt} = 1.21T_{TR-R}^{1/2} - 0.53T_{R-R} - 0.31 \quad \text{s} \qquad (5)$$

$$T_{T-Wave} = 1.06T_{TR-R}^{1/2} - 0.51T_{R-R} - 0.33 \quad \text{s} \qquad (6)$$

$$T_{S-TSeg} = -0.09T_{TR-R}^{1/2} + 0.13T_{R-R} + 0.04 \quad \text{s} \qquad (7)$$

These equations are used as the basis for providing an ECG profile which alters over varying heart rate with genuine ECG *in vivo* variation [5].

III. Methodology

The design is based on the PIC24 family of 16-bit microcontrollers. This device provides all the power consumption and flexibility advantages traditionally associated with microcontrollers whilst offering the accessibility and functionality usually associated with faster processors. The device is available in a 100-PinTQFP package that contains 84 I/O pins, 128 KB of program memory, 8 KB of data memory and a port known as a Parallel Master Port (PMP). The PMP enables the PIC to be readily interfaced to LCDs, USB interfaces and wireless networks. This allows the signal generator to retain the user networking and accessibility advantages normally associated with PC-based designs but remain battery isolated, relatively cheap and portable. The PIC24F is programmed and developed using the Microchip Explorer 16 Development Kit. The block diagram shown in Fig. 2 represents the high level structure of the signal generator.

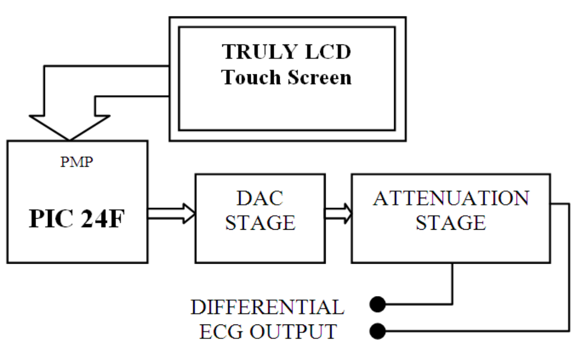

Fig. 2 Block Diagram of the ECG Signal Generator.

IV. Software Design

A. The Graphical User Interface (GUI)

The software design for the signal generator provides the user with a Graphical User Interface (GUI) to input the required component parameters and observe the resulting timing parameters and a representation of the Lead II signal as it is refreshed across the LCD screen.

The GUI interface is provided on a Truly 320x240 pixel color TFT LCD touch screen. The advantage of using the TRULY screen is that it is supported by the Microchip Graphics Solution software. The software consists of a number of C language libraries that provide the low level communications code for interfacing the PIC to LCD and touch screen technologies. The source code for the signal generator uses the graphics solution libraries to control the LCD screen and capture touch screen inputs. The library also aids in the inclusion of animations and icons to be used in the generators operation.

B. Software to Control the ECG Signal Generation Process

As the GUI captures the user inputs, the software algorithm converts the user input parameters to integer and floating point representations so as to calculate the required durations for each component of the ECG. Using the user inputs and calculated durations the algorithm controls the DAC stage of the signal generator to create a precisely timed and amplitude controlled Lead II signal from a previously synthesized ECG stored in the PIC memory. The algorithm uses a number of timers to ensure that the output samples are timed accurately and that above 163 bpm (found as the merging point) the P and T wave of successive pulses begin to merge. The amplitude of the P and T wave during this merging process are calculated as the vector sum of the P and T wave samples. Fig. 3 shows the user path through the signal generators operation.

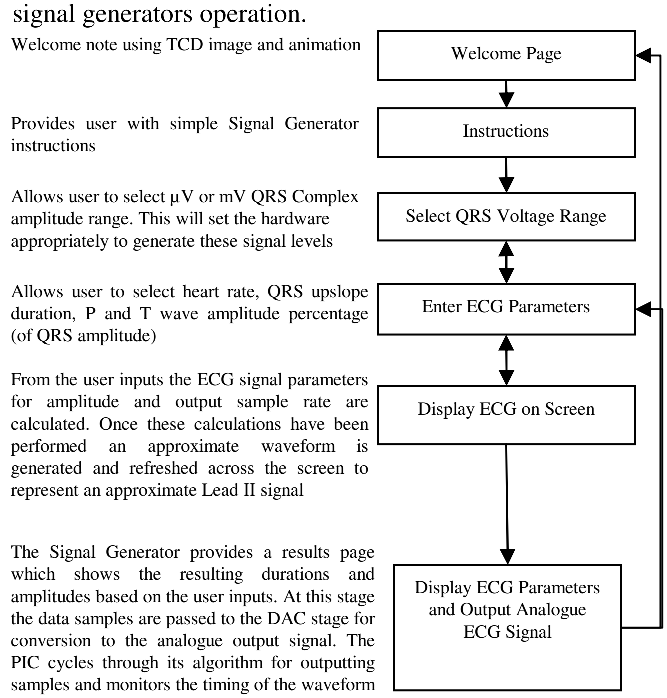

Fig. 3 Software Structure and Operation.

The source code consists of 15 functions and initialization code totaling 2,500 lines of C language. The source code also calls upon 16 other C files from the graphics library.

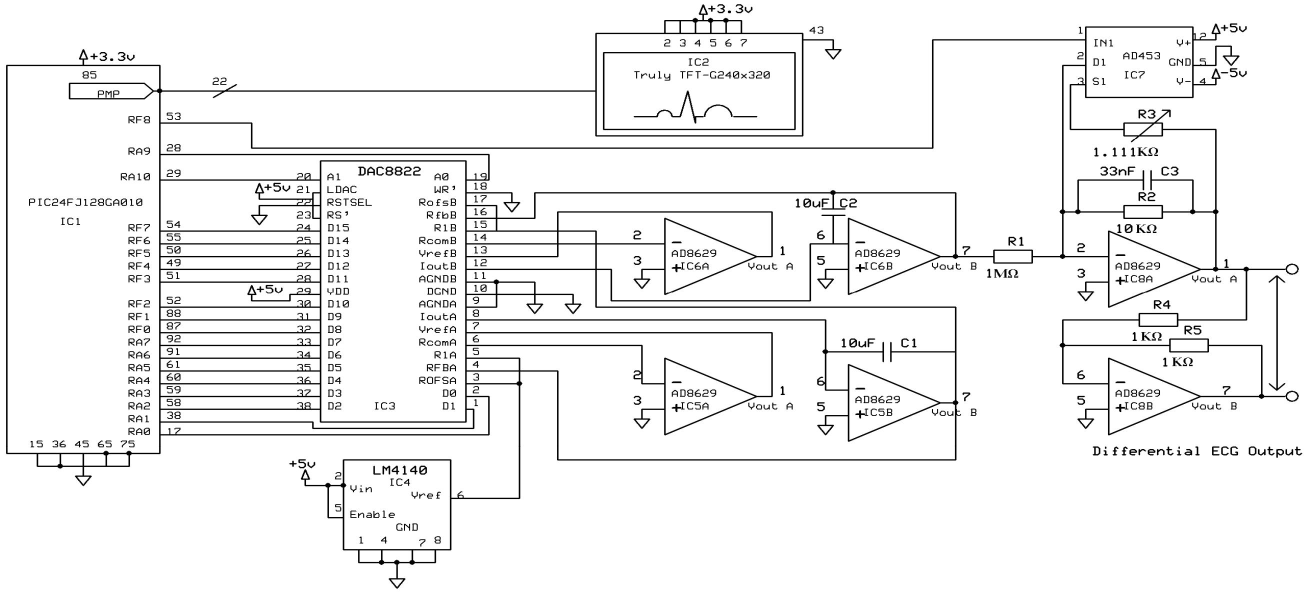

Fig. 4 Schematic Diagram of Signal Generator.

V. Hardware Design

A. Power Regulation and Control

Fig. 4 is the schematic diagram of the signal generator. To isolate the device from mains earth the entire system is run on Li-ion batteries. Although not shown in Fig. 4 (to maintain clarity) each device's power connections are de-coupled with the appropriate capacitors.

B. Digital to Analogue Conversion (DAC) Stage

Speed and noise calculations were carried out to identify the appropriate resolution to generate the ECG with varying degrees of accuracy. It was determined that 14-bit resolution would guarantee a Signal to Quantization Noise Ratio (SQNR) of 90 dB over the full QRS amplitude range. The DAC selection process identified the DAC8822 dual current output 16-bit DAC (IC3) by Texas Instruments as the most appropriate DAC for this application. The DAC provides up to 16-bit resolution (15 data + 1 sign bit), parallel inputs and generates the required QRS ramp from input code 0…000-1…111 (16,384 steps) within the required minimum QRS upslope duration of 15 ms due to its 2 Mega Samples per Second (MSPS) processing speed.

DAC A is used to step down the 2.048 V reference voltage supplied by the LM4140 precision reference voltage chip IC4. The reference is stepped down to the appropriate levels required to generate the QRS, P and T wave amplitudes as per the user inputs. DAC B is then used to receive the digital samples from the PIC and generate the analogue ECG signal.

C. The low Amplitude DAC Output Problem

By test and also communication with DAC suppliers it became evident that a multiplying DAC's performance greatly deteriorates as the required output signal reduces in amplitude. In fact tests on a number of DACs (DAC8822, AD5547 and AD394) have shown that commercially available DACs are not capable of outputting analog signals at amplitudes lower than 10 mV accurately. Using the DAC to output signals below the 1 mV range and beyond is not recommended by DAC suppliers and under test proved impossible to attain. The authors believe that this is the main source of error in many ECG signal generator designs.

To overcome this problem the ECG signal is output at 100 times the required amplitude to generate mV range QRS amplitude signals and 1000 times the required amplitude to generate μV amplitudes. The signal is then attenuated using a low noise and low offset amplifier circuit to provide the required level.

D. Attenuation Stage and Op-Amp selection

The attenuation stage requires the use of an inverting amplifier to attenuate the output signals appropriately (IC8A). Operational amplifiers are also required to convert each of the DAC *current* output signals to *voltage* signals (IC5B and IC6B); to invert the reference voltage to allow the bi-polar representation of ECG signals (IC5A and IC6A) and to generate the differential output signal (IC8B).

Since the op-amps are passing signals in the order of 10 μV (i.e. the scaled P and T waves) it is imperative that the devices used provide the optimum compromise between noise performance and minimum offset voltage effects. Noise models for the op-amps used in the different applications were created and resulting output noise voltage equations derived. The resulting equations were applied to 16 different devices selected from commercially available low noise op-amps. Equation (8) is an example of the output noise voltage equation derived for the op-amp arrangement around IC8B in Fig 4.

$$V_{no} = \sqrt{V_{na}^{2}\left(1+\frac{R5}{R4}\right)^{2} + \left(i_n^{2}.R5^{2}\right) + \left(V_{res}^{2}\left(1+\frac{R5}{R4}\right)^{2}\right)} \quad (8)$$

Where:

V_{no} = total output noise voltage due to all noise sources
V_{na} = voltage noise for op-amp
i_n = current noise for op-amp
V_{res} = resistor noise voltage for R1 and R2

Applied to the parameters of IC8B this yields:

$$V_{no} = \sqrt{243\times10^{-15}V\left(1+\frac{1k\Omega}{1k\Omega}\right)^{2} + \left(10\times10^{-24}A.1k\Omega^{2}\right) + \left(4.14\times10^{-15}V\left(1+\frac{1k\Omega}{1k\Omega}\right)^{2}\right)} \quad (9)$$

$$V_{no} = 0.99\mu V$$

The results obtained by using these output noise voltage models indicate that the Analog Devices AD8629 dual op-amp device provides a perfect balance between low voltage offset (1 µV), offset drift (0.005 µV/C°) and very low output noise voltage performance.

IC7 is an analogue switch that is used to alter the attenuation stage between 40 dB and 60 dB by altering the resistance in the feedback loop for IC8A. The capacitor C3 is in place to low pass filter the ECG signal and remove the quantization staircase resulting from the DAC process. The first order filter has a cut-off frequency of 500Hz ensuring the ECG signal spectrum is not filtered or the profile phase distorted.

VI. Verification and Results

The waveform used by the signal generator is a synthetic signal created using a program developed with Matlab. A recorded real life ECG could not be used as they tended to have large amounts of noise resulting from the original recording process.

Amplitude and timing accuracy were verified over the full range of operation. The overall duration accuracy can be resolved with an accuracy of 31.25ns per sample resulting in a maximum error of 500µs per beat. Amplitude accuracy is not significantly limited by SQNR (0.0061% of total amplitude) but the voltage offsets of available op-amps result in 5µV total offset. Further work shall attempt to correct this.

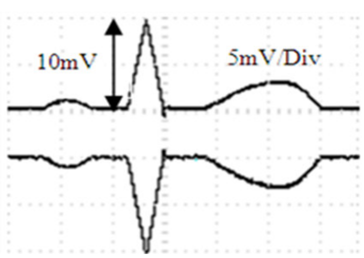

Fig. 5: 10mV ECG signal @ 60 bpm, 35 ms upslope with P and T wave of 10 and 30% respectively.

Fig. 5 shows a differential output signal of 10 mV QRS amplitude. The output signals are of such low amplitude that a pre-amplifier with variable gain was required so that the Tektronix TPS2014 isolated oscilloscope could detect the signal. The signals in Fig. 5 were amplified by 40 dB. The distortion observed on each of the QRS waves is due to a lack of screen resolution of the oscilloscopes.

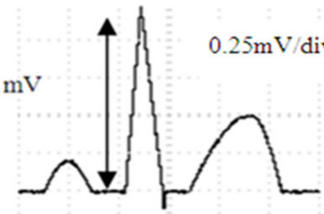

Fig. 6: 1 mV ECG signal @ 100 bpm, 30 ms upslope, with P and T wave of 20 and 40% respectively.

Fig. 6 is the signal output from IC8B with QRS amplitude of 1 mV. This output signal was amplified by 60 dB. The output noise levels at mid-amplitude range and heart rate remain low, preserving the Lead II profile.

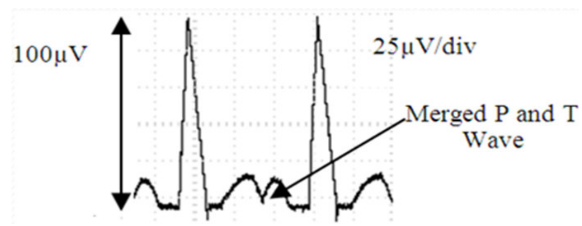

Fig. 7: 100 µV signal @ 184 bpm, 20 ms upslope and merging P & T waves of 10 and 20% respectively.

The output in Fig. 7 is a 100 µV QRS signal amplified by 80 dB. Note how successive P and T waves begin to merge.

VII. Conclusion

The signal generator operates over the full amplitude and heart rate range as verified by the results. The instrument provides the user with an easy to use industry standard color GUI similar to those found in professional biomedical instruments. The device is not only low cost, accurate and portable but the choice of the PIC24F as a central processor means that the device could be readily interfaced to a PC or wireless network using the PMP and other C libraries similar to the Microchip Graphics Library used in this design.

VIII. References

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