ELEC 390 Main Project: Accessible Electronics Instrumentation

TeachEE
Presented for ELEC 498
Group 18

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I confirm that the team has consulted me regarding the project and the material described in this proposal.

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Abstract

The movement to online education and remote work has necessitated the need for a new kind of electrical instrument. Students can no longer use the expensive tools on university campuses for their engineering labs. As a result, professors have had to send students individual lab kits that require curricular compromise in the lab procedures.

This report proposes a solution in the form of TeachEE, which combines the signal generator and oscilloscope functionality into a cheap device specifically for engineering labs. The impact of this device will be making available a cheap oscilloscope that also provides a sophisticated software package. The result is greater access to electronics for all students.

There are five steps in the development of the solution. These consist of PCB design, embedded code development, microcontroller driver code development, OS driver code development, and application development. Development will begin on September 1st and is scheduled for a mid-January finish to allow time for testing of the prototype.

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1 Problem Description

Since the onset of the COVID-19 pandemic, universities and all other education institutions have had quickly transition to an online mode of delivery. While this new form of education has been an adjustment for all students it is particularly difficult for engineers and other students partaking in programs with an emphasis on hands-on lab activities. In the case of ECE students, the most glaring compromise of online lab delivery is circuits labs and analyzing circuits that have been constructed in the remote environment. Before the pandemic, circuit data was collected using monolithic and expensive oscilloscopes available to students in school lab spaces. These oscilloscopes integrate display and processing functionality into one single device. While efficient and effective in the lab environment, it is not economically possible to send each individual student one of these instruments to complete their lab work. The solution to this issue has been to use handheld oscilloscopes and signal generators that lack the data capture functionality of their more expensive counterparts. Additionally, this solution does not provide any means of porting data from instrument to computer for calculations and analysis.

This problem is endemic for both students and professors. Students find the cheaper equipment harder to use in addition to requiring several separate power outlets for the circuit, signal generator, and oscilloscopes. Professors must make difficult decisions with regard to pairing down the scope of lab activities since students can no longer effectively capture data from their physical circuits.

1.1 User Study

Professor Sean Whitehall is an Electrical and Computer Engineering professor at Queen's University. Dr. Whitehall teaches both ELEC 252 and ELEC 353 which involve the construction and characterization of amplifier circuits. In the fall 2020 semester, Dr. Whitehall taught ELEC 353 remotely. In order to build students' skills in the construction of physical circuits, Dr. Whitehall provided lab kits to all students enrolled in the course. While the lab kits worked well, students accidentally broke their signal generators through over-voltage and labs had to be scaled down to accommodate the lesser instrumentation equipment. Dr. Whitehall is supervising this capstone project and is interested in an economic solution to the current pitfalls of remote lab work.

2 Impact

2.1 Economic

Unfortunately, proper economic evaluations of the oscilloscope market lay behind massive paywalls [1]. This necessitates the re-creation of research which already exists, albeit, with a specialized scope and reduced fidelity. The scope is reduced to the target market, which includes universities with oscilloscope labs.

At Queen's University there are approximately 19000 undergraduate students [2]. That gives $19000/4 \approx 5000$ students in each year. ELEC 221 is the introduction to circuits class. As an approximation, it is assumed that everyone who needs to use an oscilloscope takes that class. In the Fall of 2019, there were 169 people enrolled in ELEC 221. This means that $169/5000 \approx 3\%$ of students require an oscilloscope.

In 2019, there were 1.36 million students in Canada [3]. Extrapolating 3% of 1.36 million gives 40k undergraduate students in Canada that require oscilloscopes.

2.2 Cultural

As discussed later in Section 3.1, even the cheapest of oscilloscopes are quite costly. The expectation is that an oscilloscope is a bulky expensive tool which requires thousands of dollars to purchase. This expectation is understandable since this type of oscilloscope is all that is seen by the average person. TeachEE would change this norm, and re-brand what is considered an average oscilloscope.

2.3 Social

Electronic hobbyists have diminished over the past 40 years. This is due to a variety of factors, including: the growing complexity of the field, change in economics due to cheap offshore manufacturing, and the failure of supporting companies such as RadioShack [4]. The lack of simple cheap oscilloscope certainly does not improve the vitality of the hobby. This product will provide opportunity for more people, and will boost interest in the electronics field in general.

3 Solution

The proposed solution to the issue discussed in Section 1 is called TeachEE, which stands for Teach Electrical Engineering. The TeachEE bundles oscilloscope and signal generator functionality into a single device that connects to the students' computer via USB. This USB connection takes care of both power and data transmission. This allows students to work from their computers without the need for several power outlets. The waveforms from the TeachEE's input are displayed on the student's computer screen in a Graphical User Interface (GUI) reducing hardware cost by avoiding the need for a display. Moreover, all signal processing tasks are computed on the student's computer, leveraging their powerful processors, thus keeping the compute resources on the physical device as cheap as possible. Additionally, since the data is sent to the computer for processing, it can also be exported from the GUI to an excel format for students to use in their lab reports and analysis. The GUI on the student's computer resolves problems with ease of use and data export. The TeachEE will also resolve reliability issues by implementing both over-voltage and over-current protections.

3.1 Existing Solutions

There are two existing solutions for this problem. The first existing solution is sending out lab kits with discrete oscilloscopes and signal generators independent of the computer. Section 1 discusses the issues with this approach in terms of curricular limitations and reliability. The second existing solution are other USB oscilloscopes. The most similar USB oscilloscope is the BitScope, specifically the (cheapest) BS05U model [5]. The BitScope website shows it clearly targets the in-person lab environment [6]. This device from BitScope performs a similar task in having a GUI software and signal generator. However, the device is prohibitively expensive to send to individual students at a cost of $145 USD per unit. The price is likely high due to the high sample rate and 20 Mhz bandwidth. While this extra bandwidth is helpful when working with high speed signals on printed circuit boards, all university labs where circuits are constructed on prototyping boards by hand do not exceed 1 Mhz as indicated by Dr. Whitehall. Thus, the extra bandwidth provided by the BitScope is not helpful in this context and should be exchanged for a lower cost device. For example, the oscilloscopes sent to students in the ELEC 353 circuits class at Queen's are less than half the cost of the BitScope at $46 USD on Amazon [7].

3.2 SWOT Analysis

Table 1 contains the SWOT analysis for TeachEE.

Table 1: SWOT Analysis Matrix

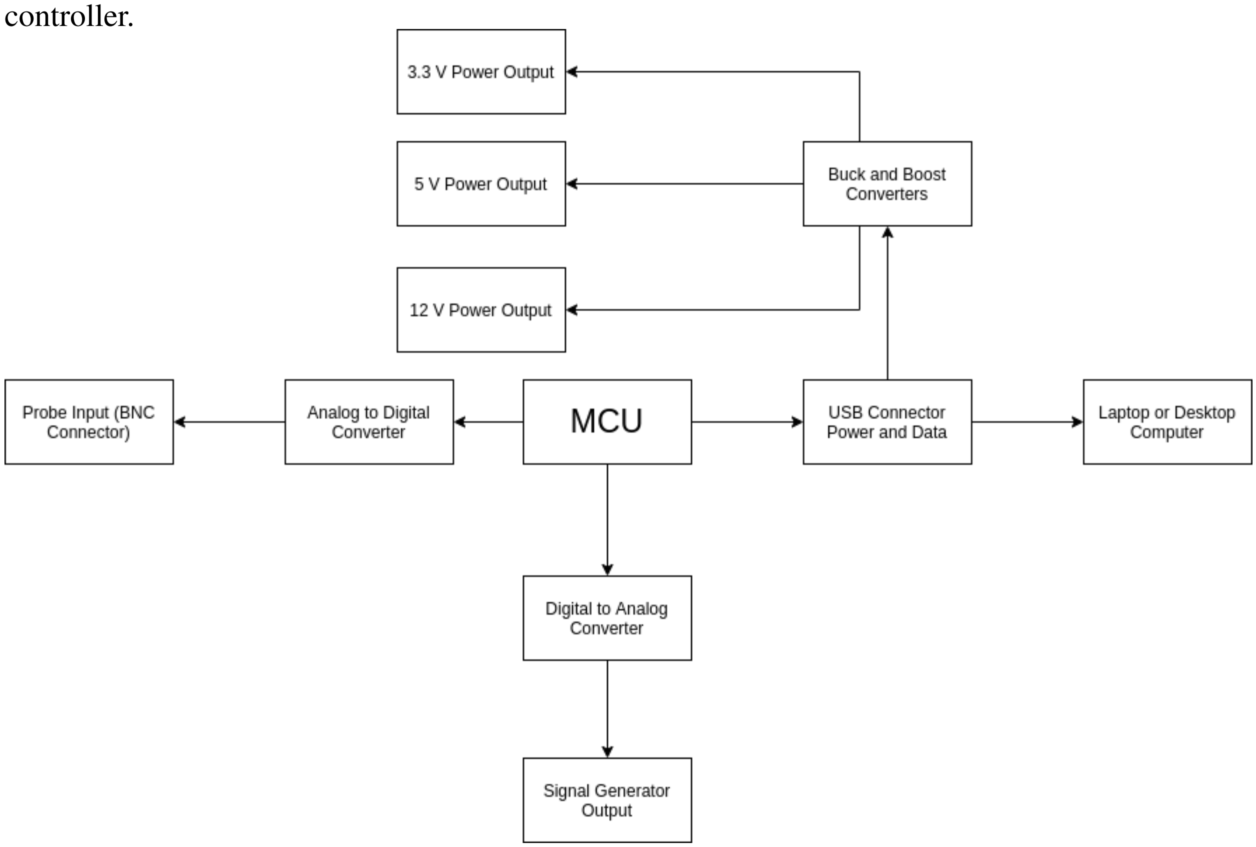
Strengths	Weaknesses
• Understanding of the needs of the educational market achieved by performing user interviews with Queen's ECE professors. • Ability to minimize hardware cost by drawing on the computational power of computers that students already own. • Understanding of students' needs due to being in the university environment.	• The device has the minimum feature set needed for Electronics labs and nothing more. • The device will have lower bandwidth and sample rate in comparison to more expensive competitors.
Opportunities	**Threats**
• The current remote delivery of university classes presents an opportunity in marketing the device to secondary and post-secondary institutions alike. • As remote work and education become normalized after the pandemic, demand will be greater for devices like TeachEE that help close the gap with in-person work.	• Other oscilloscope manufacturers compete in the education market in order to familiarize students with their technology. As such, universities are spoiled for choice in who they buy their instruments from. • Competitors could see the TeachEE and aim to replicate its unique value proposition of accessible remote instrumentation.

4 Components and Design

4.1 Hardware

The physical TeachEE device will come in the form a custom Printed Circuit Board (PCB) design. This PCB will power and provide debugger access to a microcontroller through a USB connector. Additionally, the PCB will have a BNC connector mounted on it for probe compatibility with other oscilloscopes. The connector will be connected to the Analog to Digital Converter (ADC) of the microcontroller. A second BNC connector is provided for the signal generator output which will be connected to the Digital to Analog Converter (DAC) on the microcontroller. A system block diagram representation of the PCB is given in Figure 1.

Figure 1: System Block Diagram of the TeachEE PCB. Note that "MCU" represents the microcontroller.



As shown in the figure above, the USB connector not only powers the microcontroller (MCU) but also connects "buck" and "boost" circuitry to provide the student with different output supply voltages. The 5V output is created directly from the 5V provided over USB. The 3.3V output is made using the buck converter circuit to step down the voltage from 5 to 3.3 V. A linear regulator solution could also be used here since the voltage drop is small but the use of a buck converter will allow students to drive their circuits with more current without heating the TeachEE as rapidly. It should be noted that the ability to drive higher current circuits is dependent on the power rating of the USB port the device is connected to. By default, the TeachEE will have a current of 500 mA as per the USB specification [8]. However, the student could choose to override this and go higher, it is in these cases where a buck topology is essential. The 12V output is produced via boost converter circuit which will take the 5V supply from USB and boost it 12 V at the cost of current draw capability.

4.2 Software

4.2.1 Firmware

The firmware running on the microcontroller will be written in C. It will take inputs from two sources: the oscilloscope probes and the microcontroller driver. It will sample voltages measured by the oscilloscope probes and pass it to the driver. By offloading all signal processing to the desktop or laptop computer, the firmware can be made very lightweight and fast, reducing microcontroller resource usage. The firmware will also be responsible for setting signal generator settings, such as signal frequency, signal amplitude, and DC offset. These settings will be communicated from the application whenever the user supplies the signal generator parameters through the user interface.

4.2.2 Drivers

The driver on the user's computer will be written using Microsoft's kernel-Mode Driver Framework (KMDF) via Visual Studio. The driver must be a kernel-mode driver to allow direct memory access for fast writing of sample data. It uses C++, and has a vast swath of examples and a large community [9]. The computer driver should be encapsulated in an easy to use library for the application, which will include a class that has the following:

- A static factory method, which blocks until a device is connected.
- Fields which are populated by the device's information.
- Functions that wrap the sending of configurations to the device.
- A function which returns a pointer to the current sample data.
- Exceptions for when a device is disconnected.

The other side of the driver sits on the device. It will be written in C, and provide a header for the rest of the firmware, which will provide a function for sending sample data, and an interrupt for when configurations are received.

4.2.3 Application

The desktop application will be written in C++ as it is fast in execution and provides the ability to directly manage OS resources without being too low-level compared to C. Currently, the planned target platform is Windows as it is the most used OS among university students. The application will have the following features:

Table 2: Feature table for desktop application.

Feature	Description
Fast Fourier Transform	FFT will be applied on the voltage values to obtain amplitude as a function of frequency. This information will be used to lock on to a specific frequency when plotting and for plotting voltage vs frequency.
Waveform Display	The application will take voltage values from the OS side driver and plot them. The plotting will be done at an automatically adjusted frequency based on the incoming data to produce a stable plot of voltage vs time or voltage vs frequency (after FFT analysis).
Sample saving	Users will be able to click a button to export the displayed samples to a CSV file. This will allow them to easily analyze experiment results.
Voltage generator settings	Users will be able to adjust signal generator parameters (e.g. signal frequency) by entering values into text boxes. These settings will be passed to the OS side driver, which will send the instructions to the microcontroller.

The software API that will be used is Qt. Qt was chosen because it allows developers to write GUIs using C++ and is cross platform, which allows the project to be implemented on other platforms if the team decides to do so. Furthermore, team members have experience working with this framework, which will result in faster code development.

5 Risk Analysis

The risks associated with the TeachEE project fall into two major categories of Operational, and Licensing and IP risk. Each risk category is further analyzed in the following subsections. In order to proceed as expected with the TeachEE development process, it is assumed that the team will not encounter any of these risks.

5.1 Operational Risk

The primary operational risk to the project is hardware functionality issues. The worst case scenario is that the PCB is ordered and does not work whatsoever. This is a low risk but very high impact scenario as the cause of failure must be deduced and another iteration must be ordered. A second fabrication run of the device has financial implications in addition to delaying software development efforts.

A higher risk but less harmful scenario is a partially working device where the MCU can be programmed and debugged but the sampling and signal generator is not fully operational. This scenario is more likely than the device not working at all and also has a lower impact since software development may continue while the hardware issues are resolved. However, if a second fabrication of the PCB is needed, financial costs will be incurred.

The highest probability risk to the TeachEE will likely be data throughput. Since the device will be taking up to millions of voltage samples each second, the software and hardware must be capable of keeping up with such speed. Potential bottlenecks could come from the USB hardware on the MCU or result from software. In the software case, more performance could likely be achieved through driver protocol modifications while the hardware case will likely result in a smaller achievable bandwidth. In both cases, the risk is very low impact since project development can proceed as normal.

5.2 Licensing and IP Risks

The TeachEE circuit board will be designed using a licensed EDA software called Altium. However, as with most educational licenses, a product made with the license cannot be monetized. This presents a licensing risk to TeachEE, however, it can be easily resolved through the purchase of a full Altium license.

There are also Licensing risks to the software development effort on TeachEE. Many open source tools that the team may employ use the GPL license. Projects that use the GPL license must also be open source which presents a risk to the privacy of the TeachEE codebase [10]. The GUI framework Qt has an open source version, however, additional licensing fees may be incurred if the team chooses to make use of features in the premium product.

6 Budget

This project requires that two hardware components be purchased: the oscilloscope probes and the assembled PCB. Oscilloscope probes can be purchased from Amazon for $25.99 [11]. The PCB will be ordered from PCBWay in a bundle of five, which is the minimum number of units that the website allows for a design. Based on similar past projects involving the same company, the PCB order will cost approximately $200 [12]. The actual cost of the PCBs will vary depending on the number and types of parts to be soldered on and cannot be determined until the PCB design is laid out.

Based on these component costs, the total cost of the project is estimated to be approximately $226, which is within the $400 budget allocated for the project. However, if the ordered PCBs turn out faulty and another order is placed, the total cost will exceed the budget. Careful design of the hardware will be necessary to avoid this scenario.

7 Development Plan

The project work can be divided into five components: PCB design, embedded code development, microcontroller driver code development, OS driver code development, and application development. Designing the PCB will involve planning and laying out the microcontroller and its components, and testing after receiving the parts from the manufacturer website. Embedded code development will require writing C code on the microcontroller for voltage sampling and the signal generator. Writing the driver code on the microcontroller side will consist of determining the packet format and error correction method of voltage samples sent to the laptop/PC. Writing the driver code on the OS side will require determining the packet format and error correction method of user instructions sent to the microcontroller. Work will also have to be done for interfacing both drivers and ensuring that protocols used by both are compatible. Application development will involve developing and implementing the fast fourier transform algorithm for the voltage packets, the visual plotting code, the sample saving functionality, and the user interface to configure the signal generator.

PCB design and application development do not depend on any other tasks as they can be fed sample data for testing purposes (e.g. the application takes voltage values and plots or saves them). Therefore, PCB design and application development can be started on the project start date. The other three components cannot be started until PCB design is finished. Embedded code development and microcontroller driver code will not be possible without the PCB available as errors early in development will not be found until the code is programmed into the PCB and run, at which point it may be too late to fix the errors. Similarly, the OS driver code will require external inputs from a USB for it to be run.

The project will begin on September 1st and is scheduled for a mid-January finish. This schedule will allow for final testing of the product before the prototype demonstration in February.

The team will use GitHub issues to track tasks and bugs and a GitHub repository to collaborate on project files.

A Gantt chart is shown on the next page outlining the details of the project development plan.

ID	Num	Task Mode	Task Name	Duration
1	**1**		**Design PCB**	**55 days**
2	1.1		Schematic design	3 wks
3	1.2		Layout	3 wks
4	1.3		Design review	3 wks
5	1.4		Order from manufacturer website	0 days
6	1.5		Assembly and verification	2 wks
7	**2**		**Develop embedded code**	**40 days**
8	2.1		Voltage sampling code	4 wks
9	2.2		Signal generator code	4 wks
10	**3**		**Driver code for microcontroller**	**35 days**
11	3.1		Develop sending packet format (voltage samples)	2 wks
12	3.2		Implement receiving packet format (user instructions)	1 wk
13	3.3		Develop error correction code	2 wks
14	3.4		Interpret instructions from desktop/laptop	2 wks
15	**4**		**Driver code for OS**	**40 days**
16	4.1		Develop sending packet format (user instructions)	2 wks
17	4.2		Implement receiving packet format (voltage	1 wk
18	4.3		Develop error correction code	2 wks
19	4.4		Implement message passing to application	3 wks
20	**5**		**Develop application**	**70 days**
21	5.1		Develop and implement FFT algorithm	2 wks
22	5.2		Implement visual plotting	1 mon
23	5.3		Implement sample saving	1 mon
24	5.4		Develop user interface to configure signal generator	1 mon

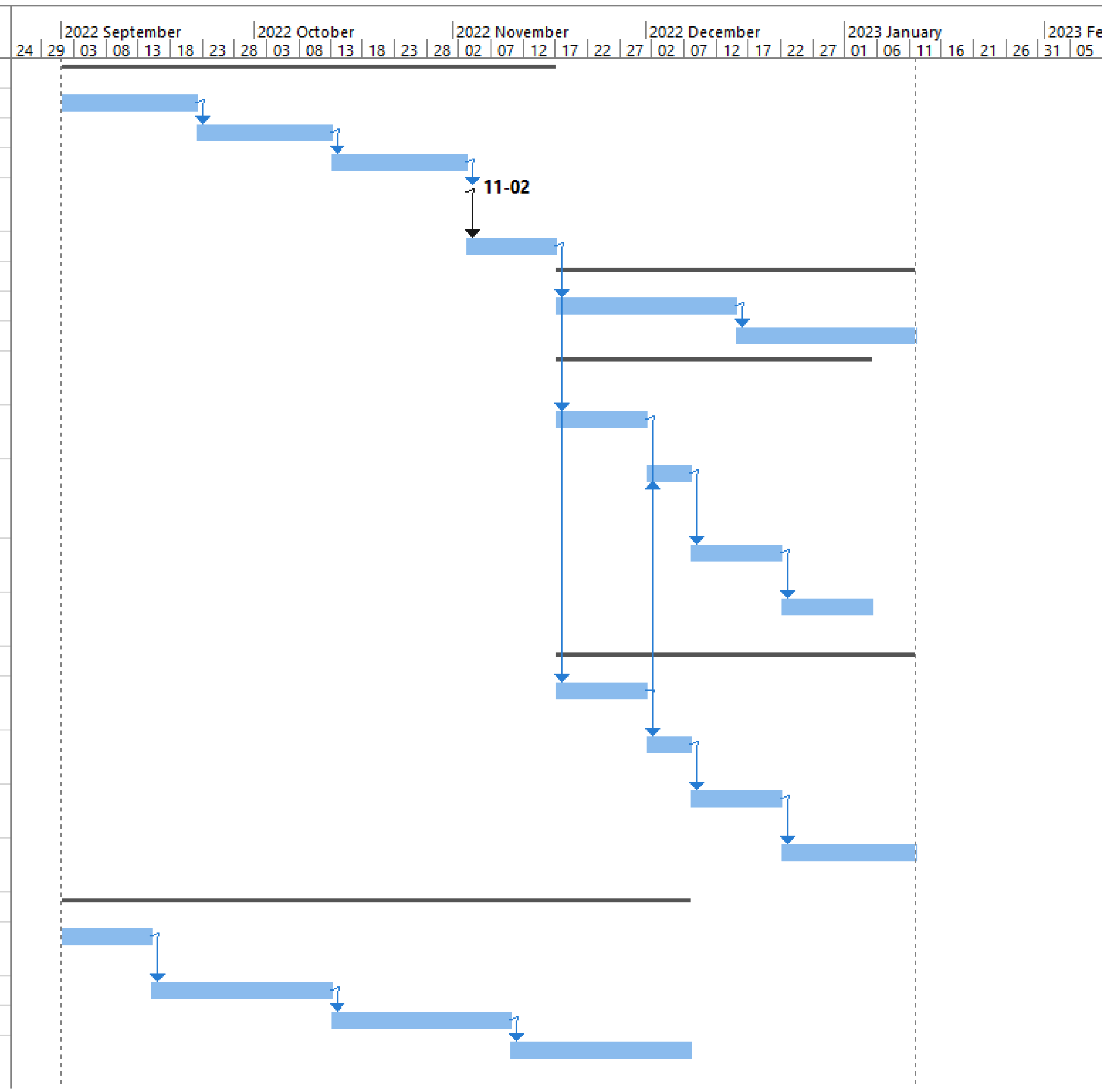


Figure 2: Gantt chart displaying the breakdown and timing of project tasks.

8 Test Plan

8.1 Printed Circuit Board (PCB)

The table below outlines the planned test cases for the PCB and the requisite test result.

Table 3: Table of PCB test cases and the expected result.

Description	Expected Result
Case 1: Probe the power and ground nets on the PCB using a continuity checker to ensure there are no shorts.	No continuity between power and ground.
Case 2: Connect the PCB to power via the USB port.	Power LED should turn on and there should be no short circuiting.
Case 3: Connect a JTAG debugger to the PCB	Microcontroller shows up in the JTAG chain of the debugger interface.
Case 4: Flash firmware to the MCU	Effect of running firmware is observed (Ie. blinking LED).
Case 5: Connect the signal generator output of the TeachEE to the voltage input and emit a waveform from the signal generator.	The same waveform is sampled properly and observed at the voltage input. Success in this test covers the function of both the ADC and DAC on the MCU.

The following subsections describe debugging actions that can be pursued if a specific test case fails.

8.1.1 Case 1

If Case 1 has failed, there is a connection between power and ground. In this case, the short circuit is present even when the device does not have power indicating that the two nets are physically connected somewhere. The debugging process will consist of checking for soldering and component orientation errors.

8.1.2 Case 2

If Case 2 fails, then the short circuit is only triggered on power up. Debug this by looking for components that behaved as open circuits when powered off but behave as shorts when powered on. Look for components that are producing heat. Heat radiating off a certain part indicates that the short current is flowing through it.

8.1.3 Case 3

If Case 3 fails, Then the debugger is not detecting the MCU it is connected to. Check the physical connections to the debugger and ensure they are secure. Check that the debugger is functioning properly by connecting it to another MCU that is known to be working. Check that the MCU is powered properly. Check that the supply voltage from the debugger is being used and not another power supply (too much deviation from the logical voltage level of the debugger may create connection issues).

8.1.4 Case 4

If Case 4 fails, then the debugger has established a connection but was unable to flash firmware. Check the physical connections to the board. Check the data rate and try slowing it down. Check the boot mode and reset pins of the MCU and cross reference the datasheet to ensure they are in the correct state for JTAG debugging.

8.1.5 Case 5

If Case 5 fails, then there could either be a hardware issue with the ADC or DAC or a software issue with how they were configured. Start by using a secondary oscilloscope to check that the signal is being outputted properly from the DAC. If it is not, revise the software configuration. Once the DAC is functional, check that the signal is arriving correctly at the ADC input. If no signal is being read into the MCU's memory, then revise the software configuration to handle this.

8.2 Device Driver (OS Level)

8.2.1 Case 1

A randomly generated message will be sent from the driver to the computer. The message will then be manually verified for equivalence. The same will be completed from the computer to the driver.

8.2.2 Case 2

A known message with an incorrect checksum should be sent from the computer to the device. The device should detect the error, and apply the proper error correction procedure. The same will be completed from the device to the computer.

8.2.3 Case 3

A simulated disconnection of the device should occur at critical times of the application process. This will ensure the proper handling of a sudden disconnect.

8.3 Application

The desktop application takes voltage/time values and user inputs as input. The outputs are plots of voltage vs time and voltage vs frequency, a CSV file containing displayed information, and signal generator settings.

To test the FFT algorithm, a unit testing framework, such as Google Test, can be used. Test cases will contain various kinds of voltage/time inputs and their corresponding expected outputs. Running the tests will automatically compare the actual and expected outputs and indicate whether the tests passed or failed. The input and output from each test case will be obtained by using an existing FFT implementation.

Waveform plotting will be manually verified to be correct by supplying a set of test voltage/time values and observing the resulting waveform. A correct display will show a stable waveform with horizontal and vertical scale adjusted based on the test inputs.

Sample saving will be tested by manually checking the CSV file for some test data when the "export" button is clicked. Correctness can be verified by checking that the displayed data is in the same range as the exported data and that the voltage vs time and voltage vs frequency data present in the CSV file match the data displayed on the waveforms.

Verifying that signal generator settings are outputted correctly can be done by supplying the parameters in the text boxes and ensuring that the values entered by the user match the data sent to the OS side driver.

9 Team

The team consists of 3 members: John, Eric, and Ethan. Each team member's competencies and role in the project are enumerated in the following subsections.

9.1 John

John is a Computer Engineering student responsible for communication between the device and the desktop application. This includes defining a protocol which supports the transfer of sample data, and miscellaneous device configuration signals. He will write the driver which allows the OS to communicate with the device, and encapsulate it for easy use in the desktop application.

9.2 Eric

Eric is a Computer Engineering student and will be responsible for working on the desktop application and message passing to the OS side driver. He is chosen for this role because he has experience with C++ and OS-level development from coursework and work experience, with an upcoming internship on virtual machine development. He also has experience working with GUI frameworks in C++.

9.3 Ethan

Ethan is a Computer Engineering student who will be managing and executing the hardware side of the project. This role is defined as designing and testing the PCB and configuring the development environment for John and Eric to use. Ethan is selected for this role because he has worked in circuit design on internships and has taken the computer hardware stream within ECE. Ethan also has software engineering experience from internships and will be assisting wherever possible in the software development process.

10 Project Management Software

The project's code will be hosted on a private GitHub repository. This will allow for collaboration despite team members being in different locations or timezones. Github also provides a robust issue system; a member can outline a bug, labelled with a priority, and assign it to the respective member. A pull request can be made once the issue has been resolved.

Our team will follow an Agile Development Methodology, with a focus on frequent short meetings, and with no members being restricted to a specific scope. This will work well since the team is small and competent, which complements a development style that is relatively flexible and unstructured.

11 Deliverables

The deliverables listed in the following subsections are representative of the prototype the team will be developing in ELEC 490. If a prototype of this scope is completed sooner than expected then the team will begin work on some of the planned features listed in Section 12.

11.1 Hardware

The initial hardware prototype will be limited to a single voltage input and signal generator output. These limitations match existing lab kits after discussions with ECE professors and will minimize hardware complexity. The bandwidth limitations of the device will be bounded by sample rate and filtering. Following discussion with Dr. Whitehall, it was determined that a sample rate amounting to 20 samples per period will ensure a correct waveform with some interpolation. Most of the MCU options have ADCs with 1-2MSps. Assuming 1MSps, the initial prototype will achieve a bandwidth of 50Khz. Assuming an equal sample playback rate on the DAC, the signal generator will produce up to 50Khz waveforms. Filtering could also limit bandwidth. The TeachEE will use a Low Pass Filter (LPF) defined entirely in software. The software defined LPF will allow users to adjust the characteristics of their sampling setup in the laboratory. However, this data pre-processing will tax the Digital Signal Processor (DSP) unit on the MCU and potentially slow down sample throughput. This issue can likely be mitigated by iterating on the filter design.

11.2 Software

The final product will consist of a software package that users can install on their desktop or laptop computer. It will feature the driver code for the sending and receiving of data on the OS side and the frontend desktop application. The application will feature a graphical user interface that plots the received voltage samples as well as allowing users to adjust the PCB's signal generator settings and export test results as a CSV. These are the minimum deliverables for the project; future iterations of the project may add more user functionality to the application.

12 Beyond ELEC 390/49X

Technology is inherently iterative, with TeachEE being no exception. The following includes the most useful features that exist outside the minimum viable product's scope, which should still be considered prior to the product's launch, should one occur.

12.1 Self Validation

There should exist a mode that tests the entire pipeline, from the device to the application. The device would generate a known signal, which is then sampled. If the sample is outside of an acceptable range, an error should be displayed. The sampled data could then be echoed back to the device via the computer to detect error in the device's connection. The application could also verify that the graphics are displayed correctly onto the screen by checking for suitable overlap with a simulated waveform.

12.2 Signal Preset Support

A professor should be able to specify a signal via a user interface and export the signal's specifications to a file. A student should then be able to load the signal as a preset, and select a preset to be used by the device's signal generator. This would decrease the time spent on application specific interface details, and free up time for learning.

12.3 Cloud Support

A user's sampled data and presets should be synced via a user account. This should be organizable via compartmentalizing into different labs and courses. This would require extensive database and cloud development, and an extension of the existing user interface onto web browsers.

12.4 Higher-Quality Tier

There should exist a more-expensive version of the device which includes better components. Different ADC and DAC components would give better sample rates and bit-depths. This version should include more leads to sample more signals concurrently. It must have a more aesthetically pleasing enclosure as well.

12.5 Cross-platform Expansion

The minimum viable product is required to function on a minimum of one platform. When it is being developed, a cross platform framework is not guaranteed to be selected. If this is the case, then some sections may need to be re-written in different frameworks. This would include the device drivers, which are typically written such that they are dependent on the operating system and hardware.

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