

GBECG

Marcel Cremmel

Lots of electronics hobbyist dream of recording an electrocardiogram (ECG) using a circuit built at home. Usually out of technical curiosity, as numerous problems have to be resolved in order to properly sample the heart's electrical activity. Alternatively, some people require personal medical monitoring while under a cardiologist's care. And then it's great to be able to make your own ECG and show it to your GP or clinical staff.

The idea of using a Nintendo Gameboy games console equipped with a special cartridge was inspired by the world-famous Elektor GBDSO [1] (a big thank you goes out to Steve Willis for his help with this project).

Our electrocardiograph utilizes three electrodes: one on each wrist, the third on the left leg. The electronic device, built on a cartridge that slips into any Gameboy model, processes the sampled signals and produces a very high quality ECG scrolling across the LCD (see the various illustrations).

The electrocardiogram implements the method of M. Einthoven (see the inset on the next page). It only uses two active electrodes, a third being used to set the no-signal level of the first two. All leads are single-ended. Despite this simplicity, the results are noticeable and even recognized as usable by a cardiologist. The electrocardiograph easily meets the initial specifications for which it was

designed: to monitor tolerance to the anti-malaria medication.

To do that, we measure the QT interval (see **Figure 1**) which should remain 'normal'. Figure 1 [2] matches up the electrical activity sampled and the cardiac cycle phases, as follows:

P-Wave: Auricular contraction; the blood coming from the veins is pushed into the ventricles.

QRS Complex: Ventricular contraction; the blood contained inside is pushed into the arteries.

Both of these waves produce the 'lub-dub' heartbeat sounds.

T-Wave: Repolarisation of the ventricles; the ventricular muscle returns to rest.

The electronics!

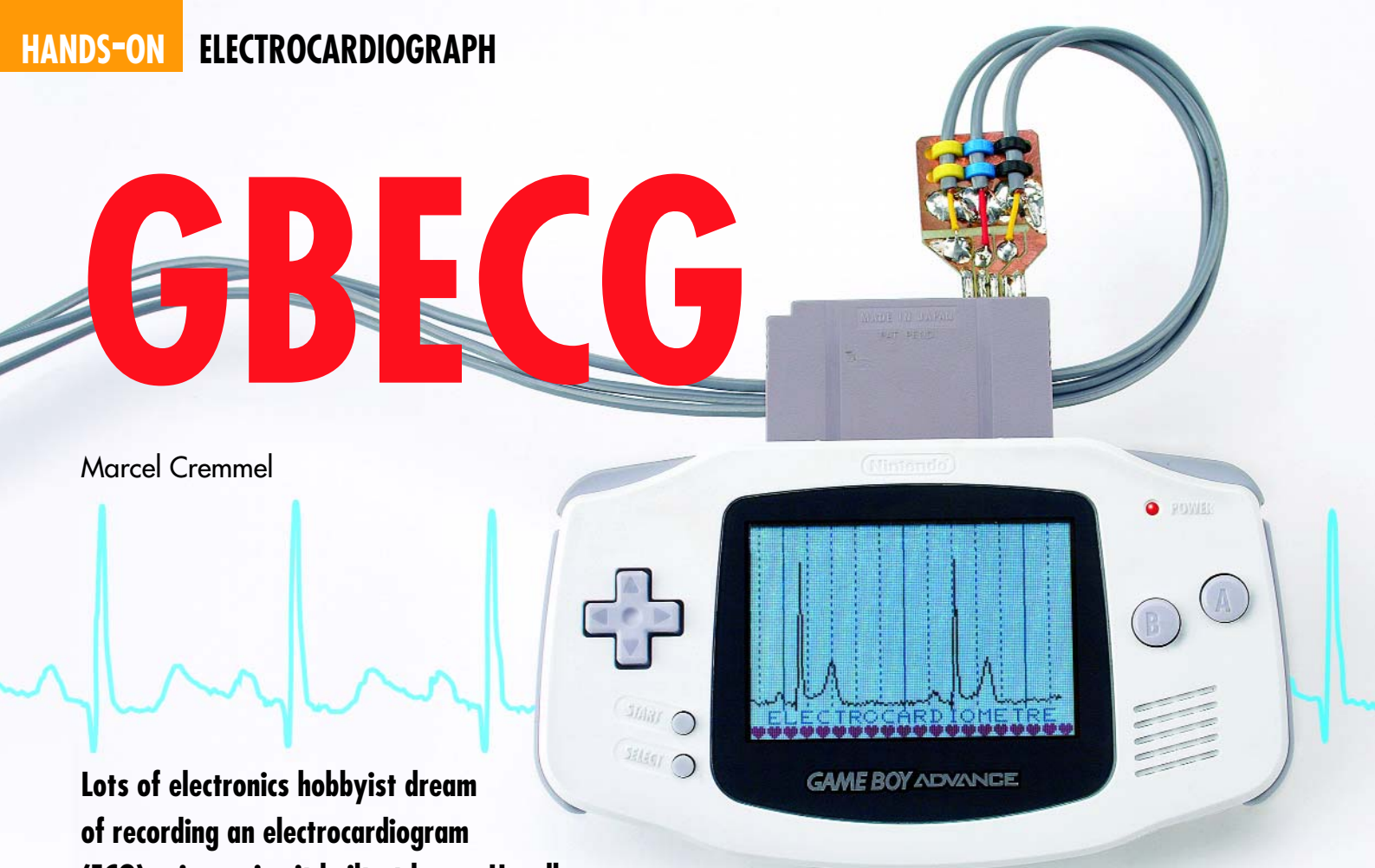
After this little 'dose' of general knowledge, let's deal with our favourite subject: describing the GBECG electronic structures and making the board.

Just as with the **GBDSO** [1] (*Elektor Electronics* October and November 2000), the specific electronics and software (in Flash memory) are grouped onto a cartridge that slips into the console's connector. In this way, the Gameboy is transformed into a powerful electrocardiograph!

The electronic device processes the very low voltages sampled between the two active electrodes. The single-ended leads are designated DI, DII and DIII according to their localisation (see drawing in **Figure 2**).

The most common lead is DI. Due to its low peak-to-peak amplitude (of the order of one mV), the EMF (electromotive force) measured is considerably amplified (about 1000×) before it can be converted to 8-bit digital. The sampling frequency selected is 477.84 Hz, compatible with the spectrum of an ECG signal.

The digital signal is then taken care of by the console processor. It is then placed in an 8 kBytes cyclic buffer



GameBoy ElectroCardioGraph

Characteristics:

- Cartridge compatible with Nintendo Gameboy consoles type Classic, Pocket, Colour or Advance
- Single-ended connections using 3 electrodes
- Sensitivity: 1.6 mV full scale
- Common mode rejection: 100 dB
- Trace memory : 68 s
- Scrolling display
- Temporal window: 2.6 s in acquisition mode (1.3 s or 2.6 s in consultation mode)
- Heartbeat indicator
- Battery power supply required
- Approx. 2 hours use from battery power

The Electrocardiogram (ECG)

It is practically impossible to grasp the operation of this home-made electrocardiograph instrument without a minimum of medical knowledge. We deal with the heart of the subject. First of all...



A bit of history...

In passing, let us pay homage to Willem Einthoven who discovered the relationship between electrical phenomena and muscular contraction of the human heart about 100 years ago. He received the Nobel Prize in 1924 for that discovery.

Willem Einthoven, inventor of the electrocardiograph.

and a bit of biology...

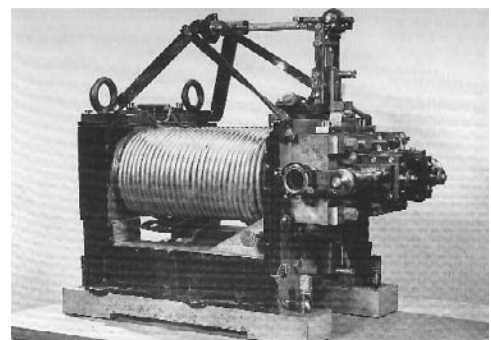
The heart is an autonomous muscle: it is the only one not controlled by the brain. The 'sinus node', located in the right auricle, triggers nerve flows that control the heart muscles. These contract ('depolarisation' in medical lingo) and relax ('polarisation') in order to make up the blood pump that gives us life. The contraction is caused by a change in electrical polarity on each side of the cellular membranes. During the relaxation phases, the electrical charges find their state of equilibrium before being stimulated again.

The resulting potentials are transmitted to the skin surface. They can then be sampled by cutaneous electrodes, as the human skin is sufficiently conductive.

A wise placement of the electrodes allows a cardiologist to deduce the heart's mechanical behaviour (and its defects!) by analysing the electrical activity.



Technology has greatly evolved since the 1920s. The first patients dipped their hands and feet in basins full of very salty water!



String galvanometer, The U-shaped magnet ends are enveloped in water cooling tubes (well before PCs!)

Photos : Stichting Einthoven Foundation

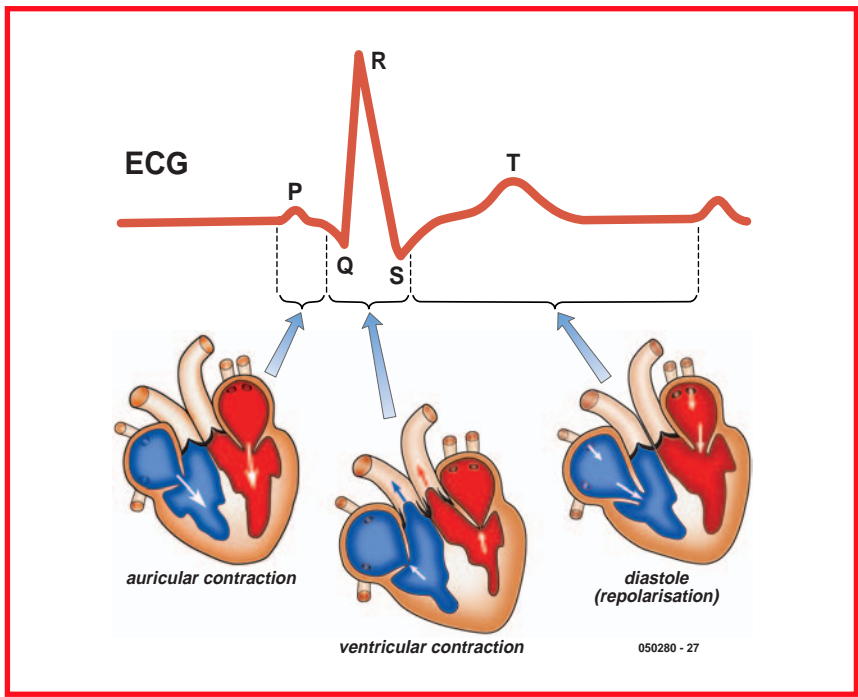


Figure 1. Relationship between the measured electrical activity and the cardiac cycle phases.

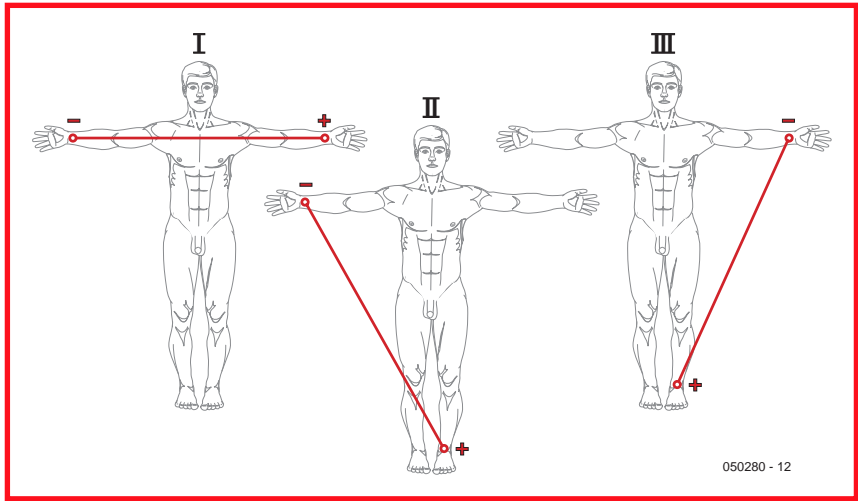


Figure 2. These single-pole leads are used to implement the electrocardiograph.

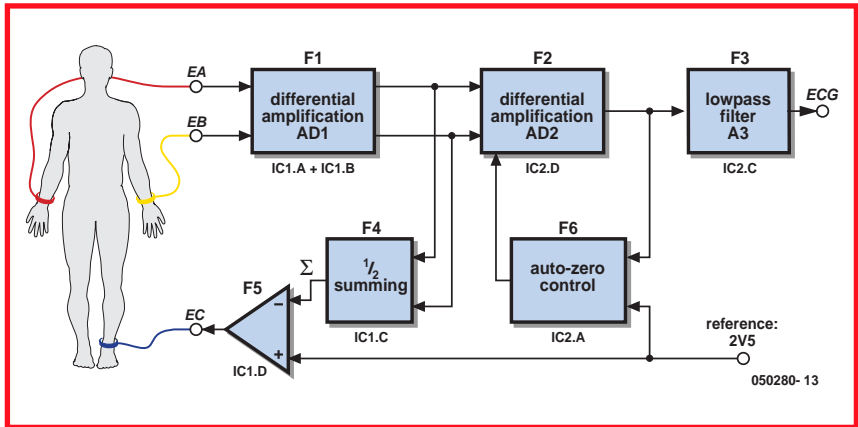


Figure 3. Block diagram of the analogue part of the circuit.

memory and reread to show the ECG in real time on the screen, in 'scrolling' mode.

The analogue part

Presenting an adequate signal to the input of the digital analogue converter presents a challenge to the electronics engineer because there are a number of technical problems to analyse and resolve.

Differential amplifier

The peak-to-peak amplitude of the signals sampled between the electrodes is very low at just 2 mV max.

Also, both the human body and the connecting wires to the electrodes are strongly influenced by high noise levels radiated by mains wires and other power carrying leads inside buildings. Capacitive coupling, although very low, produces a relatively high voltage (often over 1 V) to appear with respect to ground, despite the relatively low frequency of just 50 Hz or 60 Hz.

To begin with, it would seem difficult to isolate the useful signal because its amplitude is 1,000 times lower than all the interference around! Moreover, the mains frequency is included in the useful spectrum; so the filtering solution does not work here.

However, considering the wavelength of the mains voltage (6,000 km!), it is safe to assume that that each point on the skin receives the same induced potential thanks to its conductivity. Therefore, a common-mode voltage is developed with respect to the electrodes.

In this case, the solution becomes obvious: we're going to use a differential instrumentation amplifier with an adequate common-mode rejection ratio (CMRR):

$$CMRR \geq \left[\frac{S_p}{S_{ECG}} \right]_{dB} + \left[\frac{S}{N} \right]_{dB}$$

In this formula:
 S_p = amplitude of the interference: 1 V
 S_{ECG} = ECG amplitude: 1 mV
 S/N = signal to noise ratio: 40 dB
Or : CMRR ≥ 100 dB.

In addition, the amplifier must be characterised by a very high input impedance (> 10 MΩ) and a low offset voltage.

Numerous integrated instrumentation amplifiers exist (the AD624, for exam-

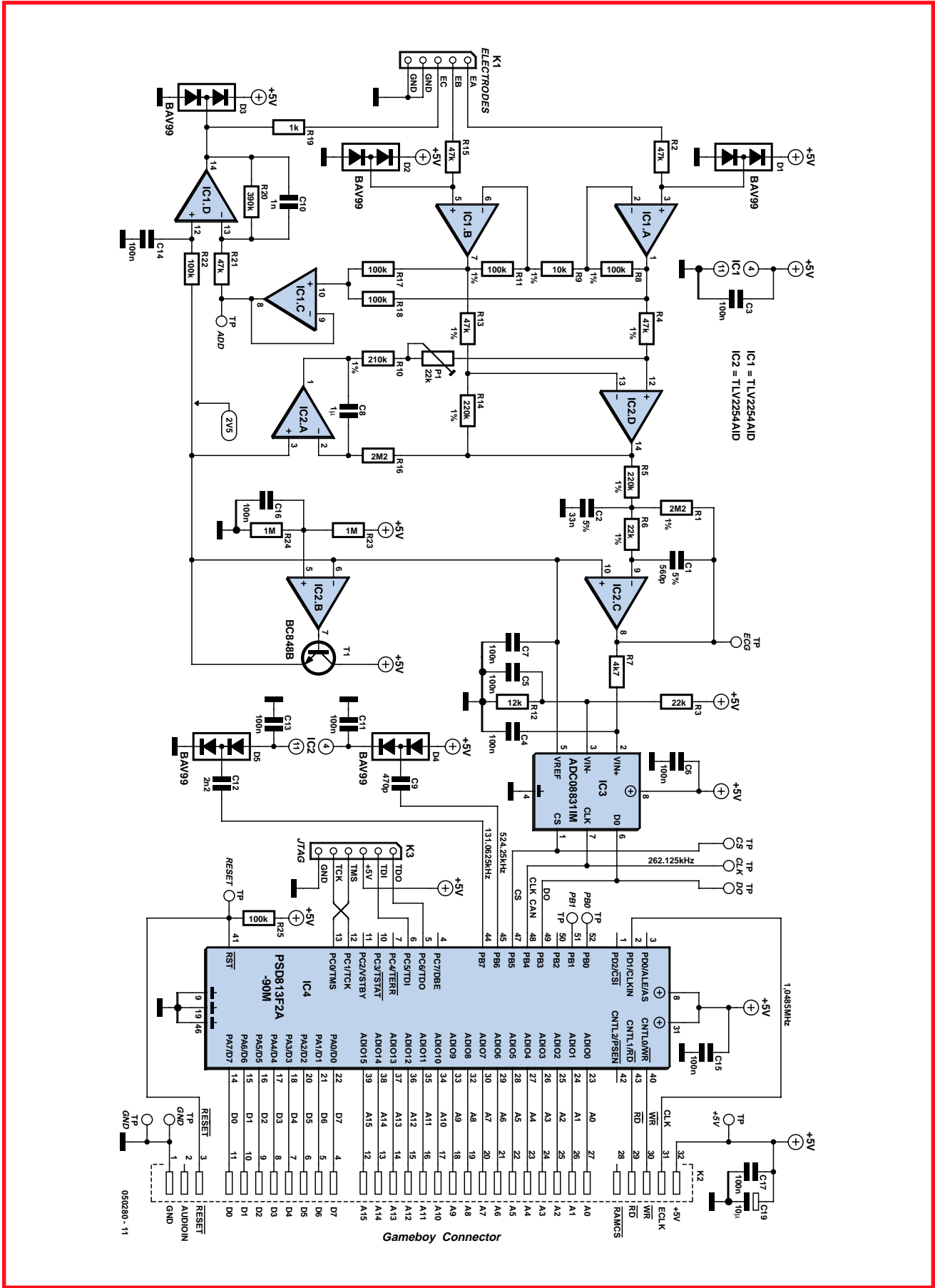


Figure 4. The bulk of the work is handled by the ISP flash memory, IC4 and IC3, an A/D converter, Serial I/O. The Gameboy processor handles the processing.

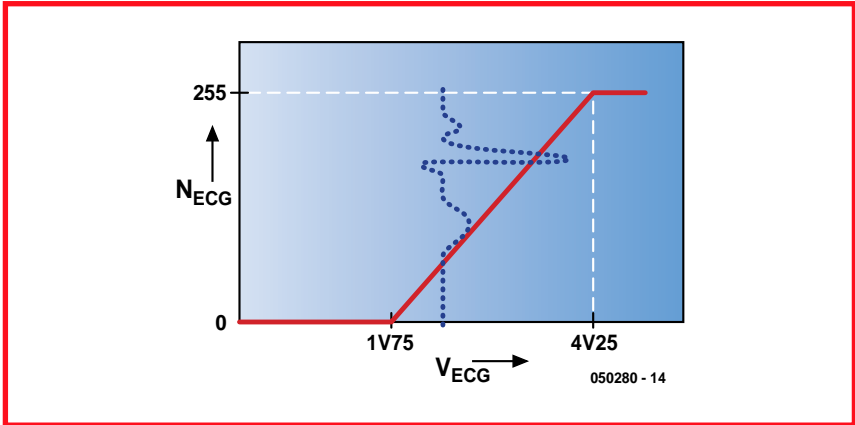


Figure 5. The transfer function is determined by divider bridge R3/R12.

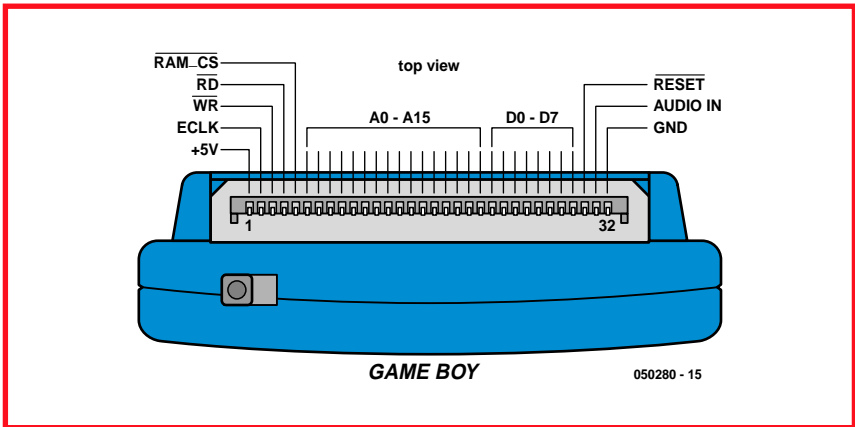
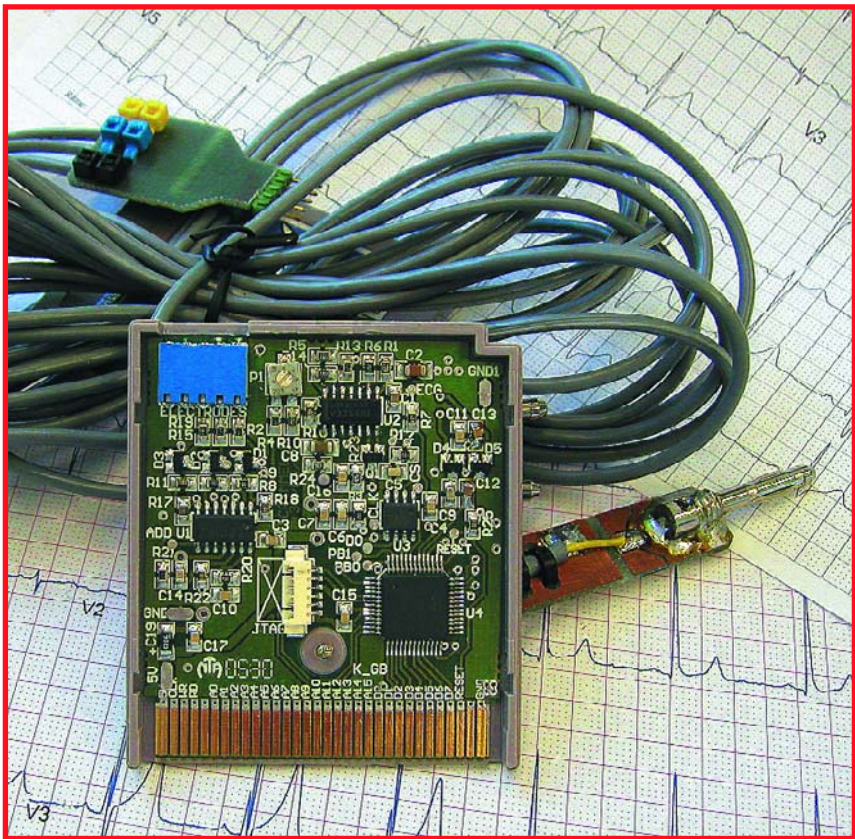


Figure 6. Connector pinout for the Gameboy cartridge (view from above).

ple). These are very high-performance devices and need no adjustment. But quality comes at a cost.

We decided to make the differential amplifier using more economical operational amplifiers. This also allows significant savings in cost and power consumption. Moreover, these opamps function perfectly with a single 5 V power supply (this is not the case for the AD624). The disadvantage is the presence of an adjustable potentiometer to optimise the CMRR.

Block diagram and wiring diagram

Figures 3 and 4 respectively give the block diagrams for the analogue part and the complete circuit diagram. The references associated with each function (ICx.y) identify the operational amplifiers for the structural diagrams that show the functionality.

The instrumentation amplifier is made up of functions F1 and F2. Function F3 is a 2nd order low pass filter with a roll-off of 170 Hz and a damping factor *m* of 0.73 (i.e., near Butterworth). It will faithfully attenuate all unwanted components outside of the useful frequency spectrum and replaces the anti-aliasing filter for the DAC (digital/analogue converter) that follows it.

The gain distribution in the circuit is as follows: A1 = 21x, A2 = 4.7x and A3 = 10x. The total amplification is 987, in compliance with our objectives. The other functions (F4, F5 and F6) assist the instrumentation amplifier in order to ensure its proper operation. In fact, the operational amplifiers have a supply voltage of between 0 V and 5 V. The ideal no-signal voltage on each of the terminals is 2.5 V. Setting this level is not a problem in most cases: a divider bridge with two resistors is appropriate (R23 and R24). It is harder for the two input amps because we must take care not to compromise their input impedances.

The problem is solved using the third, common, ECG electrode (see Figure 3) and the functions of F4 and F5.

It can be shown that the voltage *S* equals half the sum of the voltage (*EA* + *EB*). It is compared to the '2.5-V' setting, and the error voltage is amplified to produce an ECG signal that can be processed. As there is no current flow in the electrodes, voltages *EA* and *EB* are equal to *EC* (give or take a few mV). In this way, the human skin actually helps to keep *EA* and *EB* equal to the target level of 2.5 V. That is the goal

we are seeking: the no-signal voltage of the opamps is as desired without reducing the input impedance.

Moreover, a natural, but very annoying phenomenon occurs when we place the electrodes: an electromotive force (EMF) contact potential is produced between the skin and the electrode metal. This 'micro-cell' is very weak (a few mV) but it is not eliminated by the instrumentation amplifier. On the contrary, it is amplified!

Functions F4 and F5 partially reduce this effect, but the offset in S1 and S2 may still reach 1 V in differential mode. This value is unacceptable and is therefore compensated by function F6. F6 compares the average S3 signal value with the 2.5 V setting. The error voltage is integrated (time constant $R16C8 = 2.2$ s) in order to produce the ZERO signal. This continuous voltage offsets the S3 signal until its average value is stabilised at 2.5 V.

To increase the amplitude of this compensation, two diode pumps C9-D4-C11 and C12-D5-C13 produce -3 V and $+8$ V supply voltages for IC2.

The digital part

The digital-analogue conversion is performed by IC3. It integrates a real differential amplifier, but requires an external reference voltage. This is simply derived from the 5 V power supply using a potential divider (R23/R24) buffered by T1. The precision and the stability are average at best, but still sufficient for this application. The divider R3/R12 determines the transfer function (see **Figure 4**).

The asymmetry with respect to 2.5 V is justified by the asymmetrical shape of an ECG in relation to its average value. The DAC provides its NECG results in 'serial' format. It is controlled by the CS and CLK signals — the first triggers the conversion (its frequency is 477.84 Hz) and the second clocks the data output (on DO).

The PSD813F2

A Gameboy cartridge plugs into a connector which accommodates the console's microprocessor buses:

- Addresses: A15 to A0
- Data: D7 to D0
- Check: \overline{ECLK} , \overline{WR} , \overline{RD} and \overline{RESET}

The first Gameboy games consoles on the market from about 1989 had a microprocessor similar to the old Z80, which explains the size of the buses.

The most recent consoles are equipped with much more powerful CPUs, but for commercial reasons the old cartridges (and even older than those) still operate on the current Gameboys. That is also the case for our electrocardiograph!

The PSD813F2 is an integrated circuit that's perfectly adapted for making a cartridge for a Gameboy console. Unfortunately, we do not have enough space in this article to describe its complete functionality (see [3]). In summary, the PSD813F2 includes:

- a configurable microprocessor interface that can be adapted to all 8-bit microprocessors on the market,

- 27 I/O configurable ports;
- 2 kBytes RAM (not used).

Moreover, a JTAG interface is used to completely configure the 'on circuit' component via connector K3, which should not fail to interest all of you electronics hobbyists. The PSDSoftExpress development environment can be downloaded for free on the manufacturer's website.

As you can see from the diagram (**Figure 4**), the connection between the console bus and the PSD813 is simple: the signals of the same name are connected.

The only particularity that could be

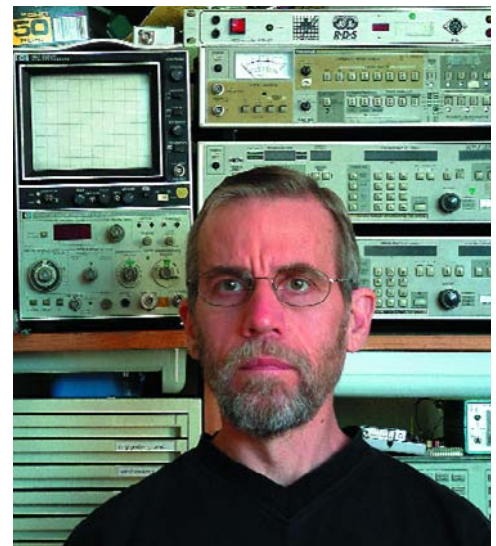
The author

The author, Marcel Cremmel, has been a qualified teacher in Electrical Engineering (with Electronics option) since 1979 (French National Education state diploma).

After having initially taught at the Mohammedia de Rabat Engineering School in Morocco as a participant in the Cooperation program, he was assigned to the Louis Couffignal High School in Strasbourg in 1982, in the BTS EL section (Certificate, Senior Electronics Technician).

Although his profession forces him to deal with all domains of electronics Marcel has a preference for telecommunications, video, microcontrollers (MSP430 and PIC) and programmable logic circuits (Altera). In addition to electronics, his other passion is motorcycles in all forms: touring, races, etc.

His personal website is at <http://electronique.marcel.free.fr/>



including the vintage Z80;

- 128 kBytes of Flash memory (only 32 kBytes are utilised by the electrocardiograph object code, which leaves space for extensions or other things...);
- a complex programmable logic device (PLD) that takes care of the address decoding;
- a 16-cell sequential Complex Programmable Logic Device (CPLD). It is responsible for the serial-to-parallel conversion of the DAC frames to relieve the CPU and produce the squarewave signals required for the diode pumps;

interpreted as an error: the data bus connections are crossed! That enabled us to simplify the board layout and the binary file of the GBECG control program was changed to suit.

The software

The software is entirely written in assembly language. The author used the 'Gameboy Assembler Studio' environment by Nicklas Larsson (freeware available on the web [4]).

The assembly language was necessary because the specifications require a 'scrolling' display in real time. That

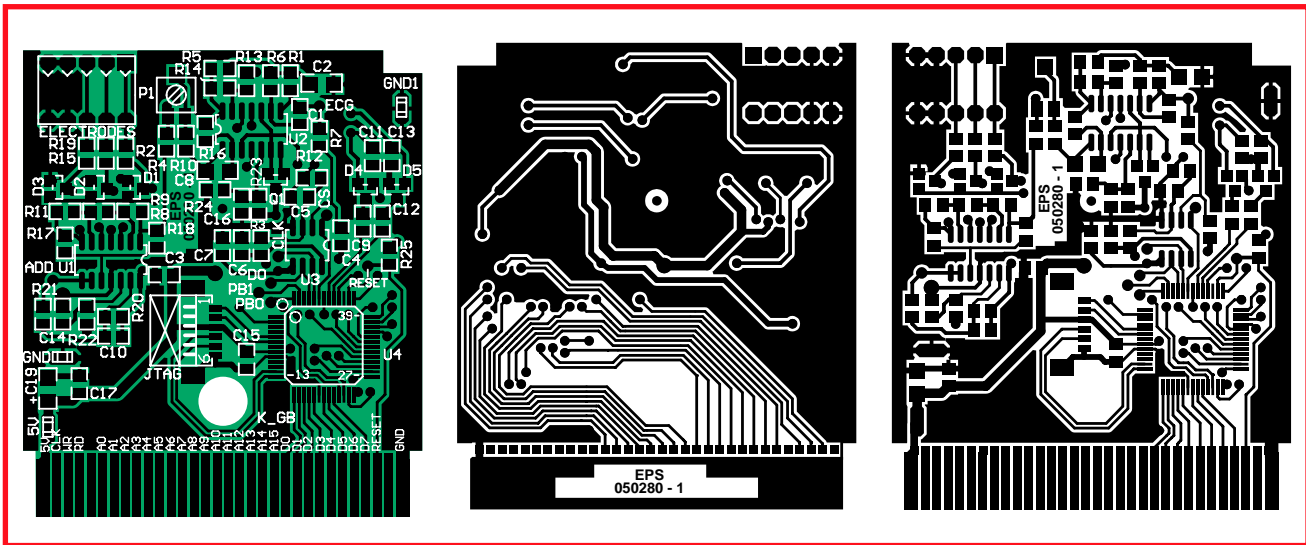


Figure 7. Copper track layout and component mounting plan of the double-sided board designed for the GBCEG. Soldering of IC3 is particularly difficult, so we're supplying the board with all components pre-soldered.

occupies the CPU of the first consoles at a level of 80% due to the 'old' manner in which the screen memory is organised (separate screen memory and character memory). The software can be thought of as handling four tasks:

1. Initialisations

This task is executed at switch-on or after a reset,

- Initial assignment of variables.
- Configuration of I/O ports.
- Initialisation of the LCD. The screen has 160 x 144 pixels, but for technical reasons, the useful part is reduced

to 160 x 96 pixels. The lower part (160 x 48) is utilised for fixed messages.

- Internal timer: this is programmed to produce interrupts at a rate of 477.84 Hz (sampling frequency).
- Sound generator: this is pre-programmed to produce a cardiac 'beep' when required.

2. Main loop

The main loop simply detects the action of certain keyboard keys and modifies the operating mode:

- Start: **acquisition** mode
- Select : **stop** mode

- Δ : zoom _1 in stop mode
- ∇ : zoom _2 in stop mode

3. Timer interrupt program

This task is executed a rate of 477.84 times per second. It carries out the following functions:

- Debounced readout of the keyboard state.

In **run** mode:

- triggers a new conversion;
- acquisition of the last sample (result of the previous conversion);
- all 4 samples (or 119.46 times per second);
- calculation of the 'average sample'

COMPONENT LIST

(all SMD, except K1)

Resistors

(all 0805 case)

- R1 = 2M Ω 1%
- R2,R15,R21 = 47k Ω
- R3 = 22k Ω
- R4,R13 = 47k Ω 1%
- R5,R14 = 220k Ω 1%
- R6 = 22 k Ω 1%
- R7 = 4k Ω
- R8,R11 = 100k Ω 1%
- R9 = 10k Ω
- R10 = 210k Ω 1%
- R12 = 12k Ω
- R16 = 2M Ω
- R17,R18,R22,R25 = 100k Ω
- R19 = 1k Ω
- R20 = 390k Ω
- R23,R24 = 1M Ω
- P1 = 22 k Ω preset (Bourns 3314G)

Capacitors

(all 0805 case except C8 and C19)

- C1 = 560pF 5%
- C2 = 33nF 5%
- C3-C7,C11,C13-C17 = 100nF
- C8 = 1 μ F (1208)
- C9 = 470pF
- C10 = 1nF
- C12 = 2nF2
- C18 = not fitted
- C19 = 10 μ F (1208P)

Semiconductors

- IC1,IC2 = TLV2254AID
- IC3 = ADC08831IM (Analog Devices) or TLC0831CD (Texas Instruments)
- IC4 = PSD813F2A-90M (STMicroelectronics), programmed, order code **050280-41**
- D1-D5 = BAV99
- T1 = BC848B

Miscellaneous

- K1 = Molex connector, 5-way, Dubox

89882-405, Digikey # 90148-1102-ND

Programming connections:

K3 = Molex connector, 6-way, 1.25mm lead pitch, type 53261-0671 (Digikey # WM7624CT-ND)

Optionally: FlashLink programming connection:

Molex 6-way connector, 1.25mm lead pitch, female (Digikey # WM1724-ND)

6 wires with pin terminations for Molex connector (Digikey # WM1775-ND)

Electrodes:

Cutaneous probes or clips are available from medical supplies outlets

5-way SIL pinheader

4 mm plate (3x)

6 m screened audio cable

PCB, with all components ready fitted, tested, order code **050280-91**

- = average of the last 4 samples;
- detection of the R-wave in order to trigger the cardiac 'beep';
- loading the 8 kBytes cyclic buffer with the average sample.

4. Interrupt program, V-Blank

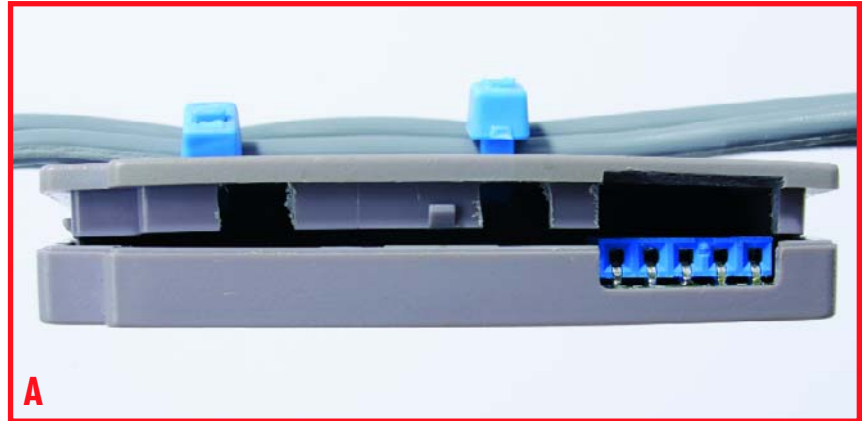
This interrupt is produced at the end of each LCD vertical sweep. The rate is: $f_v = 59.73 \text{ Hz}$; or every two averaged samples.

The program also takes care of refreshing the display.

- **Run** mode: the LCD shows the last samples (or 320 averaged sampled values on the cyclic buffer), which traces the last 2.68 s on the screen width.
- **Stop** mode: depending on the zoom value: $\times 1$ or $\times 2$, the LCD shows the last 320 or 160 samples, which traces the last 2.68 s or 1.34 s on the screen width.

In **stop** mode, the program also detects action on the \triangleright or \triangleleft keys allowing the use to move around within the screen memory.

During the display of the ECG trace, the program draws the vertical and horizontal scales. The latter moves with the trace in order to improve readability. The source code file of the



GBECG control program is available as a free download from the *Elektor Electronics* website, the file number is **050580-11.zip**, see under month of publication. Improvements and additions are welcome.

Building it

The use of SMD components is unavoidable. In fact, the underside of the board must be perfectly smooth (therefore, no through wires or pins) so that it can slip into the cartridge case. To save you the trouble of struggling with (and losing) those tiny SMD parts, we are supplying the GBECG printed

circuit board with all components already soldered in place, and the PSD813 programmed, all at an affordable price (see the inset). The order code is **050280-91**.

All that is left to do is find an old Gameboy cartridge case and clear out the two half-shells a little. **Photo A** illustrates the cutouts to make.

The wider cutout in the upper half-shell is due to potentiometer P1 which otherwise prevents closing the case.

Adjustment

The only adjustment consists in optimising the CMRR of the differential

The electrodes

A good ECG can only be obtained with good, well-placed and properly-wired electrodes.

To limit the effect of undesirable signals, it is recommended that you use shielded cables. Electronically, 'audio' cables are perfectly suited to this function. In practice however they are much too fragile. We therefore propose making small adaptors on which the cable clasps eliminate practically all risk of breaking (see **Figure F**),

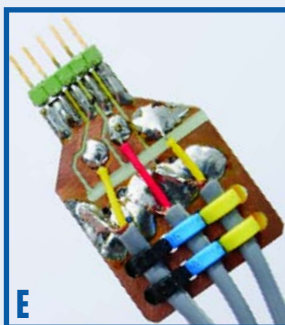
You will see that the shielding is only connected at the cartridge side and that it is isolated on the electrode side in order to avoid any contact with the skin.

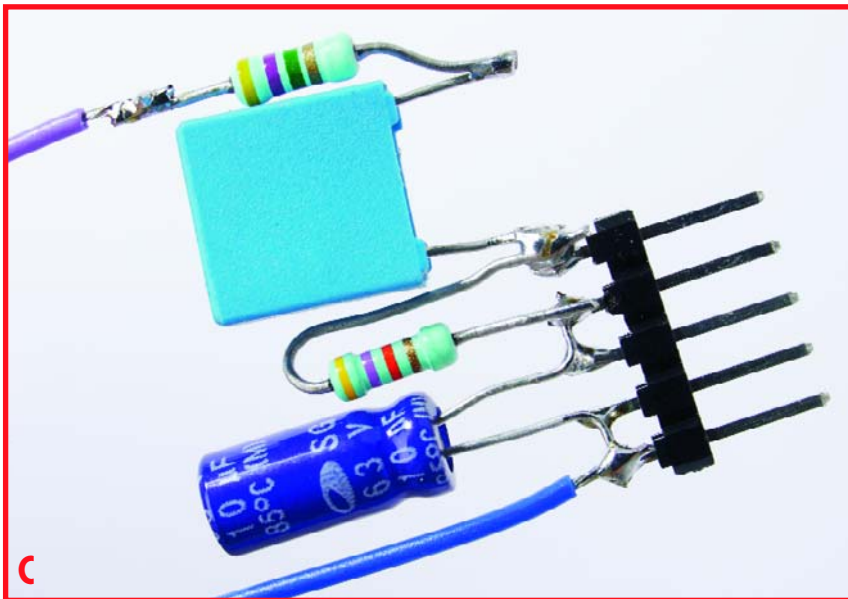
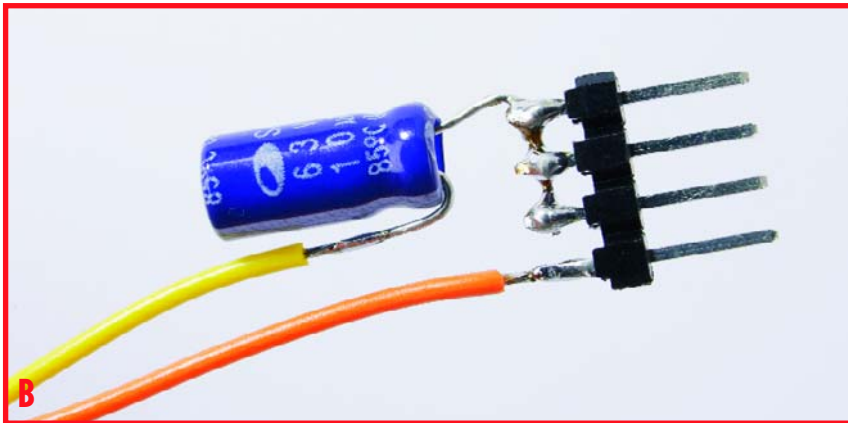
'4 mm' type plugs make it possible to use commercially available electrodes (**Figure G**).

The clip is very practical and adapted for children. But the price of these two electrodes may discourage many readers (more than £6 each and you will need three off!)

Homebrew electrodes can be made from coins as illustrated in the opposite photo. The author used French Florin (FF) coins which are made from nickel. Solder a 4-mm socket and the electrode (**Figure H**) is ready to use.

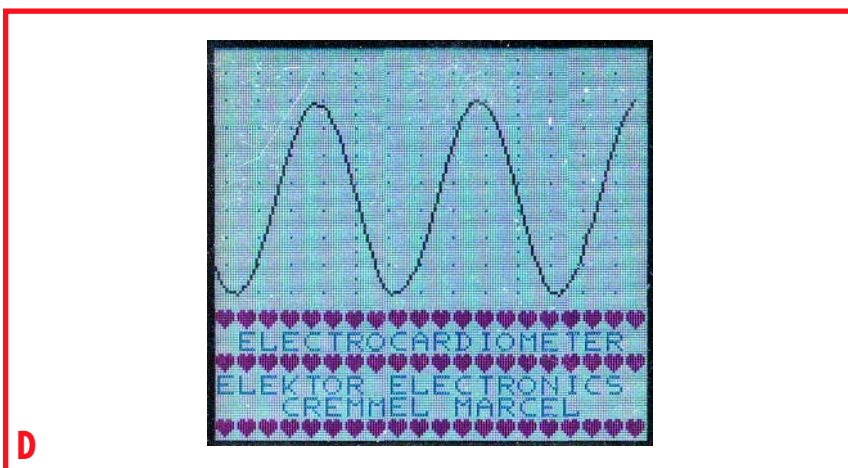
Three rubber bracelets keep them in place on the wrists and the lower calf. These bracelets can be made by cutting ribbon for straps to the proper length and gluing them to the self-adhesive 'Velcro' tape at both ends. We can also use sections from air chambers from a motorcycle or a scooter.





amplifier. For that, you need a function generator and an oscilloscope or an AC voltmeter. Begin by making the measurement circuit in **Figure B** (the capacitor has a capacitance of $10\ \mu\text{F}$). Top to bottom: EA, EB, EC, GND. Plug the device into the fixed connec-

tor K1, observing the orientation, and only then connect the generator. In this way, we inject a common-mode test signal. Adjust the generator: 50 Hz sine wave with amplitude 1 V. Insert the cartridge in the Gameboy with the upper half-shell removed in order to



access the ECG test point. Turn on the power and measure the AC component of the ECG signal. Then adjust P1 to minimise the peak-to-peak amplitude. It should be less than 25 mV in order to obtain an S/N ratio in excess of 40 dB.

Final check

This step is not strictly required. Its purpose is to ensure proper operation of the electrocardiograph by injecting a signal and by verifying the result on the screen.

Most benchtop signal generators are incapable of reliably producing the very low levels required for this check. Therefore, we must greatly attenuate the GBF signal. That is what the device shown in **Figure C** does.

The signal is effectively divided by 100. In this way, we inject a 1 Hz sinusoidal signal and a 140-mV DC amplitude signal. These should result in an image on the LCD screen similar to that in **Figure D**.

The sinewave is aligned with the first dotted line and has a DC amplitude of 7 divisions, or $7 \times 200\ \mu\text{V} = 1.4\ \text{mV}$.

The fixed connector K1 on the cartridge is not very sturdy. To limit the risk of deformation or of it being torn out, restrain the three shielded cables on the cartridge cover with two cable ties, as illustrated in **photo E**.

The cable ties we used on our prototype of the GBECG do not touch the internal components. They require four 2 mm holes to be drilled which do not significantly weaken the shell.

(050280-1)

We would like to extend our thanks to Professors Schaliq and Maan, Leiden University Hospital, the Netherlands, for their valuable assistance.

Bibliography

[1] GBDSO — Gameboy Digital Storage Oscilloscope, Elektor Electronics October and November 2000.

Internet references and links

[1] <http://chem.ch.huji.ac.il/~eugeniiik/history/eindhoven.html>

Attention

The GBECG electrocardiograph described in this article has not received medical approval and is therefore not intended for professional use. The instrument must always be powered by batteries in order to respect protection category III.

Operating instructions

Placement of the electrodes

It is absolutely necessary to clean the skin and the electrodes well with a cotton and ether or alcohol. In this way, the electromotive force EMF on the contacts, which may saturate the amplifiers, are limited considerably.

The standard lead is 'DI':

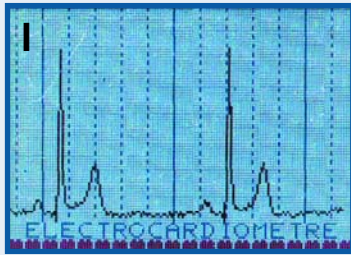
- EA electrode: right wrist
- EB electrode: left wrist
- EC electrode: left foot (lower calf)

Utilisation of 'contact' products based on potassium chloride considerably improve the quality of the measurements.

The best ECGs are obtained when the patient is calm and lying down so that the only muscle in action is the heart.

Operation

- Live start-up: welcome screen is displayed.
- Go to the acquisition screen: press Start, A, B or Select.



- ECG acquisition: if the electrodes are properly placed and the patient is calm, the reading should be stabilised in a few seconds and look like the one illustrated in **Figure 1**.

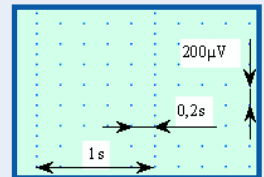
Do not use this ECG as a reference; the shapes may vary appreciably from one individual to another.

If no trace appears after thirty seconds, clean the skin below the electrodes using a pad and ether or alcohol.

Irregularity of the trace may be reduced by using a 'contact' product.

- Stop mode: pressing the Select button stops the acquisition. You can then analyse the memory which contains 68.6 s worth of ECG.

- △: zoom x 1
- ▽: zoom x 2 (see below)
- ▷: Move ahead
- ◁: Move backwards



Scales (zoom 1x)

A beep sound will be heard each time an R wave is detected. The volume can be adjusted with the volume button on the console.

Attention: The screen memory is erased when power is removed.

[2] <http://www.e-cardiologie.com/examens/ex-electro2.shtml>

[3] <http://www.st.com/stonline/products/>

[4] <http://www.devrs.com/gb/>

Additional documents and program sources on

<http://www.elektor.com>

<http://www.infoscience.fr/histoire/biograph/biograph.php3?Ref=128>

PSD813 datasheet

<http://www.st.com/stonline/products/literature/ds/7833.pdf>

ADC08831M datasheet

<http://www.ortodoxism.ro/datasheets2/6/Orcoik1ywhx1dj2ogg8wid7sfcy.pdf>

