MTRX2700  Mechatronics 2

Major Project

ELECTROCARDIOGRAM (ECG)

The class is required to work in groups consisting of an integer number of students each containing no more than 2 and no less than 1 persons (preferably 2). The objective of the assignment is to design and implement a microprocessor-controlled ECG which must operate as described in the specifications below. Each group must work independently of the other groups. The design, implementation and documentation presented by a group must be the work of the group members only.

Organisation
The group should partition the project so that each member has clearly defined responsibilities, and a fair share of the work load. As described below, it is necessary in the final written report to identify each group members’ contribution to the project.

Product Specification
The instrument shall conform to the following general specification.
1. The instrument shall have a identifying product name.
2. The instrument shall be capable of measuring the number of beats per minute of the heart of the user, and to display this information to a user (both audibly and visually).
3. The Oscilloscope shall be used as a visual display of the ECG waveform.
4. Any logic required shall be implemented principally by an EVBPlus2 68HC11 Evaluation Board.
5. Additional interfacing circuits should not be necessary. However, if a group wishes to interface to additional hardware, please see a tutor to have the design approved.
6. 68HC11 Software shall be written in C and/or assembly language. 68HC11 code shall be generated by the IAR Systems ICC6811 compiler, or the Motorola assembler. If code is written to run on the Windows PC, it shall be compiled by the Microsoft Visual C++ compiler and be written in C or C++.

The instrument shall conform to the following functional specification:
1. The ECG circuit provided to you will be used as the main functional element of the system. This circuit MAY NOT be modified, and MUST be used exactly as specified in the accompanying documentation.

2. On power-up, the system shall calibrate itself. More information on this function can be found in the attached documents.

3. When the system has successfully initialised, it shall provide a continuous output of the users heart rate, in beats per minute.

4. As a minimum, the system shall display heart rate on the 7-segment display, as well as providing an audible tone each time a heart beat is detected. The LCD display, serial transmission, or any other device may also be used to implement the user interface.

5. If serial data transmission is used, it shall conform to the RS-232C standard. The serial data format shall be 1 start bit, 8 data bits, 1 stop bit, no parity. The baud rate shall be 9600 baud.

6. A user must be able to initiate a calibration at any time. This shall be achieved using the serial interface to the PC. When a calibration has been initiated, the current offset voltage (see attached documentation) must be displayed on the 7 segment display for a period of exactly 3 seconds. Show the voltage correct to 1 decimal place. After this period, the ECG should resume its original functioning.

7. A user interface must be implemented on the PC (using serial communications and the PC terminal emulator). This interface (at a minimum) must be capable of showing a list of available commands when the user presses the ‘h’ key on the PC keyboard.

8. An IBM-compatible PC shall be the remote terminal.

9. The ECG shall power-up and power-down in a well-defined way.

10. Appropriate electrodes for the ECG shall be manufactured by each group.

The above lists represent the minimum requirements for this assignment. Any group is free to add additional functionality.

**Extension**

All groups are encouraged to build upon the basic specifications listed above to introduce additional functionality to the device. However, make sure that the basic specifications are completed first, and that any additional functionality extends, but does not replace the basic functionality of the device.

As with the short labs, if no extensions are attempted, the maximum possible mark is 75. For this assignment groups will be expected to create their own extension problems. Consult with the Lecturer or Tutors if you are not sure what would constitute a valid extension.

Suggestions for extensions:

- Conduct research into signal processing techniques used for detecting different ECG patterns. Implement one or more! You might need to visit a library for this one. There are some excellent, and relatively easy to read text books out there.
- Warnings and/or display if an irregular heart beat is detected (must first implement point above)
- External key-pad or buttons for local user interface
- Fancy graphical user interfaces.
- Other – whatever you can think of…
Commissioning of the Instrument
Instructions will be given during the course of the semester.

Report
Each group shall submit one report which documents the development and final configuration of the instrument. The contributions made by individual group members to the project must be identified and signed by each group member. The report must be submitted electronically, in either Word or PDF format (preferably PDF). The report must be submitted through the WebCT site for MTRX 2700. Reports are due on Friday the 3rd of June. No submissions will be accepted after Friday the 10th of June.

The report should include a discussion of the major hardware and software design decisions: reasons should be given as to why various alternative designs were accepted or rejected. A commentary should be given on problems encountered during the instrument development, and on their resolution.

The report should also provide full documentation of the instrument. In this context, it should contain a functional description of the instrument, together with testing and calibration procedures, circuit diagrams if applicable (drawn with Protel), state transition diagrams and/or data flow diagrams, a memory map, and operating instructions. An annotated listing of all 'C' and assembly language programs should be provided as well. Any assembly language code used should be self-documenting, with well-defined entry and exit states, register requirements, and details of flags affected and of timing.

The ‘C’ programming language is used, the code should be documented using ‘doxygen’ style comments, and the doxygen documentation (in HTML format) should be provided as an appendix or as supplementary reference material to the report.

The report should contain a simple user guide for the instrument. This guide should provide sufficient documentation for a new user to understand how to operate the device. This user guide will be required at the commissioning session.

Assessment
The ECG implementation will be worth 70% of the major assignment mark. The report will be worth 30% of the major assignment mark. The implementation will be assessed on the following basis:

Is the basic functional specification met? [45%]

Extension
does the ECG implement any extra functionality? [25%]

The criteria used in assessment will include (but are not limited to) the following:

- is the program design of high quality
- is the man-machine communication well designed?
- is the software well documented?
- how error proof is the system?
- how easy to use and well-behaved is the instrument?
- does the ECG implement any extra functionality?

The marking scheme is detailed below.
MTRX 2700 Major Assignment Marking Scheme

Meets Specifications (45%)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>5</td>
</tr>
<tr>
<td>Beat Detection</td>
<td>5</td>
</tr>
<tr>
<td>Electrodes</td>
<td>2</td>
</tr>
<tr>
<td>User Interface</td>
<td>5</td>
</tr>
<tr>
<td>Power up/down in well defined way</td>
<td>5</td>
</tr>
<tr>
<td>Program Design</td>
<td>8</td>
</tr>
<tr>
<td>Software Documentation</td>
<td>5</td>
</tr>
<tr>
<td>Reliability / Stability / Error Handling</td>
<td>5</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>5</td>
</tr>
</tbody>
</table>

Extension (25%)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional Features</td>
<td>25</td>
</tr>
</tbody>
</table>

(see body of this document for details).

Report (30%)

The report template will be made available in Microsoft Word format on the MTRX 2700 WebCT site. The template outlines the requirements and expectations for the report.
Background to the Electrocardiogram

Notes by Richard Grover

Introduction
This assignment requires the students to become familiar with the basic principles and operation of a bioelectrical measurement system. This document examines the minimum background information required to complete the assignment satisfactorily. It is intended as a starting point only and it will be expected that marks in the distinction and high-distinction ranges will require further additional research. Please remember that the main goal of this assignment is to develop as complete a microprocessor based ‘product’ as you can. The medical aspects are intended to make the task as interesting as possible.

Warning! This experiment involves connecting a human to an electrical device. While every effort has been taken to ensure the safety of the subject, we expect every student to take extreme care throughout. Tomfoolery will absolutely not be permitted and students found doing so can expect to get a zero for the assignment immediately and your actions may be referred to the head of department. Nevertheless, if you treat this assignment seriously then it should be a fun and rewarding exercise.

Anatomy of the Human Heart
The human heart is a muscular double two-stage pump to move blood through the circulatory system. Blood carries oxygen, glucose and nutrients to the cells of the body and removes waste products including carbon dioxide and urea from them. This is shown in figure 1, where it can be seen that the right-hand side circulates blood from the body into the lungs where carbon dioxide is liberated and oxygen absorbed. The left-hand side pumps this oxygenated blood, including the digestive system, where glucose and waste products are removed. Since the whole body, it is considerably larger than the right, clenched fist.

Each side consists of two stages: the atrium (located at the top and acting as a ‘priming’ pump) and the ventricle (the main pumping element). The superior and inferior vena cava are the main veins draining blood from the body into the right atrium. When the atrium is almost full, the one-way AV valve separating the atrium from the ventricle opens, the opening of the vein into the atrium narrows and the atrium contracts, squeezing the blood into the right ventricle. This stage is known as diastole (pronounced dye-as-toe-ly) and is shown in figure 2. Approximately 180ms later the ventricle begins to contract. This forces the AV valve to close (it is a one-way valve) and the blood is pushed into the pulmonary artery (which carries it to the pulmonary system – i.e. the lungs), see figure 3. This stage is known as systole. The left side operates simultaneously and identically, pumping blood from the pulmonary vein, through the atrium and ventricle and into the aorta. The structure of the heart showing this blood flow can be seen in figure 4.

The audible heart beat is made by the closing of the valves in the heart, the first being the AV valve and the second shortly afterwards is the semi-lunar valve.

Figure 1 – The circulatory system
Figure 2 – Heart during diastole
Figure 3 – Heart during systole
Figure 4 – Heart showing blood flow
Basic Electrophysiology

Nerve Conduction
The electrical behaviour of the cardiac muscle is very closely related to that of a neuron (or nerve cell). A sketch of a neuron is shown in figure 5. The cell wall, particularly along the axon, is a semi-permeable membrane which selectively allows ions to be transferred through it. When the neuron is not activated, this membrane actively transfers Na$^+$ ions from the surrounding fluid into the cell body and K$^+$ ions from inside the cell to the surrounding fluid. Since the Na/K ‘pump’ is unbalanced, the result is a potential of approximately -70mV across the membrane (measured from the inside to the outside).

When the neuron is stimulated (through electrical or chemical means) by raising the potential to approximately -55mV, the cell membrane becomes permeable to Na$^+$ ions, which rush into the cell as a result of the potential across it. They keep flowing in until the potential has reversed (known as depolarisation in the medical literature), it reaches approximately +35mV. When this sudden inrush happens, the area immediately outside the depolarised section of the axon suddenly drops in potential and the positive ions in neighbouring regions move to fill in the ‘gap’. This means that the adjacent regions become less negatively polarised and the potential there eventually rises to a point where that region also depolarises. This is shown in figure 6. Following this depolarisation, the K$^+$ ions inside the cell rush out of the cell and the cell is repolarised. The cell cannot accept another impulse until the Na/K pump has time to restore the -70mV resting potential and appropriate concentrations of the Na$^+$ and K$^+$ ions. This period of insensitivity is known as the refractory period. The electrical signal as measured at the surface of the axon is known as the action potential and a typical example is shown in figure 7.

Muscle Cell Activation
Muscle cells can be found in three main types depending on their behaviour and control. Skeletal muscles are under voluntary control (you can choose to move them), appear striated
under a microscope and are separately innervated. This means that each individual cell is electrically and functionally separate from its neighbours. Thus, different levels of force can be generated in a muscle by activating different numbers of the cells. Smooth muscle is autonomous and is generally much slower to react and contract. This type of muscle is found in the digestive system and other parts of the body over which we have no voluntary control. Finally, cardiac muscle is striated (like skeletal muscle), reacts relatively quickly, is fatigue resistant (doesn’t get tired, which is useful), is involuntary and is collectively innervated, that is the cells are electrically connected and when one contracts the neighbouring cells are also triggered to contract.

Muscles are triggered to contract by the release of acetyl choline (a neurotransmitter) from a motor neuron attached to the cell. Following the Na\(^+\) inrush, the contraction of the muscles is triggered by the inrush of Ca\(^+\) ions. This means that the action potential lasts significantly longer before the K\(^+\) ions outrush. Also, the magnitude of the action potential is lower than that of nerves. An example of a muscular action potential is shown in figure 8.
Cardiac Electrophysiology
Since the muscle cells in the heart are electrically connected to one another, the activation of one will promote its neighbours to contract also. These in turn cause their neighbours to contract and a ‘wave’ of contraction passes through the cardiac tissue. The heart, cannot, therefore, pump harder or softer, but can only change in its rate of pumping. Most importantly, however, the heart muscle must contract in a particular way so that the contracting muscle tissue forces the blood out of the chamber effectively. It contracts from the inside of the ventricle outwards, and starts at almost exactly the same time over the inner surface of the ventricles. This means that the ventricular muscle contracts almost simultaneously, squeezing the blood out of the chamber.

Also, since the atria and ventricles operate independently, there is an electrically insulating layer between them. Figure 9 shows the nerve structures responsible for initiating the contraction sequences. The main part of this system is the sino-atrial (SA or ‘pacemaker’) node, which generates the impulses to contract the atria. This bundle of fibres will independently cause the heart to beat at approximately 90 beats per minute (bpm), but this rate is lowered or increased by stimulus from the central nervous system. The SA node has dedicated conduction fibres which pass into the appropriate parts of the atria to cause them to contract appropriately.
Contraction of the ventricles is initiated through the atrio-ventricular node, located at the bottom of the right atrium and adjacent to the septum (the wall separating the left and right atria). The SA node is connected directly to the AV node by three high-speed conduction fibres. From the AV node, action potentials reach the ventricular tissue via additional bundles of high speed fibres called the bundle of His. There is a delay of approximately 150ms between the action potential reaching the AV node and its appearance at the bundle of His – allowing time for the atria to finish contracting. These fibres branch out and run along the inside wall of the ventricles causing the cells to contract as required.

The Electrocardiogram

Because the heart contracts in this complicated double wave pattern, the resulting electrical pattern produced at its surface is also quite complicated. The ECG signal is the result of the summation of all the depolarising and repolarising myocardial cells, as seen at the surface of the chest. Since the polarisations move through the heart, this appears as an approximate dipole field in the position of the heart – changing in magnitude and orientation over time. A dipole is a system with one positive and one negative charge. Figure 10 shows some action potentials at various places in the heart and a typical ECG signal. Note that the various parts of the wave are labelled with the letters P through T. The P ‘wave’ represents the depolarisation of the atria, the QRS ‘complex’ the depolarisation of the ventricles and the T ‘wave’ due to the repolarisation of the ventricles.

Since the shape and magnitude of the waveform depends on the orientation of the heart, the location of measuring leads and on the individual’s body composition, twelve standard positions are used to eliminate many of these effects. The first three, known as I, II and III
(you’d never have guessed) measure the voltage across the patient’s limbs. With the right ankle connected to ground (0V) the various leads measure the voltage across the patient’s limbs. Position I measures the voltage of the left arm (wrist) with respect to the right arm, position II the left leg (ankle) with respect to the right arm, and position three the left leg to the left arm. These three leads make a vector triangle known as Eindhoven’s triangle, which can be used to calculate the third vector if the other two are known. These positions and Eindhoven’s triangle is shown in figure 11.

![Image of lead positions I, II and III and Eindhoven’s Triangle](image)

Figure 11 – Lead positions I, II and III and Eindhoven’s Triangle

Positions IV, V and VI measure the signals at the same locations relative to a combined reference called Wilson’s Central Terminal (which links limbs through resistive loads). The last six lead positions use the Wilson’s Central Terminal as a reference and the active electrode is placed directly onto the chest. For more information on these lead positions, you should consult a specialist textbook.

The ECG signal has a very small amplitude and is easily swamped by noise from other electrical interference. The most important of these is due to the action potentials of other muscles. Remember that the ECG is itself only the action potentials of the heart muscles contracting and that the measurements will be made at the end of your limbs, while the source of the signal is deep within the chest. Movement of the muscles, particularly in the legs or arms will result in other signals being present. The magnitude of these will be the summation of the action potentials of the muscles involved and will, generally, be much greater than the heart (particularly for large muscle groups between the active electrodes, eg. biceps/triceps). The patient must, therefore, remain still in order for the best signal to be obtained. Other effects such as ionisation at the electrodes or capacitive effects at the electrodes will also
introduce noise. The signal at the skin is a few millivolts in magnitude and is a bipolar (positive and negative) waveform.

The electrodes are normally attached to the body with a layer of conductive gel to improve the detection of the signals. Most conductive gels are basically salty pastes designed to conduct very well. For this experiment this can be most easily obtained using a water based gel and adding salt. A water based gel such as KY jelly can be used for this, and only this, purpose in the lab.

**Common ECG arrhythmias**

There are many different arrhythmias which are easily identifiable in the ECG signal and this section will briefly introduce three of them. These are slow rhythms (Bradycardia), fast rhythms (Tachycardia) and Ventricular Fibrillation.

**Bradycardia**

These effects are caused by ‘blocks’ in the SA-AV node conduction fibres and the severity of the problem depends on the level of blockage. A first-degree block involves a lengthening of the PQ interval (that is, the time between a P wave and the QRS complex) to up to 360ms or twice as long as normal. This is generally a minor problem and of no major consequences for the patient. A waveform showing a first degree block is shown in figure 12.

![Figure 12 – Waveform for first-degree block](image)

A Second-degree block involves the skipping of a QRS complex occasionally. There are two types – a Mobitz type, where a QRS complex is just missed and all others remain normal; and a Wenkebach type where the PQ interval lengthens until a QRS complex is missed. These are
more concerning for the patient (if noticed) than dangerous. See figure 13 for an example of each of these.

Figure 13 – Waveforms for second-degree block, showing Mobitz and Wenkenbach types
A Third-degree (or complete) block, however, is quite a dangerous situation. Here there is no SA-AV conduction and the atrial contractions are not timed with the ventricular contractions. The body’s internal feedback mechanisms raise the rate of the SA pacing to compensate for the lower pumping, but this simple speeds up the atria and has no effect on the ventricles, which are now electrically isolated. Thus the atria pace at the internal rate of approximately 90bpm, while the ventricles spontaneously contract at approximately 36bpm. This condition usually requires a pacemaker. Figure 14 shows a complete block rhythm.

Tachycardia
If a region of local dead tissue is found in the myocardium, a contraction wave can cause a positive feedback effect to occur. The dead tissue conducts much more slowly than healthy tissue and it is possible for a slow wave to reach tissue that has been previously depolarised by the normal wave and excite it again. This means that an additional contraction will occur. If the slow wave circles the dead tissue slowly enough, the wave can indefinitely travel around the defect and initiate irregular contractions. Since the heart doesn’t contract in the most efficient manner, there is a loss of blood pressure in this case. An ECG signal for a ventricular tachycardia is shown in figure 15. There are no visible P waves and the QRS complexes are irregular and wider than normal.
**Ventricular Fibrillation**

If the heart rhythm is upset it is possible for different areas of the heart to contract out of synchronisation. Fibrillation is the condition where spiral waveforms are generated at many locations in the tissue. These waveforms drift about, initiate partial contractions and spawn other such ‘rotors’. Since the heart tissue has a refractory period, these waves collide and extinguish each other where they meet, however, other parts of the heart are ready to be excited and the contraction is no longer uniform. In fact, in this state, rather than contracting, the heart wriggles as the waveforms travel about within it. Without intervention the patient will die in less than 3 minutes as the heart no longer pumps blood. The only effective way to counteract a fibrillation is to depolarise the entire myocardium to extinguish all the rotors at once and then await a normal SA-AV contraction impulse to trigger the contraction. This is normally achieved using a defibrillator, a device designed to impart a huge voltage (often approximately 4000V) across the patient’s heart to achieve this (we are considering doing the defibrillator as next year’s major assignment). Figure 16 shows a fibrillation waveform.

![Ventricular Fibrillation](image)

*Figure 15 – Tachycardia waveform
Figure 16 – Waveform for Ventricular Fibrillation*

**The ECG Amplifier Board**

The board provided as part of this lab is a specialist differential amplifier, with a high common-mode rejection characteristic. It consists of a three stage differential amplifier and is constructed such that the amplifier and all other ‘patient-side’ circuitry is electrically isolated from the microprocessor side. Much of the circuitry on the board exists to achieve this isolation. The schematic for the board is attached to the end of this document.

The first stage of the amplifier is an coupled dual input stage, amplifying the active lead signals with respect to the common ground attached to the right ankle. These amplifiers are very high impedance units and are implemented on the same chip to make the two halves as identical as possible under manufacturing constraints. Once the signals have been amplified in the input stage, they are fed into the second stage, a high-common mode rejection differential amplifier, which gives an output signal which is the amplified difference between the two inputs. Finally, a third (and variable gain) stage is added to amplify and offset the signal to put the signal into the range of 0 to 5V for capture using the 68HC11 microprocessor’s analog to digital converter.

Three adjustments are possible with this amplifier – the differential balance (to correct for any differences in the input stages), the final gain (to adjust the magnitude) and the offset voltage.
(to make the signal unipolar) can be adjusted independently. For this laboratory, these three values will be adjusted by the tutors to be in the correct values before you get the board and they should not be modified by the students. If you think there is a problem with your board, let a tutor know and we will have a look at it. Note that the zero voltage for the signal will not occur at an input voltage of 0V, so that it is important that your system knows how to calibrate and adjust itself. One of the digital outputs on the board is connected to a relay that shorts the two input leads together, switching this on will cause the input to the amplifier stage to be set to zero for automatic calibration.

Once the signal is in the appropriate range, it is converted into a pulse-width modulated (PWM) signal and passed through an isolating optocoupler. This provides approximately 1kV isolation between the two sides. The PWM signal has a frequency of approximately 1MHz and is low-pass filtered on the output side to retrieve the analog signal. The relay for auto-calibration and the power supply to the boards are also rated to give at least 1kV isolation.

There are four different connections available on the unit – J1 (the lead terminals), J2 (a probe connection point), J3 (a 60-pin header for connection to the EVBplus board) and J4 (the power input). Power must be provided to the units using the leads provided and from the laboratory bench power supplies, taking careful note of the polarity of the signal. The sensing leads must be attached using the plug provided and, without the permission of the tutors, may not be modified in any way. The 60-way ribbon cable plugs directly onto P1 of the EVBplus board. The CRO probes may be attached to the signals on J2 to show either the PWM signal or the low-pass filtered analog output voltage.

Resources
There are many resources available for further information regarding the ECG and the Cardiac system. As a starting place, try the University’s Medical Library and look for Cardiovascular or Cardiopulmonary journals or textbooks. Specific details on the processing and interpretation of ECG signals can be found in textbooks related to biomedical signal processing. The internet is another excellent source of information. If you reference information on the net, you must cite it properly. It is customary to include the full URL, the date the page was accessed and the date of last revision. If in doubt, give as much information as possible. A search on Google reveals many useful and interesting sites.

The figures and content of these notes were condensed from lectures by Dr Peter Nickolls at The University of Sydney during 1999. They formed part of the ELEC3801 Biomedical Electrical Engineering course material.