

## ECG SIMULATOR FOR TESTING AND SERVICING CARDIAC MONITORS AND ELECTROCARDIOGRAPHS

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**Abstract:** This paperwork presents the design and test of a microcontroller-based ECG (electrocardiogram) simulator. The ECG simulator is capable of generating nine ECG signals and a calibrated square wave (1 Hz, 1 mV at Lead II). The synthesized signals are: normal sinus rhythm (60 beats per minute – BPM, and 90 BPM), sinus bradycardia (30 BPM), sinus tachycardia (120, 180 and 240 BPM), sinus rhythm with tall T wave (6EC0 BPM), ventricular tachycardia (120 BPM), and a rhythm for asynchronous ventricular pacemaker (60 BPM). The simulated ECG signals can have their amplitudes continuously varied from zero to 2 mV at lead II, through a panel potentiometer, whose knob position does not affect the amplitude of the square wave calibrated signal. The technique used to synthesize the ECG signals, a modified direct digital synthesis (DDS), appeared superior in permitting the generation of signals of very good quality and yet using a relatively small amount of memory. This latter feature enabled the use of a simple 8-bit microcontroller together with an external precision D/A converter and a 2-pole low-pass active filter. The designed ECG simulator can be a handsome instrument to daily ECG machine test, maintenance and demonstration by hospital personnel and medical equipment maintenance groups and shops.

**Key words:** ECG simulators, electrocardiographs, cardiac monitor, maintenance, medical instrumentation.

### 1. INTRODUCTION

The ECG is the single most frequent clinical exam carried out worldwide everyday. It is intensely used in hospitals and others health care organizations. The ECG bears information about the heart muscle's electric activity and can reveal malfunction in impulse generation, conduction and rhythm. It is very often monitored in intensive care units (ICU). National and international standards determine minimum performance for electrocardiographs and cardiac monitors.

In the last 33 years, many different techniques and circuits have been devised to create ECG simulators. These instruments help technicians and engineers servicing electrocardiographs and cardiac monitors. ECG simulators are also useful for demonstration of these equipments, training of health care personnel, and as signal sources in the development of new ECG equipments.

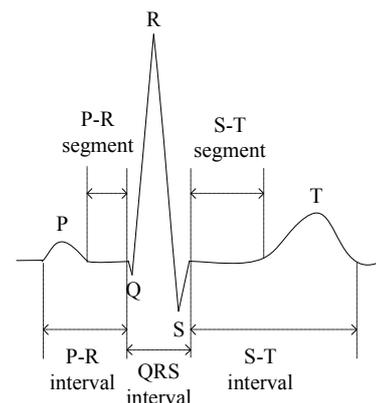


Fig. 1. Electrocardiogram's waves, segments and intervals.

First ECG simulators synthesized the ECG waveform (Fig. 1) by pulse shaping circuits that included active filters, summers and amplifiers [1]. The quality of the simulated ECG signal was inappropriate. An exam of the ECG trace fast revealed its man-made nature. In general, only one type of QRS wave was generated, owing to the difficulty to create abnormal QRS complexes. Modern ECG simulators are heavily based on digital techniques, among them direct digital synthesis (DDS) and arbitrary waveform generation (AWG) [2]. These techniques allow the creation of virtually any bizarre waveform (common in arrhythmias) with physiological quality. The other major group of ECG simulators relies on mathematical modeling of the ECG signal to synthesize signals [3], [4], [5]. In spite of enabling the creation of ECG rhythms with very high quality and a great variety of waveforms, at least from the maintenance (clinical engineering) viewpoint, these approaches often seem overkill, given that they utilize either powerful processors or a great amount of nonvolatile memory.

This paperwork presents an ECG simulator designed specifically to serve technicians and engineers of clinical engineering teams. It is based on a simple and cheap 8-bit microcontroller and simulates fundamental ECG rhythms with physiological quality, just what is needed by maintenance personnel.

### 2. SIMULATOR ARCHITECTURE AND IMPLEMENTATION

Fig. 2 shows a block diagram for the ECG simulator designed and developed in this research, whereas Fig. 4



voltage reference (National Semiconductor LM336-2.5V) that injects a fixed voltage into a summer circuit.

To simulate the asynchronous ventricular pacemaker rhythm, the controller generates a 1.6 ms pulse on the RA0 port output that is introduced immediately before the simulated ventricular response in every cycle, with the help of the summer circuit.

A resistive network attenuates the summer output signal from approximately 1 volt to 1 mV in lead II (RA-LL). Though the simulated ECGs are physiologically significant in lead II only, in practice, they are quite appropriate to test all the 12 leads (i.e., lead I, II, III, V1 through V6, and the three augmented leads), because the amplitudes and polarities are known a priori in all the leads.

The control program was written in assembly language (using Microchip's MPLAB). Besides controlling the waveform synthesis, the program detects keyboard hit and indicates whenever a battery (9-V alkaline type) replacement is needed. A low dropout voltage regulator has been employed (National LM2931) to extend battery life. An integrated dc-dc converter helps supplying the ICs with suitable voltage levels. These last two circuits are not shown on the block diagram or schematics.

### 3. RESULTS AND DISCUSSION

The designed ECG simulator circuits were mounted on a printed circuit board and housed in a standard plastic enclosure, as shown in Fig. 5. Five snap type electrodes facilitate connecting the ECG simulator to an electrocardiograph or cardiac monitor, using the cables that accompany these equipments.

After connecting the prototype to a commercial electrocardiograph, a record (in thermal paper) of each of the 10 simulated signals was made. For these records, the electrocardiograph settings were lead II, 25 mm/s (for the paper speed) and 20 mm/mV (for the gain). Then, the traces were scanned for inclusion in this text file as an image. Fig. 6 shows the recorded signals. The signals are labeled on the right top corner of every trace. The numbers represent the signal frequency in beats per minute. It can be seen that the simulated signals are of very good quality and mimics perfectly a physiological ECG. Note that the pacemaker pulses are clearly rejected by the ECG machine.

Because the records for the last two signal of Fig. 6 are somewhat difficult to examine, these signals were captured by a digital oscilloscope and shown in Fig. 7. As before, one can observe the good quality of the traces. In general, the records indicate the adequate performance of the ECG simulator. Moreover, the prototype is user's friendly, small and lightweight. Its low power circuitry enables it to operate continuously for more than 60 h on a single alkaline 9-volt battery.

Frequency precision, accuracy and stability of all signals are, above all, a function of the performance of the crystal oscillator. A crystal of 300 ppm was used in the project.

Precision, accuracy and stability of the amplitude of the square wave (calibration signal) rely on the similar parameters of the operational amplifier (B e C, in Fig. 4),



Fig. 5. Photograph of the ECG simulator prototype.

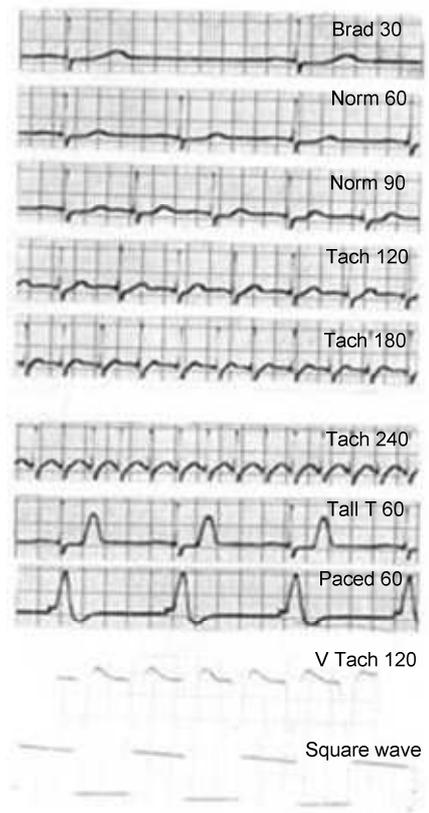


Fig. 6. Simulated signals as recorded by a commercial electrocardiograph (25 mm/s, 20 mm/mV).

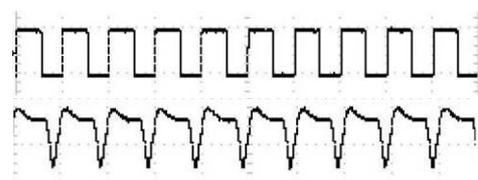


Fig. 7. Simulated calibration square wave and ventricular tachycardia as recorded by a digital oscilloscope.

the precision voltage reference (LM336-2.5V), and the eleven precision resistors (1% rating) employed with these semiconductors. Of course, components showing superior performance (e.g., 0.1%-tolerance resistors) could have been employed, to enhance the similar performance, but that is just not needed in practice.

#### 4. CONCLUSION

The ECG simulator designed in this research is tailored to test, demonstration and service of electrocardiographs and cardiac monitors. It generates nine important ECG rhythms and a calibrated square wave. The technique utilized to generate the signals permitted the use of a microcontroller with relatively small program memory, which is a positive facet. The simulated ECG signal's quality is quite appropriate for use in maintenance activities. Its simplicity is an advantage when compared with ECG simulators found in literature.

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#### REFERENCES

- [1] P. J. Howlett, S. A. Pearson, "Simple ECG Arrhythmia Simulator", *Medical and Biological Engineering and Computing*, vol. 16, n. 2, pp. 217-218, 1978.
- [2] N. Kontodimopoulos, N. Pallikarakis, I. Christov, I. Daskalov, "In-House Development of Test Equipment for Quality Control and Training. Case Study: a Prototype ECG Simulator-Tester", *Medical Engineering & Physics*, vol. 20, n. 10, pp. 717-721, 1998.
- [3] J.-R. C. Chang, C.-C. Tai, "Accurate Programmable Electrocardiogram Generator Using a Dynamical Model Implemented on a Microcontroller", *Review of Scientific Instruments*, vol. 77, pp. 075104-1 – 074104-5, 2006.
- [4] J.-R. C. Chang, "Design of Programmable Electrocardiogram Generator Using a Microcontroller and the CPLD Technology", *The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Nov. 5-8, Taipei, Taiwan, pp. 2152-2157, 2007.
- [5] G. P. Shorten, M. J. Burke, "A Precision ECG Signal Generator Providing Full Lead II QRS Amplitude Variability and an Accurate Timing Profile". *31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Minneapolis, USA, September 2-6, pp. 3008-3011, 2009.
- [6] National Instruments Inc. (2008). Tutorial: "Understanding Direct Digital Synthesis (DDS)". [Online]. Available: <http://zone.ni.com/devzone/cda/tut/p/id/5516>