EE 344: Electronic Design Lab

Report: Group DD17

Digital Oscilloscope

Anmol Kagrecha, 15D070024
Karan Taneja, 15D070022
Pranav Kulkarni, 15D070017

Prof. P. C. Pandey
T.A. Abhishek Modani
IIT Bombay

April 15, 2018

Abstract

The aim of the project was to build a Digital Oscilloscope module to convert a PC into a versatile Oscilloscope. We aimed to focus on facility for differential inputs, implementing consecutive sampling and building a wireless battery-operated module.
We provide support for frequencies up to 10 kHz. Wireless communication between the microcontroller and the PC is established using a Bluetooth module. Wireless communication isolates the PC from the hazards that may take place in the microcontroller and the analog signal acquisition system.
A GUI was made for viewing the acquired signals. All controls are being provided to the user in the GUI. The user can perform time scaling, voltage scaling, time shifting, voltage shifting as well as playing and pausing (RUN/STOP). We also provide automated measurement tools which give information like mean, max and min values of signal, peak to peak voltage as well as the frequency.
The overall goal was to build a cheap but useful DSO for low frequency applications that can measure differential inputs and isolate various subsystems using wireless communication.

Contents

1 Introduction

1.1 Background and Motivation

Oscilloscope is one of the most important tools in an electrical engineers' toolbox, helping them analyze, debug and understand complex circuits by viewing voltage waveforms against time axis in a calibrated scale.
DSOs available in the market are expensive and make it difficult for students and hobbyists to acquire them. Screens of the DSOs are the primary reason for their cost. This limitation can be tackled using screens of PCs for display.
Another major limitation with most current DSOs is that they lack functioning to handle differential inputs with high common mode. Lack of differential inputs leads to problems in many applications and handicaps the user. Our oscilloscope tackles this problem.
Circuits can sometimes produce high voltages and currents which might harm the entire DSO. More importantly, a wired connection will harm the PC as well. Bluetooth communication provides a good solution to this problem. Hence, we established communication between microcontroller and PC using Bluetooth.
The project serves as a proof of concept for DSO module. The signal bandwidth is limited to low frequency signals up to 10 kHz. This helped in completing the prototype by using a microcontroller with on-chip ADC and bread-boarding the circuit and later assembling it on a 2-layer PCB.
The design can be later extended to larger bandwidth by using 4-layer PCB, amplifiers with larger bandwidth and high speed ADC.

1.2 Project Goals

As described in the section above, our major goals were -

1. Providing differential voltage measurement in the DSO
2. Providing GUI to the user on PC to reduce the major cost component
3. Establishing wireless communication between the PC and the micro-controller

1.3 Specifications

1.3.1 Customer Specification

We believe our device will can be useful for students and hobbyists. The users will be able to easily work with the DSO for their hobby projects. Hobbyists can also not worry about their PCs getting harmed - thanks to the wireless communication between the PC and the micro-controller. DSO will work well for any periodic wave with less that 10 kHz frequency. Input voltage range has 3 common voltage modes 100 mV, 1 V and 10 V. User can also see output from basic measurement tools given in technical specifications. The probe of the DSO consists of 3 wires. Two wires should be put across the differential voltage to be measured and the third wire should be grounded (or conneced to the reference volage of the external circuit).
We couldn't provide the option of equivalent sampling in interface as proposed earlier.

1.3.2 Technical Specifications

- Common Voltage Modes: C0 : $\pm 10\,\text{V}$, C1 : $\pm 1\,\text{V}$, C2 : $\pm 100\,\text{mV}$ - can be controlled through GUI.
- Minimum differential mode peak to peak voltages at different common modes voltages[1] (assuming 20% tolerance to the noise getting assed to the square wave signal) -

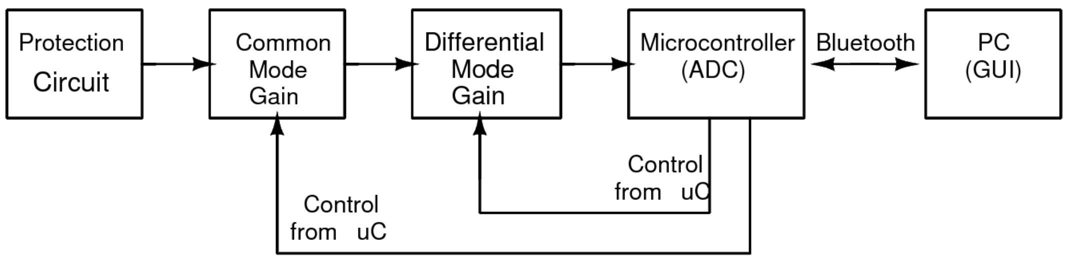
V_{cm}	$V_{pp}(min)$
0V	$20mV_{pp}$
0.1V	$20mV_{pp}$
1V	$250mV_{pp}$
5V	$2.5V_{pp}$

[1] $V_{cm} = 10V$ and $V_{pp}(min)$ lesser than $20mV_{pp}$ could not be tested because of inability of AFG in WEL to provide the necessary waveforms

- Single channel differential input
- Input impedance : 1 MΩ
- GUI Specifications:
  - Time Scaling ($200\mu s$ to $5s$)
  - Voltage Scaling ($1mV$ to $5V$)
  - Play and Pause
  - Trigger options
    * Auto Trigger
    * Normal Trigger (+ve and -ve slope)
  - Automated Measurement Tools
    * Max
    * Min
    * Average (1 to 64 samples in powers of 2)
    * Frequency
    * Peak to peak voltage

2 Project Design

2.1 System-level overview and Sub systems



2.2 Battery System

The DSO module works on a 5V supply. It can be provided using a power bank, a laptop or any other 5V source. Power banks are usually capable of providing currents up to 2 A.

2.3 Protection Circuit

To protect the module from high input voltages, a protection circuit has been designed using diodes.

2.4 Common Mode Gain Control

The common mode voltage of the inputs can vary between 0 to 10V. We provide different gains (or attenuation) for common mode voltages in range of 100mV, 1V and 10V. Having a single gain (or attenuation) for all voltages degrades the signal with smaller amplitudes.

2.5 Differential Mode Gain Control

The differential mode voltage of the inputs can also vary. We provide different gains for different differential mode voltages. Having higher gains for signals that have higher attenuations in common mode control stage, improves the differential signal output.

2.6 Microcontroller

For prototyping purposes, the on board ADC in the microcontroller is used. The ADC can sample at rates up to 1.1 MSPS. The samples are sent to the PC via bluetooth module. This isolates the analog front-end from the PC. Bluetooth communication happens at a rate of 115200 bits/s.

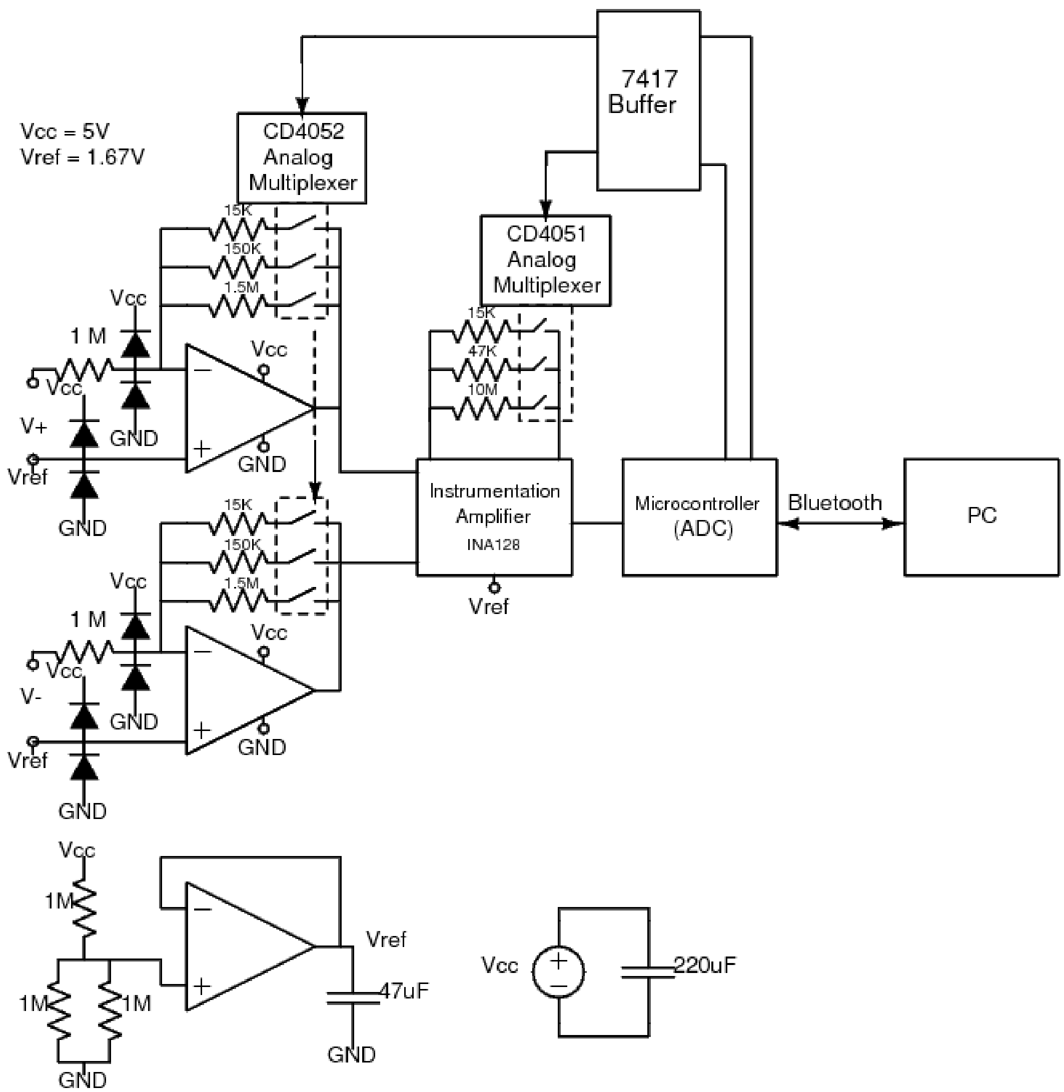
2.7 Graphical User Interface

The GUI displays the differential of the inputs. GUI provides information about the signal like max, min, average, frequency and peak to peak voltage. It also provides the user to control the common mode and differential mode gains to improve the waveform displayed. Following controls are provided in the GUI:

- Time per division control
- Voltage per division control
- Play and Pause control
- Channel On and Off control
- Trigger level control
- Trigger lsope options
- Simple auto-trigger control
- Common mode controls
- Differential mode controls
- Averaged waveform option

3 Project Implementation

3.1 Circuit Diagram



3.2 List of Components Used

Following components were used in making of our project:

- TIVA TM4C123G Micro-controller
- Bluetooth Module HC-05
- LM 358 Low-Power, Dual-Operational Amplifiers
- CD 4051/4052 CMOS Analog Multiplexer/Demultiplexer With Logic-Level Conversion
- INA128 Differential Input Instrumentation Amplifier
- SN7417 Hex Buffers and Drivers With Open-Collector High-Voltage Outputs

All components are available in WEL lab. Nothing was ordered from outside.

3.3 Battery System

We use 5V power bank to provide 5 V supply to various sub-systems of our design. The circuit draws around 150 mA of current. The power bank has a current rating of 2 A. If using other supplies, care must be taken about the current specifications.
A decoupling capacitor of value $220\mu F$ is connected in parallel to the supply and on the PCB, supply voltage traces were of 32 mils to reduce the noise in the signal.

3.4 Protection Circuit

The protection circuit is implemented using IN4148 diodes. Peak forward repetitive current specification of IN4148 is 500mA. So the circuit is protected for voltages up to 0.5A $\times$ input resistance (1 MΩ) which is 0.5 MV.

3.5 Common Mode Gain Control

Common mode gain control is implemented using two op-amp inverting amplifiers. The gain is controlled according to mode set by the user on GUI. The mode specifies the range of the common mode input voltage.
Gains (and attenuations) are adjusted such that the output voltage of the op-amps will be nearly equal to permissible input voltage values for the instrumentation amplifier. This will ensures high SNR of the differential output.
We used LM358 op-amps. The variable resistance of the op-amps is controlled digitally by switching modes of analog multiplexer CD4052, according to user specified voltage range. CD4052's minimum high input voltage is 3.5V which is supplied by 7417 buffer connected to the microcontroller. We perform ganged operation of changing gains for both the inputs simultaneously using CD4052.

3.6 Differential Mode Gain Control

Differential mode gain control is implemented using INA128 - an instrumentation amplifier. The gain is controlled by varying R_g of the amplifier. Gain equation is G = 1 + 50kΩ/R_G. The variable resistance is controlled digitally by switching modes of analog multiplexer CD4051, according to user specified voltage range for the differential input.

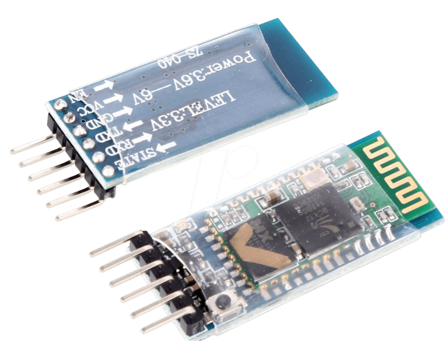
3.7 Microcontroller

The microcontroller is receiving input from the on-board ADC. It is communicating with the PC via the Bluetooth module. We don't do any signal processing in the controller. All the samples are sent to the PC for processing. We used TIVA-TM4C123G microcontroller operating at frequency of 80MHz. Micro-controller is programmed to respond to 'instructions' from the PC, for example, 's' means that micro-controller should sample 400 times and send samples to PC, 'd2' means differential mode should be set to 2, 'f1000' means sampling frequency should be set to 1000 and so on. Sampling routine implemented is (current implementation using $n = 400$):

Consecutive Sampling

```
initialize variables
when timer overflows:
  sample 'n' samples
  send 'n' samples via Bluetooth
```

3.8 Bluetooth Module



Bluetooth module HC-05 is used to transmit data wirelessly, sampled by the micro-controller, to PC. The baud rate we've used is 115200 bit/s. The sampled values are converted to string and ended with end-line character. This strings when received by PC, are separated by the end-line character and converted back into integers for further processing.

3.9 Graphical User Interface

GUI has two windows viz. panel and display. Panel contains all the controls which are explained below. Display is the window where waveform is observed. Record length used is 400 out of which 200 samples are displayed on screen.
GUI has following buttons and sliders:

- *Auto-connect*: automatically searches for a COM ports and connects to the first one available.
- *Find Available COM Ports*: finds all the available COM ports and adds them to drop-down menu above it.
- *Connect*: connects to the available COM port selected in drop-down menu to the left of it.
- *Run/Stop*: run and stop the display respectively. (Internally it stops sending the instruction for sampling.)
- *Disconnect*: disconnect from the COM port being used.(To be used only after stopping the sampling using 'Stop' button.)
- *Common and Differential Modes*: to select the common and differential mode.
- *Time Scale*: Adjust the time per division for the display. (Internally, it changes the sampling rate.)
- *Voltage Scale*: Adjust the voltage per division of display.
- *Trigger Point*: Adjust the trigger point on display.
- *Time shift*: Move the waveform left and right on display to observe out-of-screen region.
- *Average/Max/Min/Pk-Pk*: Average, maximum, minimum and peak-to-peak voltage from waveform. These include the complete record length and not just what is displayed.
- *Frequency*: Displays the frequency of the waveform. It internally uses the trigger point and trigger type mentioned and counts the number of crossings to calculate frequency.

- *Auto Trigger*: Triggers the currently displayed waveform. It uses the mentioned trigger type and brings the trigger level to average of the waveform.
- *Positive/Negative Slope*: Select the type of trigger to use.
- *Average 1/2/4/8/16/32/64*: How many samples to take in while averaging the waveform. 1 means there is no averaging.
- *White sub-panel*: The white sub-panel at the bottom of panel shows a log of activities in bluetooth connection.

Display has a black background, 5 vertical and 5 horizontal divisions in thin white lines. On the left bottom side, it shows the voltage per division. And to the left of it, is the time per division. Waveform appears in green coloured line, trigger level in red-coloured line. The time and voltage zero-levels are displayed in thick white lines[2] .

[2]Pictures of waveforms will be added soon

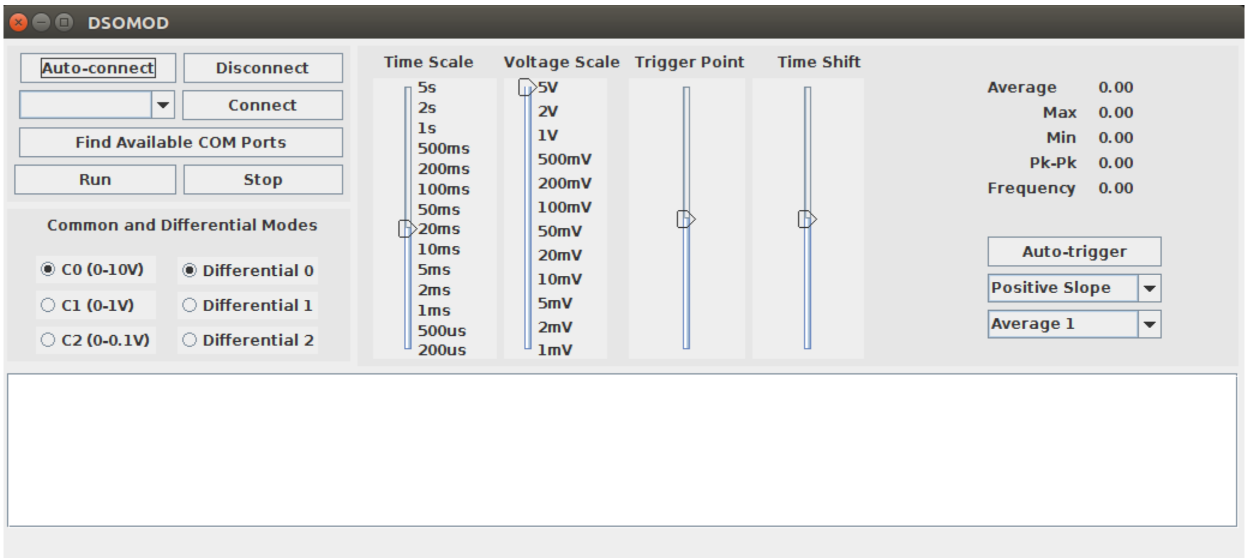


Figure 1: GUI Panel

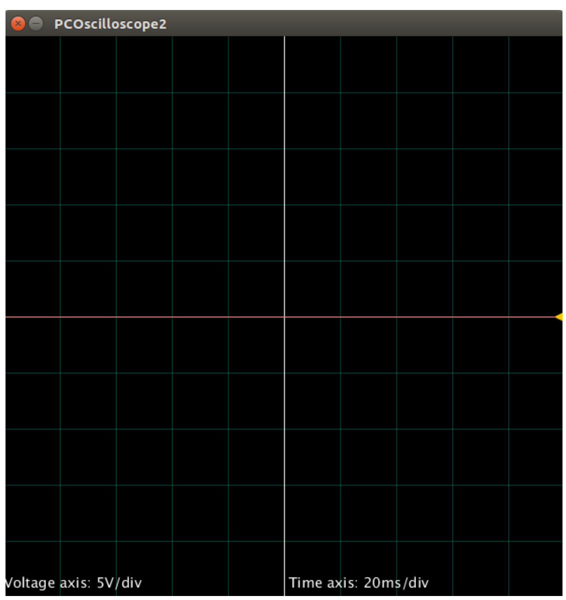


Figure 2: GUI Display

4 Performance Evaluation

We tested the our module for and got the following results. Note the following -

1. We applied the signals $V_{cm} + V_{ac}$ and V_{cm} to our module.
2. V_{ac} is a square wave with peak to peak voltage V_{pp} and frequency 500 Hz
3. The minimum V_{pp} indicates that the noise below this voltage is more than 20% of applied V_{pp}.
4. The maximum V_{pp} indicates the limit for linear operation of the module.
5. The $V+$ indicates that the testing function generator could only supply V and the maximum voltage for linear operation is greater than V.
6. The $V-$ indicates that the testing function generator could only supply V and the minimum voltage that meets the noise criterion is smaller than V.
7. The term **saturation** indicates the operation of the module is not linear.

4.1 $V_{cm} = 0V$

Common Mode Gain	**Differential Mode Gain**	**Maximum** V_{pp}	**Minimum** V_{pp}
0.015	4.33	20+	2.2
0.015	2.1	20+	6
0.015	1	20+	10
0.15	4.33	2.5	0.3
0.15	2.1	4.3	0.75
0.15	1	6.6	1
1.5	4.33	0.250	0.020-
1.5	2.1	0.430	0.050
1.5	1	0.650	0.100

4.2 $V_{cm} = 0.1V$

Common Mode Gain	**Differential Mode Gain**	**Maximum V_{pp}**	**Minimum V_{pp}**
0.015	4.33	20+	2.5
0.015	2.1	20+	5
0.015	1	20+	9
0.15	4.33	2.3	0.3
0.15	2.1	4.2	0.6
0.15	1	6.4	0.9
1.5	4.33	0.080	0.020-
1.5	2.1	0.250	0.060
1.5	1	0.450	0.100

4.3 $V_{cm} = 1V$

Common Mode Gain	**Differential Mode Gain**	**Maximum V_{pp}**	**Minimum V_{pp}**
0.015	4.33	18+	2.2
0.015	2.1	18+	5
0.015	1	18+	10
0.15	4.33	1.7	0.25
0.15	2.1	3	0.5
0.15	1	4.6	0.85
1.5	4.33	saturation	saturation
1.5	2.1	saturation	saturation
1.5	1	saturation	saturation

4.4 $V_{cm} = 5V$

Common Mode Gain	**Differential Mode Gain**	**Maximum V_{pp}**	**Minimum V_{pp}**
0.015	4.33	10+	2.5
0.015	2.1	10+	5
0.015	1	10+	10
0.15	4.33	saturation	saturation
0.15	2.1	saturation	saturation
0.15	1	saturation	saturation
1.5	4.33	saturation	saturation
1.5	2.1	saturation	saturation
1.5	1	saturation	saturation

We can measure a difference signal of $20mV_{pp}$ (and posibly lower voltages) reliably when $V_{cm} = 0V$ and measure a difference signal of $2.5V_{pp}$ reliably when $V_{cm} = 5V$. The performance of the module is good at low common mode voltages but is not as good at higher common mode voltages.
All the outputs were measured and displayed on the built GUI. The circuit was powered using a 5V battery and communication was established using a Bluetooth module.

5 Conclusion

5.1 Objectives Achieved

We were able to build a proof of concept for a DSO module that achieved the following objectives -

- Capable of measuring differential signals for frequencies up to 10 kHz
- Has a GUI for displaying waveforms and controlling the output that can be used on Ubuntu operating system.
- Has Bluetooth communication between the personal computer and the analog front-end.

5.2 Improvements and Extensions

- The performance of the module (minimization of amplitude of differential signal that can be measured at higher common mode voltages) could be improved by using rail to rail operational amplifiers and rail to rail instrumentation amplifiers.
- Having an ADC which can measure voltages between 0 to 5 V instead of 0 to 3.3 V and can operate at higher frequencies will also improve the performance and the frequencies that can be measured.
- Equivalent sampling can also be implemented to measure signals of higher frequencies. More channels could be added to the module using multiple ADCs.