Design and Implementation of a Black Box for Vehicles G-Force Measurement and Analysis

H. TARIQ[1], Y. A. MALKANI[2], J. A. MAHAR[3], AND A. KEERIO[1]

[1]School of Engineering and Design, University of Sussex, Brighton, United Kingdom
[2]School of Informatics, University of Sussex, Brighton, United Kingdom.
[1]Faculty of Engineering, Science and Technology, Hamdard University, Karachi.

*Corresponding author: H. Tariq, E-mail: ayazkeerio@hotmail.com Cell. No. 03322617305

Abstract: Gravitational force (g-force) is a ratio of acceleration and gravity, which affects the high speed moving objects such as bullet train and high speed cars etc. Its analysis plays a vital role in a variety of engineering and scientific fields, such as astrophysics, planetary science, rocket science, and also in the engineering of several machines (e.g. race cars, fighter jets, and large engines, etc). This paper presents our experience of the design and implementation of a black box that facilitates the logging of a vehicle's g-force in a memory-chip, and later on these logged results can be retrieved from it for subsequent analysis process. To achieve these goals, 3D accelerometers along with an EEPROM memory are used. This paper also presents various important technical as well as software implementation aspects related to the g-force applications.

Keywords: G-force, embedded systems, black box, acceleration.

INTRODUCTION

G-force plays an important role in the fields of aerospace, automotive, military and in the industry such as theme parks. It is the ratio of the acceleration with the gravitational force acting at Earth's inertial frame of reference. It is important to know that how much g-force an object is experiencing when it is moving at a very high speed. The effects of such g-force can be very lethal for human body and the design of the high speed vehicles. The most common application of g-force is in the design process of objects that move at a very high speed, such as jet fighters, missiles, roller coasters and formula-one cars etc. In automotive industry g-force measurements are usually taking into account during the design phase of high-speed cars, such as Jaguar, because g-force is considered to be an important factor in the production of cornering force experienced by these vehicles. (**Fig. 1**) shows a car breaking at g-force of 1g.
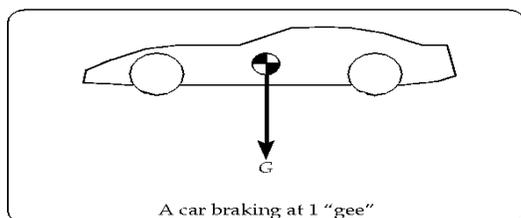

Fig. 1. A car breaking at 1 "gee"

In this paper, we have presented the design and implementation of a black box, which can log g-force experienced by a vehicle in all three dimensions (i.e. x, y and z). This is achieved by utilizing the 3D medium-range accelerometer, which provides the acceleration measurements at any given moment through its x, y and z interface pins. These measurements are in the form of analogue voltage. The phyCORE-167 microcontroller kit is then used to convert the measured analogue voltages into digital form, and store them in an EEPROM. The proposed system (black box) starts logging the results when it is switched on. Then, the user can retrieve the logged data through connecting it with a serial port of the computer, and the retrieved data can be viewed through hyper terminal.

The remaining part of this paper is organized as follows: section 2 is background that briefly describes the technical concepts relating to the designed system. Section 3 is about the design and implementation of the black box. It covers hardware as well as software design of the system. In section 4, we have discussed some results and observation along with brief analysis. Finally section 5 provides future directions and concludes the paper.

MATERIAL AND METHODS

1. Background

A. *G-Force*

G-force is referred as the measure of an entity's acceleration and is denoted by g, which is a non-SI unit. It is equal to the nominal acceleration of gravity on Earth at sea level, which is defined as 9.80665 m/s2. The reaction force, which an entity feels as a result of the acceleration, is proportional to the g-force. For instance, on a high speed car a lower g (i.e. less than normal g) is experienced when the vehicle moves from upward to downward on a huge inclination. In contrast, a high +ve g will be felt while the vehicle moves from downward to upward. In first case driver feels as if he/she weighs more than usual, which is opposite to the second case in which driver feels much lighter. Apart from the g-force impact on the design and the durability of a vehicle, it also acts explicitly on a human body. Human tolerances to g-force depend on the duration or time g-force applied, its magnitude, the location where it is being applied, human body's posture, and the direction in which it acts. In order to measure the g-force acting on an entity, which is at rest on Earth, it is essential to keep an account of Earth's inertial reference frame. For detailed survey, discussion and calculation process for g-force, refer (Wahlberg, *et al.,* 2000, Williams, *et al.,* 1983 Dicke, *et al.,* 1962).

Some of the well known areas, where analysis of g force plays a significant role while designing the system include: aerospace – a light aircraft can tolerate 4.4g, a transport aircraft can sustain 2.5g and military aircrafts can sustain up to 9g with the help of special g- force suits for pilots. Further, the military units, such as GPS (Global Positioning System) and IMU (Inertial Management Units), which are used in missiles for guidance, need to tolerate more than 15000g in order to carry on the firing operation smoothly. The other areas where g-force analysis plays an important role and has significant impact include automobile and roller coasters industry, theme parks and traffic monitoring and control systems (Wahlberg, *et al.,* 2000).

A. *Accelerometers*

As it is described in previous section, g-force is the ratio of the force an entity experiences while in a given acceleration to the force which it feels while at rest with the Earth's inertial frame of reference. So, if some one successfully measures the acceleration of an object, then he/she can find the g force experienced by that object. Thus, we need appropriate accelerometers to measure the acceleration. The device, which is used to measure the acceleration force, is known as accelerometer. The acceleration force could be static (e.g. the constant force of gravity pulling at your feet), or it could be dynamic (e.g. caused by vibrating or moving the accelerometer). Accelerometers can also be exploited to find out the angle of tilt and to measure the dynamic acceleration with respect to the Earth, which helps to know whether an entity is moving or not 2008.

Accelerometers Suitable for the Proposed System:

A variety of accelerometers are available. Each of which is suitable for certain design requirements, such as range, nature frequency, and damping. The basic difference is the method of mass displacement measurement 2008, Chang, *et al.,* (1995). Some of the most common types of accelerometers include Potentiometric, LVDT, Variable Reluctance, Piezoelectric, and iMEMS 2008. According to the descriptions of accelerometers as provided by the manufacturers, the iMEMS accelerometers are the most suitable one for the proposed system due to their efficiency and tiny structure. We also need to consider the fact that rather than using three different accelerometers to measure the acceleration on all three dimensions, it is better to use a single 3D accelerometer which should be capable of measuring acceleration on all three dimensions. As a result, we selected the DE-ACCM3D, which is a complete 3D±3g analog accelerometer-based kit that includes ADXL330 accelerometer from Analog Devices 2008. It has also integrated op-amp buffers for direct connection to a microcontroller's analog inputs, or for driving heavier loads 2008.

In this section, we discuss the hardware design of the implemented system. **(Fig. 2)** presents the high level design of the hardware modules; while the detailed low-level hardware design is shown in figure 3. It can be seen in the high-level design **(Fig. 3)** that 3D-accelerometer is interfaced with A/D converter of phyCORE-167 development kit, while the EEPROM which is used here as memory to store results, has been interfaced with I2C bus of phyCORE-167. Detail of each module is described below:

2. Design and Implementation

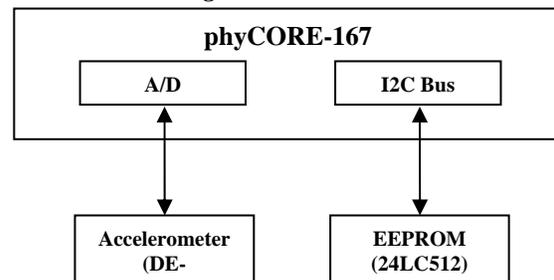#### A. *Hardware Design*

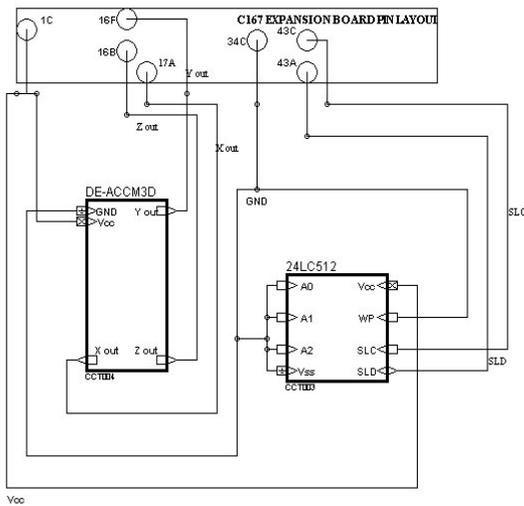**Fig. 2: High-level design abstraction**

Fig. 3: Main hardware schematic of the designed system

1) The phyCORE167, AD/Converter and I2C Bus: phyCORE167 is a rapid development kit which includes phyCORE167 Carrier Board and PCM-988 expansion board. The phyCORE167 Carrier Board is installed with Infineon C167CS-LM microcontroller which provides the built-in peripherals of A/D Converter and I2C bus to interface external devices with the microcontroller.

For analog signal measurement, a 10-bit A/D converter with 24 multiplexed input channels, a sample and hold circuit has been integrated on phyCORE167. The A/D converter is capable of 4 modes of conversion. First one is the standard Single-Channel conversion mode. In this mode, the analog level on a specified channel is sampled once and converted to a digital result. In the Single-Channel-Continuous mode, the analog level on a specified channel is repeatedly sampled and converted without software intervention. In the Auto Scan mode, the analog levels on a pre-specified number of channels are sequentially sampled and converted. In the Auto Scan Continuous mode, the number of pre-specified channels is repeatedly sampled and converted. In addition, the conversion of a specific channel can be inserted into a running sequence without disturbing the sequence, this is called Channel Injection Mode (C167CS Datasheet, 2009) A/D converter is attached with port 5 of microcontroller and microcontroller is configured to convert analogue inputs from external devices. In the implemented system, we have used channels 0, 1 and 2 of A/D converter, which are port numbers 5.0, 5.1, and 5.2 of microcontroller.

The I2C bus is provided with phyCORE-167, and SCL (Clock Line) for I2C is connected with port 3.4 of microcontroller while SDA (Data and Address Line) is connected with port 3.3 **(Fig. 4)**.
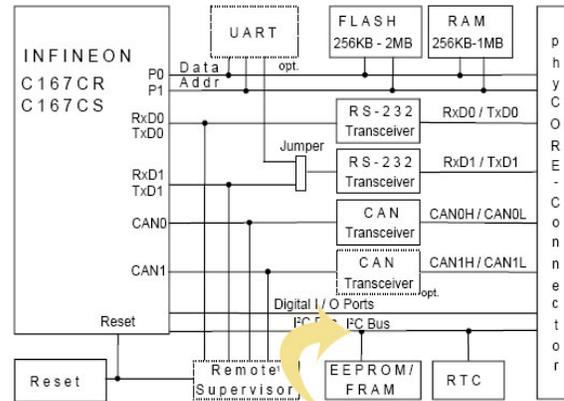

Fig. 4: I2C bus of phyCORE-167(phyCORE-167, 2009)

2) Accelerometer (DE-ACCM3D): The DE-ACCM3D is a device with onboard ADXL330 accelerometer and calibrating components already installed on it so that one can use DE-ACCM3D straight-away without worrying about voltage input requirements and noise effects. It has a 3.3V onboard regulator along with the capacitors required to calibrate the outputs from x, y and z-axis pins of ADXL330.

The layout of DE-ACCM3D accelerometer device is shown in **(Fig. 5)**. As discussed earlier, the g-force is a measure of ratio of acceleration and gravity in accordance to inertial frame of reference of Earth. If an object is changing angles, the g-force acting on it, is changing too.
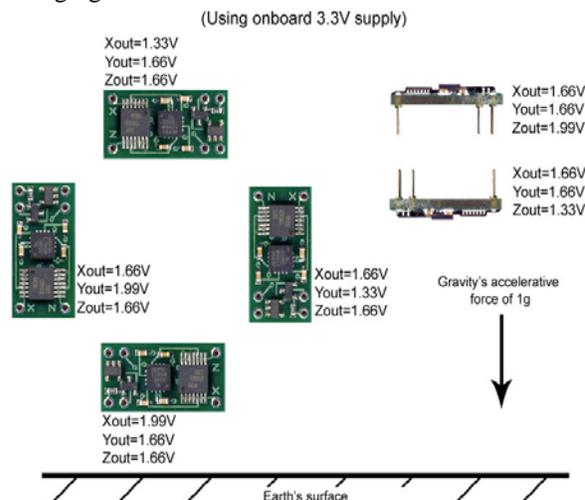

Fig. 5: DE-ACCM3D accelerometer layout

Fig. 6 shows illustrations when a DE-ACCM3D accelerometer device is changing its position with reference to Earth's inertial frame of reference. In the illustrations **(Fig. 6),** one can see the default g-force a device experiences while being placed on these typical angles, such as 90º and 180º. Note that these calculations are based on the fact that the device is in rest with respect to Earth. If device is in acceleration, these measurements could be different.
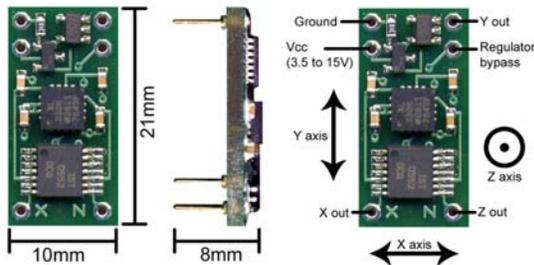

Fig. 6: Measurements according to tilt for DE-ACCM3D accelerometer.

3) Connection configuration of A/D converter and Accelerometer: The connection configuration of A/D converter and accelerometer (DE-ACCM3D) is illustrated in **(Fig. 7)**. The A/D converter repeatedly converts inputs coming from x, y and z-axis of accelerometer. We have used Single Fixed Conversion mode of A/D converter as it is in accordance with the written software code/module.
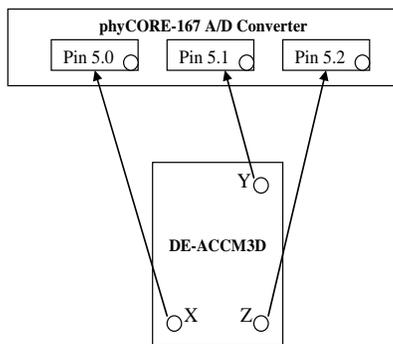

Fig. 7: Connection configuration of A/D converter with DE-ACCM3D

4) EEPROM (24LC512): For keeping the log of results 24LC512 EEPROM is used. It is capable of storing 512Kbit of data in 64Kx8bit organization.

The pin configuration of 24LC512 EEPROM is shown in **(Fig. 8)**. The 24LC512 use the pins from A0 to A2 for multi-device operations. The logic levels on these pins are compared with the corresponding bits in the slave address and the chip is selected only when the comparison result is true. It is capable of connecting maximum 8 devices to the same bus by utilizing several combinations of Chip-Select bits. The pins (A0–A2)must be connected to either VCC or VSS.
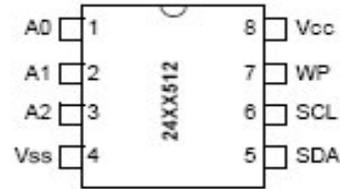

Fig. 8: Pin configuration of 24LC512

Usually, the address pins (i.e. A0-A2) are wired to logic '1' or logic '0'. In order to transfer the addresses and data, a bidirectional pin Serial Data (SDA) is used. Since it is an open-drain terminal, therefore SDA bus requires a pull-up resistor to VCC. For normal data transfer, SDA is allowed to change only during SCL low. Changes during SCL high are reserved for indicating the Start and Stop conditions. SCL is used to synchronize the data transfer from and to the device. WP pin must be connected to either VSS or VCC. If tied to VSS, write operations are enabled. If tied to VCC, write operations are inhibited but read operations are not affected 2008.

5) Connection configuration of I2C Bus with 24LC512: The connection configuration of I2C bus with 24LC512 is illustrated in **(Fig. 9)**. The SCL of I2C bus is connected with Pin 3.4 of microcontroller, so the SCL pin of our 24LC512 (EEPROM) is connected with Pin 3.4 and SDA pin is connected with Pin 3.3 which is connected with SDA line of I2C bus.
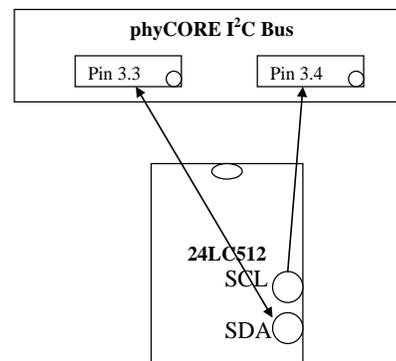

Fig. 9: Pin connections of phyCORE I2C bus with 24LC512

B.   *Software Design*

We have two software design requirements for this project: (a) convert and store results of ADC channels, (b) retrieving stored results efficiently from EEPROM for analysis purposes. The high level abstraction of software design is shown in **(Fig. 10)**.
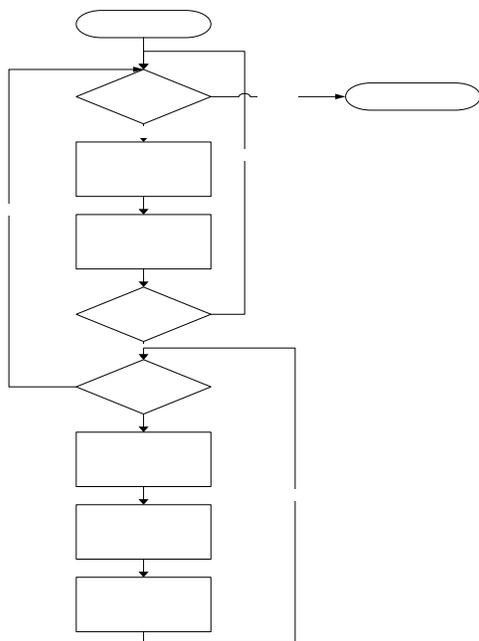
Fig. 10: Flow chart for design abstraction of software

We have used Keil μvision3 as compiler for the code written to drive the hardware circuit described earlier in previous section. DaVE is used to configure peripherals of phyCORE-167 along with FlashTools3 by Phytec to write (burn) the code on to the programmable memory of microcontroller.

1) Conversion of Accelerometer Results: When Keil μvision3 is used along with DaVE, it provides functions to read the output of A/D conversion provided that the channels are configured properly and an external device is attached with them to input the analogue signals with voltage levels. Three main functions that are used to read the output from A/D converter channels are:
ADC_vConfConv(ubMode,ubChannel),ADC_vStartConv(), and ADC_uwReadConv().

The first 2 levels of flowchart in **(Fig. 11, a)** are illustrated for ADC_vConfConv(ubMode, ubChannel). This is the default function to configure the ADC channels. In the software code, we repeatedly converted the output coming on 3 channels of A/D converter one-by-one by selecting the Single Fixed Conversion mode. At the 3rd level of flowchart **(Fig. 11, a),** system starts conversion, and on 4th level it reads successful conversion through the function ADC_uwReadConv(). This function returns the 10-bit result from ADDAT register. At this stage, we have results of the conversion (i.e. we know the results from each output pin of the accelerometer).

2) Writing results on EEPROM: Once we have results from accelerometer, we need to store them into the memory for retrieval later-on. To achieve this, system has to communicate with I2C bus according to the software protocol. At first the master device (microcontroller) sends out a start sequence. This alerts all of the slave devices (24LC512 EEPROM) on the bus that a transaction is starting, and they should hear it in case it is for them. Next the master sends out the device address. The slave that matches this address continues with the transaction, all of the others ignore the rest of this transaction and wait for the next. Having addressed the slave device, the master must now send out the internal location or register number inside the slave that it wishes to write or read from. Having sent the I2C address and the internal register address, the master can now send the data byte(s). The master continues to send data bytes to the slave. These bytes are being placed in its subsequent registers. When master finishes writing all of the data to the slave, it sends a stop sequence that indicates the completion of the transaction.

Ten functions are written to implement I2C protocol. Two main functions in use are EEPROM_set() and EEPROM_get(). Flowcharts describing these functions are given in **(Fig. 11 b and 11, c)** respectively.
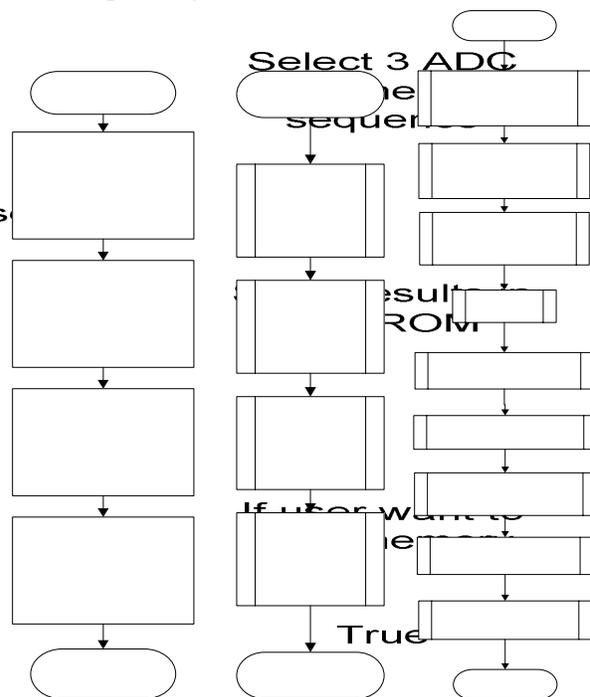

Fig. 11(a)   Fig. 11 (b)   Fig.11(c)

Flowcharts for ADC conversion 11 (a), EEPROM_set() function 11 (b), and EEPROM-get() function 11(c).

3) Memory Calculations: The memory in use is 512Kbit 24LC512 EEPROM with 64Kx8 arrangement 2008. Which means we can write 64K bytes into the memory. Results that the system is reading from ADDAT register of A/D converter are of 10-bits. It is required to store these results in their actual form, so that later-on one can easily perform any operation on this real data. Since the memory discards any bits on a single write cycle that are larger than 8-bits, so the system divides 10-bit result into two bytes through masking and stores that result in two consecutive memory locations. In fact ADDAT raw result is consist of 16-bits, from which 10-bits are actual result. The implemented system first masks ADC result with 0xFF. This way, the most significant 8-bits are ready to be written into the memory. Then, system masks the ADC result again with 0x0300 to select the remaining two bits, shifted them to 8-bits to the left so that these can get ready to be written on next consecutive memory location. For example, refer the calculations as shown in **(Fig. 12)**.

$$ADDAT = 0xFF90$$
$$1111 - 1111 - 1001 - 0000$$
$$ADC\ result = ADDAT\ \&\ 03ff$$
$$0000 - 0011 - 1001 - 0000$$
$$1^{st}\ byte = ADC\ result\ \&\ 00FF$$
$$1001 - 0000$$
$$2^{nd}\ byte = ADC\ result\ \&\ 03FF$$
$$0011$$
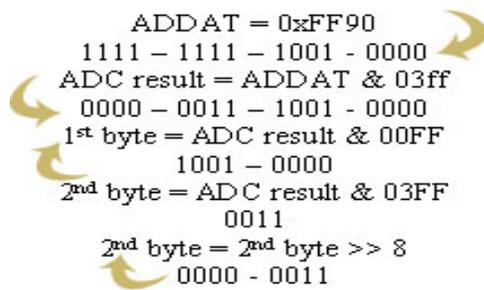$$2^{nd}\ byte = 2^{nd}\ byte >> 8$$
$$0000 - 0011$$

Fig. 12: Calculations for EEPROM

In the same way, when we need to extract the information from the memory, the above procedure is reversed to make original 10-bit ADC result.

4) Calculating the G Force: The system is storing 10-bit ADC result from ADDAT register straight to memory. When the user wants to retrieve the data and wants to know how much g-force the vehicle/object has experienced, the system has to calculate the g-force and to send it to the serial port for the user to view and/or analyze.

An input voltage to the accelerometer is 3.33V; the 0g point at 1.66V is approximately 1.66V; and sensitivity at 3.33V is 0.333V. Since the goal is to measure the actual g-force as experienced by the vehicle rather than the acceleration, we need to subtract the effect due to gravitational force of Earth when the object is at rest. At 3.33V supply, accelerometer gives 1.66V at 0g. But due to ADC conversion at accelerometer, there are some voltage drops, so we

found that actual 0g point with reference to interfacing (in our case) is approximately 1.6130V. So, we need to subtract the result and as sensitivity of accelerometer is also an issue, we need to divide the result with sensitivity. Below is given an example calculation when the accelerometer is in the position as shown in **(Fig. 13)**.

Fig. 13: Position of accelerometer with respect to the Earth.

Xout= 1.66V
Xout= 1.66 – 1.66 = 0.00/0.333 = 0g
Yout= 1.66V
Yout= 1.66 – 1.66 = 0.00/0.333 = 0g
Zout= 1.99V
Zout= 1.99 – 1.66 = 0.33/0.333 = 0.99g

The formula for 3D g-force as described in 2008 is sqrt ($x^2+y^2+z^2$). Therefore, sqrt ($0.015^2 + 0.015^2 + 0.8954^2$) = 0.98g, where the value of x and y is 0.015, and the value of z is 0.8954. In this case, accelerometer is experiencing g force of 0.98g.

RESULTS AND DISCUSSUON

When we interfaced accelerometer with A/D converter and checked the output on hyper terminal via serial port, in most cases results are as below in the case of single axis:

X-axis = 1.6106, y-axis =1.6015, and z-axis = 1.9384

Since the output of A/D converter is not giving exact 1.66V on x and y-axis, we calibrate the 0g point to 1.6100V. Based on these parameters, below is the calculation for g-force on each axis:

Xout= 1.6106V
Xout= 1.6106 – 1.6100 = 0.00065/0.333 = 0.0018g
Yout= 1.6015V
Yout= 1.6015 – 1.6100 = -0.0085/0.333 = -0.025g
Zout= 1.9384V
Zout= 1.9384 – 1.6100 = 0.3284/0.333 = 0.98g

When the accelerometer is in the position as shown in figure 13, the average g-force acting on it is 0.9872g. The ideal g-force experienced by the accelerometer was 0.99g when in up-straight position with x-axis and y-axis giving 1.66V each and z-axis

giving 1.99V. In our case, this is not happening. Instead x-axis and y-axis are giving approx. 1.61V, while z-axis has the average value of 1.93V. It is because of the A/D converter itself. The reason is that the A/D converters normally use capacitors to store the analogue results and then after reaching at a pre-defined level, they convert the analogue signal into digital signal. Since the difference in our case is of 0.05V, which is affecting the computation of g-force in turn. So, we calibrated the 0g point back from 1.66V to 1.61V. 0g point is in fact the value of Earth's inertial frame of reference. The accelerometer is giving us acceleration on each axis i.e. x, y and z axis, we need to subtract the force, which an object must experience due to the gravitational force in Earth's inertial frame of reference. This gravitational force may also act differently at different altitudes. However, the difference shouldn't be large when the object is at rest with the position of Earth's inertial frame of reference. The difference of 0.05V is very minimal and can be neglected in this case. The calculations - as shown above **-** show that the g-force acting on the accelerometer in upward direction should be 0.99g, which is a cumulative sum of g force acting on all 3 i.e. x, y and z axis. In our case the result is 0.9872g. When we round of 0.9872 up to the 2nd degree after decimal, the number we have is 0.99g. It demonstrates that our implemented system is working properly, and is logging correct g-force related information. Further, observations and results are obtained by changing the position of black box in different angles by taking Earth as a reference. It is observed that different g-forces act on the box when it is in different angles, and this is because of the inclusion of z-axis. Z-axis is widely used in the devices where some one wants to measure the tilt of the object/device as well as the acceleration. If we eliminate the z-axis measurements, then x and y axis g-force effect becomes negligible in the situation when the object/vehicle reaches at rest with reference to the Earth. In fact, x and y axis are the axis that play a vital role in a vehicular g force measurements. While, z-axis has great importance when we talk about roller coasters and fighter jets, because these objects change angle of motion while on move, and thus experience different g-force on each different angle regardless of the speed of their movement.

CONCLUSION

G-force measurement and analysis play a significant role for the reliable design of high speed moving objects such as vehicles and air crafts. It is important to keep log of g-force data, especially for the high speed vehicles that carry humans, because exposure to a continuous high g-force for longer duration could have serious safety consequences; that's why the design of such systems capable of logging and analysis of g-force measurements are highly desired. Towards this; in this paper the design and implementation of a black box is presented, which can log g-force acting on a vehicle that can be retrieved and analyzed easily and efficiently. The obtained results show that the memory space of the proposed black box is limited; that's why the designed software needs to be modified while working with complex scenarios that require logging information much faster than it is doing at present. Alternatively more space can be achieved by setting up a grid of eight 24LC512 EEPROMs. Further it is suggested that this work can be extended by logging time stamps along with g-force results and attaching an LCD to the accelerometer so that a user can easily analyze live results.

REFERENCES

Accelerometers, *Dimension Engineering*. (2009) Available at: http://www.dimensionengineering.com /accelerometers.htm.

Chang, F.I., (1995) *Gas-phase Silicon Micromachining with Xenon Difluoride*, Proc. SPIE Microelectronic Structures and Microelectro-mechanical Devices for Optical Processing and Multimedia Applications, 117-128.

Dicke, R. H. (1962) *Mach's Principle and Equivalence,* in Evidence for gravitational theories: proceedings of course 20 of the International School of Physics "Enrico Fermi", ed C. Møller (Academic Press, New York).

Dimension Engineering, (2009) *DE-ACCM3D Datasheet,* Available from: http://www.dimen sionengineering.com/datasheets/DE-ACCM3D.pdf.

iMEMS Accelerometers, (2009) *Analog Devices.* Available from: http://www.analog.com /en/mems-and-sensors/imems-accelerometers/products/index.html.

Infineon Technologies, (2009) *C167CS Datasheet.* Available from: http://www.phytec. com/products/sbc /C166-xc166-st10-xa/phyCORE-167.html.

Kahng, D. and S.M. Sze, (1967) *Floating-gate and itsAapplication to Memory Devices,* The Bell System Technical Journal, vol. 46, No. (**4**): 1288-1295.

Microships, *24LC512 Datasheet,* (2009) Available from: http://docs-europe. Electro components.com /webdocs/0b04/0900766b80b04a0c.pdf.

National Instruments, (2009) *Types of Accelerometers.* Available from: http://zone.ni.com/devzone/cda/ph/p/id/284.

phyCORE-167, (2009) *Phytec America LLC*. Available from: http://www.phytec.com /products/sbc/C166-xc166-st10-xa/phyCORE-167.html.

Society for robots, (2008) *Sensor Accelerometers*. Available: http://www.societyofrobots.com/sensors_accelerometer.shtml.

Wahlberg, A. E. (2000) *The relation of acceleration force to traffic accident frequency: a pilot study*, Transportation Research Part F: Traffic Psychology and Behaviour, Vol. 3, Issue (**1**): 29-38.

Williams, D. E., J. Richman, and B. Friedland, (1983) *Design of an integrated strapdown guidance and control system for a tactical missile.* Collection of Technical Papers (A83-41659 19-63), American Institute of Aeronautics and Astronautics, 57-66, New York.