International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 10 | Oct - 2026 SJIF Rating: 8.659 ISSN: 2582-3930

Handheld Oscilloscope Multimeter using Raspberry Pi Pico (RP2040): A Low-Cost, Open-Source Integrated Instrument for Measurement, Waveform Generation and Display

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Abstract: Oscilloscopes, multimeters and function generators are the basic tools of electronics education and field service, but bench-top units are costly, heavy and closed-source, and commercial handheld ScopeMeters cost several thousand dollars. A student therefore usually owns none of them, and a technician usually carries two or three separate devices. To overcome this, we propose a handheld instrument that integrates all three functions in one battery-powered unit built around the Raspberry Pi Pico (RP2040). A voltage-divider front-end with Schottky clamping and a buffer amplifier conditions inputs of 0–30 V for the on-chip 12-bit ADC. One processor core performs sampling and waveform rendering on a 3.5-inch TFT display while the other handles the push-button interface. Sine, square and triangular waveforms of 1 Hz to 10 kHz are generated by filtered PWM, and the multimeter mode measures DC voltage, true-RMS AC voltage, DC current, resistance and continuity.

The prototype costs about USD 25–35. It provides a 20 kHz oscilloscope bandwidth, DC voltage errors of 0.42–0.53% and a current error of 1.3% against a Fluke 87V reference, and runs for four to six hours on one charge.

Keywords: Raspberry Pi Pico, RP2040, handheld oscilloscope, digital multimeter, function generator, embedded instrumentation

I. INTRODUCTION

Electronic instruments that detect, measure and display voltage, current, resistance, frequency and waveform shape are needed at every stage of a product's life, from design and prototyping to production test and field repair. Integrated circuits, microprocessors and FPGAs have made such instruments far more capable over the past decades, yet the three most commonly needed ones, the oscilloscope, the digital multimeter (DMM) and the function generator, are still bought as separate devices. Together they can cost more than USD 1000 per laboratory bench, which is beyond the reach of many students and small institutions.

Portability is a second problem. Bench instruments are large, need mains power and are unsuitable for electrical cabinets, vehicles or rooftop solar sites. Handheld oscilloscopes such as the Hantek 2C72 or SainSmart DSO213 cost USD 50–200 and normally have no multimeter, while integrated ScopeMeters such as the Fluke 199C cost several thousand dollars. Almost all of them are closed-source, so a student cannot study or modify the hardware and firmware, which is an important part of learning instrumentation.

To overcome these problems, this work builds the instrument around a low-cost microcontroller and moves as much of the measurement and user-interface logic as possible into firmware. The objectives are: (i) condition inputs of 0–30 V DC for the 3.3 V ADC, (ii) display waveforms in real time up to about 20 kHz, (iii) measure voltage, current and resistance with an error of about 1% or less, (iv) generate sine, square and triangular waveforms up to 10 kHz, and (v) package the electronics in a battery-powered 3D-printed enclosure that weighs under 200 g.

The main contributions are as follows. First, an integrated oscilloscope, multimeter and function generator is presented on a single RP2040, using the two cores to separate time-critical sampling and rendering from user-interface tasks. Second, a simple analogue front-end and firmware measurement chain are described, including true-RMS computation, automatic ranging and a trigger-based waveform capture. Third, the prototype is evaluated against a calibrated reference instrument on a practical circuit, and its cost and specifications are compared with existing instruments. The rest of the paper is organised as follows. Section II reviews related work, Section III describes the hardware and firmware design, Section IV presents the experimental results, Section V discusses the findings and limitations, and Section VI concludes the paper.

II. LITERATURE REVIEW

As we are working on a low-cost handheld instrument, earlier work on microcontroller-based oscilloscopes and multimeters helped us find the limitations of existing platforms and decide where to focus. Arduino boards [5] were the first widely used platform. The ATmega328P has a 10-bit ADC and samples at only about 9.6 kSPS in normal mode, so the usable bandwidth is a few kilohertz, and with no DMA the processor is fully busy during acquisition and cannot update a display at the same time.

The ESP32 offers 240 MHz dual-core processing, Wi-Fi and a 12-bit ADC. Alvarez et al. [7] built an ESP32 oscilloscope with a 2.8-inch TFT that captured signals up to about 50 kHz and streamed them to a browser, but the ADC non-linearity of up to ±3% of full scale makes it unsuitable for multimeter use without external linearisation. Kumar and Sharma [6] used an STM32F4 at 1 MSa/s with a programmable-gain front-end and reached ±2% accuracy up to 100 kHz, showing that Cortex-M class devices are

adequate for software-defined instruments. At the other extreme, Chen et al. [8] combined a Spartan-6 FPGA with a 125 MSa/s ADC to reach 50 MHz bandwidth, but the component cost exceeded USD 150 and the power use exceeded 2 W, which rules out a small battery-powered unit.

The Raspberry Pi Pico, released in 2021, is built on the RP2040, which has two 133 MHz cores, 264 KB of SRAM, a 12-bit ADC and programmable I/O [1], [2]. Open-source Pico oscilloscopes sample at up to 500 kSPS with a usable bandwidth of 20–50 kHz, and a board costs about USD 4. For the multimeter function, Patil and Desai [9] showed that true-RMS measurement of non-sinusoidal signals needs synchronous detection and digital filtering, although a sigma-delta ADC is too slow for oscilloscope use. Zhang and Li [10] reduced the current of a portable instrument by 40% through adaptive sampling and display dimming, and Rajan et al. [11] found that dedicated push buttons are preferred over touch screens when users wear gloves. The signal-processing, signal-conditioning and circuit theory used here follow [12]–[16]. Table 1 compares representative instruments with the proposed design.

Table 1: Comparison of existing instruments

Instrument	Functions	Bandwidth	Cost (USD)
Fluke 199C ScopeMeter	Scope + DMM	200 MHz	Thousands
Rigol DS1054Z	Scope only	50 MHz	~350
Hantek 2C72 / DSO213	Scope only	Low MHz	50–200
Arduino-based scope [5]	Scope only	A few kHz	Low
ESP32-based scope [7]	Scope only	~50 kHz	Low
Proposed system	**Scope + DMM + FG**	**20 kHz**	**25–35**

No affordable, open-source instrument that combines an oscilloscope, a multimeter and a function generator in one handheld unit was found in the literature. This gap is what the proposed design addresses.

III. PROPOSED METHOD

The proposed instrument divides the work between an analogue domain and a firmware domain. The analogue front-end attenuates, clamps and buffers the input signal. The RP2040 samples it, computes the measurements and renders the result on the TFT, and a PWM channel followed by an RC filter produces the function-generator output. The complete signal flow is shown in Fig. 1.

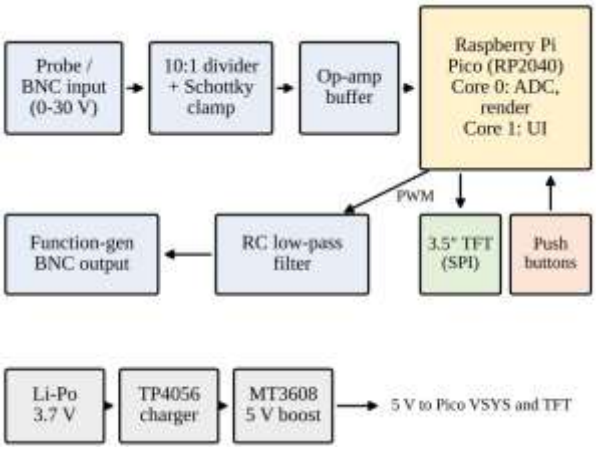


Fig. 1: System block diagram of the handheld oscilloscope multimeter

Design rationale: The design favours affordability, openness and usability over raw bandwidth. A 20 kHz oscilloscope and a 1% multimeter are adequate for audio-frequency, power-supply and sensor circuits, and these are what students and field technicians actually measure. Keeping the hardware simple and placing the signal processing in firmware also keeps the cost low and lets users change the algorithms, which a closed commercial instrument does not allow.

Voltage divider and protection: The input divider uses R1 = 9 Mfi (series combination of standard values) and R2 = 1 Mfi, both 1% metal-film, so that

$$k = R2 / (R1 + R2) = 1/10$$

and the maximum input of 30 V DC is mapped to 3 V at the ADC, leaving 0.3 V of margin. A compensation capacitor in parallel with R2 keeps the response flat against the parasitic capacitance of R1. Two Schottky diodes at the divider output clamp the signal to within one diode drop of the 0 V and 3.3 V rails, so an oversized or reversed input cannot reach the ADC. A 100 fi series resistor limits the clamp current, and a 10 nF capacitor at the ADC pin forms the anti-aliasing and noise filter.

Buffer and ADC interface: A rail-to-rail unity-gain op-amp buffer [20], powered from the 3.3 V rail, keeps the input impedance high and drives the ADC on GPIO26 (ADC0). The RP2040 ADC is a 12-bit SAR converter whose 48 MHz clock divided by 96 gives a maximum rate of 500 kSPS over a 0–3.3 V range [2]. The resolution is therefore 3.3/4095 = 0.81 mV at the ADC pin, which is 8.06 mV referred to the 30 V input.

Dual-core firmware: The firmware is written in the Arduino framework using the arduino-pico core [3]. Core 0 runs the timer-driven ADC sampling and the display rendering, and Core 1 scans and debounces the buttons and updates the parameters (time base, voltage range, mode) that are passed to Core 0 through a mutex-protected shared region, as shown in Fig. 2. This keeps the user interface from disturbing the sampling timing. A top-level state machine switches between oscilloscope, function-

generator, multimeter and settings modes, and each mode has its own nested states.

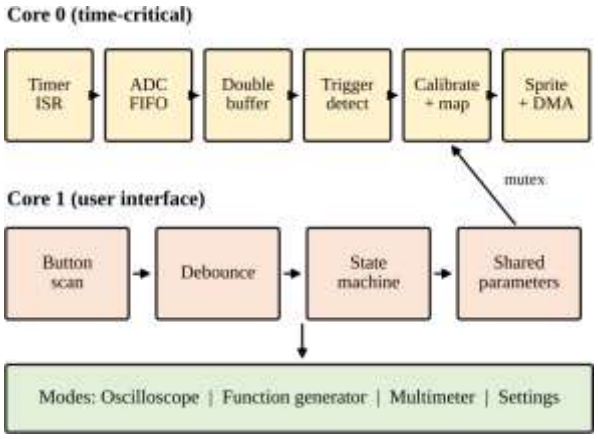


Fig. 2: Dual-core firmware processing pipeline

Oscilloscope mode: A timer interrupt reads the ADC FIFO and stores each raw 12-bit value in a circular buffer without any computation, and two buffers are used alternately so that no samples are lost while one is processed. A level trigger with rising or falling edge selection centres a window of 320 pre-trigger and 320 post-trigger samples on the trigger event. Each sample is converted to a calibrated voltage and then to a pixel row,

$$V = (ADC \times 3.3 / 4095) \times 10 - V_off$$

$$y = y_c - round(V / V_div \times 30)$$

where V_off is the stored offset, V_div is the volts-per-division setting and 30 is the number of pixel rows per division. Time bases run from 50 µs/div to 50 ms/div and voltage scales from 100 mV/div to 10 V/div, both in a 1-2-5 sequence. The firmware also reports peak-to-peak voltage, period, frequency, duty cycle and DC offset, where the frequency is the number of trigger crossings in the window divided by the window length. The tracing loop of one acquisition is given in Algorithm 1.

Algorithm 1: Per-capture oscilloscope loop

1. Start the timer ISR at the sampling rate of the selected time base and fill the active buffer with raw ADC values.
2. When the buffer is full, swap buffers and let the ISR continue filling the other one.
3. Search the full buffer for a crossing of the trigger level in the selected direction; if none is found, show the previous frame and return to step 1.
4. Copy 320 samples before and 320 after the trigger point and convert each to a calibrated voltage.
5. Map each voltage to a pixel row and draw the vertical segment between adjacent samples into the sprite.
6. Compute the automatic measurements, push the sprite to the TFT by DMA and return to step 1.

Display: The 3.5-inch ILI9488 TFT (320 × 480) is driven over SPI0 with the TFT_eSPI library [4], [17] at up to 40 MHz, and the backlight is dimmed by a PWM pin to save energy. The waveform is composed in a 320 × 240 off-screen sprite and sent by a single DMA transfer, which removes flicker and leaves the CPU free for the next capture. The waveform is drawn in green on a dark-grey grid, with a status bar and soft-key labels around it. Table 2 lists the pin assignment.

Table 2: RP2040 pin assignment

Signal	Pin	Connected to
Analogue input	GPIO26 (ADC0)	Buffer output
SPI MOSI	GPIO11	TFT data in
SPI SCK	GPIO10	TFT clock
TFT chip select	GPIO09	TFT CS
TFT data/command	GPIO08	TFT DC
TFT reset	GPIO07	TFT RST
Backlight PWM	GPIO06	TFT BL
Supply input	VSYS	5 V boost output

Function generator: The RP2040 PWM runs at 125 kHz with 16-bit duty resolution, and an RC low-pass filter removes the carrier to leave the wanted waveform [15]. For a sine wave, a 256-entry look-up table in flash is stepped by a timer interrupt and each value is written to the duty register. A square wave toggles the duty between its limits every half period, and a triangular wave ramps it up and down. At higher output frequencies fewer table points are used per cycle so that the update rate stays below the PWM carrier. The frequency is set from 1 Hz to 10 kHz by the up and down buttons, the amplitude is scaled in software up to about 3.3 V peak, and the output is available at a BNC connector.

Multimeter mode: Five functions are provided. For DC voltage, 1024 consecutive samples are averaged, corrected for gain and offset and multiplied by the attenuation factor, and the range (0–3 V, 0–10 V, 0–30 V) is chosen automatically by switching the front-end through an analogue switch. For AC voltage, 4096 samples covering at least one full cycle are acquired, the mean is removed, and the true RMS value is

$$V_rms = sqrt((1/N) \Sigma (x_i - \bar{x})^2), \quad N = 4096$$

which is valid for sinusoidal, square, triangular and complex waveforms, unlike a fixed form-factor conversion. For DC current a 1 fi, 1 W shunt is placed in series and measured on a separate ADC channel, giving I = V_shunt / R_shunt. The 3.3 V ADC limit allows about 3.3 A, but the shunt power rating limits continuous use to about 1 A. Resistance up to 1 Mfi is found from the voltage across the unknown resistor, and a continuity test uses a low threshold with a buzzer.

Power system and enclosure: A 3.7 V, 2500 mAh Li-Po cell is charged from USB Type-C by a TP4056 module [18] with constant-current/constant-voltage charging at 1 A, a 4.2 V cut-off and a DW01A/FS8205A protection circuit that cuts off at 2.5 V. An MT3608 boost converter provides 5 V for the Pico VSYS input and the display, and the Pico's own regulator supplies 3.3 V. At the typical current of 400–500 mA this gives four to six hours of operation, and a full charge takes about 2.5–3 hours. The circuit is built on stripboard for validation, and a two-layer KiCad layout with a ground guard ring around the ADC trace is prepared for later fabrication. The enclosure is a snap-fit PLA print

of 120 × 75 × 30 mm that weighs about 180 g with the battery. The itemised cost is given in Table 3.

Table 3: Approximate prototype cost

Component	Cost (USD)
Raspberry Pi Pico	4
3.5-inch TFT display	8–12
Analogue front-end parts	< 2
TP4056 charger and protection	1–2
MT3608 boost converter	1
Li-Po cell, 2500 mAh	5–6
Stripboard, connectors, buttons	4–6
3D-printed enclosure (PLA)	2–3
Total	**≈ 25–35**

IV. EXPERIMENTAL RESULTS

The prototype was tested on a simple LED driver consisting of a 9 V battery, a 470 fi resistor and a red LED in series. The test used all three modes: the multimeter measured the voltages and the current, the oscilloscope displayed the circuit behaviour, and the function generator drove the circuit with a square wave. A calibrated Fluke 87V DMM served as the reference.

In the DC voltage test the device read 8.96 V across the battery, 7.07 V across the resistor and 1.89 V across the LED, against expected values of 9 V, 7.1 V and 1.9 V. The errors were 0.44%, 0.42% and 0.53%, within the 1% target. For the current test the 1 fi shunt was inserted in the LED path, and the device read 15.1 mA against 15.3 mA on the reference, a difference of 1.3%. The slightly larger error comes from the shunt tolerance and its self-heating, and from the small voltage (about 15 mV) that the ADC must resolve across a 1 fi shunt. The results are summarised in Table 4.

Table 4: Multimeter accuracy on the LED driver circuit

Quantity	Reference	Measured	Error (%)
Battery voltage	9.00 V	8.96 V	0.44
Resistor voltage	7.10 V	7.07 V	0.42
LED voltage	1.90 V	1.89 V	0.53
LED current	15.3 mA	15.1 mA	1.3

In the oscilloscope test the time base was 10 ms/div and the voltage scale 2 V/div, while the function generator produced a 10 Hz square wave. The display showed a clean square wave with stable triggering that matched the generator setting, so the oscilloscope and function-generator modes work together correctly. During the session there were no problems with battery life, display readability or mechanical robustness, and the menu was found easy to use. Table 5 compares the measured performance with the targets.

Table 5: Target versus achieved specifications

Parameter	Target	Achieved
Oscilloscope bandwidth	20 kHz	20 kHz
ADC resolution	12 bit	12 bit
DC voltage error	≤ 1%	0.42–0.53%
DC current error	≈ 1%	1.3%
Generator range	1 Hz–10 kHz	1 Hz–10 kHz
Battery life	4–6 h	4–6 h
Size / weight	Handheld	120×75×30 mm, 180 g

V. DISCUSSION AND LIMITATIONS

Accuracy: The voltage errors of about 0.5% are consistent with the error budget, which is made up of the 1% resistor tolerance of the divider, the ADC quantisation, op-amp offset and thermal drift [14]. Averaging 1024 samples lowers the noise below the 8.06 mV step of the 30 V range, and the software gain and offset calibration removes most of the divider error. The current measurement is the weakest, and a larger shunt or a gain stage would improve the resolution at low currents.

Bandwidth: The ADC runs at up to 500 kSPS, so the Nyquist frequency is 250 kHz [12], but the anti-aliasing filter and the front-end limit the usable bandwidth to about 20 kHz, which is enough for audio and low-frequency electronics but not for radio-frequency or fast digital signals. The relative cost is small: the prototype costs about 90% less than entry-level commercial instruments of similar integrated functionality.

Limitations: The input range is unipolar, 0–30 V, because of the 3.3 V logic level, and AC measurement is limited to about 21 V RMS. The function-generator output is limited by the PWM resolution and a simple RC filter, so its waveform quality is lower than that of a DDS generator. The evaluation used a single low-voltage circuit and one prototype, so it does not cover high-frequency signals, temperature drift or unit-to-unit variation. The circuit is built on stripboard rather than a fabricated PCB, and there is no wireless data transfer. These limits should be considered when comparing the instrument with commercial equipment.

Applications: The instrument is useful for teaching laboratories, field diagnosis of solar, automotive and industrial systems, and debugging of IoT and embedded boards, where its function generator can also stimulate audio circuits, filters and sensors.

VI. CONCLUSION

In our project, a handheld instrument that combines an oscilloscope, a digital multimeter and a function generator was designed and tested using the Raspberry Pi Pico and a 3.5-inch TFT display. The dual-core firmware keeps sampling and rendering independent of the user interface, and the simple analogue front-end handles inputs of 0–30 V. The prototype achieves a 20 kHz bandwidth, 12-bit resolution, DC voltage accuracy within 1% and a 1 Hz–10 kHz function generator, and runs for four to six hours on one charge. Its cost of about USD 25–35 is far below that of commercial equivalents.

In the future, the internal ADC can be replaced by an external converter such as the MCP3204 or AD9226 to reach 1 MHz or more of bandwidth, the PWM generator by

a DDS chip such as the AD9833 [19] with sweep and modulation, and Wi-Fi or Bluetooth can be added through an ESP32 for data logging and FFT display on a phone or laptop. Power-saving measures from [10], a fabricated PCB and guided measurement tutorials for students would further improve the instrument.

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