

Modeling and Simulation of Electronic Instruments in Virtual Labs

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ABSTRACT

In higher education, laboratory classes are an essential component of many science and engineering courses. Without hands-on lab experiences, comprehension of theoretical principles and concepts is often challenging. Electronic instruments such as function generators and oscilloscopes are frequently used in electronic laboratory courses. This paper describes the development of modeling and simulation of the above-mentioned electronic instruments in a virtual laboratory environment, including simulation methodology and modalities of user interactions. A function generator is a signal source that generates multiple waveforms of various shapes, the most common types being sine wave, square wave, and triangle wave. To overcome the discrete nature of computing systems and ensure signal integrity, we use mathematical equations to represent continuous signals. The virtual signal generator takes the time t as inputs and generates the corresponding outputs. An oscilloscope is an instrument that converts electrical signals into waveforms for display purposes. The oscilloscopes simulated in this paper are digital storage oscilloscopes (DSOs), which contain a data processing subsystem that samples the data and then displays data over a period of time. We emulate the real-world situation by sampling the signal at the oscilloscope side. The virtual oscilloscope provides the sampling time information and stores the received sampling data in an array structure for later waveform generation. C# delegates were adopted to implement the interfacing between devices; this advanced programming technique ensures that information is transferred between simulated electronic devices through the occurrence of events. The proposed approach guarantees the sampled data follow the Sampling Theorem and assures low coupling between software components and high cohesion of individual software components. The proposed approach can be reused for rapid development of other virtual laboratories that involve electronic instruments.

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INTRODUCTION

The development of online education has made it possible for people to access educational resources anywhere, regardless of their geographic locations. While online education has become increasingly common, online-laboratory components of courses are still not a common part of the academic culture in the United States (Boschmann, 2003). Laboratory courses are a crucial component in higher education, especially for science and engineering majors, where hands-on laboratory experiences are an essential component of the curriculum (Bhute, Inguva, Shah, & Brechtelsbauer, 2021). Labs allow students to learn, apply, and test the theoretical principles and concepts they have learned in the classroom, improving their comprehension of these subjects.

Various approaches have been utilized to offer online students some kinds of laboratory experience without accessing the real labs. For example, some teachers have provided recorded videos of real labs as a way to continue instruction, which is a passive experience for students, as the procedures and perspective are fixed, and students do not have the opportunity to actively control the lab and explore different options. This limits the learning experience, including making mistakes that is an important element of the learning process. One potential solution to this problem is the use of modeling and simulation to replicate the appearance and functionality of electronic instruments in a virtual laboratory environment. Virtual laboratory environment allows students to conduct experiments and analyze results without the need for physical access to the equipment. In this paper, we will discuss the development of a virtual laboratory environment that includes modeling and simulation of electronic instruments such as function generators and oscilloscopes. This virtual lab will be used in both in-person and online circuit laboratory courses, providing students with a convenient and safe way to gain hands-on experience with these essential tools.

Electronic instruments such as oscilloscopes and function generators are essential tools in electronic laboratories, as they allow students to generate and analyze electronic signals and understand the behavior of electronic circuits. These instruments are frequently used in electrical engineering and physics to help students obtain hands-on experience with electronic circuits and systems. However, there are several challenges associated with using these instruments in the laboratory. For example, students may not have access to the equipment due to limited lab schedules. On the other hand, using electronic instruments can be hazardous if proper safety precautions are not followed, such as a short circuit that may damage instruments or cause injury to students.

To address these challenges, we are developing a virtual lab that enable students to interact with electronic instruments in a virtual laboratory environment. By leveraging computer-based simulation, we are able to replicate the appearance and functionality of real-world equipment, allowing students to perform experiments and analyze results without the need for physical access to the instruments. One advantage of using modeling and simulation in virtual laboratory is that it allows students to access the equipment anytime and anywhere, as long as they have the program installed. In addition to providing convenient and safe access to electronic instruments, modeling and simulation also has the potential to improve the educational experience by allowing students to perform experiments that may not be possible in the real world. For example, students can use simulations to explore the behavior of electronic circuits under extreme conditions or to test hypotheses in a controlled environment.

RELATED WORK

There are many studies that have focused on the use of modeling and simulation in education. A number of studies have shown that interactive computer simulations can be effective tools for facilitating learning and engagement in science education. For example, D'Angelo found that using simulations to teach middle school students about energy and energy transformations resulted in increased understanding of the concept and improved attitudes towards science (D'Angelo, 2014). Makransky et al. found that when comparing the value of using an immersive simulation or a video of the simulation on the topic of DNA-analysis, the immersive simulation group reported significantly higher gains on interest and social-outcome expectations than the video group (Makransky, Petersen, & Klingenberg, 2020).

Alpote et al. presented a software tool using the Microsoft .NET XNA Framework and 3D modeling in the teaching of physics at universities (Alpote, Zivkovic, Branovic, & Popovic, 2017). Their results showed that the use of modern information and computer technologies, in conjunction with traditional forms of education, can greatly enhance the teaching experience and improve the overall quality of education.

Ren et al. addressed the challenge of performing laboratory experiments for off-campus and distance learning students (Ren, Zhu, McKenzie, & Shen, 2018). Their research indicated that traditional engineering laboratory experiments require hands-on experience, making it difficult for students who are unable to attend on-campus classes. To overcome this challenge, an Android-based 3D interactive mobile app is introduced.

Zhu et al. highlighted the advancements in the design and development of a simulation application for simulating programmable control logic (PLC) using a combination of mechanical, electrical, and pneumatic components (Zhu et al., 2018). With their Virtual Lab, students can perform circuit wiring for combined electro-pneumatic experiments. The use of Virtual Lab by students has shown positive results and effectiveness.

Singh et al. conducted a control experiment. In their research, a VR-based learning environment is developed to give engineering students prior training on electronics laboratory hardware (Singh, Mantri, Sharma, & Kaur, 2020). Their result showed that the VR approach had a significant positive impact on student knowledge, learning motivation, and cognition, as compared to the standard teaching approach. By interacting with 3D virtual models of laboratory instruments, students showed an improved understanding of the concept and had reduced anxiety about equipment malfunction, which enhanced their confidence.

Li et al. presented methodologies and preliminary findings on rapid development of advanced virtual labs using modeling and simulation for in-person and online education (Li et al., 2022). The main objective of this paper is to design and implement a virtual circuit lab that mimics a physical circuit lab for the physics course at Old Dominion University. The virtual circuit lab will provide students with a simulated environment to conduct experiments, analyze circuits, and understand the behavior of electronic components.

Although scholars have established a sound foundation for the use of simulation and emulation in education, many issues remain to be addressed. For instance, this paper focuses on the simulation of more sophisticated electrical instruments and their communication mechanisms, as well as leveraging advanced C# programming techniques, such as delegates.

DEVELOPING ENVIRONMENT

Autodesk Maya

The 3D models in this paper were generated using Autodesk Maya, which is a professional 3D computer graphics software tool used for creating animated film, television series, and visual effects. It is developed and produced by Autodesk, Inc. and is widely used in the entertainment and media industry. Maya is a comprehensive software that includes tools for modeling, texturing, rendering, and animation (Maya, 2023).

Unity Game Engine

The simulation development in this paper was in Unity engine. Unity is a powerful cross-platform engine developed by Unity Technologies, which is primarily used to develop video games for computers, consoles, and mobile devices. Many researches also use Unity to create visualizations, simulations, and other interactive 3D applications as it allows developers to create immersive and interactive 3D environments that can be tested in real-time (Dealessandri, 2020).

C# and .NET Framework

C# is the primary programming language supported by Unity, which is an object-oriented programming language developed by Microsoft. It is a powerful and flexible language that is widely used for building a variety of applications, including web, mobile, desktop, and gaming. C# is part of the .NET framework, which provides the runtime environment for executing C# code and a set of libraries for building and running applications.

PREVIOUS WORK

Before delving into the simulation of oscilloscopes and function generators in this paper, it should be noted that the modeling and simulation of the necessary functionality of a Digital/Analog Trainer has already been completed. The Digital/Analog Trainer is a complete mini-lab for building and testing analog and digital circuits. Figure 1 shows the 3D model we generated in Autodesk Maya.



Figure 1. 3D model of the Digital/Analog Trainer in Autodesk Maya

The Digital/Analog Trainer contains five main panels. (1) The digital trainer section located at the top of the trainer; (2) The DC power supply section is located at the trainer's middle-left section; (3) The AC power supply section is at the center of the trainer; (4) The function generator section is at the middle-right part of the trainer; and (5) A breadboard and two undedicated potentiometers are at the bottom of the trainer. Each panel has its own set of functions, and these sections work together to provide a comprehensive training experience for users. For example, Figure 2 shows the DC power supply panel of the Digital/Analog Trainer, which provides up to +15V and -15V DC voltage.



Figure 2. DC power supply section of the Digital/Analog Trainer

As described above, the equipment used in virtual lab typically has multiple functions; it is important to consider naming conventions for each section and button when modeling the device. A well-thought and unified naming convention can facilitate future development and provide a well-structured hierarchy for the model. The naming convention that was adopted for the model involves capitalizing the first character of each word in the original name of the part and using an underscore when additional information is needed. For example (Figure 3), the name of the

power supply panel is *PowerSupply*, and each component in the power supply panel was grouped under the power supply panel.

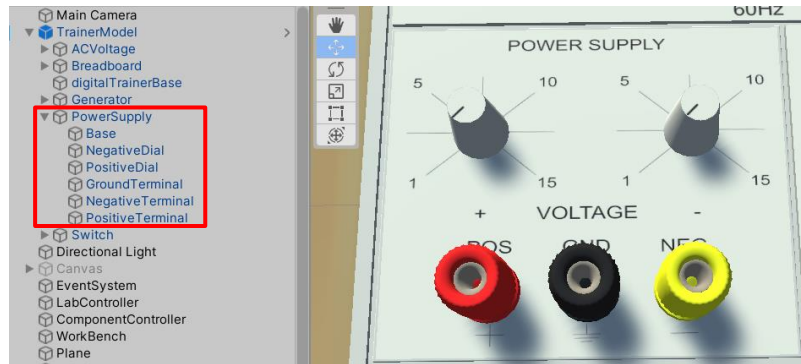


Figure 3. Naming convention and model hierarchy

This creates a clear and readable naming structure that makes it easy for developers to understand the purpose of each component and button in the model. The use of underscores also allows for additional information to be added to the names in a consistent and organized manner, which is especially important for large and complex models. Overall, the naming convention helps to improve the readability and maintainability of the model.

SIMULATION OF OSCILLOSCOPE

An oscilloscope is a type of electronic instrument that is used to measure and display electrical signals. Similar to other electronic equipment, oscilloscope can be classified into two categories - analog oscilloscope and digital oscilloscope. Digital oscilloscope can be further classified into digital storage oscilloscope (DSO), digital phosphor oscilloscope (DPO), and digital sampling oscilloscope.

Digital Storage Oscilloscope

This paper simulated a digital storage oscilloscope. A digital storage oscilloscope consists of a screen, which displays the signal being measured, and a set of controls that allow the user to adjust the display and measurement settings. A DSO is able to store the waveform of a signal and analyze it over time, making it useful for identifying problems in electronic circuits such as noise, distortion, and signal loss. A DSO consists of two essential systems: vertical system and horizontal system. The vertical system is the first input stage of a DSO. Its vertical controls allow user to adjust the amplitude and position range of the signal. The horizontal system includes an analog-to-digital converter (ADC) that samples the signal at discrete points in time and converts each sample into a digital value. This process is often referred to as digitizing a signal. The digital values are then stored in memory and processed by the processor to create the waveform display on the screen (Tektronix, 2009).

Sample rate is an important factor that determines the accuracy and resolution of the waveform display on a digital oscilloscope. The sample rate is the number of samples that the ADC takes per second and is typically measured in samples per second (S/s). The higher the sample rate, the more accurately the waveform of the signal can be captured and displayed. However, higher sample rates also require more processing power and memory, which can impact the performance of the oscilloscope. The sample rate is often determined in the horizontal system, as it determines how often the ADC takes a sample of the waveform (Tektronix, 2009). It is important to choose an appropriate sample rate based on the characteristics of the signal being measured and the requirements of the measurement.

The device modeled is TBS-1000C series (TBS-1052C) from Tektronix. It has two input channels, and all channels have 1 GS/s sample rate. The TBS-1052C is a 50 MHz bandwidth model, and it has a maximum of 20k point record length on all channels. In this model, the sample rate is automatically adjusted based on the time scale and the record length that user selected. The autose function on the modeled oscilloscope can also automatically determine the sample rate based on the input signal.

The autoset function on an oscilloscope automatically adjusting the oscilloscope's settings to optimize the display of the signal. This typically includes setting the correct vertical and horizontal scale. The exact method of autoset may vary between different oscilloscope models. We observed and recorded the sample rate when utilizing the autoset function, part of the observations are showed in Table 1. The record length options of TBS-1052C are 20k, 2000, and 1000. Based on different record length, the oscilloscope analyzes input signal and determines the sample rate and time scale parameters.

Table 1. Sampling rates used by the autoset function

Record Length	AutoSet								
	20k			2000			1000		
	Time Scale	Sample Rate	Autoset Total Record Time Length	Time Scale	Sample Rate	Autoset Total Record Time Length	Time Scale	Sample Rate	Autoset Total Record Time Length
555KHz	1 μ s	1.00GS/s	20 μ s	1 μ s	125MS/s	16 μ s	1 μ s	62.4MS/s	16 μ s
278KHz	1 μ s	1.00GS/s	20 μ s	1 μ s	125MS/s	16 μ s	1 μ s	62.4MS/s	16 μ s
277KHz	2 μ s	500MS/s	40 μ s	2 μ s	62.5MS/s	32 μ s	2 μ s	31.2MS/s	32 μ s
119KHz	2 μ s	500MS/s	40 μ s	2 μ s	62.5MS/s	32 μ s	2 μ s	31.2MS/s	32 μ s
118KHz	4 μ s	250MS/s	80 μ s	4 μ s	31.2MS/s	64 μ s	4 μ s	15.6MS/s	64 μ s
56kHz	4 μ s	250MS/s	80 μ s	4 μ s	31.2MS/s	64 μ s	4 μ s	15.6MS/s	64 μ s
55kHz	10 μ s	125MS/s	160 μ s	10 μ s	12.5MS/s	160 μ s	10 μ s	6.25MS/s	160 μ s
28kHz	10 μ s	125MS/s	160 μ s	10 μ s	12.5MS/s	160 μ s	10 μ s	6.25MS/s	160 μ s
27.5kHz	20 μ s	62.5MS/s	320 μ s	20 μ s	6.25MS/s	320 μ s	20 μ s	3.12MS/s	320 μ s
12.0kHz	20 μ s	62.5MS/s	320 μ s	20 μ s	6.25MS/s	320 μ s	20 μ s	3.12MS/s	320 μ s
11.90kHz	40 μ s	31.2MS/s	640 μ s	40 μ s	3.12MS/s	640 μ s	40 μ s	1.56MS/s	640 μ s
5.55kHz	40 μ s	31.2MS/s	640 μ s	40 μ s	3.12MS/s	640 μ s	40 μ s	1.56MS/s	640 μ s

3D Model of the Oscilloscope

Figure 4 shows the 3D model of TBS-1052C we generated using Maya. To make it easy to develop the interactive elements of the model, all buttons and knobs have been modeled independently and are interactable or operable mesh parts. The ability to manipulate these controls independently allows the user to interact with them and allows for more flexibility in the testing and experiment.

In the virtual lab we are developing, several essential functions are necessary for users to be able to use the virtual oscilloscope, including adjusting the vertical system, horizontal system, selecting autoset button, and observing the waveform on the display.

In order to accomplish these needs, the simulation of oscilloscope was separated into two major components: one component is to sample the input signal and the other is to handle the waveform display. The signal sampling component samples the input signal according to the sample rate and stores the sampled point into an array for the waveform display component to display. The waveform display component was responsible for displaying the sampled signal on the virtual oscilloscope's display. We used Unity's built-in graphics capabilities to render the waveform in real-time and project the waveform to the virtual display. The implemented features also include adjustable vertical and horizontal scaling, as well as the ability to trigger the display based on the input signal.

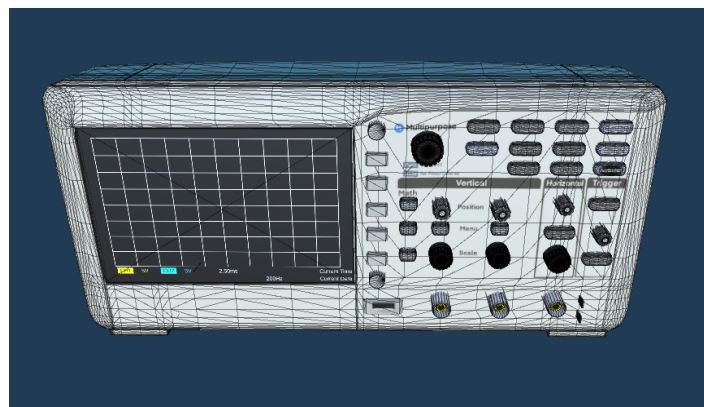


Figure 4. 3D model of the TBS-1000C

SIMULATION OF FUNCTION GENERATOR

A function generator is an electronic instrument that is commonly used in electronic laboratories to generate signals of various shapes and frequencies. One of the most common types of waveforms generated by a function generator is the sine wave, which is a smooth, periodic waveform that oscillates between positive and negative values. Other common waveforms include square waves, which have a sharp transition between high and low levels, and triangle waves, which have a linear rise and fall. These signals can be used to test and troubleshoot electronic circuits, as well as to analyze the frequency response and other characteristics of these circuits.

The 3D model of the function generator was generated based on a device from GW Instek of the GFG-8200A product family (GFG-8215A) shows in Figure 5. Similar to the 3D model of the oscilloscope, all knobs and buttons on the function generator are modeled independently for user interaction. This device has the frequency range of 0.3 Hz to 3 MHz. In the virtual lab we are developing, several essential functions are necessary for students to be able to use the virtual function generation effectively. These functions include adjusting the frequency dial and frequency button to select the desired frequency, changing the frequency of the signal being generated, switching between different waveform shapes, and powering the device on and off. In our implementation, users are able to adjust the output frequency of the generator by using the frequency button and dragging the frequency knob on the left side of the model. They can also click the waveform button to select the desired output waveform. This allows users to easily fine-tune the virtual function generator's output to meet their specific requirements. Additionally, same to its real-world twin, the virtual function generator provides visual feedback to the user through light indicators on top of each button. When a button is clicked, the corresponding light indicator turns green, which allows the user to confirm their selections quickly and easily. This feature provides a clear and intuitive way to monitor the generator's settings and status, allowing students to focus on their work without being distracted by the need to constantly check the settings.



Figure 5. 3D model of the function generator

To represent these signals and keep the signal integrity on the virtual function generator, we use equations to describe the shape and behavior of the signal instead of generating voltage value directly. For example, the equation for a sine wave is $y = A\sin(2\pi ft + \varphi)$, where y is the output signal, A is the amplitude of the signal, f is the frequency of the signal, t is time, and φ is phase shift. This equation describes how the signal oscillates with respect to time. Figure 6 shows a sine wave signal with frequency of 300 Hz.

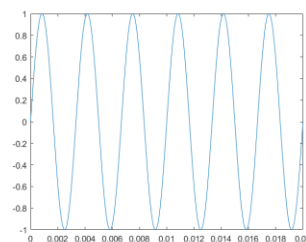


Figure 6. Sine wave signal at 300 Hz frequency

In a virtual function generator, an interface was provided to signal acquirer, in this case, the virtual oscilloscope. Depending on the frequency and waveform selected by the user, the virtual function generator switches the equation to which the interface is directed to. The time step t is the input argument and the corresponding y values are calculated and output to the signal acquirer. In summary, by using mathematical equations to represent these signals, we can overcome the discrete nature of computing systems and ensure signal integrity. Virtual function generators provide a convenient and cost-effective way to generate these signals, allowing users to perform experiments and analyze results from anywhere with the virtual lab.

As the signal was represented by a mathematical equation, Sampling Theorem can be followed without additional programming. The Sampling Theorem states that a signal can be perfectly reconstructed if it is sampled at a rate greater than twice its highest frequency component (Shannon, 1949). This means that if the student accidentally chooses an incorrect sample rate, the signal acquirer will provide a time step t that is not suitable for the input signal, resulting in incorrect sample points generated by the oscilloscope and leading to an inability to reconstruct the original signal.

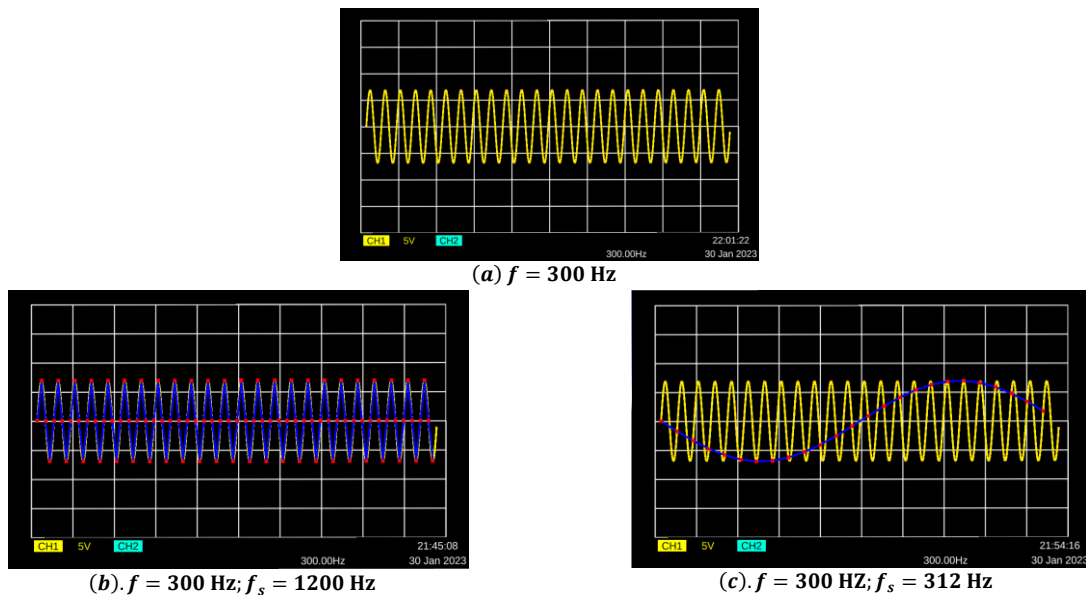


Figure 7. Testing of Sampling Theorem on virtual oscilloscope

The Sampling Theorem can be demonstrated by comparing the sampled signals in different sample rate, as shown in Figure 7. The well-constructed waveform is displayed in yellow, which is automatically generated when user use the autosest function of the oscilloscope. The blue waveform shows the reconstructed signal when different sampling rate was adopted, which should closely match the original signal if the Sampling Theorem is being followed. And the red dots represent the sample points in that sampling rate. In this way, the virtual oscilloscope and function generator closely simulated the real-world scenario, allowing students to gain a deeper understanding of how digital signals are processed and how to properly sample signals in real-world applications.

As mentioned previously, The TBS-1052C oscilloscope has an autosest function that automatically sets the sample rate and time scale based on the features of the input signal for an optimized display. Thus, when the user clicks the autosest button in the virtual oscilloscope, the program identifies which frequency range the output frequency of the virtual function generator lies in and sets the appropriate sample rate and time scale accordingly.

INTERACTION MACHANISM BETWEEN DEVICES

Other than the modeling and simulation of these devices, we are also focusing on the interaction mechanism between there devices (Figure 8). In order to maintain low coupling in the virtual lab, we used C# delegates to implement the interaction mechanism between devices. This means that the different electronic instrument of the virtual lab, such as

the virtual oscilloscope and function generator, can communicate and interact with each other without having a direct, tightly coupled relationship.

C# delegates are a powerful programming technique that are used to implement the interfacing between devices in virtual lab. Delegates represents a method or function, and it can be used to pass methods as arguments to other methods. In the case of virtual lab, delegates can be used to transfer information between simulated electronic devices through the occurrence of events. This allows for communication between devices with low coupling and enables the virtual device to behave in a similar way to a real device.

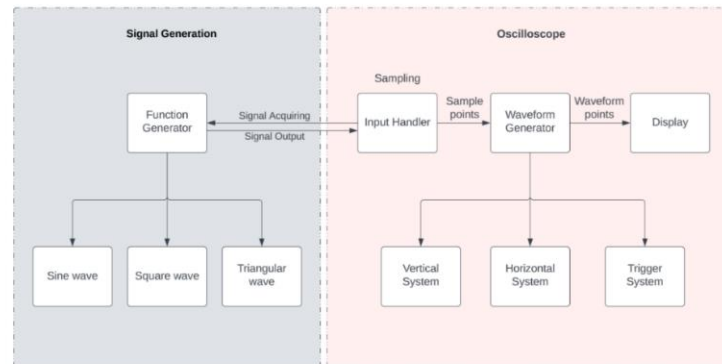


Figure 8. Devices interaction flow

In a computer-based simulation, it is important to ensure that resource usage is optimized to prevent unnecessary wastage. This is particularly important when it comes to the interaction between the signal generator and oscilloscope, as these two devices are constantly running in real scenario, which can place a significant computational cost if simulated in such way. To optimize resource usage, we have implemented a mechanism that ensures the calculations are only performed when necessary. This mechanism involves a two-way communication between the oscilloscope and function generator, with events being triggered by each device to initiate the necessary actions. For example, when the user adjusts the frequency on the function generator, a frequency changed event is triggered, and the oscilloscope is notified to re-acquire and redisplay the signal. This ensures that the oscilloscope is only acquiring new samples when it is necessary to do so, rather than constantly acquiring new samples regardless of whether the user has made any changes. Similarly, when the user adjusts the vertical or horizontal systems on the oscilloscope, the oscilloscope triggers an event to acquire new sets of sample points, this event initiates a call to the appropriate method on the function generator, ensuring that the function generator is only generating signals when necessary. Overall, the use of this optimization mechanism allows the virtual laboratory to function more efficiently and effectively, while also reducing computational cost. By ensuring that calculations are only performed when necessary, we can make the most usage of the available resources and provide a more realistic and engaging virtual laboratory experience for students. Additionally, adopting C# delegates to implement the interfacing between devices in a virtual lab is a highly effective and efficient approach that ensures smooth and reliable communication between devices. Noticing that different from its real-world counterpart, the virtual function generator only outputs signal when there is a signal acquirer.

The interaction between user and virtual lab was implemented using delegates as well. This implementation aims to ensure that the user interface (user interaction components) is separated from the core part of the virtual lab and allows for more flexibility in the development process, as any changes to the user interface can be made without affecting the underlying functionality of the virtual lab. Figure 9 shows the user interface of the virtual lab.



Figure 9. The user interface of the virtual lab

CONCLUSIONS AND FUTURE WORK

This paper described the current work on developing computer models of electronic instruments and devices for virtual lab. Specifically, it described the modeling and simulation of virtual oscilloscope and function generator. This paper also presented the interaction mechanism between these virtual instruments. By simulating real-world electronic instruments and devices, students are able to conduct experiments and gain hands-on experience with the same equipment they would use in a traditional laboratory setting.

The future work of this project will include the simulation of Digital Multimeter (DMM), the integration and communication between existing and newly added electrical devices, as well as the implementation for different labs.

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