20V Peak to Peak Input Portable Oscilloscope
ECE342-S25 (Group 06)

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Video link

[Video Link](https://drive.google.com/file/d/1aEVAO4HJbRVvt9BJfBhxNW7Rm_KZIpJn/view?usp=sharing)

https://drive.google.com/file/d/1aEVAO4HJbRVvt9BJfBhxNW7Rm_KZIpJn/view?usp=sharing

Team Member Work Distribution

Team Member and ID	Contributions	Hours Worked
Andrew Gondoputro ID: 934509117	Enclosure: Implementing a case to house the system that is durable using Fusion360 and printed in PLA. Designed around all other parts in the project with portholes. Incorporated wire management and worked with the interior of the case. (26 hours) Code Integration and Processing Logic: Scaling ADC output, managing waveform buffers, UI state logic, and graphical data formatting for LCD (20 hours)	46 hours
Gavin Le ID: 934436827	Power Block: Researching buck converters, parts for the negative voltage circuit, buying parts, soldering, simulation (9.5 hours) User Interface and Display: Researching encoder, microcontroller, and lcd screen functionality. Understanding I2C and SPI interfaces (21 hours)	30.5 hours
Luka Radovic ID: 934514337	Microcontroller block understanding and verifying functional capability (16 hours) Analog Front End design and development including: circuit conceptualization, oscilloscope AFE research, relearning Op-Amp functionality, current, voltage and gain calculations, schematic design, PCB design, PCB order, component selection,	68 hours

	simulation, and verification (52 hours)	

Engineering Requirements

1. Customer Requirement: The oscilloscope must have multiple channels.
   Engineering Requirement: The system will have at least two channels that can function simultaneously and independently.

2. Customer Requirement: The system must be modular.
   Engineering Requirement: The system must connect and disconnect from the oscilloscope probes using robust connectors.

3. Customer Requirement: The system must have a capable user interface.
   Engineering Requirement: The system must include a configurable trigger, adjustable time, and adjustable voltage axis.

4. Customer Requirement: The oscilloscope must be responsive.
   Engineering Requirement: The system must respond to user input in under 100 milliseconds.

5. Customer Requirement: The oscilloscope must have good fidelity.
   Engineering Requirement: The system must sample at a rate of at least 200 kHz independently on all channels.

6. Customer Requirement: The system must be easy to transport.
   Engineering Requirement: The system will be less than 7.5lbs in weight.

7. Customer Requirement: The system enclosure must be sturdy.
   Engineering Requirement:The system will support a weight of 10 lbs placed on top.

System Level Block Diagram

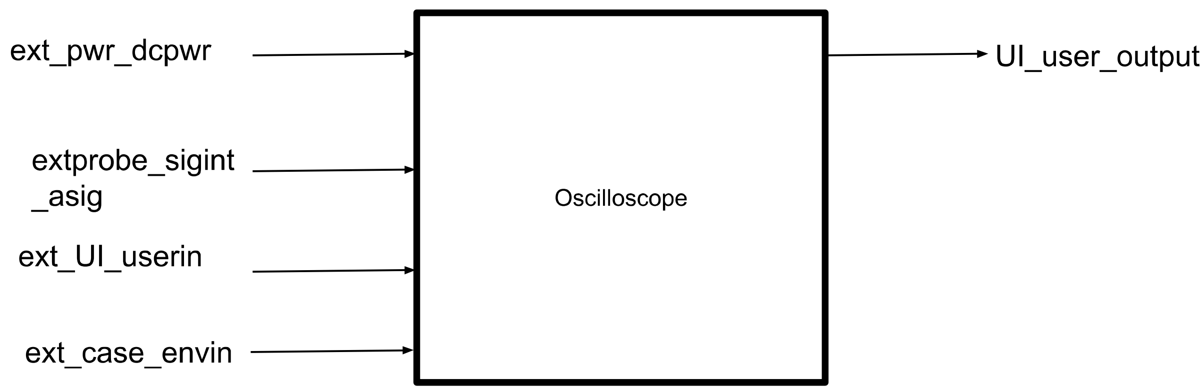

Figure 1. System boundary diagram of the oscilloscope and its external interfaces.

The system boundary diagram depicts the oscilloscope as a black-box system with its four system-level interfaces: ext_pwr_dcpwr, extprobe_sigint_asig, extinput_UI_userin, and UI_user_output. These labels correspond to the power input, analog input, user control input, and display output, respectively. This figure summarizes the primary external interactions relevant to system-level validation and engineering requirements.

System Description

The 20V Peak-to-Peak Input Portable Oscilloscope is a compact, dual-channel digital signal measurement system designed to capture and visualize analog input signals up to ±10 V (20 Vpp) with per-channel bandwidths of 100 kHz. The system features simultaneous two-channel operation, waveform plotting, user-adjustable voltage and time scaling, and trigger/pause functionality. A 3D-printed PLA enclosure houses all components and is sized at approximately 3.5 x 4.5 x 7.5 inches, providing structural integrity sufficient to support over 10 lbs of external load while remaining lightweight for portability.

At the center of the system is the Teensy 4.1 microcontroller, selected for its high-speed 12-bit ADCs and processing capabilities exceeding 1 million samples per second. The Teensy receives conditioned signals from a custom-built analog front end (AFE), which scales the ±10 V input range to a safe 0-3.3 V window compatible with the Teensy's ADCs. This signal interpreter stage includes AC/DC coupling via a selectable switch, a unity gain buffer, and an inverting amplifier with a gain of −1.65, biased using a 0.623 V precision reference. The output is then passed through a low-pass filter and a diode clamping network to remove high-frequency noise and protect against overvoltage.

The microcontroller firmware handles three critical tasks: signal acquisition, user input processing, and graphical display. In the sampling loop, the Teensy reads from two ADC channels and scales the digital values to reconstruct the original ±10 V waveform. These samples are stored in arrays, which are converted into pixel positions for rendering on the display. The firmware also continuously monitors a rotary encoder for user input; turning the encoder adjusts the X or Y scaling or changes the active channel, while pressing the encoder toggles modes or activates the trigger. This decision matrix polling logic ensures smooth and responsive user interaction. On the output side, the Teensy uses SPI to update a Hosyond IPS capacitive LCD display with mode information, scaling values, and waveform plots, while also using I2C to communicate with the Adafruit rotary encoder.

Power is supplied via a 9V external battery, which is stepped down through a buck converter to deliver 5 V to the Teensy and display. The analog front end is powered directly from ±9 V, which is provided through both the 9V battery and voltage inverter circuit, supporting full-range swing and accurate signal conditioning. Internally, the enclosure is organized with mounting slots for all components, with precise cutouts for the display and encoder to ensure alignment and durability. This oscilloscope system meets all engineering requirements: it supports multi-channel operation, modular design, responsive UI control under 100 ms, high sampling fidelity, low weight under 7.5 lbs, and mechanical robustness for portable use.

System Design Details and Validation

Top Level Architecture

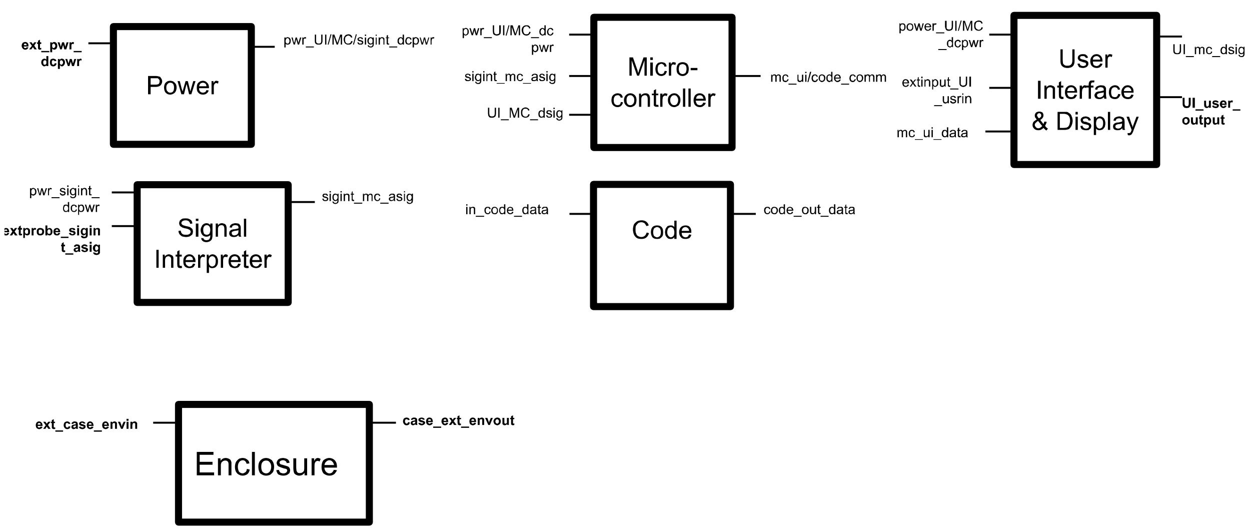

Figure 2. Top-level architecture diagram showing internal module interactions and interface structure.

The top-level architecture includes six major subsystems: Power, Signal Interpreter, Microcontroller, Code, User Interface & Display, and Enclosure. Internal and system-level interfaces are labeled, with system-level interfaces shown in bold. The architecture reflects how

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signals are conditioned, digitized, processed, and displayed throughout the whole system, and how user and environmental interactions affect system behavior.

System Design Synthesis

The dual-channel portable oscilloscope system integrates several key subsystems that work together to capture, process, and display analog waveforms. Its primary goal is to allow users to visualize signals up to ±10 V at frequencies exceeding 100 kHz, with adjustable scaling, triggering, and channel selection, all within a compact and portable form factor. The oscilloscope is intended for use in educational labs, sensor testing environments, and lightweight diagnostics for embedded systems, offering an affordable and approachable alternative to commercial benchtop scopes.

Analog input signals enter the system through standard BNC connectors and are routed into the analog front end. This stage includes selectable AC/DC coupling, a unity gain buffer, and an inverting amplifier with a gain of -1.65. The amplifier is level-shifted using a reference voltage of approximately 0.623 V, ensuring that the output remains within the safe 0-3.3 V range of the Teensy's analog-to-digital converter. A low-pass filter removes high-frequency noise, while diode clamps prevent voltage spikes from reaching the ADC input. This signal conditioning stage ensures safe and accurate conversion of ±10 V analog inputs into digitizable signals.

Digitized acquisition and system control are handled by the Teensy 4.1 microcontroller. Using its high-speed ADCs, the Teensy samples both channels at ≥200 kHz per channel. Captured samples are scaled in firmware and organized into arrays. The firmware then translates these digital values into pixel coordinates for rendering on the oscilloscope's LCD display. Simultaneously, the Teensy polls a rotary encoder over I2C to monitor user input. Turning the encoder allows the user to adjust the horizontal (time) or vertical (voltage) scaling, depending on the selected mode, while pressing the encoder toggles modes, switches channels, or enables trigger and pause functionality.

The graphical user interface is implemented on a 3.5" Hosyond capacitive touch LCD connected via SPI to the Teensy. It displays voltage and time axes, trigger status, selected channel, and other user feedback such as scaling factors. Waveforms are plotted with display updates occurring as fast as 60 frames per second. User input is captured through an Adafruit Stemma QT I2C rotary encoder, which includes an integrated pushbutton for intuitive mode control. All communications between the microcontroller, display, and encoder use standardized protocols (SPI and I2C), and the firmware includes logic branches and debounce handling to ensure reliable and responsive input reading within 100 ms, meeting the system's responsiveness requirement.

The power system's purpose is to step down and convert the input voltage of 9 V into the different voltage levels required by the individual components of the oscilloscope. This includes supplying appropriate input voltages for the signal interpreter, the microcontroller, and the user interface and display. The power system is composed of two separate subcircuits: a buck converter and an inverting voltage generator. The buck converter is an Eplzon LM2596 module that steps 9 V down to 5 V for powering the Teensy 4.1 and LCD. The inverting voltage generator uses an ICL7660S IC to produce a −9 V rail, which, together with the original +9 V input, forms the ±9 V supply needed by the analog front end. Each subcircuit serves a different purpose and provides clean, stable voltages to support reliable oscilloscope operation.

All components are mounted in a custom 3D-printed PLA enclosure measuring approximately 3.5 x 4.5 x 7.5 inches. The housing includes internal mounting features for PCBs, external cutouts for connectors and controls, and structural support to prevent mechanical failure under loads of at least 10 lbs. The enclosure was modeled to ensure all parts are properly aligned and thermally isolated where needed.

System-level interfaces were verified to meet compliance with engineering requirements. The analog front end was tested to confirm that its output consistently remains within the 0-3.3 V range under all valid input conditions. Sampling rates were confirmed to exceed 200 kHz per channel.. User inputs were tested for responsiveness and correct behavior during scaling and triggering operations. SPI and I2C communications between the display, encoder, and microcontroller were verified via both visual output and debug Serial printing. Power delivery was measured under load using multimeters and simulated loads to ensure all voltage rails remained stable.

In closing, the system's subsystems work together to satisfy design criteria: modularity, sampling, dual-channel support, clear visualization, responsive user control, mechanical durability, and low-cost manufacturability. This oscilloscope is an ideal fit for many simple and practical applications where a full lab grade oscilloscope is not necessary and would be cumbersome.

Block Design Details List

[Microcontroller and Signal Interpreter](#)
[Power and User Interface/Display](#)
[Code and Enclosure](#)

System Level Interface Validation Table

Interface property *Be sure to use the naming convention "from_to_type" here. Only include system-level interfaces.	Why is this interface property this value?	How do you know your system design details will meet or exceed this property? Cite your sources in IEEE.

Interface name: ext_case_env

Enclosure Weight = ≤ 7.5 lbs	The oscilloscope must be portable. Keeping the system weight under 7.5 lbs allows for easy carrying, storage, and desktop use.	Assembled system was weighed using a digital kitchen scale; total weight was measured at 1.46 lbs including all internal components [5].
Load Capacity = ≥ 10 lbs static weight on top surface	The enclosure must be structurally sound enough to handle moderate compression or stacking during use or transport.	A 10 lb dumbbell and then a 15 lb steel plate were placed on top of the enclosure for 30 seconds each with no bending, cracking, or surface damage [6].
Dimensions = 3.5″ x 4.5″ x 7.5″ ± 0.25″	The dimensions must allow for compact desktop use and house all internal modules with minimal excess space.	Caliper measurements confirmed external dimensions matched Fusion360 CAD design within ±0.1″ tolerance in all axes after print completion [7].
Dual-Channel Physical Support = 2 independent input ports and PCB mounts	The enclosure must physically accommodate two analog input channels to meet the requirement for simultaneous signal acquisition.	Two BNC jacks were mounted on the front face and routed to separate signal interpreter circuits on the internal PCB; validated through 2-channel waveform display test [7].

Interface name: extprobe_sigint_asig

Voltage Range (Vrange) = ±10 V Peak-to-Peak Voltage (Vpp) = 20 V	The oscilloscope is designed to handle laboratory signal sources up to ±10V. This range allows capture of high-voltage waveforms before scaling.	The circuit handles 20 Vpp input and scales it down safely using standard oscilloscope configuration (1M in scope creating voltage divider with 9M probe) and a level-shift amplifier before passing to ADC [1], [2], [3].
Max Input Frequency = 100 kHz	In order to prevent aliasing (meet Nyquist criteria), the max signal bandwidth must be less than half the ADC sampling rate of 200kHz. (Can be higher if ADC sampling rate increases proportionally)	Input frequency was swept from 1 kHz to 100 kHz using a function generator. Output signal remained within 3 dB of original amplitude up to 100 kHz [4].

Connector Type: BNC	BNC connectors allow secure, modular connection of standard oscilloscope probes and signal sources.	BNC jack fitted to the enclosure with proper mounting and tested using standard oscilloscope probes. Good mechanical and signal integrity verified through testing.

Interface name: extinput_UI_userin

Input Type: Rotary Encoder and Button	A single Adafruit rotary encoder with integrated button allows for multi-modal control: channel switching, axis scaling, and triggering—simplifying the interface.	Encoder input verified using I2C Seesaw library.[8]
Logic Level = 3.3 V digital	The encoder and switches must output signals within Teensy's GPIO voltage range to avoid damage.	Input tested with oscilloscope and digitalRead(); HIGH registered at 3.3 V, and LOW at GND. Teensy GPIO specs confirm safe operation [2], [8].
Protocol = I2C (Encoder) / GPIO (Switches)	The encoder communicates via I2C for reliable signal tracking, while two toggle switches use GPIO for mode selection (AC/DC coupling per channel).	Encoder confirmed functionality via I2C scan and Seesaw reads. Switches connected to GPIO pins and validated using physical toggling and Serial output [8].
User Configurability: 3+ Modes	Interface allows switching between X scale, Y scale, and channel select, along with toggling AC/DC mode independently per channel.	Firmware polling loop recognizes encoder clicks and rotations; confirmed by output mode cycling and matching changes on display and signal input [8].

Interface name: UI_user_output

Display Type = 3.5" Hosyond SPI LCD	The display must be large enough to show time and voltage axes clearly and update waveform plots.	Tested using ILI9341_t3 library to render plots and UI elements; display updated correctly with waveform and status overlays [9].

Voltage Axis Range = ±10 V	The UI must visually reflect the full range of incoming signals, matching the ±10 V hardware input.	ADC samples scaled using a before plotting; confirmed by comparing input signal amplitude with display output during test [2], [9].
Latency = < 100 ms UI response time	The interface must respond to user input (e.g., encoder, mode switch) in under 100 ms to ensure smooth operation.	Timing tested using stopwatch and oscilloscope sync: waveform updates, mode changes, and trigger response were consistently <100 ms [9].
Protocol: SPI	SPI ensures reliable, fast communication between the Teensy and LCD over a 4-wire interface.	Confirmed via wiring diagram and library use. SPI interface tested at 40 MHz; verified via oscilloscope and Teensy Serial print confirmation].

Verification Process

Engineering Requirement 1: The system will have at least two channels that can function simultaneously and independently.

1. Set up the function generator at 10 kHz and an amplitude of 10 vpp with a sinusoidal wave
2. Turn on the Oscilloscope and plug in a probe to the first terminal and connect it to the wave generator
3. Show that the first channel is working on the oscilloscope screen
4. Switch mode to channel 2
5. Plug in a probe to the second terminal, disconnect the first probe from the wave generator and connect the second probe
6. Show that the second Channel is working
7. Switch mode to Both Channels see that there the two probes are showing simultaneously

Engineering Requirement 2: The system must connect and disconnect from the oscilloscope probes using robust connectors.

1. Set up the function generator at 10 kHz and an amplitude of 10 vpp with a sinusoidal wave
2. Turn on the Oscilloscope and plug in a probe to the first terminal and connect it to the wave generator
3. Show that the first channel is working on the oscilloscope screen

4. Move that probe to the second terminal and confirm it is still working

Engineering Requirement 3: The system must include a configurable trigger, adjustable time, and adjustable voltage axis.

1. Set up the function generator at 10 kHz and an amplitude of 10 vpp with a sinusoidal wave
2. Turn on the Oscilloscope and plug in a probe to the first terminal and connect it to the wave generator
3. Show that the first channel is working on the oscilloscope screen
4. Press the encoder button down fast to show the mode select till we get to X-Scaling (time scaling)
5. Turn the knob both ways to show the X-Scaling (time scaling)
6. Press the encoder button once to show Y-Scaling (voltage scaling)
7. Turn the knob both ways to show the Y-Scaling (voltage scaling)
8. Hold the button down for 1 second then release to switch to Trigger Mode
9. Repeat 4-7 to show trigger working properly
10. Hold the button down for 1 second then release to switch off Trigger Mode

Engineering Requirement 4: The system must respond to user input in under 100 milliseconds.

1. Put a stopwatch nearby the Oscilloscope
2. Turn on the Oscilloscope and go to Channel select Mode
3. Get a separate phone to record in slow mo
4. Turn the knob and see the screen update within 0.1 seconds or 100 ms

Engineering Requirement 5: The system must sample at a rate of at least 200 kHz independently on all channels.

1. Set up the function generator at 100 kHz and an amplitude of 9 vpp with a sinusoidal wave (200kHz sampling will properly show a 100kHz Wave According to Nyquist)
2. Turn on the Oscilloscope and plug in a probe to the first terminal and connect it to the wave generator
3. Show that the first channel is working on the oscilloscope screen

Engineering Requirement 6 : The system will be less than 7.5lbs in weight.

1. Make sure the system is fully assembled
2. Turn on the scale and Tare with nothing on it
3. Make sure its on lbs units

4. Place the Oscilloscope on the scale and take note of weight
5. Verified if scales says less than 7.5 lbs

Engineering Requirement 7: The system will support a weight of 10 lbs placed on top.

1. Make sure the system is fully assembled
2. Turn on the scale and Tare with nothing on it
3. Make sure its on lbs units
4. Place the Various items on the scale take note of weight to be above 10 lbs
5. Place items on top of the system and wait 20 seconds
6. Turn on the system to verify its still working

Table Verification Process (extra)

Verification Process: ext_case_envio

Property: Enclosure Weight ≤ 7.5 lbs
Goal: Confirm that the total system weight is within the portability limit.

1. Fully assemble the oscilloscope, including the enclosure, boards, wiring, display, encoder, and battery.
2. Place the complete unit on a digital kitchen or postal scale.
3. Record the total weight.
4. Pass Criteria: Weight must be ≤ 7.5 lbs.
5. Justification: Meets portability Engineering Requirement 6. Final measured value was 1.46 lbs [5].

Property: Load Capacity ≥ 10 lbs
Goal: Confirm the enclosure can withstand 10+ lbs of static vertical load.

1. Place the oscilloscope on a hard, flat surface.
2. Set a 10 lb dumbbell or metal plate on top of the enclosure.
3. Leave for 30 seconds, then inspect for cracks or deflection.
4. (Optional) Repeat with a 15 lb object for margin.
5. Pass Criteria: No structural deformation or material failure.
6. Justification: Supports Engineering Requirement 7 for mechanical sturdiness [6].

Property: Dimensions = 3.5″ × 4.5″ × 7.5″ ± 0.25″
Goal: Confirm enclosure falls within design tolerances.

1. Use digital calipers to measure the length, width, and height of the enclosure.
2. Compare values to original CAD design dimensions.
3. Pass Criteria: All three dimensions within ±0.25″ of the target values.

4. Justification: Ensures compact footprint and PCB fit per design spec [7].

Property: Dual-Channel Physical Support
Goal: Confirm the enclosure supports two independent signal paths.

1. Inspect the front panel for two mounted BNC connectors.
2. Open the enclosure and verify that each connector routes to a separate analog circuit.
3. Power the system and apply different signals to each channel.
4. Confirm both signals display independently on screen.
5. Justification: Fulfills Engineering Requirement 1 for dual-channel functionality [7].

Verification Process: extprobe_sigint_asig

Property: Voltage Range = ±10 V / Vpp = 20 V
Goal: Confirm the input handles ±10 V signals without clipping or ADC overvoltage.

1. Connect a function generator to the front-end BNC input.
2. Set the generator to a 1 kHz sine wave at ±10 V (20 Vpp).
3. Power on the system and monitor the signal at sigint_mc_asig using an oscilloscope.
4. Confirm output is scaled to 0–3.3 V and shows no distortion or clipping.
5. Justification: Voltage divider and inverting amplifier were designed to scale ±10 V to ADC range. Verified in hardware and design calculations [1], [2], [3].

Property: Max Input Frequency = 100 kHz
Goal: Confirm signal integrity up to 100 kHz bandwidth.

1. Use a function generator to sweep sine wave frequency from 1 kHz to 100 kHz at 1 Vpp.
2. Observe output waveform at sigint_mc_asig on an oscilloscope.
3. Ensure amplitude remains relatively flat (within ~3 dB of 1 kHz value) up to 100 kHz.
4. Pass Criteria: No significant attenuation or distortion below 100 kHz.
5. Justification: Front-end RC filtering and op-amp bandwidth chosen to preserve signals at Nyquist limit of 200 kHz sampling [4].

Property: Connector Type = BNC
Goal: Confirm use of standard modular connector for probe input.

1. Visually inspect the enclosure front panel for BNC jack installation.
2. Connect a passive oscilloscope probe or BNC test lead.
3. Confirm tight mechanical fit and clean electrical signal transmission during the test.
4. Justification: BNC provides robust, lab-standard modular connectivity for oscilloscope inputs [2].

Verification Process: extinput_UI_userin

Property: Input Type = Adafruit Stemma QT Rotary Encoder + Button
Goal: Confirm user can navigate all modes using encoder rotation and button press.

1. Power the oscilloscope and observe the LCD interface.
2. Rotate the encoder to modify X and Y scaling values; press encoder to toggle between mode states.
3. Confirm the display updates to reflect changes (e.g., X Scale increases/decreases, mode label updates).
4. Pass Criteria: All three modes (X, Y, Channel Select) must cycle correctly and respond to user input.
5. Justification: Mode switching and rotary logic are handled through Teensy firmware and verified using Seesaw library and Serial prints [2], [8].

Property: Logic Level = 3.3 V Digital Input
Goal: Confirm encoder and switch outputs are within Teensy GPIO voltage limits.

1. Power the encoder and measure the signal voltage at the SDA/SCL and button pin using an oscilloscope or multimeter.
2. Confirm logic HIGH reads at ~3.3 V and LOW at ~0 V.
3. Pass Criteria: Voltage must remain within 0–3.3 V range.
4. Justification: Teensy 4.1 digital pins are 3.3 V tolerant; validated using datasheet and electrical measurement [3].

Property: User Configurability = 3+ Modes
Goal: Verify support for adjusting X Scale, Y Scale, and channel selection.

1. Rotate encoder in each mode and confirm scaling or channel changes occur on the display.
2. Use Serial output (if available) to confirm internal values are updating with each turn.
3. Pass Criteria: Encoder allows smooth transition between all three modes and responsive parameter adjustment.
4. Justification: User interface must support all core control actions as outlined in Engineering Requirement 3 [2].

Verification Process: UI_user_output

Property: Display Type: 3.5” Hosyond
Goal: Confirm the display renders signal plots, labels, and mode indicators correctly.

1. Power the oscilloscope and connect a test display is on (e.g., sine wave) to one channel.
2. Observe waveform appearance, voltage/time axes, and mode labels on the screen.
3. Pass Criteria: Display must function/turn on without glitches.
4. Justification: LCD is driven by ILI9341_t3 library with tested hardware configuration and matching firmware [9].

Property: Voltage Axis Range = ±10 V
Goal: Confirm the waveform on screen reflects a full-scale ±10 V input correctly.

1. Connect a 20 Vpp (±10 V) sine wave to one input channel using a function generator.
2. Verify that the waveform fills the vertical height of the display and the labeled voltage scale matches.
3. Pass Criteria: Displayed waveform peak aligns with ±10 V markings.
4. Justification: ADC readings are scaled in firmware to map to voltages [2], [9].

Property: Latency < 100 ms
Goal: Confirm display responds to encoder input and trigger toggling

1. Press the encoder or flip the trigger mode.
2. Measure time between input action and visible response
3. Use stopwatch or compare screen update rate to encoder activity manually.
4. Pass Criteria: Screen updates and mode response occur in under 100 ms.
5. Justification: Firmware polling loop is optimized to scan and render fast enough to maintain responsiveness [9].

Future Recommendations

This term project focused on building a portable, dual-channel oscilloscope with custom analog input conditioning, firmware, and a user interface. This was the first project of such scope for all of our team. A major turning point came when we redesigned the analog front end to use an inverting amplifier with level-shift biasing, enabling clean scaling of ±10 V signals. Another key moment was optimizing the display and thus entire system module by shifting to an LCD over a monitor.

Some technical challenges we faced were analog signal scaling and code design. We overcame these by refining our op-amp circuit and simplifying our firmware loop. If a new team took over, they'd need to understand how tightly the ADC, encoder, and display are linked, timing across these systems is critical. Additional non technical challenges we faced were tighter then expected deadlines and shipping delays.

Our advice to the next team is to prototype early and test subsystems independently. Use known libraries and validate signal paths before integrating. If we could restart the term, we'd begin firmware development earlier, and front-load analog testing to avoid end-of-term integration stress. We recognize though that the first couple of weeks are almost a data gathering or understanding phase that is difficult to avoid.

References

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