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Development of a Portable Data Acquisition System for Human Performance Assessment in the Field - Phase IIa

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DEVELOPMENT OF A PORTABLE DATA ACQUISITION SYSTEM FOR HUMAN PERFORMANCE ASSESSMENT IN THE FIELD

PHASE IIA

Design and Implementation of Module 2 – Physiological and Biomechanical Variables

by

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Abstract

The second stage of the development of a portable human performance assessment system, based on the Embla data acquisition unit, is described in this report. The objective of the portable system development is to produce a modular system, which will allow the user to select a combination of variables to be measured from freely moving human subjects, e.g. soldiers carrying out field exercises. The specific objectives of this work were to solve problems previously identified with the Embla data acquisition system and identify, design and produce a second portable system module.

Two problems were noted with the Embla data acquisition unit – the data storage medium supplied with the unit was inadequate and the file format, in which the sampled data are stored, is not compatible with other software applications. The original storage device was replaced with a compact flash card, which was found to be robust and provided good storage capacity. Software to convert Embla data files to Matlab format was obtained from the manufacturer of the Embla (Flaga[hf], Reykavik, Iceland). Once the data are converted to Matlab format, they can be processed in the Matlab environment or exported for use in other applications, e.g. Excel.

A second data collection module (module 2) was designed to measure whole body acceleration in six degrees of freedom, heart rate, skin surface temperature and backpack strap tensions. Module 2 includes two triaxial accelerometers, two ECG channels, two temperature probes and six load cell channels, which are interfaced to the Embla recorder. Appropriate sensors were selected, the interface hardware was designed and an interface unit was constructed. Operation of the sensors and the interface unit has been tested. All channels are operating as expected, except the ECG channels which are excessively noisy. Module 2 has been designed as a dedicated stand-alone unit. A design concept to provide more flexibility in selecting physiological and biomechanical variables to be measured is presented at the end of this report.

Résumé

Le présent rapport décrit la deuxième étape du développement d'un système portatif d'évaluation de la performance humaine, fondé sur le dispositif de saisie de données Embla. Le développement de ce système portatif a pour objectif de produire un système modulaire qui permettra à son utilisateur de sélectionner une combinaison de variables à mesurer sur les humains se déplaçant librement, p. ex. des soldats effectuant des exercices en campagne. Les objectifs spécifiques des travaux sont de régler les problèmes relevés dans le système de saisie de données Embla et d'identifier, de concevoir et de produire le deuxième module du système portatif.

Les deux problèmes suivants ont été identifiés en ce qui a trait au dispositif de saisie de données Embla : le support de stockage des données fourni avec le dispositif était inadéquat, et le format de fichiers utilisé pour le stockage des données d'échantillonnage n'était pas compatible celui des autres applications. Le dispositif de stockage original a été remplacé par une carte flash compacte qui est robuste et dotée d'une capacité de stockage suffisante. Le fabricant du système Embla (Flaga^{hf}, Reykjavik, Islande) a fourni un logiciel de conversion des fichiers de données Embla au format Matlab. Une fois que les données ont été converties dans le format Matlab, celles-ci peuvent être traitées dans l'environnement Matlab ou exportées pour utilisation dans d'autres applications comme Excel.

Un deuxième module de collecte des données (module 2) a été conçu afin de mesurer l'accélération du corps entier dans six degrés de liberté, la fréquence cardiaque, la température de la surface de la peau et les tensions des bretelles du sac à dos. Le module 2 comprend deux accéléromètres triaxiaux, deux canaux ECG, deux capteurs de température et six canaux de cellules de pesage, qui sont reliés à l'enregistreur Embla. Des capteurs appropriés ont été sélectionnés, le matériel d'interface a été conçu, et l'interface a été construite. Les essais de fonctionnement des capteurs et de l'interface ont été effectués. Tous les canaux fonctionnent comme prévu, sauf les canaux ECG qui produisent un bruit excessif. Le module 2 est un dispositif autonome. La fin du rapport présente un concept visant à fournir plus de souplesse dans la sélection des variables physiologiques et biomécaniques à mesurer.

Executive Summary

This report describes the design and construction of the second module (module 2) of the portable Human Performance Assessment System (H-PAS). This module has been built around the Embla data acquisition system and is designed to measure how a soldier moves in three-dimensional space and how much work the soldier performs when he/she is involved in training exercises. Since field training and field deployment often require the use of a backpack, module 2 also provides the capacity to measure the tension in the shoulder straps and waist belt of a backpack. This will provide a picture, over time, of how the soldier initially adjusts his/her backpack as well as how often he/she re-adjusts the pack by loosening or tightening the shoulder straps and waist belt. As an integrated unit, module 2 provides information regarding the level of the soldier's performance and how this performance is affected by carrying a loaded backpack.

In a separate study, a mathematical model of the dynamics of human load carriage is being developed using data gained from biomechanical and physiological measurements of soldiers. The research has resulted in the development of load carriage simulators with which much of the same type of data has been acquired for comparative purposes. For this reason, load carriage dynamics are the example of choice for testing and validating the H-PAS.

Data gathered using the H-PAS will be used to create acceleration histories of training tasks and these will be used as input to the human load carriage models currently under development. As well, field data will be used to validate model predictions and outcomes measures. Ultimately the H-PAS and the human load carriage models will provide flexible tools for assessment of a soldier's performance in the field and how this performance is affected by the soldier's clothing, equipment and training.

Sommaire

Le présent rapport décrit la conception et la construction du deuxième module (module 2) du système portatif d'évaluation de la performance humaine (H-PAS). Ce module a été conçu en fonction du système de saisie de données Embla afin de mesurer la façon dont un soldat se déplace dans un espace tridimensionnel et la quantité de travail qu'il doit effectuer durant les exercices d'entraînement. Étant donné que les exercices et le déploiement en campagne nécessitent souvent l'utilisation d'un sac à dos, le module 2 permet également de mesurer la tension aux bretelles et à la ceinture du sac à dos. Cela fournira un portrait temporel de la façon dont les soldats ajustent leur sac à dos initialement et du nombre de fois qu'ils le réajustent en relâchant ou en resserrant les bretelles et la ceinture. Lorsqu'il est intégré, le module 2 fournit de l'information sur le niveau de performance des soldats et sur la manière dont leur performance est réduite par le transport d'un sac à dos rempli.

Dans le cadre d'une étude distincte, un modèle mathématique de la dynamique du transport d'une charge par des humains est élaboré à l'aide des données provenant des mesures biomécaniques et physiologiques des soldats. Ces recherches ont permis de développer des simulateurs de transport de charge qui ont servi à recueillir un grand nombre de données de type similaire aux fins de comparaison. Pour cette raison, la dynamique de transport de charge constitue la méthode de choix pour mettre à l'essai et valider le fonctionnement du H-PAS.

Les données recueillies avec le H-PAS seront utilisées pour créer un historique des accélérations subies durant les tâches d'entraînement et serviront d'entrées aux fins des modèles de transport de charge par les humains en cours d'élaboration. Aussi, les données de campagne serviront à valider les prévisions obtenues à partir des modèles et les mesures de résultats. Enfin, le H-PAS et les modèles de transport de charge par les humains sont des outils souples qui serviront à l'évaluation de la performance des soldats en campagne et de la façon dont cette performance est modifiée par leur habillement, leur équipement et les exercices d'entraînement.

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Introduction

Development of a portable system to measure biomechanical and physiological effects of operational tasks directly on humans in the field was begun under a previous contract[1]. The design goal was to produce a modular system, in which sets of input sensors would be interchangeably connected to a common data storage platform. Under that contract, the Embla recorder, manufactured by Flaga[hf] (Reykavik, Iceland) was selected as the portable data storage unit. The unit is compact, light weight and robust, and it has 16 freely configurable input channels, which are sampled simultaneously. The Embla was originally designed for sleep studies, and a number of sensors which measure parameters relevant for sleep studies, e.g. respiration rate, blood oxygenation level, ECG, etc., interface directly with the recorder. Only some of these measures are potentially useful for assessing human performance in the field, specifically during military training exercises. Thus, a primary goal in developing a portable human performance measurement system, based on the Embla recorder, was to identify potentially interesting measurement parameters and determine how the sensors for measuring such parameters can be interfaced to the Embla recorder.

A portable gait assessment unit was chosen as the initial module to be developed. Gait analysis requires knowledge of the relevant joint angles (hip, knee and ankle) and the forces at the joints, which are derived from the ground reaction force and centre of pressure on the feet. Shape Tape™ manufactured by Measurand, Inc. (Fredericton, NB) was investigated for its ability to track its own position in space in 6 degrees of freedom (DOF) and thus permit determination of joint angles. A unit to interface model #1680 Shape Tape to the Embla recorder was constructed. However, several issues in using the Shape Tape for portable gait analysis, as detailed in the previous contract report (Morin et al., 2001), remain to be resolved. A preliminary investigation of the requirements of an in-sole pressure sensor to measure ground reaction force and centre of pressure was done. Continued development of the gait assessment module, including resolving the issues with the Shape Tape and finalizing the design of the in-sole pressure sensors, is being done under a separate contract[2].

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[1] DCIEM Contract no. W7711-997598/A – A Portable Data Acquisition System for Human Performance Testing in the Field

[2] DRDC Contract no. 7711-0-7632/01-TOR; Call-up no. 7632-05

In the previous contract, two problems were identified with the Embla recorder. Firstly, the rotating hard disk cards which were supplied with the recorder were extremely delicate and easily damaged if not handled properly. This is acknowledged on the Flaga web site[3]: "*Over the years, we have acknowledged that the biggest source of problems for users doing ambulatory studies are the PC cards (PCMCIA). Primarily, the rotating disks are very fragile and must be handled with care and secondly, it is very important to stop the cards in the computer using the appropriate software (e.g. CardWizard). However, despite good handling, the PC cards sometimes start causing problems, such as recordings stopping prematurely, even though there is apparently plenty of disk space.*" Given these problems, it was felt that recording data on this medium during high levels of activity and for long durations was risky and the availability of a more stable recording medium should be investigated. Secondly, the Somnologica software which is provided with the Embla, saves the data in one of two file formats (the Embla file format, and the European file format) neither of which is compatible with other software packages, such as Matlab and Excel. Although Somnologica does provide some data analysis capacity (e.g. Fourier transforms) other packages, in particular Matlab, provide more powerful signal processing capabilities. Thus, a means of converting the Embla data into a format that can exported for further processing is required.

A scientific and industrial survey done under the previous contract, revealed that there are two major means by which human performance is assessed: using physiological measures and using biomechanical measures. Estimates of metabolic energy expenditure and level of fatigue can be obtained from specific physiological measures; biomechanical measures permit the assessment of task performance through analysis of whole body and/or limb motion and joint forces and moments. By combining these two types of assessment variables, the operational effectiveness of the soldier in the field can be evaluated over time. To complement the gait analysis module, a second module to measure physiological and biomechanical parameters relevant to energy expenditure and task performance is indicated. Together, these two modules will provide a quantitative and comprehensive picture of human performance in the field.

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[3] www.flaga.is

Objective

The specific tasks to be completed under this contract are:

- To solve the problems with the Embla recorder identified under the previous contract. This will include obtaining and testing a more stable data storage medium for use with the recorder and exploring data file conversion from the Embla format to a format acceptable by Matlab and Excel.
- To develop the necessary interface hardware for a second portable system module to collect physiological and biomechanical data relevant to human performance. The recorded biomechanical data will be used in the development of a biomechanical model of load carriage, being undertaken by the Ergonomics Research Group at Queen's under a separate contract.[4]

Storage and Conversion of Embla Data Files

Data storage

The Embla recorder samples analog signals at its 16 inputs and stores the data on a portable medium. The medium supplied with the Embla system was a rotating hard disk with 540Mb storage capacity. It was found that these disks are easily damaged and, under Phase I of the project, we were not able to store and retrieve data reliably using them. Technical support at Embla suggested replacing the rotating hard disks with compact flash cards which are more robust. Compact flash cards are available in a range of capacities from 8Mb to 1.0Gb. They can withstand 2000G and can achieve write speeds of up to 2.8Mb/s. Their power consumption during read/write operations is less than 30mA. Two flashcards (SDCFBS-64-101-50 SanDisk[5] CompactFlash™, storage capacity 64Mb) were purchased and found to be robust and reliable for data storage. Complete specifications for these flash cards are reported in Appendix A.

Data file conversion

Somnologica stores the Embla data in a specific format. Data files have the extension, .ebm and there is one file for each measured channel of data. For each recording session, one *events* file is created with the extension, .ebe. A description of the Embla file format is included in

[4] DRDC Contract #7711-0-7632/01-TOR Call-up #7632-02 ; Principle Investigator: Dr. J. Stevenson
[5] SanDisk Corporation, Sunnyvale CA, www.sandisk.com

Appendix B. These formats cannot be read directly by other software, e.g. Excel and Matlab. Flaga provides a developer's kit which contains software to access .ebm files or convert the files to Matlab format. Once converted, the files can be processed in Matlab or exported from Matlab for use in other applications. A description of the developer's kit is also included in Appendix B.

Development of Portable System Module 2

A generic portable system module is shown in Figure 1 below:

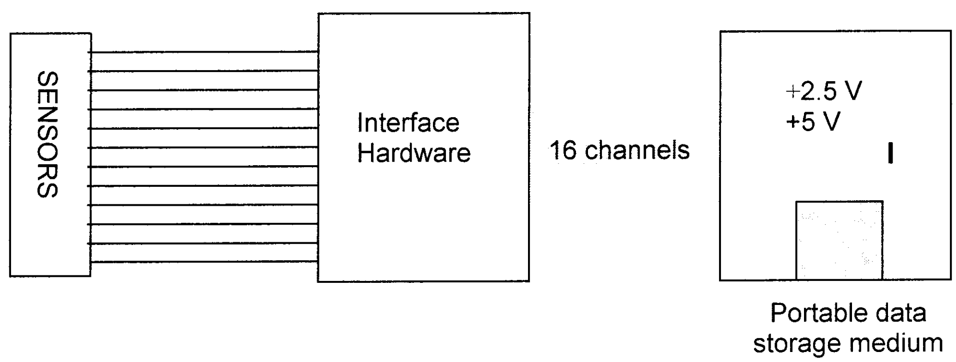

Figure 1: Generic portable system module

The module comprised of a set of measurement sensors, interface hardware and a portable data acquisition unit.

The module is comprised of a number of measurement sensors, which are affixed to the subject or equipment worn by the subject; necessary cabling and electronics to interface the sensors to the Embla recorder; and the recorder itself. The portable unit is to be carried by the subject, generally in a backpack or a day pack. Design of a portable system module involves selection of relevant measurement variables, identification of appropriate sensors and interfacing the sensors to the Embla recorder. The interface hardware must process the signal outputs available from the sensors, such that they are in the appropriate voltage and frequency range for sampling and storage by the Embla recorder. The interface unit must be battery powered to allow for portability and the size should be comparable to that of the Embla recorder (4.5 cm × 8.3 cm × 13.3 cm) to produce a compact module.

Selection of Relevant Measurement Variables

Portable system module 2 is to be designed to collect data relevant to the estimation of energy expenditure during activity and to the development of a biomechanical model of load carriage. An accurate and precise measure of energy expenditure is obtained by indirect calorimetry (Murgatryod et al., 1993). This involves measuring O_2 consumption and CO_2 production by collecting and storing expired air directly from a subject via a mask or mouthpiece. Although this can be done using portable units, the use of a mouthpiece or mask would negatively impact a soldier's ability to operate effectively in the field. Other means of estimating the metabolic cost of activity include using heart rate (HR) or full body acceleration. A direct correlation between O_2 consumption during physical activity and HR exists, so the energy cost of an activity can be estimated from HR measured over the course of the activity (Murgatryod et al., 1993). This method requires individual subject HR-O_2 calibration and is unreliable under resting conditions. The accuracy of the estimate is limited by the effects of factors such as fitness level, ambient humidity, ambient temperature, emotional state, posture, thermogenic substances (e.g. nicotine and caffeine), and digestion. The use of whole body acceleration to estimate energy expenditure has been documented in several published reports (e.g. Bouten et al., 1997; Luke et al., 1997; Hendelman et al., 2000). Measured acceleration and energy cost has been shown to be linearly correlated for level locomotion (Hendelman et al., 2000; Bouten et al., 1994) but energy cost is not accurately estimated from acceleration data for other activities, including indoor and outdoor household tasks and playing golf (Hendelman et al., 2000). Herren et al. (1999) found that both speed of locomotion and incline could be predicted from accelerometer recordings taken at the lower back and heel and Schutz et al. (2002) reported that whole body acceleration in the antero-posterior direction was significantly correlated with speed. It may be possible to use an estimate of walking/running speed to predict energy cost, since there is a relationship between running speed and the rate of energy expenditure. However, the error in the speed estimate may result in an unacceptably high error in the energy cost estimate (Herren et al., 1999).

Since locomotion is a major activity in military field exercises, it should be possible to derive an estimate of a soldier's energy cost over the course of a training exercise using whole body accelerometry. Small, light-weight accelerometers are available and can be affixed to the trunk in unobtrusive locations. Energy cost estimates are improved by measuring both body motion and HR (Luke et al., 1997) however it may be necessary to develop individual calibration curves. Acceleration data can also potentially be used to differentiate between different tasks and an activity profile could be created for soldier after he/she has completed a particular field exercise. And lastly, placing a second accelerometer within the load volume of a backpack would permit an analysis of relative motion between the backpack and the wearer, which is important information for the biomechanical model of load carriage. It was decided that module 2 would include the following:

- six acceleration channels, to accommodate two tri-axial accelerometers
- one ECG channel, from which HR will be determined and a second ECG channel for redundancy – this channel could also be used to measure other bio-electric signals, e.g. EMG, however the down-sampling done within the Embla (from 2000 Hz to 200 Hz-max) would have to be by-passed
- two thermistor channels, for detecting skin surface temperature, at the location of the body-mounted accelerometer and a separate location
- six strain gauges for measuring strap tension in the shoulder straps, load lifter straps and waist belt of a backpack

This last measurement – strap tensions – will be used with the pack-person motion information in the biomechanical model of load carriage. In particular, strap tension information is necessary for modeling the backpack suspension system. Queens University is currently developing a three dimensional dynamic model of human load carriage under a separate contract entitled Development of a Dynamic Biomechanical Model (DBM) of Human Load Carriage Phase III. The overall purpose of the DBM is to improve the understanding of human load carriage capabilities and to understand the benefits of load carriage system design features to human health and mobility.

Selection of Measurement Sensors

There are a number of commercially available accelerometers, both uni-axial and tri-axial. Uni-axial accelerometers can be mounted orthogonally to measure acceleration about more than one axis, however, the mounting must be done carefully to insure that the accelerometers are exactly orthogonal or there will be off-axis effects. Since, the literature suggests that better estimates of energy expenditure are obtained when acceleration is measured along three axes, it was decided to purchase two tri-axial accelerometers. Based on low cost and acceptable stated performance, the Crossbow[6] model CXL10LP3 was selected. This model can measure accelerations in the range of ±10g with a sensitivity of 200mV/g; the stated noise performance is 10mg rms and the operating bandwidth is dc-100 Hz. The dimensions of the unit are

[6] Crossbow Technology Inc., San Jose, CA, USA

1.9×4.76×2.54 cm and the weight is 46 gm (for the standard nylon package). The Crossbow requires a +5V power supply. The output voltage at 0g is 2.5±0.1 V; the output voltage range is 0.5 V (at –10g) to 4.5 V (at +10g). Specifications for the Crossbow accelerometer are given in Appendix C. Specifications for other commercially available accelerometers are included in Appendix D.

The ECG will be measured using standard disposable ECG electrodes (e.g. the Meditrace series 530 foam adhesive electrodes) with snap leads. It is possible to obtain EMG using the same electrodes, however, because there will be substantial subject motion during data collection, an active electrode, such as the DE-2.1 differential electrode from Delsys[7], should be considered for EMG recording.

The OMEGA Engineering Inc.[8] OL-709 Attachable Surface Temperature probe was selected for measuring skin surface temperature. This is a stainless steel, epoxy backed "banjo" shaped sensor that uses two linear 44018 thermistor elements to provide a linear response to temperature change. Specifications for the OL-709 are included in Appendix D.

Strap tensions will be measured with miniature (18 by 6.5 mm) axial load cells developed under Phase I, Part A of PWGSC Contract No. W7711-00-7632[9]. The transducer design is a full Wheatstone bridge to maximize the output signal voltage. The load cells require a +5V excitation.

Interface Hardware

An interface unit to connect the measurement sensors to the Embla recorder was designed and produced. Within the unit, power is supplied to all active devices, signal levels are amplified or attenuated to within the input range of the Embla recorder and any other necessary signal conditioning circuitry is included. Circuits for the individual sensor channels are described as follows:

Accelerometer Circuit

The Crossbow is a tri-axial accelerometer, which requires a +5V power supply. The accelerometer is attached to a 5 pin connector with:

[7] Delsys Inc., Boston, MA; www.delsys.com
[8] OMEGA Engineering Inc. Stamford, CT, USA; www.omega.com
[9] Contractor Report Part A PWGSC Contract No. 7711-0-7632/01

PIN 1 = Power in

PIN 2 = Ground

PIN 3 = x-axis out

PIN 4 = y-axis out

PIN 5 = z-axis out

Each accelerometer was factory calibrated giving the values shown in Table 1.

Table 1: Factory calibration values for the Crossbow accelerometers.

Acc #		X-axis	Y-axis	Z-axis
1	Voltage at 0g	2.475	2.466	2.463
	Sensitivity (mV / g)	203	202	204
2	Voltage at 0g	2.490	2.486	2.484
	Sensitivity (mV / g)	197	202	202

It is only necessary to attenuate the output voltage to be within the range, 0 – 250 mV for input to the Embla recorder. This is done using a simple voltage divider:

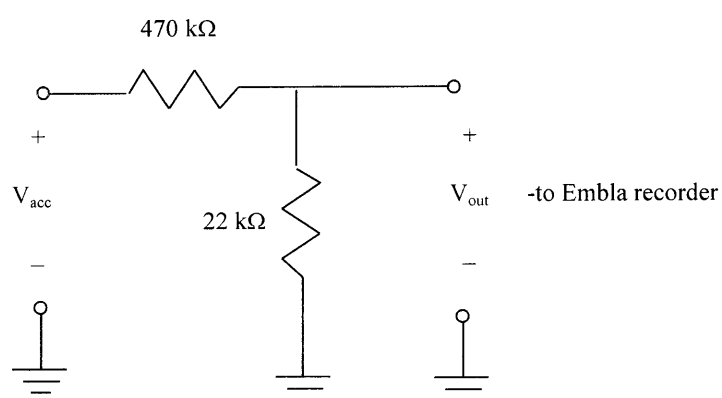

Figure 2: Voltage divider circuit for attenuation of accelerometer output voltage.

Using this circuit, $V_{out} = 0.0447 \bullet V_{acc}$ yields the attenuated calibration values shown in Table 2.

Table 2: Attenuated calibration values for the Crossbow accelerometers.

Acc #		X-axis	Y-axis	Z-axis
1	Voltage at 0g (mV)	110.7	110.3	110.1
	Sensitivity (mV / g)	9.08	9.03	9.12
2	Voltage at 0g (mV)	111.3	111.2	111.1
	Sensitivity (mV / g)	8.81	9.03	9.03

ECG Circuit

The ECG is a biological signal detected from the trunk or extremities using surface electrodes. It must be amplified to be within the input range of the Embla and both high-pass and low-pass filtered. The high pass filter removes low frequency motion and cable artifact, and the low pass filter removes high frequency noise before the signal is sampled (i.e. it acts as an anti-aliasing filter). The ECG circuit is shown in Figure 3.

The first gain stage provides 23.45× amplification and the second stage provides 89.2× giving an overall gain of approximately 2090. The filters are both first order providing a low cut-off frequency of 7.8 Hz and a high cut-off frequency of 80 Hz. Although first order filters do not provide a sharp roll-off at the cut-off, it was felt that first order was sufficient for this circuit, since the objective is simply to estimate heart rate from the ECG.

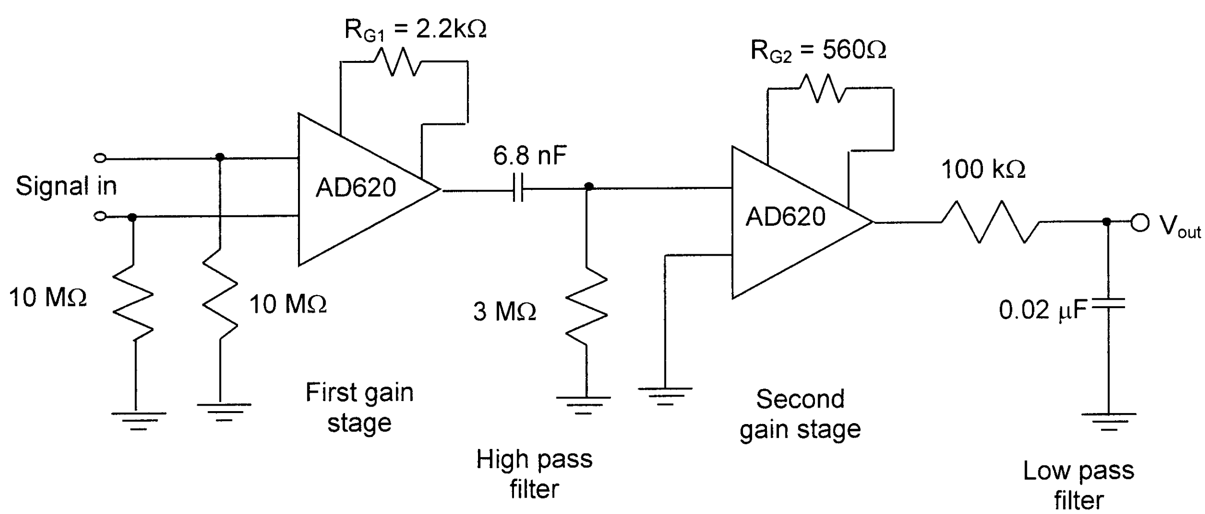

Figure 3: Interface circuit for the ECG channels.

Amplification is achieved using AD620 Instrumentation Amplifiers manufactured by Analog Devices Inc.[10] These devices were selected for their low noise and accurate performance. A gain of 1-1000 is set by an external resistor, shown as R_{G1} and R_{G2}. The gain factor is determined from: $G = \frac{49.4k\Omega}{R_G} + 1$. The amplifier requires only 1.3mA maximum current supply, making it a good choice for battery powered applications. A link to specifications for the AD620 can be found in Appendix I.

Temperature Probe Circuit

A thermistor is a variable resistor, which changes resistance with temperature. In order to track this variation as a change in voltage, the thermistor is included in a Wheatstone bridge. The bridge circuit for the OL-709 temperature probes is shown in Figure 4. The bridge is excited by a voltage source, V_{in} = 2.5 V and the measured voltage is V_{out2}. V_{out2} can be calculated as follows:

$$\begin{aligned} V_{out2} &= V_{out1} - V_{R4} \\ V_{R4} &= \frac{V_{in} \cdot R_4}{R_3 + R_4} \\ V_{out1} &= V_{in}(-0.0056846 \cdot T + 0.805858) \end{aligned} \tag{1}$$

Values of V_{in}, R_3 and R_4 determine the temperature range over which the response is linear, for a desired output voltage range. For this application the output voltage range was set to ±200 mV to be within the input range of the Embla recorder. V_{out2} was calculated for the values of R_3 and R_4 used in the circuit (330Ω and 660Ω respectively). These values are given in Table 3.

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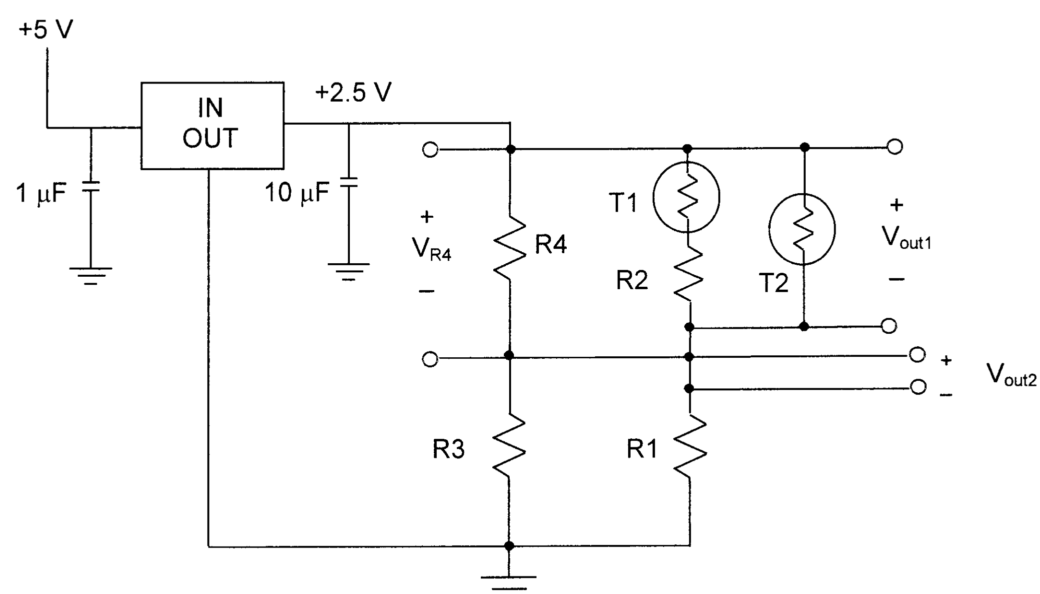
[10] Analog Devices Inc., Norwood, MA, USA; www.analog.com

Table 3: Output voltages calculated for various temperatures.

Temp (°C)	V_{out2} (mV)	Temp (°C)	V_{out2} (mV)
10.4	200.0	28	–49.9
15	134.8	29	–64.2
20	63.7	30	–78.4
21	49.5	31	–92.6
22	35.3	32	–106.8
23	21.1	33	–121.0
24	6.9	34	–135.2
25	–7.3	35	–149.4
26	–21.5	36	–164.0
27	–35.7	38.6	–200.0

The temperature range over which linear output is expected is 10.4°C to 38.6°C. This range can be shifted by changing the R_3/R_4 ratio. Linear ranges for various R_3/R_4 ratios are given in Appendix E.

Figure 4: Thermistor circuit.



V_{in} is 2.5 V supplied via a voltage regulator. The measured voltage is V_{out2}. T_1 and T_2 are the thermistors in the OL-709 temperature probe. R_1 = 5.6 kΩ; R_2 = 11.2 kΩ; R_3 = 330 Ω; R_4 = 660 Ω.

Load Cell Channels

Each load cell is configured as a full Wheatstone bridge – i.e. each arm of the bridge is comprised of a strain gauge, where the resistance of each arm changes with applied tension. The load cell requires a +5V excitation voltage. The output from the bridge must be amplified to be within the acceptable range for the Embla recorder. The load cell circuit is shown in Figure 5.

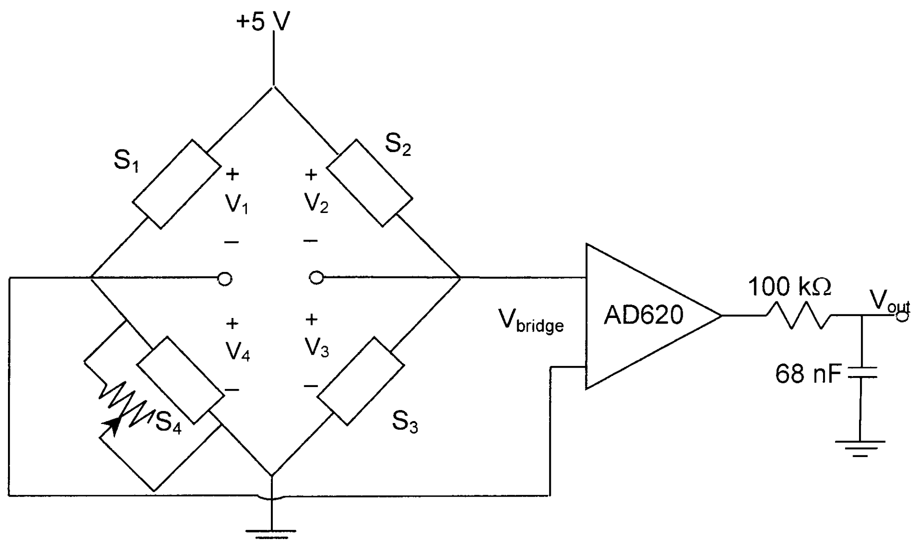


Figure 5: Load cell circuit.

The resistance values of S_1, S_2, S_3 and S_4 vary slightly; measured values, under no load, are given in Appendix F. For zero offset (i.e. $V_{bridge} = 0$) at no load, the bridge must be balanced. V_{bridge} is zero if $V_4=V_3$ and, in turn, $V_1=V_2$. This requires that: $\frac{R_2}{R_3} = \frac{R_1}{R_4}$ or that $R_2R_4=R_1R_3$, where R_1, R_2, R_3 and R_4 are the resistance values of S_1, S_2, S_3 and S_4 respectively. This can be achieved by placing a potentiometer in parallel with arm 4 of the Wheatstone bridge. Resistance values required to balance the bridge for four working load cells are given in Appendix F.

Power Supply

In addition to providing voltage for the accelerometers, thermistors and load cells, a power supply is needed to supply ±5 V to the AD 620 instrumentation amplifiers. In the initial prototype, power was supplied from three 9V alkaline batteries – two provided +5V via a voltage regulator and one provided –5V via a separate regulator. In the re-designed prototype, a single 7.2V Li-ion battery pack (Sony model #NP-550) is used to provide all power. A Burr-Brown REG103 regulator, manufactured by Texas Instruments, is used for the +5V supply. The +5V is inverted using a TPS60400 voltage inverter to obtain –5V . A second regulator – the LM2937-2.5 manufactured by National Semiconductor – is used to provide the +2.5V required for the thermistor circuit. Links to the specifications for these devices are included in Appendix I.

System Testing

Accelerometer Channels

The accelerometers have been factory calibrated and calibration values are given in Table 1. The acceleration channels were tested for proper operation by looking at the recorded output under three conditions: no applied acceleration (0g); acceleration due to gravity (1g) and applied acceleration.

Consider the schematic of the Crossbow accelerometer shown in Figure 6:

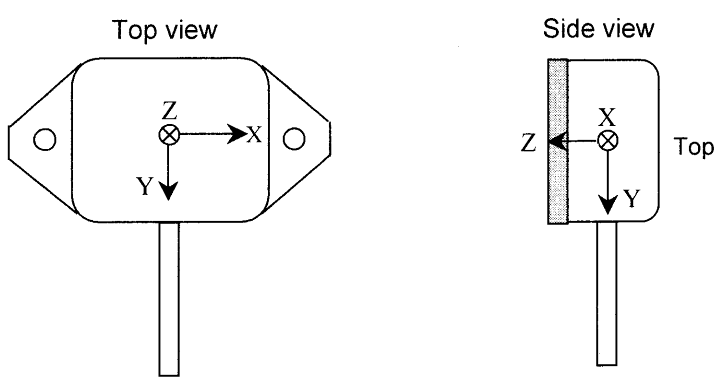


Figure 6: Top view and side view of the Crossbow accelerometer.

Figure 6 shows the definition of the axes of acceleration: X – side-to-side; Y – up-down and Z – forward-backwards.

As the accelerometer is turned in space, acceleration due to gravity is experienced on one or more axes. For example, if the accelerometer is placed face down, gravity is in the +Z direction; therefore the Z-axis will experience 1g and the X- and Y-axes will experience 0g. In this case, the voltages reported by the Embla recorder should be: 110.7 mV on the X-axis; 110.3

mV on the Y-axis and 119.2 mV on the Z axis (for Accelerometer #1; see Table 2). Voltages were recorded from both accelerometers as they were positioned to experience gravity on the +X, –X, +Y, –Y, +Z and –Z axes consecutively and these voltages are reported in Table 4. The acceleration in g's is calculated using:

$$Accel = \frac{\left[\dfrac{reported\ voltage}{nominal\ scale\ factor} - 0g\ voltage\right]}{sensitivity} \qquad (2)$$

Table 4: Embla voltages and acceleration values

Gravity is experienced on each axis of the two accelerometers. The magnitude of the acceleration vector is calculated from $\sqrt{X^2 + Y^2 + Z^2}$.

Accelerometer #1:				Factory Calibration				Calculated Calibration			
Gravity on:	X (mV)	Y (mV)	Z (mV)	X (g's)	Y (g's)	Z (g's)	Magnitude	X (g's)	Y (g's)	Z (g's)	Magnitude
+X	118.9	111.4	110.9	0.91	0.13	0.09	0.92	1.00	0.04	-0.01	1.00
-X	100.7	110.7	111.1	-1.09	0.05	0.11	1.10	-1.00	-0.04	0.01	1.00
+Y	109.4	120.0	111.2	-0.14	1.08	0.12	1.10	-0.04	0.99	0.02	0.99
-Y	110.2	102.1	110.8	-0.05	-0.90	0.08	0.90	0.04	-0.99	-0.02	0.99
+Z	109.5	110.9	120.1	-0.12	0.07	1.10	1.11	0.04	0.01	1.01	1.01
-Z	110.1	111.1	101.9	-0.06	0.10	-0.90	0.91	-0.03	-0.01	-1.01	10.1
Accelerometer #2:				Factory Calibration				Calculated Calibration			
Gravity on:	X (mV)	Y (mV)	Z (mV)	X (g's)	Y (g's)	Z (g's)	Magnitude	X (g's)	Y (g's)	Z (g's)	Magnitude
+X	120.9	112.8	112.4	1.09	0.19	0.15	1.12	1.00	0.01	0.02	1.00
-X	103.2	112.6	112.0	-0.92	0.16	0.11	0.94	-0.98	-0.02	-0.02	0.98
+Y	111.9	121.7	111.8	0.07	1.17	0.08	1.18	-0.02	1.00	-0.04	1.00
-Y	112.1	103.7	111.8	0.09	-0.82	0.08	0.83	0.01	-1.00	-0.04	1.00
+Z	112.2	112.7	121.2	0.10	0.17	1.13	1.14	0.02	-0.01	1.00	1.00
-Z	112.0	112.7	103.2	0.08	0.17	-0.87	0.89	-0.01	-0.01	-1.00	1.00

Note: shaded cells denote the axis exposed to gravity

It can be seen, for the factory calibration values, that an acceleration of ±1g is not always reported on the relevant axis and off-axis accelerations vary substantially from zero. As well, if gravity is the only acceleration present, the reported acceleration vector on the three axes should have a magnitude of 1. Two factors, which may contribute to these discrepancies, are incorrect scale factors and/or incorrect calibration values.

Individual scale factors will vary slightly on each channel due to the resistance value tolerances in the voltage divider. Resistor values in the voltage divider circuit can vary by as much as ±1%; thus they can range from 465.3kΩ to 474.7kΩ and from 21.78kΩ to 22.22kΩ.

This gives a scale factor range of .04387 to .04558 and the nominal scale factor of .0447 falls in the middle of this range. By measuring the resistance values, the actual scale factor for each channel was determined and used in calculating the g values for the "Calculated Calibration" results of Table 4. Individual channel scale factors are given in Table 5.

Table 5: Measured scale factors for each accelerometer channel

A1-X	A1-Y	A1-Z	A2-X	A2-Y	A2-Z
0.044488	0.044235	0.044507	0.044874	0.044625	0.044468

Reported data were recorded approximately 11 months after the factory calibration was done and significant error was apparent. A new calibration was subsequently performed. A ground aluminium channel with orthogonal sides and parallel faces was used to orient the accelerometer axes with gravity (±1g), see Figure 7. The average of the ±1g readings determines the sensor offset and the slope of the readings determines the sensor sensitivity. The acceleration values calculated using the new calibration values are reported in Table 4 as "Calculated Calibration". Errors of 0-4 % were achieved using the new calibration and scale factors; using the factory supplied calibration values and nominal scale factor, errors ranged from 3 to 22%. This confirms that a current calibration is necessary to achieve the stated accuracy of the device.

The noise performance of the accelerometers was investigated by extracting segments of data recorded under 0g conditions. Figure 8 shows a 0g record for each axis of each accelerometer. In all cases, the peak-to-peak output is less than 0.2mg (±0.1mg); the mean absolute values of the 0g records are given in Table 5 and the RMS values of the zero g signal is summarized in Table 6. The results indicate that the accelerometers' noise performance falls within the stated performance of 10mg rms.

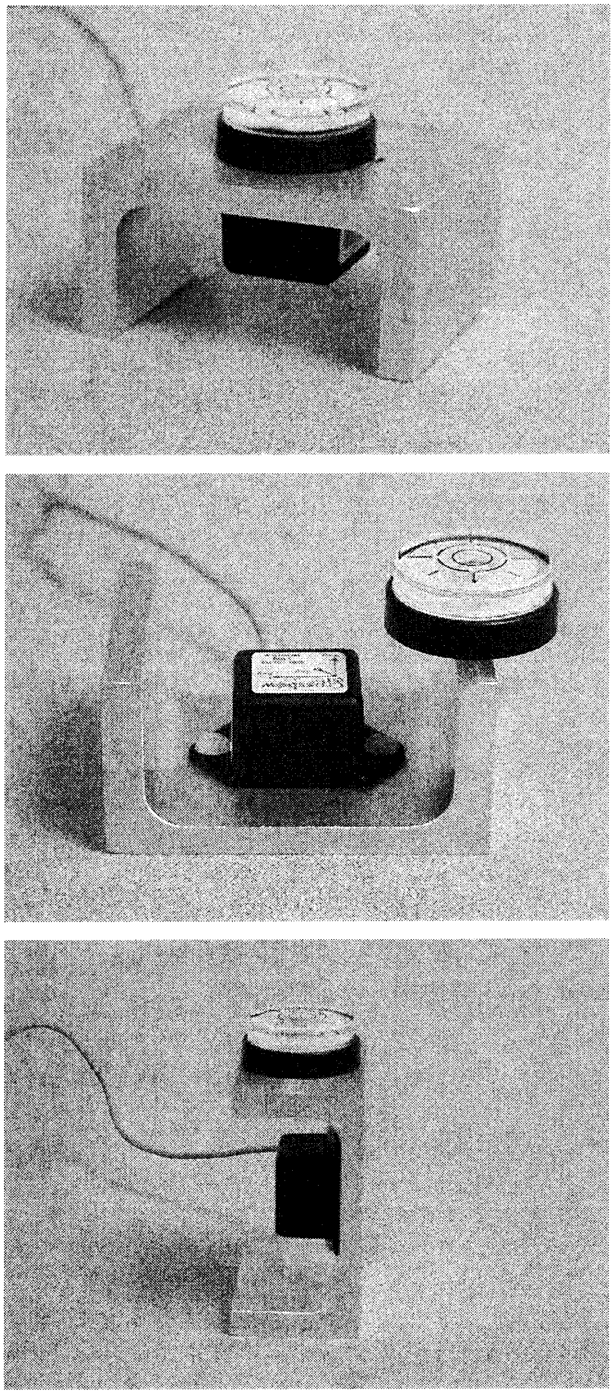


Figure 7: Calibration of the accelerometers

A square sided ground aluminium channel and spirit level were used to confirm orientation. The accelerometer can be independently positioned in all 6 orientations.

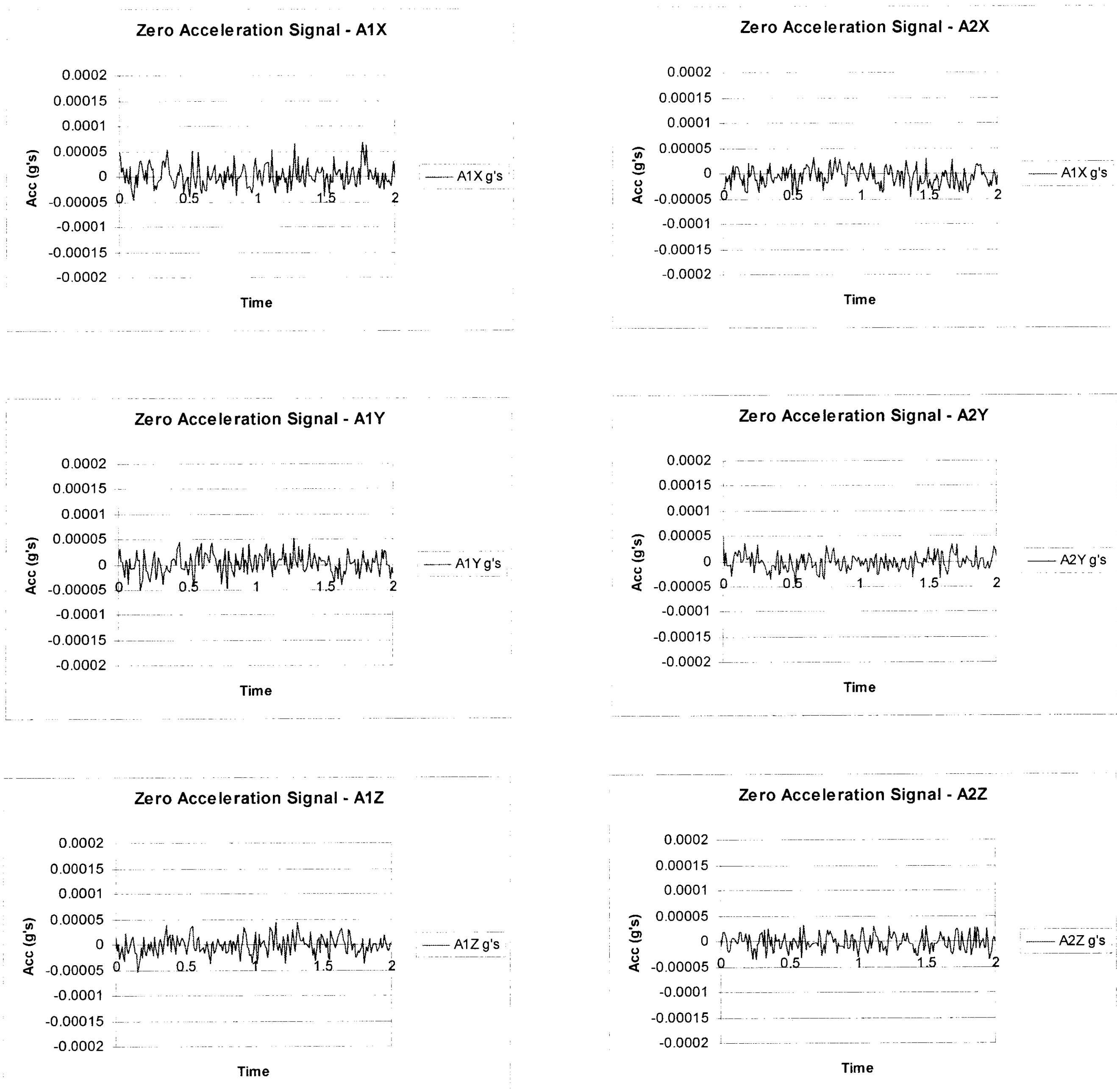


Figure 8: Zero g recordings for each axis of each accelerometer (A1 = accelerometer 1; A2 = accelerometer 2). The time scale for the plot is 2 seconds.

Table 6: Root mean square values of zero g signals

Accelerometer 1 (mg's)			**Accelerometer 2 (mg's)**		
X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
0.107	0.097	0.087	0.271	0.260	0.078

ECG Channels

The output on the ECG channels is very noisy. This is likely due to a very high common mode interference, primarily 60 Hz signal from the ac power source and equipment such as computers and fluorescent lights. The noise is reduced, but still present, when the subject is grounded through the patient ground of the Embla recorder. The noise obliterates any detected ECG.

Temperature Probe Channels

The linearity of the temperature probe response was tested by placing the probe in a water bath which was allowed to cool from a temperature of 41°C to approximately room temperature. The temperature of the bath was simultaneously measured using a mercury thermometer (CENCO 19285A), with a measurement range of 15.5 to 120 °F, (-9.2 to 48.9 °C) and an accuracy of ±0.1°F; and a digital thermometer (Life brand, model no. 5531), with a measurement

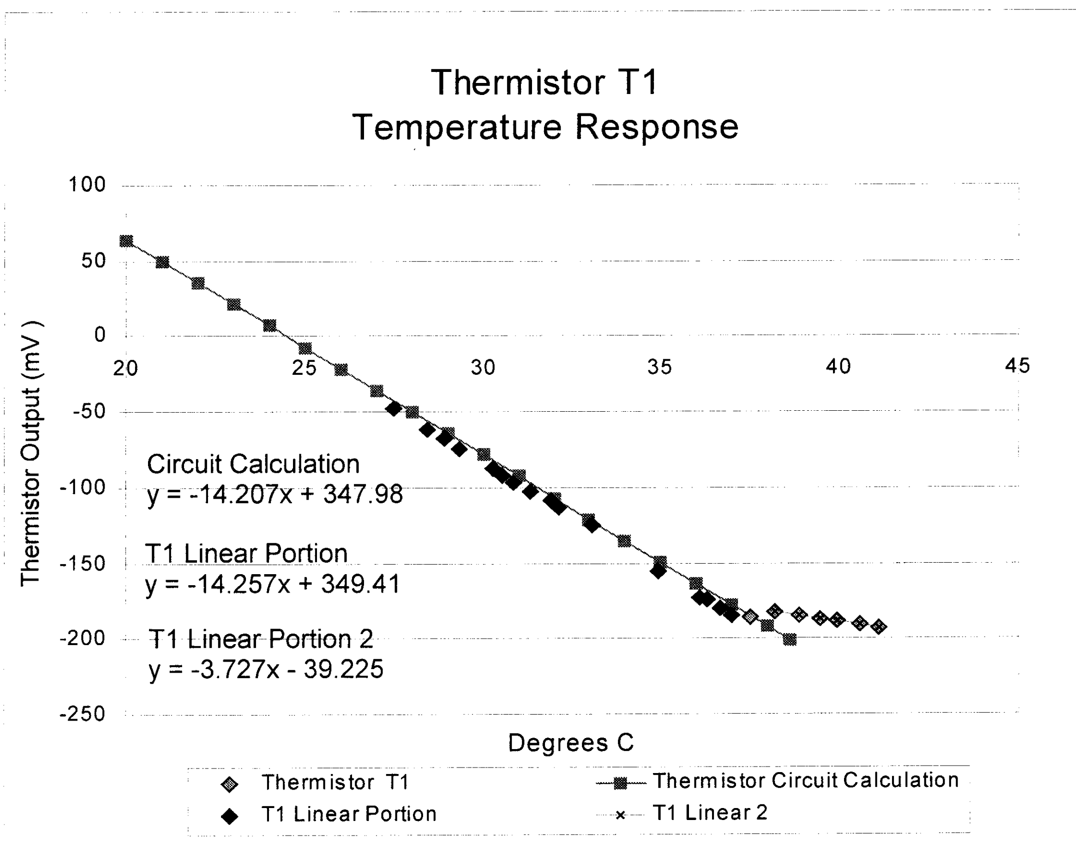


Figure 9: Measured output voltages versus temperature for a single temperature probe.

range of 32.2 to 43.3°C and an accuracy of 0.1°C from 35.5 to 41.7°C at room temperature between 18 and 28°C. The temperature probe output agrees well with the calculated values up to approximately the limit of the linear range. At 37.5°C the temperature probe output became unstable and for temperatures above this breakpoint, the output deviated from the straight line, as is evident in Figure 9.

Load Cell Channels

Each load cell channel was tested using a working load cell. Individual load cells exhibit varying degrees of initial offset due to small imbalances in the resistances on opposing branches of their Wheatstone bridge. In order to accommodate this offset range, each channel was zeroed using the potentiometer that was connected in parallel with S4 (see Appendix E) and then response to applied compression and tension was observed. Zeroing proved to be somewhat difficult on some channels, since the potentiometer resistance varied from 0 – 2MΩ with a single 360° turn. This resulted in large shifts in the offset voltage with very small adjustments of the potentiometer. However, it was possible to either remove or reduce the offset to an minimal level for testing on all channels. Once the zero offset was reduced, all channels showed the expected response for an applied compression or tension.

Conclusions and Recommendations

Data Storage

Issues with the data storage medium used with the Embla recorder and data file conversion from Embla file format to a more widely used format have been resolved. The compact flash cards, which were purchased under this contract, were used with the Embla recorder and the first Module 2 prototype in a comprehensive field trial in December 2001[11]. The flash cards proved to be robust for portable data collection and the 64 Mbyte storage capacity readily provided over 5 hours data storage for this protocol (9 channels of data at 50 Hz). It is possible to export Embla data in ASCII format, which can be readily imported into applications such as Excel and Matlab. As well, the Embla file format developer's kit provides C/C++ and Matlab code to read Embla data directly into Matlab.

[11] Results of the field trial will be included in the contract report for DRDC-Toronto contract #W7711-0-7632/01-TOR; call-up #7632-04: Development of a Portable Data Acquisition System for Human Performance Assessment in the Field, Phase IIb: Testing and evaluation of Module 2 – Physiological and Biomechanical Variables

Portable System Module 2

The Accelerometer Channels

Both accelerometers respond to accelerations on each of the three axes. Bouten et al. concluded that body fixed accelerometers fixed at waist level should typically have an amplitude range of +/- 6g and an adequate frequency response to capture 20 Hz accelerations in their summary of acceleration frequencies and magnitudes occurring during walking, running and jumping on a trampoline at different locations on the body. Response time and frequency response of the units selected is within limitations for collecting data for human motion The frequency response of the unit is dc – 100 Hz, giving a minimum rise time of 2.5 ms. The shortest response time needed would be for the rapid decelerations associated with impacts, such as in landing a jump or hitting the ground after falling. A 2.5 ms rise time will be sufficient to detect these events. A range of +/- 5 g was selected, slightly less than the suggested +/-6 g range to improve the resolution across the range of training tasks envisioned.

The accelerometers were calibrated by the manufacturer prior to shipping. Factory calibration values (the offset at 0g and change in voltage per g of acceleration) were supplied. In subsequent testing, approximately 11 months after the factory calibration was dated, it was found that the calibration values had drifted noticeably. The accelerometers were re-calibrated by positioning each axis independently in the direction of the gravitational field. The 0g offset and the change in voltage with gravity were determined. These new calibration values are included in Appendix C. These results indicate that the accelerometers should be re-calibrated regularly in order to obtain accurate measures of acceleration. The amount of drift in the response over time can be assessed by tracking the calibration results.

The hardware interface for the accelerometers is a simple voltage divider. For accurate scaling, it is necessary to measure the actual resistances on each channel and calculate the scale factors. This has been done for the current prototype interface unit.

ECG Channels

The hardware interface for the ECG channels was based on a standard ECG signal conditioning circuit. However, a large common mode interference signal, which obliterates the ECG, was present on both channels. Common mode interference is a common problem in bio-signal amplifiers, due to the large gains involved. It is often caused by component mis-match. For example, if the 10MΩ resistors between the Signal In lines and ground (see Figure 3) are not exactly matched, some common mode signal (e.g. power line interference which appears on both input lines) will be converted to a differential signal. The circuit will be carefully tested for mis-matched component values. If the common mode interference problem persists, a new circuit design will be sought.

Temperature Probe Channels

The temperature probes were found to work as expected, giving a measured linear response to temperature over the range 27.5°C – 37.5°C. Theoretically, the linear response extends from 10.4°C – 38.6°C. The range of temperatures over which the response is linear can be varied by changing the ratio of R_3/R_4, so that the temperature probe can be adjusted to environmental conditions. Details of the T_{min} and T_{max} calculations, as well as T_{min} and T_{max} values calculated for other R_3:R_4 ratios, can be found in Appendix E.

Load Cell Channels

The load cells have been designed, manufactured, validated and calibrated under a separate contract entitled: PHASE I PART A -W7711-00-7632. The calibration demonstrated a linear response with an average R^2 value of $\geq$0.993. A table summarizing the linearity and calibration factors is included in Appendix G. The single-turn potentiometer, which is used to zero the offset on the load cells, should be replaced with a multi-turn potentiometer (typically 20 turns) or two potentiometers in series, one coarse and one fine adjustment, to facilitate setting the zero offset compensation. Six signal conditioning circuits were incorporated into module 2 to allow bilateral monitoring of all load carriage equipment strapping. This data can be used to provide benchmarking data for development of DRDC's dynamic biomechanical model of load carriage.

Future Development

The interface hardware for module 2 has been constructed as a single unit providing six accelerometer channels, two ECG channels, two temperature probe channels and six load cell channels. The outputs from the unit are connected via four eight-pin Lemo connectors to the input of the Embla recorder. The output signals on each Lemo connector are shown in Figure 10. These outputs are connected, via dedicated cables to the Embla recorder. Consider the case where data from only one accelerometer is desired, requiring channels 1, 2 and 3. Since channels

4, 5 and 6 are dedicated to accelerometer-2, these channels cannot be used. Or in another case, load cell data may not be needed, potentially freeing six channels for other sensors. However, if the temperature probes are being used, channels 11 and 12 are not available since they are included with channels 9 and 10 on a single connector. The fourth connector (channels 13-16) can be left open for use with other sensors.

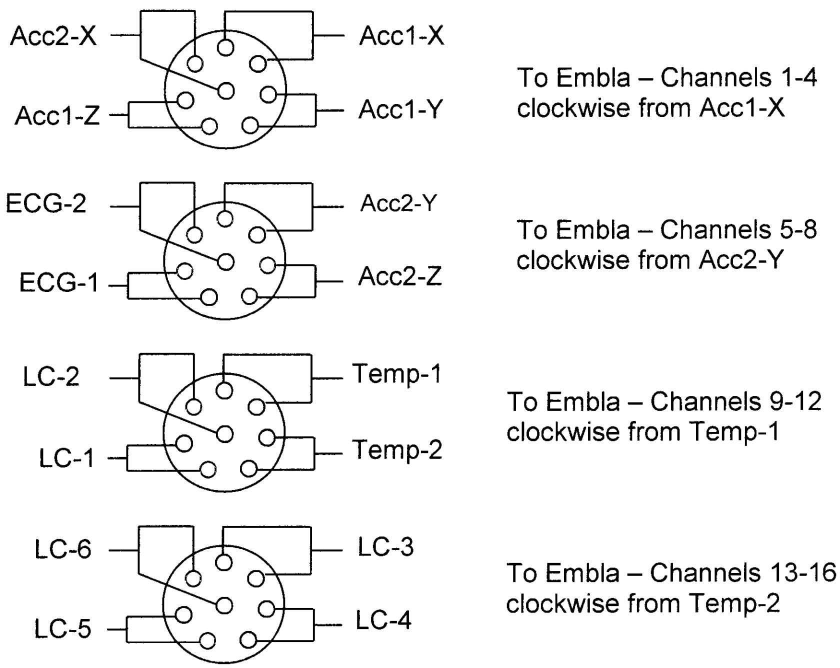


Figure 10: Output connectors from the module 2 interface box. All 16 channels are dedicated.

In a more flexible system, it should be possible to use the Embla channels individually for any desired input. This could be achieved by building a break-out box (similar to the Embla proxy) for the Embla recorder. The box would provide 16 differential channels on individual connectors. These would be connected to four 8-pin Lemo connectors which could be directly plugged into the inputs of the Embla. Signal conditioning units with individual differential outputs, would be built for each sensor type. In this configuration, as shown in Figure 10, when only one accelerometer is used, all other input channels to the Embla recorder are available.

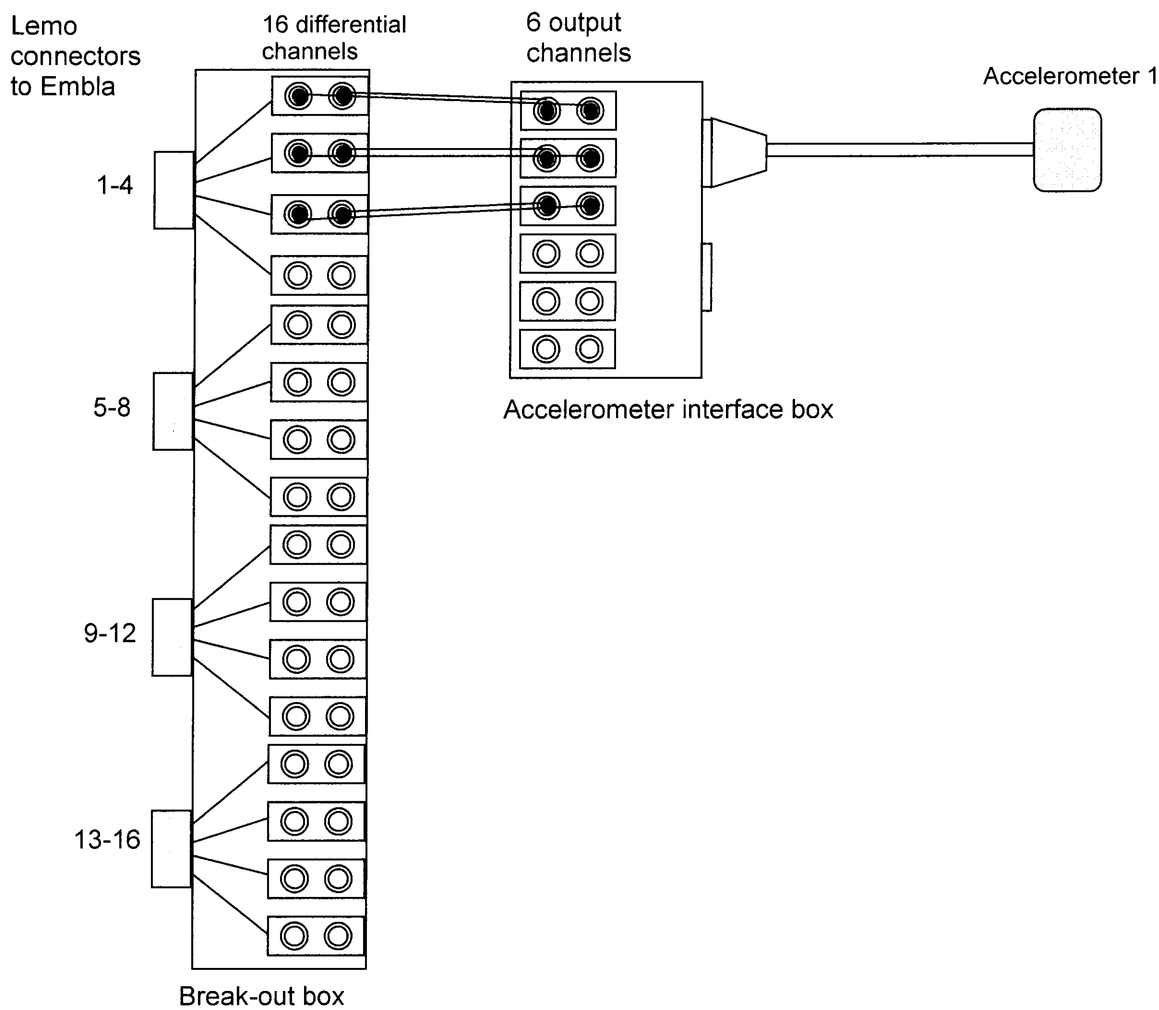


Figure 11: Breakout box design.

Figure 11 shows a single accelerometer connected to channels 1-3. This configuration provides independent access to 16 channels. The breakout box could supply power to sensors requiring excitation using either an onboard battery as developed for Module 2 or by connection to the event line on the Embla where up to 200mA current at 5 V is directly available. If this latter option is pursued, current must be limited on the sensor side of the interface since the Embla is not over current protected. The signal conditioning modules for thermistors, load cells and accelerometers would use the same circuitry developed and tested under the current contract for Module 2. This design concept is suggested for future development of the portable human performance monitoring system.

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Montoye, H.J., Washburn, H.J.R., Servais, S., Ertl, A., Webster, J.G. and Nagle, F.J., "Estimation of energy expenditure by a portable accelerometer," *Med. Sci. Sports Exerc.*, vol. 15, pp. 403-407, 1983.

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Appendices

Appendix A – SanDisk FlashCards -Technical Specifications
Appendix B – Embla File Format and File Conversion
Appendix C – Specifications for the Crossbow Triaxial Accelerometer
Appendix D – Specifications for Commercially Available Accelerometers
Appendix E – Thermistor - Linear Range Calculations
Appendix F – Strain Gauge Resistance Values
Appendix G – Load Cell Specifications
Appendix H – Interface Hardware Circuit Layouts and Parts List
Appendix I – Component Data Sheets
Appendix J - Using Somnologica v.3

Appendix A SanDisk Flash Cards – Technical Specifications:

Reference: http://www.sandisk.com/oem/cf-spec.htm

System Performance *Notes 1 & 2

Start-up Time

Sleep to Write 2.5 msec max

Sleep to Read 2.0 msec max.

Reset to Ready 50 msec typical

400 msec max.

Data Transfer Rate to/from Flash: 20.0 MB/s burst

Data Transfer Rate to/from Host: 16.0 MB/s burst

Active to Sleep Delay – Programmable

Controller Overhead Command to DRQ <1.25 ms

Power Requirements *note 1

DC Input Voltage

Commercial 3.3V ± 5%, 5V ± 10%

Industrial 3.3V ± 5%, 5V ± 5%

Typical Power Dissipation *Notes 3 & 4

Sleep 200µA (3.3V) 500µA (5V)

Read 21-45 mA (3.3V)

34-75 mA (5V)

Write 21-60 mA (3.3V)

34-90 mA (5V)

Environmental Specifications

Temperature

Operating Commercial	0 - 60° C
Operating Industrial	-40 - 85° C
Non-Operating Commercial	-25 - 85° C
Non-Operating Industrial	-50 - 100° C

Humidity

Operating	8 - 95%, non-condensing
Non-Operating	8 - 95%, non-condensing

Acoustic Noise (at 1 meter) 0 dB

Vibration

Operating	15 G peak to peak max.
Non-Operating	15 G peak to peak max.

Shock

Operating	2,000 G. max.
Non-Operating	2,000 G. max.

Reliability and Maintenance

Mean Time Between Failures) >1,000,000 hours

Preventive Maintenance None

Data Reliability

< 1 non-recoverable error in 10(14) bits read

Physical Specifications

Length:

CompactFlash	1.433 in (36.4 mm)
CompactFlash Adapter	3.370 in (85.6 mm)

Width:

CompactFlash	1.685 in (42.8 mm)
CompactFlash Adapter	2.126 in (54.0 mm)

Thickness (Body):

CompactFlash	0.130 in (3.30 mm)
CompactFlash Adapter	0.1968 in (5.0 mm)

Thickness (Removable Edge):

CompactFlash	0.155 in (3.94 mm)
CompactFlash Adapter	N/A

Weight:

CompactFlash Adapter	1.16 oz (33 g)
CompactFlash	0.40 oz (11.4 g)

Ordering Information: Order Model #

SDCFBX-YY-101-50	CompactFlash
SDCF-03	CompactFlash Adapter (See Note 5)

Where X: I: Industrial temp. grade or
S: Standard temp. grade

SDCFBX-YY-101-50 CompactFlash YY:

8: 8.0 MB
16: 16.0 MB
32: 32.1 MB
64: 64.2 MB
128: 128.0 MB
192: 192.0 MB
256: 256.9 MB
384: 384.5 MB
512: 512.5 MB

Note 1: All values quoted are typical at ambient temperature and nominal supply voltage unless otherwise stated.

Note 2: All performance timing assumes the controller is in the default (i.e., fastest) mode.

Note 3: Sleep mode currently is specified under the condition that all card inputs are static CMOS levels and in a "Not Busy" operating state.

Note 4: The currents specified show the bounds of programmability of the product.

Note 5: CF interface surface mount header and ejector may be ordered from 3M Company.
To order, call: 1-800-225-5373.

Specifications are subject to change without notice.

Appendix B Embla File Format and File Conversion

EMBLA® provides a developers kit for users planning on developing their own applications for the Embla platform. This kit contains the following documentation and utilities to support code development for C, C++ and MatLab formats. Complete documentation for the following files are included in the electronic version of this report as PDF files.

Document Name	Description
Embla-File Format Description.pdf	EMBLA File Format Description V4, this 10 page document gives an overview of the format of the data files that Embla creates during recording. Data files are written in ASCII MS-DOS format.

Embla File Format
Developers Kit - Version 2.2

Date 4.11.98 / Sigurjón Kristjánsson

Table 1 Documentation

File Name	Description
Embla - File Format Desciption.PDF	**Adobe Acrobat documentation on the Embla EBM file format construction.**

Table 2 Source code for C and C++

File Name	Description
EBMDEF.H	Include definition file defining all constants used by the Embla file format
EBMRead.cpp	Implementation of the C++ class TEBMReader. The class encapsulates the EBM file format and may be sed as a plug-in module in third party applications.
EBMRead.h	Definition file for the C++ class TEBMReader
EBMInfo.cpp	Demonstration for the class TEBMReader. Opens an EBM file and displays its attributes like sampling rate, record time etc.
EBMTest.c	Demo program in C on how to open and access the EBM file.

Table 3 Source code for Matlab™

File Name	Description
EBMRead.m	Matlab function for reading data from EBM file to Matlab.
EBMWrite.m	Matlab function to write data from generated by Matlab to the EBM file format.
CreatePhaseShiftedData.m	*Matlab function to demonstrate EBMWrite.m*
EBMInfo.m	Matlab function to retreive the properties of an EBM file. This function is similar in function to EBMInfo.cpp
EBMINFO, EBM2EDF, EBMTEST	*Utilities*

Table 4 Utilities

File Name	Description
ebminfo.exe	Opens an EBM file and displays its attributes like sampling rate, record time etc. Compiled 16 bit version of EBMInfo.cpp. MS-DOS
ebmtest.exe	Opens the EBM file and displays all records in the file in a listed format. Compiled 16 bit version of EBMText.c MS-DOS
ebm2edf.exe	Converter from the EBM file format over to the European data format EDF.. MS-DOS
ebmsetug.exe	Utility to adjust the unit gain in the file. MS-DOS
EBMSetUnitGain.exe	Utility to adjust the unit gain (nV/bit) in the file trace. Win32
EBMSetLabelAndRef.exe	Utility to adjust the label and the reference of trace. Win32

Appendix C Accelerometer Specifications and Calculations

CrossBow® Triaxial Accelerometers LP series

Accelerometer #1

Part Number: CXL10LP3

Serial Number: 0110573

Calibration Information: Room Temperature

Date of Calibration: 19/09/2001

Serial Number: 0110573	X Axis	Y Axis	Z Axis
Zero Gravity Voltage (V)	2.475	2.466	2.463
Sensitivity (V/g)	0.203	0.202	0.204

Date of Calibration: 1/09/2002

Serial Number: 0110573	X Axis	Y Axis	Z Axis
Zero Gravity Voltage (V)	2.468	2.494	2.511
Sensitivity (V/g)	0.204	0.204	0.202

Accelerometer #2

Part Number: CXL10LP3

Serial Number: 0110572

Calibration Information: Room Temperature

Date of Calibration: 19/09/2001

Serial Number: 0110573	X Axis	Y Axis	Z Axis
Zero Gravity Voltage (V)	2.490	2.486	2.484
Sensitivity (V/g)	0.197	0.202	0.202

Date of Calibration: 1/09/2002

Serial Number: 0110573	X Axis	Y Axis	Z Axis
Zero Gravity Voltage (V)	2.518	2.548	2.520
Sensitivity (V/g)	0.200	0.204	0.202

"The LP Series is a family of single and tri-axial low-power, DC response, general purpose accelerometers available in measurement ranges of +/- 4, 10, 25, 50, and 100 g. Common applications include vibration analysis, automotive testing, instrumentation, and equipment monitoring. The LP series replaces the "M" Series. Plastic (nylon) and metal housings are available."[12]

For the complete LP general purpose accelerometer product data sheet, please refer to:

http://www.xbow.com/Products/Accelerometers.htm LP Series

[12] http://www.xbow.com/Products/Accelerometers.htm

Appendix D Specifications for Commercial Accelerometers

Complete data sheets for the following parts are included in the electronic version of this report as PDF files. The Internet website URL's for these devices are included here for reference.

1. Sensotec Inc. Model SM-5, general or rugged applications, 600Hz. Available in ± 5 - 500 g
   http://www.sensotec.com/pdf/sm5.pdf

2. PCB Piezotronics Inc., Miniature Triaxial Accelerometer, 700Hz,
   http://www.pcb.com/spec_sheet.asp?model=356B11
   http://www.pcb.com/products/svs/svs356b11.html

3. Silicon Designs, Inc. Triaxial Accelerometer, Model 2420 range ± 5 - 200 g.
   http://www.silicondesigns.com/Prod.html
   http://www.silicondesigns.com/Pdf/2420.pdf

4. Silicon Designs, Inc. Triaxial Accelerometer, Model 2422 range ± 5 - 200 g. Moderately temperature stable.
   http://www.silicondesigns.com/Prod.html
   http://www.silicondesigns.com/Pdf/2422.pdf

5. Vernier Software and Technology Ltd. Triaxial Accelerometer ±5g
   http://www.vernier.com/probes/acc-din.html
   http://www2.vernier.com/booklets/3d.pdf

6. Entran Sensors and Electronics, EGCS3 Series accelerometers, range ±2 – 5000g
   EGA3 series accelerometer.
   http://www.entran.com/egcs3.htm
   http://www.entran.com/ega3.htm

Appendix E Thermistor – Linear Range Calculations

For the nominal values of R_3 = 330Ω and R_4 = 660Ω, the ratio $\frac{R_3}{R_4} = 0.5$. The voltage across R_4 for an input voltage of 2.5 V is:

$$V_{R4} = \frac{V_{in} \cdot R_4}{R_3 + R_4} = \frac{V_{in}}{\frac{R_3}{R_4} + 1} = \frac{2.5}{1.5} = 1.66667\ V$$

The measured voltage: $V_{out2} = V_{out1} - V_{R4}$, where $V_{out1} = V_{in}(-.0056846T + .805858)$ and T is temperature in °C. The output voltage range is set to ±200mV to be within the input range of the Embla recorder. The output voltage decreases with increasing temperature. The minimum and maximum temperature in the linear range is calculated by determining the temperature for V_{out2} = +200mV and V_{out2} = –200mV, respectively.

At T_{min}, V_{out2} = 0.2V; therefore $V_{out1} = 0.2 + V_{R4} = 1.86667\ V$

$$V_{out1} = 2.5(-.0056846T + .805858) = 1.86667\ Volts$$

$$T_{min} = \left(\frac{1.86667}{2.5} - 0.805858\right) \cdot \frac{1}{(-.0056846)} = 10.4°C$$

At T_{max}, V_{out2} = –0.2V; therefore $V_{out1} = -0.2 + V_{R4} = 1.46667\ V$

$$V_{out1} = 2.5(-.0056846T + .805858) = 1.46667\ V$$

$$T_{max} = \left(\frac{1.46667}{2.5} - 0.805858\right) \cdot \frac{1}{(-.0056846)} = 38.6°C$$

This gives a temperature range of 28.2° over which the output is linear. The equation of the straight line relationship is:

$$\begin{aligned} V_{out2} &= 2.5(-.0056846T + .805858) - V_{R4} \\ &= -0.01421T + 2.01464 - 1.66667 \\ &= -0.01421T + 0.34798\ \text{V} \end{aligned}$$

Or for V_{out2} in mV: $V_{out2} = -14.2T + 348\ \text{mV}$

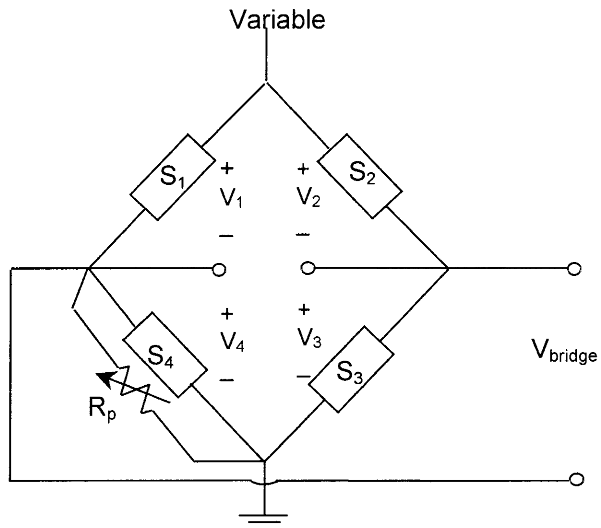
T_{min} and T_{max} can be altered by changing the ratio of R_3:R_4 but the range over which the relationship is linear will still be 28.4°C. T_{min} and T_{max} for various values of $\frac{R_3}{R_4}$ are given in Table E.1. Note, the temperature probe purchased for this project has a measurement range of –5°C to 45°C; only values within the measurement range are included in the Table below.

Table E.1: Linear temperature ranges for varying values of R_3:R_4

R_3:R_4 ratio	T_{min} (°C)	T_{max} (°C)
0.4	2.0	30.2
0.42	3.8	32.0
0.44	5.5	33.7
0.46	7.2	35.3
0.48	8.8	37.0
0.5	10.4	38.6
0.52	12.0	40.1
0.54	13.5	41.6
0.56	14.9	43.1
0.58	16.4	44.5

T_{min} and T_{max} are very sensitive to V_{in}. For example, for $\frac{R_3}{R_4} = 0.5$ and V_{in} = 2.4V, T_{min} = 15.1°C and T_{max} = 43.2°C. This underlines the importance of using a regulated voltage source for V_{in}.

Appendix F Strain Gauge Resistance Values



Measured strain gauge resistance values and calculated values for parallel resistance, R_p, to balance the bridge:

Load cell #	S_1 (Ω)	S_2 (Ω)	S_3 (Ω)	S_4 (Ω)	R_p (kΩ)
M4	263.4	263.3	263.2	263.4	693.3
M7	253.4	262.3	262.2	263.5	6.54
M8	263.7	263.7	263.6	264.4	8.7
M99	261.5	263.0	262.9	261.6	342.9

The no-load voltage with no correction for the load cells was calculated to be: 0.24 mV (M4); 24.7 mV (M7); 1.9 mV (M8) and 0.48 mV (M99). A 0 – 2MΩ single turn potentiometer was placed in parallel with S4 on each potentiometer channel. The potentiometer is adjusted to remove the no-load voltage.

Appendix G   Load Cell Specifications

Reference: PHASE I PART A PSWG -W7711-00-7632 report.

Figure F-1 shows the calibration results for the axial load cell sensors used with the Portable Data Acquisition System for human performance assessment, December 2001. The regression R^2 values ranged from 0.9934 to 0.9999 and a summary of the calibration information appears in Table F-1.

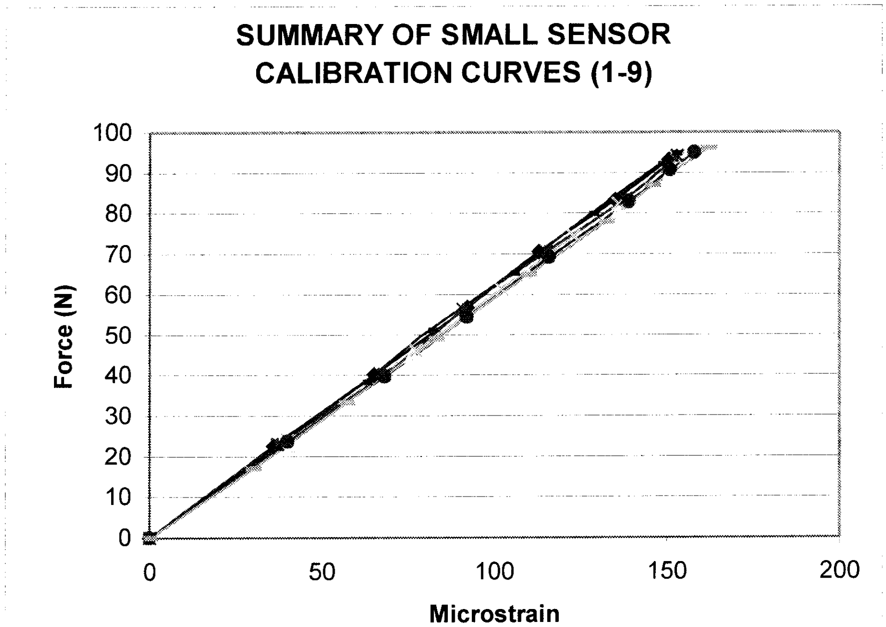


Figure F-1 Linear response of the axial load cells used for monitoring the strap tensions during human performance assessment.

Table F-1 Summary of load cell sensitivities and R^2 values. Note the variation in 0 load offset values.

Gage	Regression Equation: N vs µstrain	R^2
#1	y= 6.1355x +16.761	0.9990
#2	y= 6.1895x + 1.1204	0.9999
#3	y= 5.9705x – 6.2452	0.9997
#4	y= 6.0831x + 3.1883	0.9999
#5	y= 6.1236x – 0.8172	0.9995
#6	y= 6.015 x – 4.8406	0.9998
#7	y= 6.7419x + 37.918	0.9934
#8	y= 6.2446x – 1.0136	0.9999
#9	y= 5.9544x – 4.3228	0.9999

The load cells are constructed with four Measurements Group Inc. M-M: EA-13-062TT-350 strain gauges in a full bridge configuration. These gauges have a nominal gauge length of 1.57 mm with a nominal resistance of 350 Ohms.

Appendix H Interface Hardware Circuit Layouts and Parts List

Bill of Materials:

Date: Aug 14/02

Client Project Name: **Signal Conditioner Board**

PCB Name:

Schematic Number:

Project/Assembly Name: S.T.E.A.M.

Parts List:

Assembly Document:

Client Name: Queens University

Billing Code: 73

ITEM#	QTY	VALUE/ MFR PN	DESCRIPTION	PACKAGE	LOCATION(S)	SUPPLIER	
1	6	0.068uF	Cer. Capacitor 25V X7R	0805	C1 C2 C3 C4 C5 C6	Digikey	PCC1826CT-ND
2	4	0.022uf	Cer. Capacitor 50V Z5U	Axial leaded	C7 C8 C9 C10	Digikey	1207PHCT-ND
3	4	1uF	Cer. Capacitor 25V X7R	0805	C11 C12 C13 C14	Digikey	PCC1807CT-ND
4	1	10uF	Cer. Capacitor 25V X7R	0805	C15	Digikey	PCC1894CT-ND
5	2	.1uF	Cer. Capacitor 25V X7R	0805	C16 C17	Digikey	PCC1828CT-ND
6	1	22K ohm	RES NETW 22K OHM 16 DIP ISOLATED	Tube - DIL14	IC1	Digikey	4116R-001-223
7	1	470K ohm	RES NETW 470K OHM 16 DIP ISOLATE	Tube - DIL14	IC2	Digikey	4116R-1-474
8	1	330 ohm	RES NET 7RES 330 OHM 14PIN	DIL14	IC3	Digikey	760-3-R330
9	1	5K6 ohm	RES NET 7RES 5.6K OHM 14PIN	DIL14	IC4	Digikey	760-3-R5.6K
10	1	100K ohm	RES NET 7RES 100K OHM 14PIN	DIL14	IC5	Digikey	760-3-R100K
11	1	2K2 ohm SIP	RES NETW 2.2K OHM 16 DIP ISOLATE	SIP6	RN1	Digikey	4116R-001-222
12	1	560 ohm	RES NETW 6 SIP ISOLATED 560 OHM	SIP6	RN2	Digikey	4306R-102-561
13	2		Socket SIP 6pin	SIL 6	RN1 RN2		
14	1	1K8 ohm	RES NET 7RES 1.8K OHM 14PIN	DIL14	IC16	1.8K	4116R-001-182
15	4	10M ohm	Resistor 5%	0805	R7 R8 R15 R16	Digikey	311-10MACT-ND
16	1	100K ohm	Resistor	Axial leaded	R9 R11	Digikey	OY104K
17	2	1M ohm	Resistor 5%	0805	R10 R13	Digikey	311-1.0MACT-ND

ITEM#	QTY	VALUE/ MFR PN	DESCRIPTION	PACKAGE	LOCATION(S)	SUPPLIER	
18	2	3M3 ohm	Resistor 1%	0805	R14 R17	Digikey	311-3.30MCCT-ND

19	12	AD620	Instrumentation Amplifier	DIL08	IC6 IC7 IC8 IC9 IC10 IC11 IC12 IC13 IC14 IC15 IC17 IC18		
20	1	LM2937IMP-2.5	IC LDO REGULATOR 2.5v	SOT-223-4	IC19	Digikey	LM2937IMP-2.5-ND
21	1	REG103UA-5	Voltage Regulator 5v	SO8	IC22	Digikey	REG103UA-5-ND
22	6		Socket; DIP 14pin	DIL 14	IC1 IC2 IC3 IC4 IC5 IC16	E-SONIC	39-014-0
23	12		Socket; DIP 8pin	DIL 8	IC6 IC7 IC8 IC9 IC10 IC11 IC12 IC13 IC14 IC15 IC17 IC18		
24	1	PINHD- 2x17	Input Connector	2x17	JP1		
25	1	7V battery connector	Power Connector	1X02	JP2		
26	1	Switch	Switch Connector	1X02	JP3		
27	1		Output Connector	2x10	JP4		
28	6	2K	Trim Pot Single Turn	CA6V	R1 R2 R3 R4 R5 R6		
29	1	TPS60400DBVT	IC CHARGE PUMP INVERTER	SOT 23-5	ICU$1	Digikey	296-12013-1-ND

Bill of Materials: **Date:** Aug 14/02

Client Project Name: **Output Connector Board**

PCB Name: **Schematic Number:**

Project/Assembly Name: S.T.E.A.M. **Parts List:**

Client Name: Queens University **Assembly Document:**

Billing Code: 73

ITEM#	QTY	VALUE/ MFR PN	DESCRIPTION	PACKAGE	LOCATION(S)	SUPPLIER
1	4	EGG.1B.308.CLL	Circ. Connector 8pin LEMO			Birde Marketing Inc.
2	1		20 Pin DIL Connector	2x10		
3	1		PCB			

Bill of Materials: **Date:** Aug 14/02

Client Project Name: **Input Connector Board**

PCB Name:

Project/Assembly Name: S.T.E.A.M.

Client Name: Queens University

Billing Code: 73

Schematic Number:

Parts List:

Assembly Document:

ITEM#	QTY	VALUE/ MFR PN	DESCRIPTION	PACKAGE	LOCATION	SUPPLIER	
1	8	EGG.00.304.CLL	Circ. Connector 4pin LEMO			BIRDE MARKETING INC.	
2	1		34 Pin DIL Connector	2x17			
3	2	22-23-2051	5 CIR HEADER.100 STR FRICT LOCK	2x5		Digikey	WM4203-ND
4	4	37913	ECG Connector PIN			Plastic ONE Inc.	37913

Bill of Materials: **Date:** Aug 14/02

Client Project Name: **Battery Contact Board**

PCB Name:

Project/Assembly Name: S.T.E.A.M.

Client Name: Queens University

Billing Code: 73

Schematic Number:

Parts List:

Assembly Document:

ITEM#	QTY	VALUE/ MFR PN	DESCRIPTION	PACKAGE	LOCATION(S)	SUPPLIER
1	2		Mini Banana Plug			Electrosonic

Figure H-1
Battery board – battery2.brd

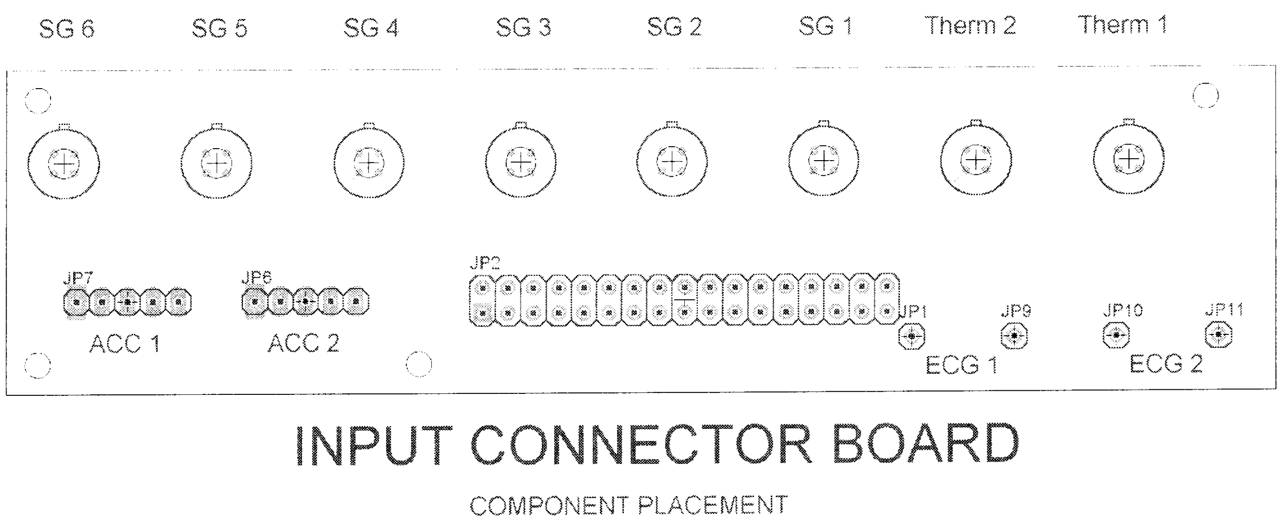
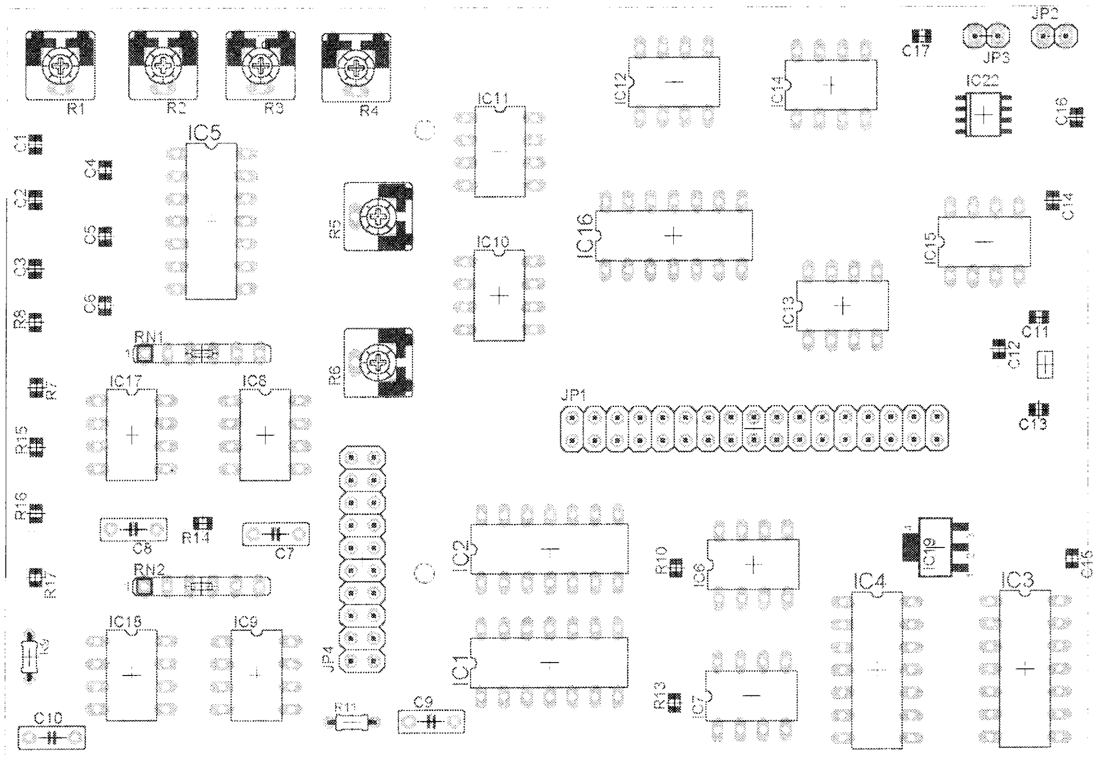


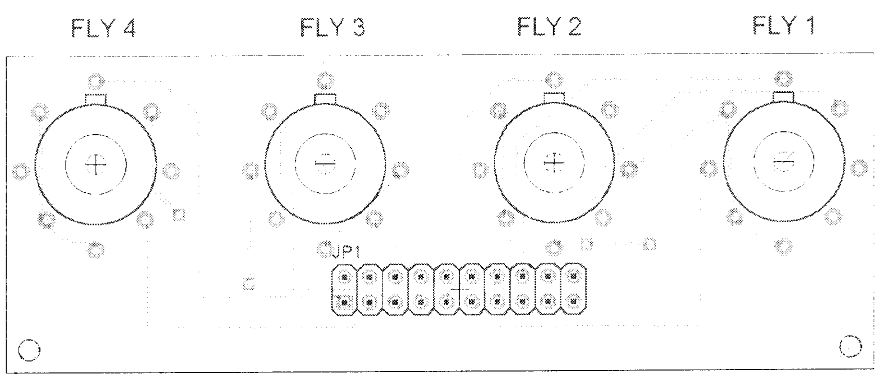
Figure H-2
Input Connector Board – Input Connector Component Placement.brd



MAIN BOARD

COMPONENT PLACEMENT

Figure H-3 Main Board
Components placed on this side



OUTPUT BOARD

JP1 SOLDERED ON THIS SIDE

Figure H – Output Connecter Board,
JP1 connectors soldered to this side

Appendix I Component Data Sheets

Complete data sheets for the following parts are included in the electronic version of this report as PDF files. The Internet website URL's for these devices are included here for reference.

1. Analogue Devices, Instrumentation Amplifier, AD620
http://products.analog.com/products/info.asp?product=AD620

2. Texas Instruments, Unregulated 60 mA Charge Pump Voltage Inverter, TPS60400
http://focus.ti.com/docs/prod/productfolder.jhtml?genericPartNumber=TPS60400
http://www-s.ti.com/sc/ds/tps60400.pdf

3. National Semiconductor, 400 mA & 500 mA Voltage Regulator, LM2937-2.5
http://www.national.com/pf/LM/LM2937-2.5.html
http://www.national.com/ds/LM/LM2937-2.5.pdf

4. Burr-Brown, DMOS 500 mA Low Dropout Regulator, REG103
http://focus.ti.com/docs/prod/productfolder.jhtml?genericPartNumber=REG103-A
http://www-s.ti.com/sc/ds/reg103-a.pdf

5. Hammond, Plastic Enclosure, 1599 series, 1599HGYBAT
http://www.hammondmfg.com/dwg6.htm
http://www.hammondmfg.com/pdf/1599HBAT.pdf

6. Lemo EEG308 & EEG304
http://www.lemo.com/lemoworld/product/lemo/ow/pdf_prod/Bmulti.pdf
pages 12 and 16

7. ECG Connector, Plastics One Inc., Part# 37913, 1.5mm TouchProof™ jack
http://www.plastics1.com/connect.htm
http://206.135.76.49/shop/default.asp

8. Panasonic SMT Capacitor 0805
http://www.maco.panasonic.co.jp/www-cgi/jvcr13pz.cgi?E+PZ+3+ABJ0004+0
http://www.maco.panasonic.co.jp/www-cgi/jvcr50pz.cgi?E+PZ+3+/www-data/pdf/ABJ0000/ABJ0000CE4.pdf

9. BC Components Axial Leaded Capacitor
http://www.bccomponents.com/
http://www.bccomponents.com/Uploads/Datasheets/monoax.pdf

10. AMP Socket Assembly
http://catalog.tycoelectronics.com/TE/bin/TE.Connect?C=105&F=0&M=CINF&GIID=28&LG=1&I=13
http://catalog.tycoelectronics.com/TE/docs/pdf/1/65/211561.pdf

11. Molex Inc. 2.54mm (.100") Pitch KK® Solid Header - Vertical, Friction Lock 6373
http://www.molex.com/cgi-bin/bv/molex/index_login.jsp
Molex part number: 6373

Appendix J Using Somnologica® V.3

Setting up an Embla Recording Session

Before beginning an Embla recording session, the recorder must be set up using the Somnological software. General instructions on recording are included in the Somnologica v.3 User Manual.

On start-up, Somnologica provides four options:

- Patient Information
- Device Control
- Analysis
- Reporting

Patient Information must be entered before the Embla recorder can be prepared for recording. It is only necessary to fill in the name field of the Patient Information screen; all other fields are optional. Whatever is entered in the name field will be used as the file name for subsequent data files. Information other than the subject's name can be used, e.g. subject ID number and date.

After the Patient Information has been entered, Device Control is selected to set up the recorder. The Embla can record in an on-line mode or an ambulatory mode. In the on-line mode, the recorder is connected to the PC via a serial connection and the data is read directly by Somnologica. This mode is useful for checking for correct operation of the recorder and any attached sensors before starting an ambulatory recording. In ambulatory recording, the Embla is disconnected from the PC and data is recorded onto the Flashcard. If battery power is used, the recorder is fully portable.

For on-line recording, select Start Online and follow the recording wizard to select a recording template. Once the proper recording template has been selected, click on Finish to begin the on-line recording. An on-line recording can be stopped by clicking the Stop icon, (■) on the playback toolbar. Recording can be started again, by pressing the play icon, (▶).

For an ambulatory recording, select Prepare Ambulatory from the Device Control screen and follow the recording wizard to select a recording template. Once the proper recording template has been selected, click on OK. Set the desired start and stop times for the recording. Click on Finish to initialize the recorder. Somnologica will check the Embla recorder and indicate when it is safe to disconnect the recorder from the PC. If the recording is successfully initialized, both the yellow and green lights on the recorder will flash.

The Recording Template

A specific template has been set up for Portable System Module 2: "Module 2 standard". Sixteen channels have been defined as follows:

Channel	Label	Sensor	Signal
1	A1X	ACC1X	Voltage-1X
2	A1Y	ACC1Y	Voltage-1Y
3	A1Z	ACC1Z	Voltage-1Z
4	A2X	ACC2X	Voltage-2X
5	A2Y	ACC2Y	Voltage-2Y
6	A2Z	ACC2Z	Voltage-2Z
7	Th1	Therm1	Temp1
8	Th2	Therm2	Temp2
9	E1	ECG1	EKG1
10	E2	ECG2	EKG2
11	LC1	Load Cell 1	Voltage1
12	LC2	Load Cell 2	Voltage2
13	LC3	Load Cell 3	Voltage3
14	LC4	Load Cell 4	Voltage4
15	LC5	Load Cell 5	Voltage5
16	LC6	Load Cell 6	Voltage6

Note, for each channel a specific label, sensor type and signal type must be defined.

Sensor definitions can be added or changed and new recording templates can be defined if needed. To add a sensor definition, select Devices on the left hand side of the Somnologica screen. Then select Settings – Embla. On the Embla Device Type Settings screen, select Sensors. From the sensor list, select Generic on AUX, then select New. Enter a new sensor name and change the settings as desired. Select OK to save the new sensor definition. To create a new recording template, select an initial template and click on New.

This will bring up the Embla Recording Template Properties screen. Enter a new template name and add or remove sensors as appropriate. To remove a sensor, simply click on the check mark on the right hand side of the screen. To add a sensor, select the desired channel. Enter the sensor and signal type. In order to enter a label, press F2 to access the label field. Note, the channel must be turned on (there must be a check mark in the box on the left hand side) in order to add a sensor. It is preferable to define a new sensor or recording template, rather than editing an existing definition, since then it is always possible to return to the original definition.

Displaying Recorded Data

To display data while recording on-line, select the Traces tab at the bottom of the screen. All channels defined in the recording template will be displayed. Previously recorded data files can be opened by selecting File – Open. Once the data file is located, a file icon will be displayed for each channel of data recorded. Select one and click on Open. All recorded channels will be displayed in Somnologica. Information on adjusting the display can be found in the Workpad Area chapter of the Somnologica User Manual.

DOCUMENT CONTROL DATA SHEET

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1b. PUBLISHING AGENCY DRDC Toronto	

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4. AUTHORS

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14. ABSTRACT

(U) The second stage of the development of a portable human performance assessment system, based on the Embla data acquisition unit, is described in this report. The objective of the portable system development is to produce a modular system, which will allow the user to select a combination of variables to be measured from freely moving human subjects, e.g. soldiers carrying out field exercises. The specific objectives of this work were to solve problems previously identified with the Embla data acquisition system and identify, design and produce a second portable system module.

Two problems were noted with the Embla data acquisition unit – the data storage medium supplied with the unit was inadequate and the file format, in which the sampled data are stored, is not compatible with other software applications. The original storage device was replaced with a compact flash card, which was found to be robust and provided good storage capacity. Software to convert Embla data files to Matlab format was obtained from the manufacturer of the Embla (Flagahf, Reykavik, Iceland). Once the data are converted to Matlab format, they can be processed in the Matlab environment or exported for use in other applications, e.g. Excel.

A second data collection module (module 2) was designed to measure whole body acceleration in six degrees of freedom, heart rate, skin surface temperature and backpack strap tensions. Module 2 includes two triaxial accelerometers, two ECG channels, two temperature probes and six load cell channels, which are interfaced to the Embla recorder. Appropriate sensors were selected, the interface hardware was designed and an interface unit was constructed. Operation of the sensors and the interface unit has been tested. All channels are operating as expected, except the ECG channels which are excessively noisy. Module 2 has been designed as a dedicated stand-alone unit. A design concept to provide more flexibility in selecting physiological and biomechanical variables to be measured is presented at the end of this report.

(U) Le présent rapport décrit la deuxième étape du développement d'un système portatif d'évaluation de la performance humaine, fondé sur le dispositif de saisie de données Embla. Le développement de ce système portatif a pour objectif de produire un système modulaire qui permettra à son utilisateur de sélectionner une combinaison de variables à mesurer sur les humains se déplaçant librement, p. ex. des soldats effectuant des exercices en campagne. Les objectifs spécifiques des travaux sont de régler les problèmes relevés dans le système de saisie de données Embla et d'identifier, de concevoir et de produire le deuxième module du système portatif.

Les deux problèmes suivants ont été identifiés en ce qui a trait au dispositif de saisie de données Embla : le support de stockage des données fourni avec le dispositif était inadéquat, et le format de fichiers utilisé pour le stockage des données d'échantillonnage n'était pas compatible celui des autres applications. Le dispositif de stockage original a été remplacé par une carte flash compacte qui est robuste et dotée d'une capacité de stockage suffisante. Le fabricant du système Embla (Flagahf, Reykjavik, Islande) a fourni un logiciel de conversion des fichiers de données Embla au format Matlab. Une fois que les données ont été converties dans le format Matlab, celles-ci peuvent être traitées dans l'environnement Matlab ou exportées pour utilisation dans d'autres applications comme Excel.

Un deuxième module de collecte des données (module 2) a été conçu afin de mesurer l'accélération du corps entier dans six degrés de liberté, la fréquence cardiaque, la température de la surface de la peau et les tensions des bretelles du sac à dos. Le module 2 comprend deux accéléromètres triaxiaux, deux canaux ECG, deux capteurs de température et six canaux de cellules de pesage, qui sont reliés à l'enregistreur Embla. Des capteurs appropriés ont été sélectionnés, le matériel d'interface a été conçu, et l'interface a été construite. Les essais de fonctionnement des capteurs et de l'interface ont été effectués. Tous les canaux fonctionnent comme prévu, sauf les canaux ECG qui produisent un bruit excessif. Le module 2 est un dispositif autonome. La fin du rapport présente un concept visant à fournir plus de souplesse dans la sélection des variables physiologiques et biomécaniques à mesurer.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Data acquisition system; portable; field hardened; data storage; electronics; interface; development.