Supporting Information to

Open-Source Potentiostat for Wireless Electrochemical Detection with Smartphones

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1. Comparison of UWED, UMED, and other open-source potentiostats

Table S1. Comparison between this work and previously reported open-source portable potentiostats. NA represents not available.

	UWED (this work)	UMED[1]	CheapStat[2]	Dstat[3]	Potentiostat/Galvanostat[4]
Features and Design	Universal potentiostat Controlled with a smartphone	Universal potentiostat Built-in control	Universal potentiostat Controlled with a computer	Universal potentiostat Controlled with a computer	Universal potentiostat Controlled with a computer
Open source	Yes	No	Yes	Yes	Yes
Connectivity to Computers	Wireless connection via Bluetooth Low Energy	Wired connection via USB/serial port (for the transfer of final raw data only)	Wired connection via USB/serial port	Wired connection via USB/serial port	Wired connection via USB/serial port
Connectivity to Mobile Phones	Wireless connection via Bluetooth Low Energy	Wired connection via Audio input (for the transfer of final raw data only)	NA	NA	NA
Techniques	POT, CA, CV, DPV, SWV	POT, CA, CV, DPV, SWV	CA, CV, SWV, ASV	POT, CA, CV, DPV, SWV	POT, CA, CV
Hardware user interface	No interface Controlled with an external device such as a smartphone	LCD display and three buttons	LCD display and joystick	No interface Controlled with a computer	No interface Controlled with a computer
Voltage Range	±1.5 V (67 µV resolution) 40 µV noise	±2.0 V (50 µV resolution) 40 µV noise	±1.0 V Resolution and noise not reported	±1.5 V (46 µV resolution) Noise not reported	±8 V (15.3 µV resolution) Noise not reported
Current Range	1 range: ±180µA 6.4 nA resolution 30 nA noise + nonlinearity	1 range: ± 200 µA 5 nA resolution, 0.5 nA noise	2 ranges: ±100 nA and ±10 µA.	7 ranges. Lowest limit of detection 600 fA.	3 ranges: ±20 mA, ±200 µA and ±2 µA. Resolution: 12 nA, 120 pA and 1.2pA and noise: 88 nA, 1.1 nA and 9.9 pA respectively to the ranges.
Reported Cost of Components	60 USD/each Calculated for 1 unit	25 USD/each Calculated for 1000 units	80 USD/each Number of units for calculation of price was not reported	120 CAD/each Number of units for calculation of price was not reported	100 USD/each Calculated for 1 unit
Power source	Rechargeable Battery	Rechargeable Battery	2 x AA batteries or USB	USB	USB

2. Acronyms

We list the definition of abbreviations and acronyms used in this work in Table S2.

Table S2. List of abbreviations and acronyms used in this work.

ABS	Acrylonitrile Butadiene Styrene	LED	Light-Emitting Diode
ADC	Analog-to-Digital Converter	LiPo	Lithium Polymer Battery
BLE	Bluetooth Low Energy	PCB	Printed Circuit Board
DAC	Digital-to-Analog Converter	SoC	System on Chip
DRC	Design Rule Check	USB	Universal Serial Bus
IC	Integrated Circuit	USD	US Dollar
LDO	Low-DropOut Regulator	UWED	Universal Wireless Electrochemical Detector

3. Hardware Design

Figure S1 shows the circuit diagram of Universal Wireless Electrochemical Detector (UWED). We designed the circuit diagram and PCBs of UWED in the free educational version of PCB layout software, EAGLE 7.3.0 (CadSoft Computer GmbH).

We hand-soldered the components to the PCB board, using a fine soldering iron tip. We inspected the soldered PCB board with a microscope and a multimeter, to ensure there are no accidental short-circuits and false connectivities. We designed the UWED case in AutoCAD 2013 and fabricated it with ABS plastic, using a 3D printer (StrataSys Fortus 250mc).

Table S3 lists the components used in the design of UWED. The UWED uses the ADC built-in the BLE microcontroller. The IC8 in the PCB design (along with voltage divider resistors of R8 and R9, and capacitors of C14 and C15) is optional and is designated for an external ADC. The

PCB design also shows the logarithmic amplifier diodes of D1–D6 that can be added as optional components to change the gain of the amplifier and the current range of the UWED.

Since the goal of this work is presenting of a device that can be fabricated in a Do-It-Yourself type development, we have chosen electronic components that would allow easy manual soldering. The BLE microcontroller of RFDUINO has this characteristic: (i) its size and accessibility of its contact pads makes RFDUINO suitable for manual soldering. (ii) RFDUINO has integrated radiofrequency antenna. Design and soldering of antennas is more difficult because of the sensitivity of high-frequency electronics. (iii) RFDUINO is compatible with the Arduino programming environment and does not require advanced programming languages. Table S4 lists alternative options (that are smaller or less expensive than RFDUINO) that can be used as a BLE microcontroller in the circuitry of UWED.

The total cost of circuit components in UWED was 58 USD plus about 10 USD for the external LiPo charger. We had ordered the circuit components in the minimum number that distributors offered. The price of UWED can be decreased by 75% (15 USD) by ordering the components in larger quantities. Changing the scale of ordering the components would decrease the price per item and also make less expensive brands available for purchasing. Table S5 provides a list of options and prices of components for large scale ordering.

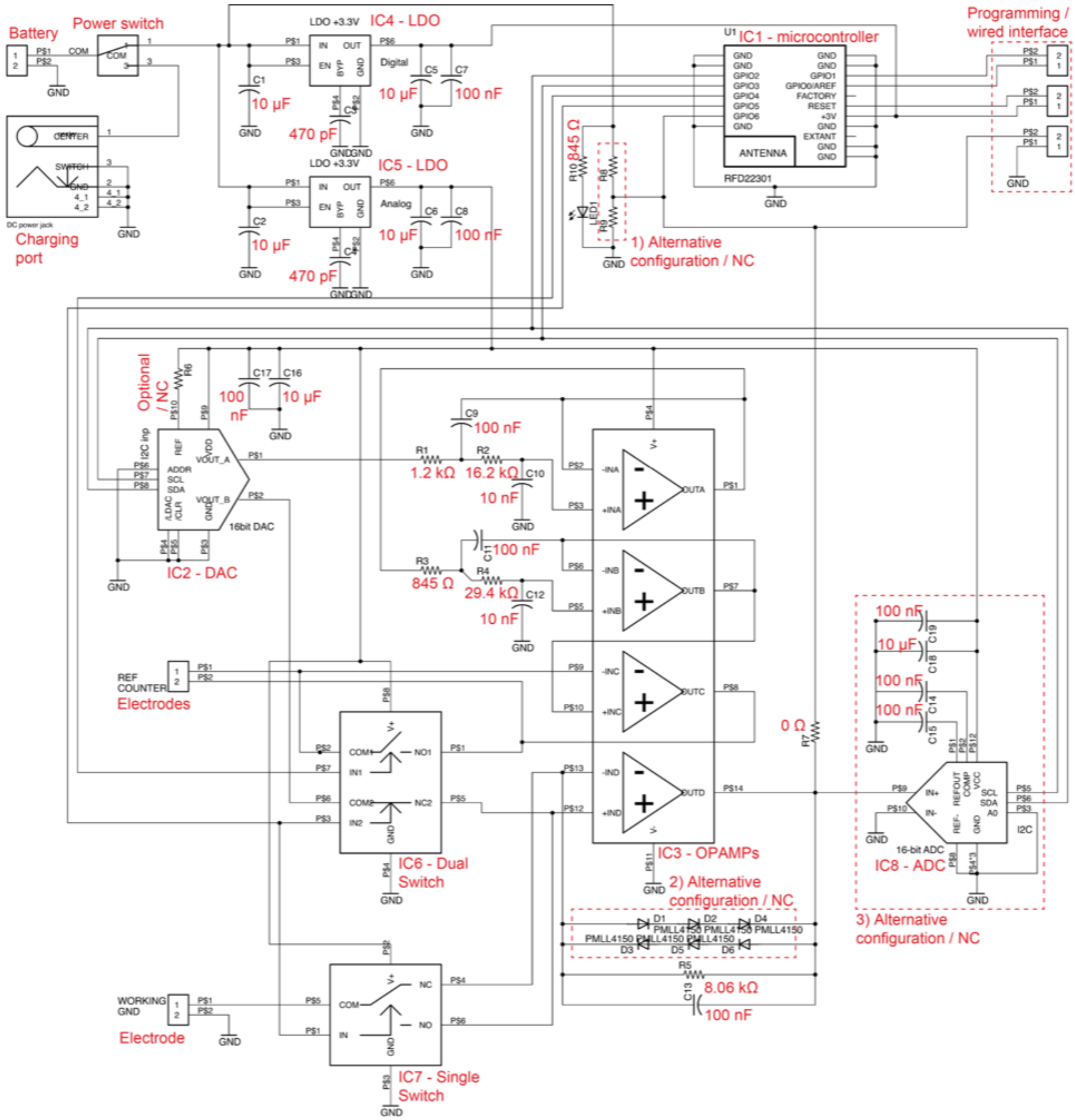

Figure S1. Circuit diagram of UWED. Table S3 lists the details of components. PADS identify the flat metallic areas on the PCB board that can be used for soldering external components to the PCB board. We used PADS to make wire connections to the PCB board. PADS1 shows the connection to the battery, PADS2 shows connections for firmware programming, PADS3 shows connections to reference and counter electrodes, and PADS4 shows connections for the working electrode and ground. The design includes three alternative configurations. The components of these alternative configurations are not connected (NC) in the final design of the UWED, but are discussed in Table S3.

Table S3. List of components used in the PCB of UWED. Part numbers are from Digi-Key unless specified otherwise. All costs are in USD for the minimal order volume on July 26th, 2017.

Part	Description	Model/Value	Part number	Cost/Unit
IC1	BLE microcontroller	RFDUINO, RFD22301	1562-1016-ND	19.55
IC2	Dual DAC. 16-bit, I^2C.	AD5667RBRMZ-2	AD5667RBRMZ-2-ND	11.04
IC3	4x operational amplifiers	AD8608ARUZ	AD8608ARUZ-ND	4.85
IC4, IC5	LDO 3.3V	MIC5205-3.3YM5-TR	576-1259-1-ND	0.41
IC6	Dual switch	MAX4643EUA+	MAX4643EUA+-ND	1.46
IC7	Single switch	MAX4644EUT+T	MAX4644EUT+TCT-ND	2.89
IC8*,[a]	16-bit ADC, I^2C	LTC2471IMS#PBF	LTC2471IMS#PBF-ND	
R1	Filter resistor	1.2 kΩ	RR12P1.2KDCT-ND	0.11
R2	Filter resistor	16.2 kΩ	311-16.2KCRCT-ND	0.10
R3	Filter resistor	845 Ω	311-845CRCT-ND	0.10
R4	Filter resistor	29.4 kΩ	311-29.4KCRCT-ND	0.10
R5	WE amplifier gain resistor	8.06 kΩ	311-8.06KCRCT-ND	0.10
R6*		Optional		
R7[b]	wire	≈0 Ω		
R8, R9*,[c]	Battery meter resistor	100 kΩ		
R10	LED resistor	845 Ω	311-845CRCT-ND	0.10
C1,C2	LDO input cap.	10 µF	478-9266-1-ND	0.68
C3,C4	LDO cap.	470 pF	1276-1300-1-ND	0.10
C5,C6	LDO output cap.	10 µF	490-3340-1-ND	0.15
C7,C8	LDO output cap.	100 nF	478-1395-1-ND	0.10
C9,C11	Filter cap.	100 nF	478-1395-1-ND	0.10
C10,C12	Filter cap.	10 nF	311-1136-1-ND	0.10
C13	WE amplifier cap.	100 nF	478-1395-1-ND	0.10
C14,C15*	Ext ADC cap.	100 nF	478-1395-1-ND	0.10
C16	DAC power cap.	10 µF	490-3340-1-ND	0.15
C17	DAC power cap.	100 nF	478-1395-1-ND	0.10
C18*	ADC power cap.	10 µF	490-3340-1-ND	0.15
C19*	ADC power cap.	100 nF	478-1395-1-ND	0.10
LED1	Power indicator	LED (blue)	VAOL-S8SB4CT-ND	0.47
D1-D6*,[d]	Logarithmic amplifier diodes			
SWITCH	Power switch		GH7540CT-ND	5.00
DC JACK	Charging connector	Jack 0.7x2.35mm	CP-032HPJCT-ND	1.05
		Components not listed in Figure S1		
	Sensor socket	Female 6 pos	A101966-ND	1.91
	LiPo battery[e]	240 mAh x 3.7 V	https://amzn.com/B00SO2WEXW	2.60
	PCB board[f]	2 Layer PCB, 0.062" FR4		5.13
	USB LiPo charger[g]	http://a.co/aMHgm3t		8.00
	Charging cable	CP-2196-ND		2.35

* Optional components

[a] External ADC can be used instead of ADC built into the microcontroller.

[b] This connecting wire is needed if UWED is used with internal ADC and it is not place when with external one (IC8).

[c] These resistors are used as voltage dividers and allow measuring battery voltage; they are not placed if UWED is configured to use the ADC of the microcontroller.

[d] These diodes are placed instead of gain resistor R5, for the logarithmic current response.

[e] Ordered from Amazon as a pack of 5 (Total: 12.98 USD)

[f] PCB boards were ordered online at http://www.custompcb.com/ from Silver Circuits Sdn. Bhd (Selangor, Malaysia) using PCB protype service. Total 4 x 3 = 12 boards were obtained for 61.5 USD (minimum order).

[g] External charger ordered from Amazon.

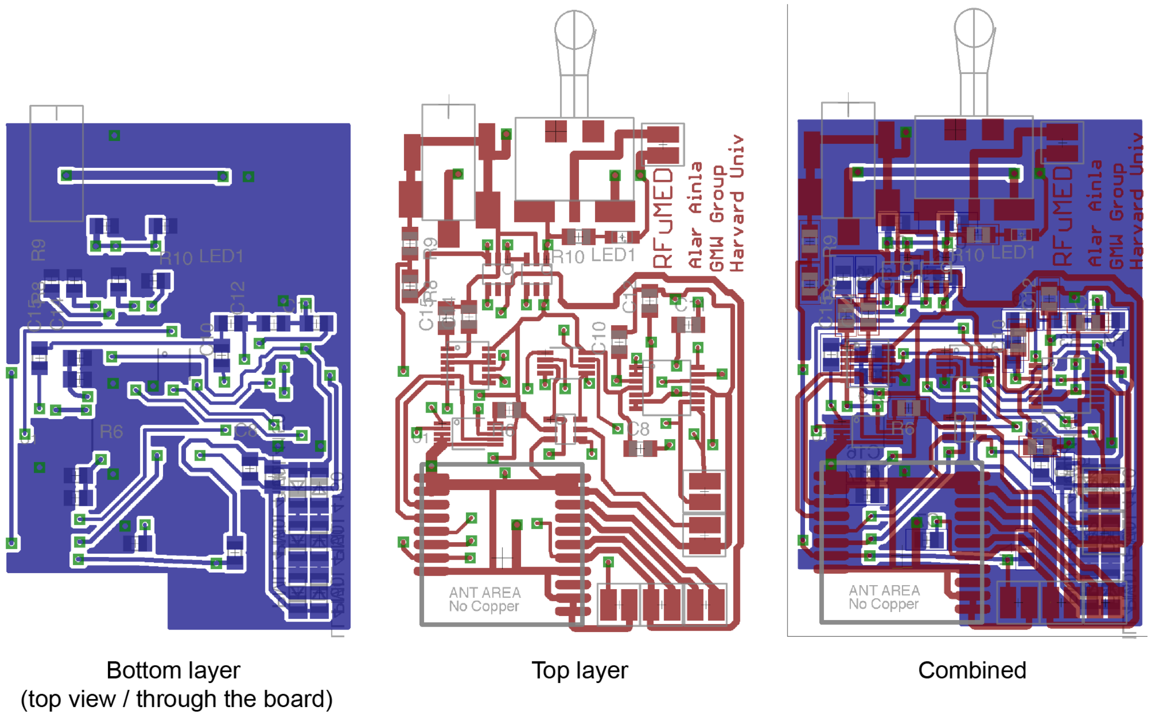

Figure S2. A schematic design of the PCB drawn with the free version of the Eagle program. The PCB source files in the Eagle format are provided as supporting materials. Prior to ordering the PCB, we validated the design with Silver Circuit's design rule check (DRC).

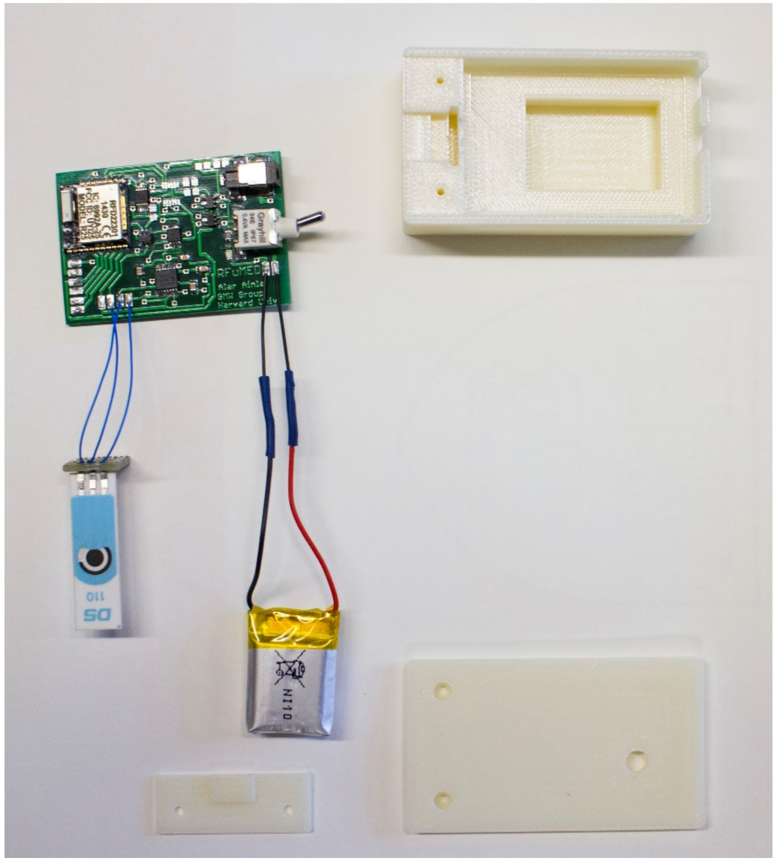

Figure S3. The components of UWED, circuit board, electrode connector, battery, and 3D-printed case, before the assembly.

Table S4. List of BLE microcontrollers that can be employed in the circuitry of UWED. We obtained the price estimations from DigiKey (MN, USA).

Brand and the Product Code	Processor	Size	Characteristics	Cost/Unit (USD)
RFDUINO™ (RFD22301)	ARM Cortex M0	15 mm x 15 mm	▪ Easy to solder manually ▪ Has integrated antenna ▪ Is compatible with Arduino programming	15.57[a]
Simblee™ (RFD77101)	ARM Cortex M0	7 mm x 10 mm	▪ Has integrated antenna ▪ Is compatible with Arduino programming ▪ Has a compact design ▪ Has a large number of IO ports and peripherals (30) ▪ The case (45-pin LGA 0.5mm) is hard to solder manually	11.25[b]
Rigado BMD-350 (Nordic nRF52832 BLE SoC)	ARM Cortex M4F	6.4 mm x 8.7 mm	▪ Has integrated antenna ▪ Has a compact design ▪ Energy efficient and versatile (many peripherals and IO ports) ▪ Has a large number of IO ports (32) ▪ Is not compatible with Arduino programming and requires development of advanced software ▪ Is hard to solder manually	7.98[c]
NRF51822 (Nordic semiconductor BLE SoC)	ARM Cortex M0	3.8 mm x 3.8 mm	▪ Is inexpensive ▪ Has a large number of IO ports and peripherals (31) ▪ Does not have integrated antenna, and requires incorporating high frequency RF antenna on the PCB design ▪ Is not compatible with Arduino programming and requires development of advanced software ▪ Is hard to solder manually	1.66[d]
Dialog semiconductor (DA14580)	ARM Cortex M0	2.5 mm x 2.5 mm	▪ Is inexpensive ▪ Has a large number of IO ports and peripherals (32) ▪ Does not have integrated antenna, and requires and requires incorporating high frequency RF antenna on the PCB design ▪ Is not compatible with Arduino programming and requires development of advanced software ▪ Is hard to solder manually ▪ Has a one-time-programmable memory	1.17[e]

[a] price per piece for ordering 1 piece
[b] price per piece for ordering 5000 pieces
[c] price per piece for ordering 1000 pieces
[d] price per piece for ordering 5000 pieces
[e] price per piece for ordering 10000 pieces

Table S5. List of circuitry components for large scale ordering.

Type	Product Details	Characteristics	# of Units per purchase	Cost per Unit (USD)
DAC	DAC8571IDGKR (16-bit, I2C)	▪ As working electrode DAC value is normally fixed, actually only single channel DAC would be sufficient.	2,500	2.81
Op amp	LM324DR2G	▪ Is inexpensive	2,500	0.082
Op amp	LMV324IDT	▪ Has low input impedance (<100 MΩ)	2,500	0.155
Op amp	LMC6036IMX	▪ Has high input impedance (10 TΩ)	2,500	1.129
Manual power switch	PCB mounted slide switch (JS202011SCQN)		1000	0.267
PCB	2-layer 0.062” FR4 substrate, quantity of 20000 inch^2		NA	0.31[a]
Battery	Lithium polymer battery 5 mAh for Bluetooth devices	▪ Battery lasts a short time (~1 h) ▪ Compact (0.6 x 15 x 18 mm^3)	3,000	2.00
Battery	Small ultra thin 3.7 V 10 mAh rechargeable lithium polymer battery	▪ Battery lasts a short time (2 h) ▪ Compact (2 x 8 x 15 mm^3) and low cost	1,000	1-2
Battery	3.7 V 50 mAh Li-Ion lithium ion battery	▪ Battery lasts a long time (10 h) ▪ Compact (3 x 13 x 20 mm^3) and low cost ▪ High power	100	1-2
Battery	3.7 V 140mAh rechargeable lithium polymer battery	▪ Battery lasts very long time (70 h) ▪ Compact (3 x 25 x 25 mm^3) and low cost ▪ High power	NA	0.5

[a] at a manufacturing (Silver Circuits) rate of 0.11 USD/inch^2, for a 3.4 cm x 5.1 cm PCB
NA shows not mentioned or identified

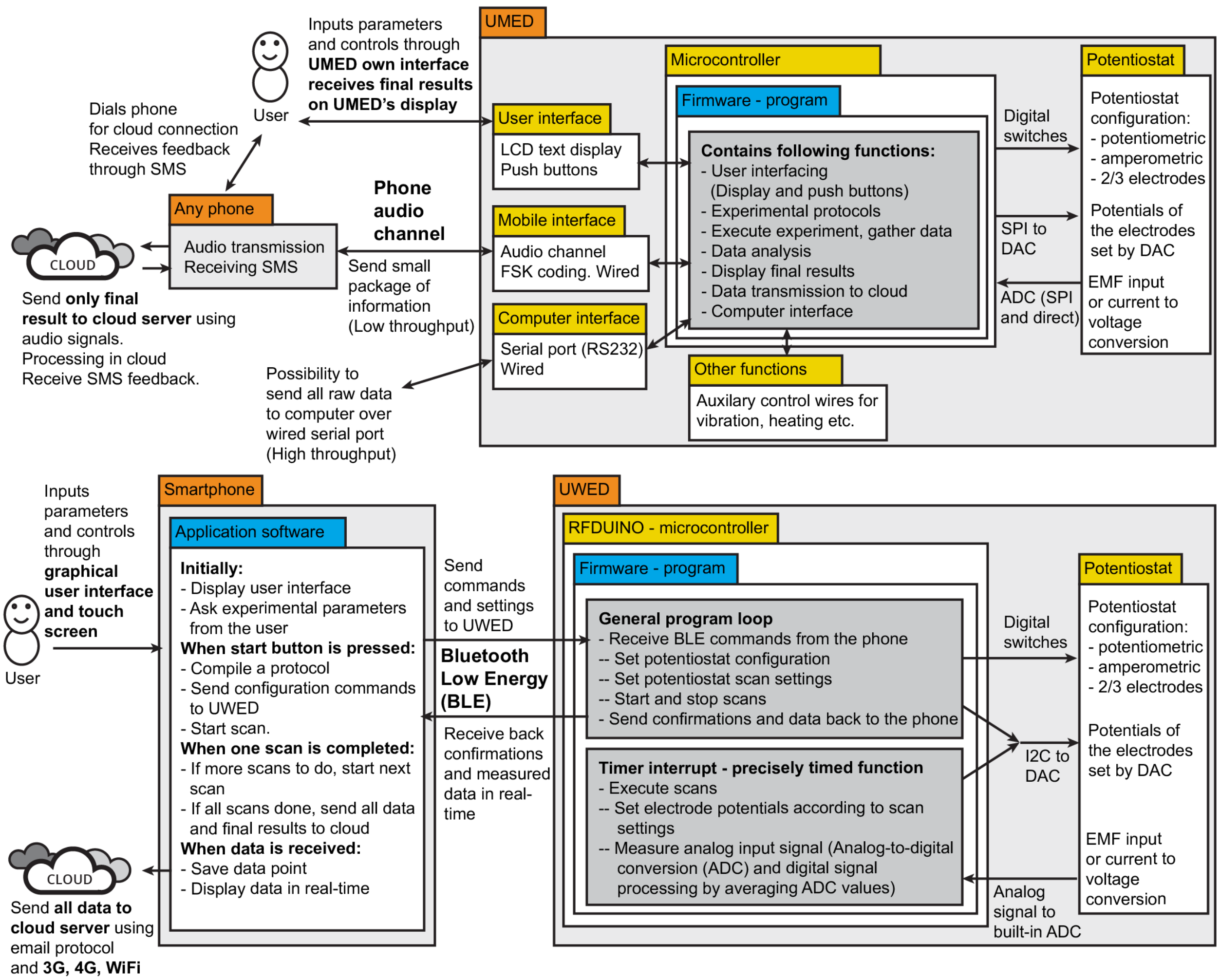

Figure S4. Block diagram of components of UMED and UWED and summary of function of their components.

4. Firmware

To run a potential scan, scan is defined in a sequence of well timed (Δt) steps (N) in which the voltage can be adjusted in increments (ΔV) and response current (I) is measured and transmitted. We have implemented possibility for different increments in case of odd (ΔV_o) and even (ΔV_e) steps. This design allows creating electrochemical techniques, such as: i) chronoamperometry (CA), where $\Delta V_o = \Delta V_e = 0$, current is measured at constant potential; ii) cyclic voltammetry (CV), where $\Delta V_o = \Delta V_e = \Delta t \cdot v$ and *v* is scan rate; iii) square wave voltammetry (SWV), where $\Delta V_e = -2A$ and $\Delta V_o = 2 \cdot \Delta t \cdot v + 2A$, and *v* is the scan rate and *A* is square wave amplitude. Time (Δt) can be also varied depending on odd or even steps for the purpose of differential pulse voltammetry (DPV). Other protocols can be constructed as a sequence of these individual scans. It is possible to change the RFDUINO firmware for entirely different types of excitation signals.

Figure S5A illustrates the timing diagram of a single measurement step, which is composed of setting the electrode potential, integrating the input signal (longer integration lowers the noise), and communicating the results to the phone or tablet. The BLE requires certain amount of processor time to maintain the communication link with the phone. Each step is precisely timed by the microcontroller timer interrupt. Figure S5B shows diagrams of common electrochemical techniques, such as CA, CV, and SWV. Controller firmware has built-in routine to perform such scans, allowing to define the time-step (Δt) and voltage increments, which can be zero (CA), same (CV) or different (SWV) for odd and even steps. Odd and even steps do not have direct electrochemical correspondence, rather they are a microprocessor friendly way to describe the electrochemical excitation signals, while values are calculated from electrochemical parameters as shown under every technique. (C) Multi-scan experiment, such as CV, can be constructed as a sequence of scans. For example one cycle of CV would be 2-3 individual scans. Each individual scan is run by UWED, while switching from one scan to another is started by the program in the tablet, which makes it easy to design experiments composed of arbitrary sequences of different scans.

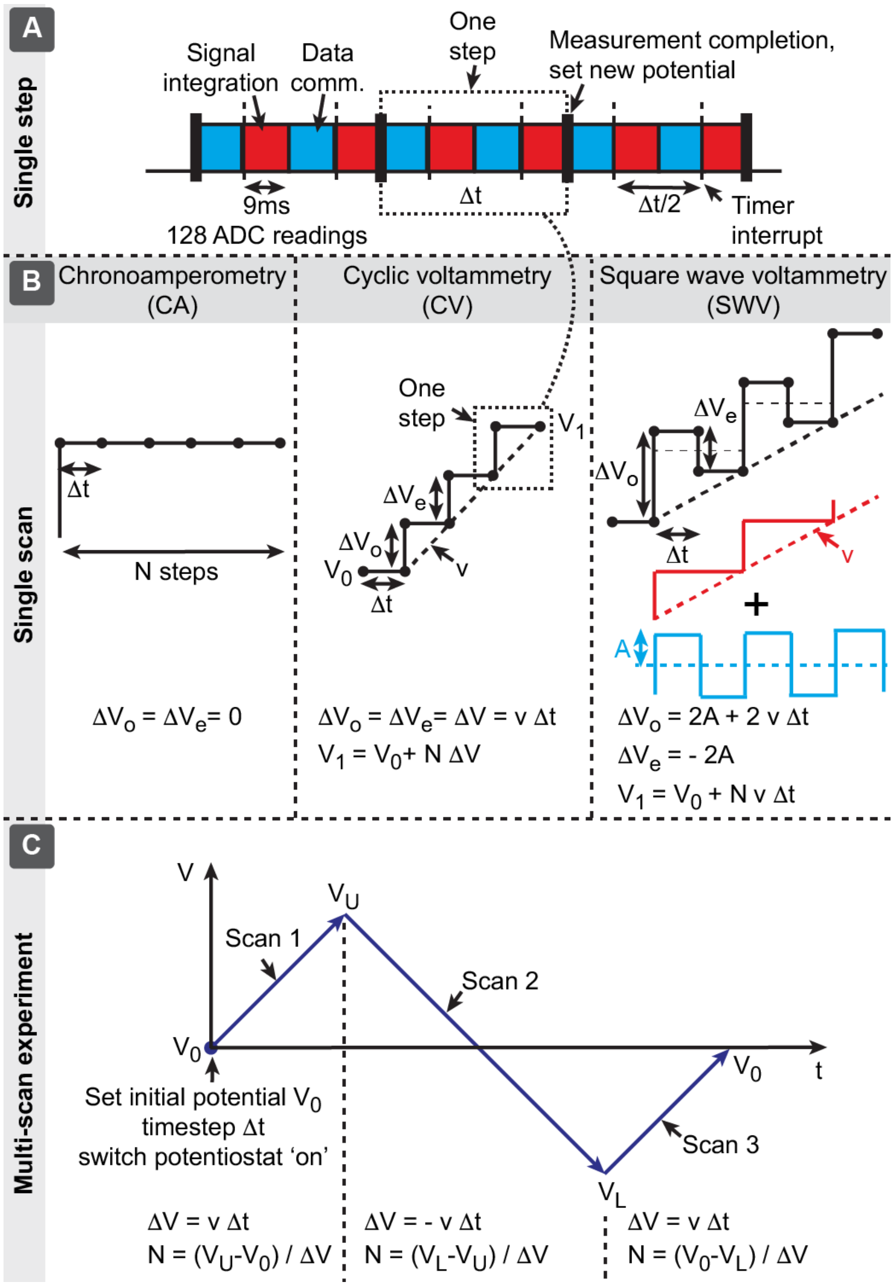

Figure S5. (A) Timing diagram of a single measurement step. (B) Construction of a scan and (C) a multi scan measurement, such as CV.

5. Communication Protocol and Software

UWED communicates with smartphones and tablets via Bluetooth Low Energy (BLE) and by sending and receiving commands in the string format (maximum 20 characters long). A universally unique identifier (UUID) labels the microcontroller for wireless communication. UUIDs are 128-bit numbers used to identify information in computer systems.

Device name is: **UWED**

Device UUID: **2220**

- read property UUID: **2221**

- write property UUID: **2222**

To begin the communications, the mobile phone or tablet sends the command "**X(number)**" to UWED, where "X" is the command code that denotes a single uppercase character in the range [A-Z], and the "number" represents a numerical value in long type (32-bit signed integer).

Once UWED receives the command, it responds back by sending the command "**Iy*sequence***" to the mobile phone or tablet. "I" is an index in the range of '0' to '9' that counts the number of messages sent by the UWED. "y" is the response code and is a single lowercase character in the range [a-z]. The "sequence" has maximum 18 characters. UWED responds to every command (sent by the smartphone) by acknowledging that the command was received; to do so, UWED sends the same small character and ":DONE" (i.e. k:DONE) back to the smartphone. Table S6 summaries the input commands.

When UWED receives the command "**M(number)**", is starts the electrochemical measurement and sends the measured values back to the smartphone in the data return format. Table S7 lists the data structure of the return.

Table S6. The description of the Input commands that UWED sends to the mobile phone or tablet over BLE.

Char	Parameter Range	Function	Description
A	0–65536	Sets the reference potential	This function sets the offset in the DAC (16-bit) value in the potential of the reference electrode. The default value is 0.
B	0–65536	Sets the potential of the working electrode	This function sets the offset in the DAC (16-bit) value in the potential of the working electrode. The default value is 0.
C	0 or 1	Sets the input mode	Mode 0 is potentiometric (default). Potentiometric state also means that potentionstat is off and no current goes through the working electrode. Mode 1 is amperometric.
D	2 or 3	Number of electrodes	In the two-electrode configuration, the counter and reference electrodes are the same. Default is three electrodes.
E	15–1000	Sets the step of the base timer	The parameter is in ms, and one timestep in the measurement is 2x of the parameter value. Default is 25 ms, which makes the measurement timestep 50ms, and the device frequency 1/50 ms (20 Hz).
F	*none*	Gets time for 100 cycles	This function measures the length of timesteps for 100 cycles. Value in ms. f:*value in ms*
G	Positive or negative value	Sets the scan increment of reference (odd step number)	This function sets how many DAC units every odd step the reference channel value will increase (positive) or decrease (negative). Default is 0. This is 16-bit int. (+/-30’000 units)
I	Positive or negative value	Sets the scan increment of reference (even step number)	Same for even number. Default 0
J	Positive or negative value	Sets the scan increment of working (odd step number)	Same for working electrode.
K	Positive or negative value	Sets the scan increment of working (even step number)	Same for working electrode
L	1…1000	Sets the number of steps	Total number of steps during the scan
M	*none*	Runs sequence	Start running the sequence At every step of the run, UWED sends a message back to the smartphone in the following format: m:DONE (Once sequence is completed)
N	*none*	Halts sequence	holds the potential of the working, counter, and reference electrode at the values at the moment that the command was received
O	0 or 15-1000	Set alternative step length for the base timer	This is similar to command ‘E’. If value is 0 (default) all timer steps are equal in length. Alternative length is used only for DPV purposes, when odd (‘E’) and even (‘O’) timer steps are different.
P…Z		RESERVED	Enables adding new commands in case of updating the firmware

Table S7. Once UWED receives the command “M(number)” from the smartphone, it starts the scan. UWED sends the measured values in the data return format, back to the smartphone. Data return response is a 20-characters long and uses mixed text and binary encoding.

Character	Description
1	Message index. Ranges from ‘0’ to ‘9’ and increases each time
2	Identifier character ‘M’. Always the same
3:4	Odd step reference potential DAC value (16-bit unsigned int binary). Higher bits come first
5:6	Odd step ADC signal reading (16-bit unsigned int binary). Higher bits come first
7:8	Even step reference potential DAC value (16-bit unsigned int binary). Higher bits come first
9:10	Even step ADC signal reading (16-bit unsigned int binary). Higher bits come first
11:14	Timestamp of even step in ms (32-bit unsigned long binary). Higher bits come first
15:16	Even step working potential DAC value (16-bit unsigned int binary). Higher bits come first.
17:18	Step index (16-bit unsigned int binary). Higher bits come first
19:20	0. Reserved

In the measuring mode (when command M is running), we do not expect to change the working potential during the run, but only the reference one, reason that working potential is not transmitted for each, but only even steps.

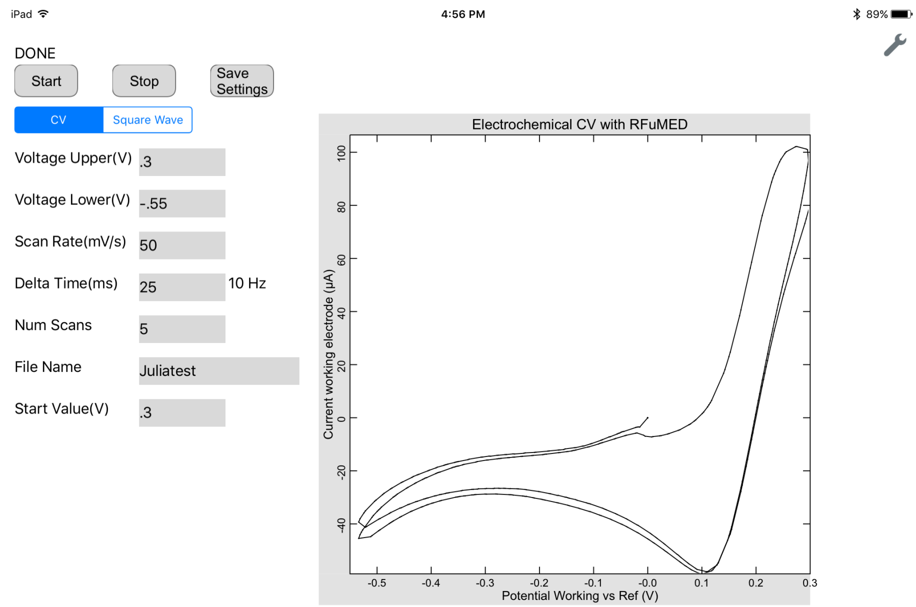

Figure S6. Example of graphical user interface (GUI) on tablet (iPad Mini).

6. Electrical Characterization of UWED

6.1 Potentiometric mode

In the potentiometric mode, we connect the reference and counter electrodes together and set the reference electrode DAC value to 22606 (potential about + 1.5 V).

The control of the working electrode potential is disconnected in the potentiometric mode. Thereafter we adjusted the potential applied to the working electrode (relative to reference) using 100 kΩ potentiometer and 1.5 V AAA battery. We measured the voltage using digital multimeter Fluke 77IV and recorded the ADC value. We found the linear calibration of voltage and ADC value to be: V[mV]=0.0503ADC-1537.5. The digital resolution of one ADC unit is 50.3 µV. We measured input noise level of 110 µV at sampling rate 20 Hz.

6.2 Amperometric mode

Figures S7, S8, and S9 show the linearity and noise of UWED.

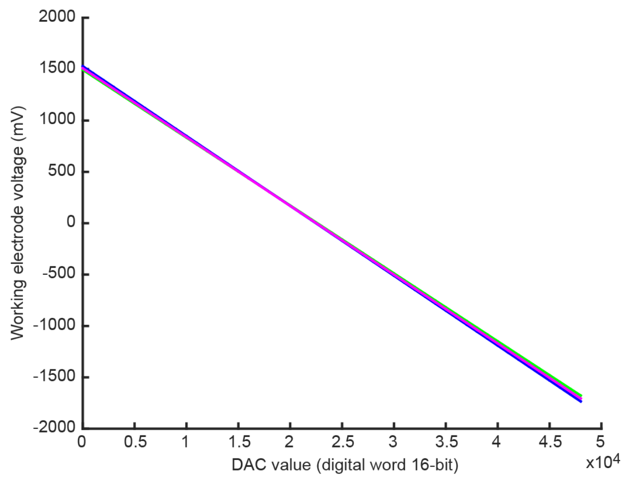

Figure S7. The calibration of electrode potential. We set the DAC value of the working electrode to 22500 (about 1.5 V), and scanned the DAC value of the reference electrode in the range of 0–48000. Values higher than 48000 will saturate the output. We measured the output voltage using Keithley 2410 Sourcemeter. UWED can cover a range of -1.5 V to +1.5 V potential difference between the working and reference electrodes. We fitted the data to a linear function (y=ax+b), where a=-0.06700±0.00096 mV/digit and b=1510±17 mV (variations are comparison between 3 different devices). Maximum deviation from linearity was 1 mV and output noise about 0.5 mV. The zero point of ADC was 22538±66.

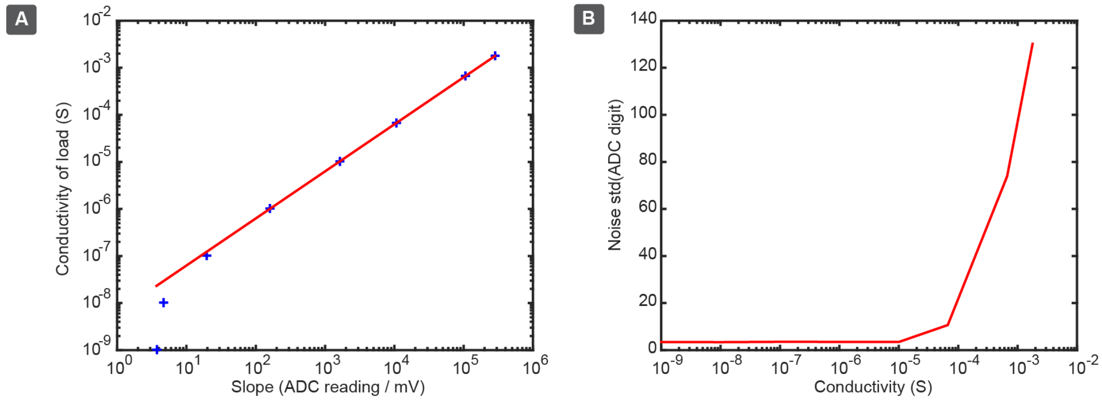

Figure S8. Measurement of current response. We measured the current in potential window of -1.5 V to +1.5 V with different resistive loads from 560 Ω to 1 GΩ. (A) shows that an expected linear relationship between the resistance and voltage can be achieved over 4-orders of magnitude. (B) Noise amplitude was calculated as standard deviation from the linear value. This combines both random electronic noise and non-linearity. At low currents the electronic noise was in the range 5–15 digits. At high currents deviations due to non-linearity were 130–240 digits. I[nA]=A*(ADCValue+B), where A=6.313±0.026 nA/digit, B=-30290±300 digits (standard deviation is for device-to-device variations of three units of UWED). For each particular device, we used their exact corresponding calibration coefficient. Typical noise <30 nA, maximum noise < 100 nA, full range non-linearity <1.5 μA, full current range ±180 μA.

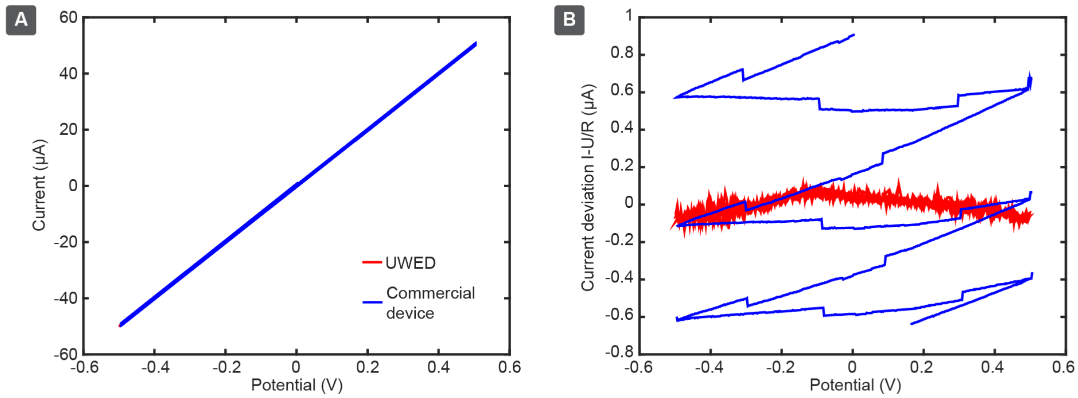

Figure S9. Comparison of UWED and a commercial device (AutoLAB). (A) Three full CV scans were recorded with AutoLAB Dummy Cell 2, where reference and counter electrodes were connected together and further connected to working electrode through a 10 kΩ resistor. We obtained linear slope as expected (Both red and blue lines overlap). Graph (B) shows deviations from linearity. Here, we inspected the same data as shown on panel (A), but subtracted U/R from current to observe deviations. We can see slight, about 0.2 µA, nonlinearity and electronic noise in case of UWED, while the commercial potentionstat has substantially lower electronic noise. The commercial potentiostat shows small steps (<100 nA) in current values, which correspond to automatic changes of current range and some gradual drift between scans (total about 1.5 µA over three scans). The exact origin of the drift in the case of the commercial device cannot be interpreted at this time.

6.3 Power consumption and battery

We measured the battery consumption using a digital multimeter Fluke 77IV. The current battery (240 mAh) should be sufficient for 45–60 h of measurements.

Table S8. Power and current consumption of UWED during different operations.

Operation	Measured average current (mA)
Standby, no communication	4.0
Active measurement, data transmission, UWED does not supply current to the working electrode, potentiometric mode	4.4
Active measurement, data transmission, UWED supplies current to the working electrode, amperometric mode	4.8

7. Comparison between performance of UWED and commercial benchtop potentiostat

We used a commercial screen-printed three-electrode cell (DRP-110CNT-GNP, DropSens, Llanera, Spain) for performing the chronoamperometry (CA), square wave voltammetry (SWV), and cyclic voltammetry (CV) on ferricyanide. This electrode contains a carbon (modified with gold and carbon nanotubes) working electrode, carbon counter electrode, and silver reference electrode. We performed the CA, SWV, and CV experiments with UWED and the benchtop commercial potentiostat (AutoLAB, PGSTAT12, Metrohm), and compared the performance of the two. For each measurement, we placed 40 µL of fresh solution of ferricyanide on the working zone of a screen-printed electrode. We prepared the solutions of potassium ferricyanide containing 1 mM KH_2PO_4, 56 mM Na_2HPO_4, 150 mM NaCl, pH 7.4, and 10 µM to 10 mM ferricyanide. For the chronoamperometry experiments, we applied a potential of 100 mV to the working electrode (vs the reference electrode), and recorded the current (from 0.5 s to 5 s). We measured the cyclic voltammograms of ferricyanide using concentrations from 10 µM to 10 mM, at scan rates from 20 to 300 mV/s. We recorded the square wave voltammograms of ferricyanide at concentrations ranging from 10 µM–10 mM. We scanned the potential of the working electrode from 0.4 to -0.2 V at a scan rate of 50 mV/s (5 mV steps), with an amplitude of 25 mV and frequency of 10 Hz.

We tested the potentiometric mode of UWED using in-house built K^+ and Na^+ ion-selective electrodes (ISEs). We fabricated the ISEs according to protocols established in the literature.[5,6] We used a double-junction free-flow Ag/AgCl reference electrode (Metler Doledo DX200) with an inner-filling solution of 3 M KCl and bridge electrolyte of 1 M lithium acetate. We measured the electrical potential of the ISEs in series of NaCl and KCl solutions with concentrations ranging over six orders of magnitude (100 mM–100 nM). We compared the potentials measured with the UWED and with a commercial precision electrochemical EMF interface (EMF 16, Lawson Labs Inc). We placed the ISEs in the K^+ or Na^+ solutions for 60 s, and collected the data over the last 30 s.

Table S9 compares the technical aspects and price of UWED and two commercial benchtop potentiostats that we used as standard equipment for evaluating the performance of UWED. We compare the performance (noise level, determined values, drifts) of UWED with a benchtop commercial potentiostat (Autolab, PGSTAT302N, Metrohm) in four techniques of potentiometry, chronoamperometry (CA), cyclic voltammetry (CV), and square wave voltammetry (SWV).

Table S9. Comparison of UWED and a commercial benchtop potentiostat and a commercial benchtop potentiometer. Properties of commercial instruments are according to the manufacturer datasheets. The EMF16 is designed for potentiometric measurements and can only measure electrical potential. We listed the price paid by our laboratory as the cost of the instruments; the current cost may vary.

Parameter	**UWED**	**AutoLAB**	**EMF16**
Range of potential that the instrument can apply	±1.5 V	±10 V	NA
Accuracy in the applied potential	±1 mV (non-linearity)	0.2% ± 2 mV	NA
Resolution of applied potential	67 µV	120 µV	NA
Resolution in the measured potential	50 µV	0.3 µV	0.6 µV
Current range	±180 µA	±2 A	NA
Number of current ranges	1	9 (between 10 nA to 1 A)	NA
Accuracy in measuring current	0.4% of range (1.5 µA non-linearity, 100nA full-range noise, 6.3nA resolution	0.2% of range	NA
Number of channels	1	1	16
Input impedance	~ 1 GΩ	>1 TΩ	10 TΩ
Power consumption	20 mW	300 W	< 5 W
Weight	56 g (of which 10 g is electronics)	~18 kg	~3 kg
Dimensions	8 x 4 x 2.3 cm^3	52 x 42 x 16 cm^3	22 x 20 x 6 cm^3
Cost	60 USD	25,000 USD	1,995 USD

7.1 Potentiometry

7.1.1 Experimental Description

Measurements: We tested the potentiometric mode of UWED using in-house built K^+ and Na^+ ion-selective electrodes (ISEs). We used a double-junction free-flow Ag/AgCl reference electrode (Metler Doledo DX200) with an inner-filling solution of 3 M KCl and bridge electrolyte of 1 M lithium acetate. We measured the electrical potential of the ISEs in series of NaCl and KCl solutions with concentrations ranging over 6 orders of magnitude (100 mM–100 nM). We compared the potential measured with UWED and with a commercial precision electrochemical EMF interface (EMF 16 Lawson Labs Inc). We placed the ISEs in the K^+ or Na^+ solutions for 60s, and collected the data over the last 30s. The sampling rate of UWED was 20 Hz and the sampling rate of commercial potentiometer was 1 Hz.

Materials: All reagents were used without any further purification. Potassium ionophore I (valinomycin), potassium tetrakis(4-chlorophenyl)borate (KTpClB, Selectophore grade), 2-nitrophenyl octyl ether (*o*-NPOE), high molecular weight poly(vinyl chloride) (PVC), sodium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (NaTFPB, Selectophore grade), N,N,N′,N′-tetracyclohexyl-1,2-phenylenedioxydiacetamide (sodium ionophore III, Selectophore grade) and tetrahydrofuran (THF, inhibitor-free, for HPLC, purity ≥ 99.9%) were all purchased from Sigma-Aldrich.

Fabrication of ion-selective electrodes: We fabricated the ion-selective electrodes according to protocols established in the literature.[5,6] We first prepared the ion-selective membrane (ISM). We dissolved the membrane components into 7 mL of THF, stirred the solution for two hours to obtain a homogenous mixture, and poured this mixture into a Petri dish (5 cm diameter), and allowed the THF to evaporate overnight to form the ISM. The potassium sensing membrane cocktail consisted of *o*-NPOE (65.85 wt. %), PVC (32.95 wt. %), valinomycin (1.00 wt. %), and KTpClB (0.20 wt. %) with a 2:1 molar ratio of ionophore to KTpClB. The sodium sensing membrane consisted of *o*-NPOE (65.71 wt. %), PVC (32.85 wt. %), sodium ionophores III (1.00 wt. %), and NaTFPB (0.44 wt. %) with a 2:1 molar ratio of ionophore to NaTFPB.

We cut the ISM (approximate thickness of ISM 200 μm) into small circular pieces (≈1 cm in diameter), wetted one end of the PVC electrode body (Tygon tubing, ≈0.9 cm diameter) with 50 μL of THF, and pressed the ISM on the wetted area of the tube to seal the end of the tube with the ISM. We filled the tube with 10 mM KCl for the K^+ ISEs and with 10 mM NaCl for the Na^+ ISE, inserted an AgCl-coated Ag wire in the tube, and sealed the end of the tube with Parafilm. We stored the electrodes in solutions identical to their inner-filling solutions.

7.1.2 Results

Figures S10 and S11 show electrical potential of K^+ and Na^+ ISEs, measured with UWED and commercial potentiometer. Figure S12 summaries the differences in noise and drift between the electrical potential measured by UWED and the commercial potentiostat. The higher noise level in measurement done with UWED (100-200μV) is partly due to shorter integration time (20 Hz vs 1 Hz) in UWED compared to the commercial device (10-40μV). Averaging the potential over 20 samples would reduce the noise level of UWED, giving a noise of 20–47 μV, which is comparable with that of the commercial device. Digital resolution for the UWED and a commercial device is 50.3 μV and 0.6 μV, respectively, while full-scale non-linearity of commercial device according to specification is 200 μV (0.002% of 10V). We also observed slightly higher drift in potential of ISEs in case of commercial device. This observation could be due to the measurement sequence (we measured first with the commercial device, followed by the UWED), and stabilization of potential of ISEs overtime. Total measurement deviations between the UWED and commercial potentiostat was <1.5 mV. Figure S13 shows the final calibration curve of the Na^+ ISE where the potential of the ISE is plotted with respect to log concentration of Na^+; We see similar results from the UWED and the commercial potentiometer.

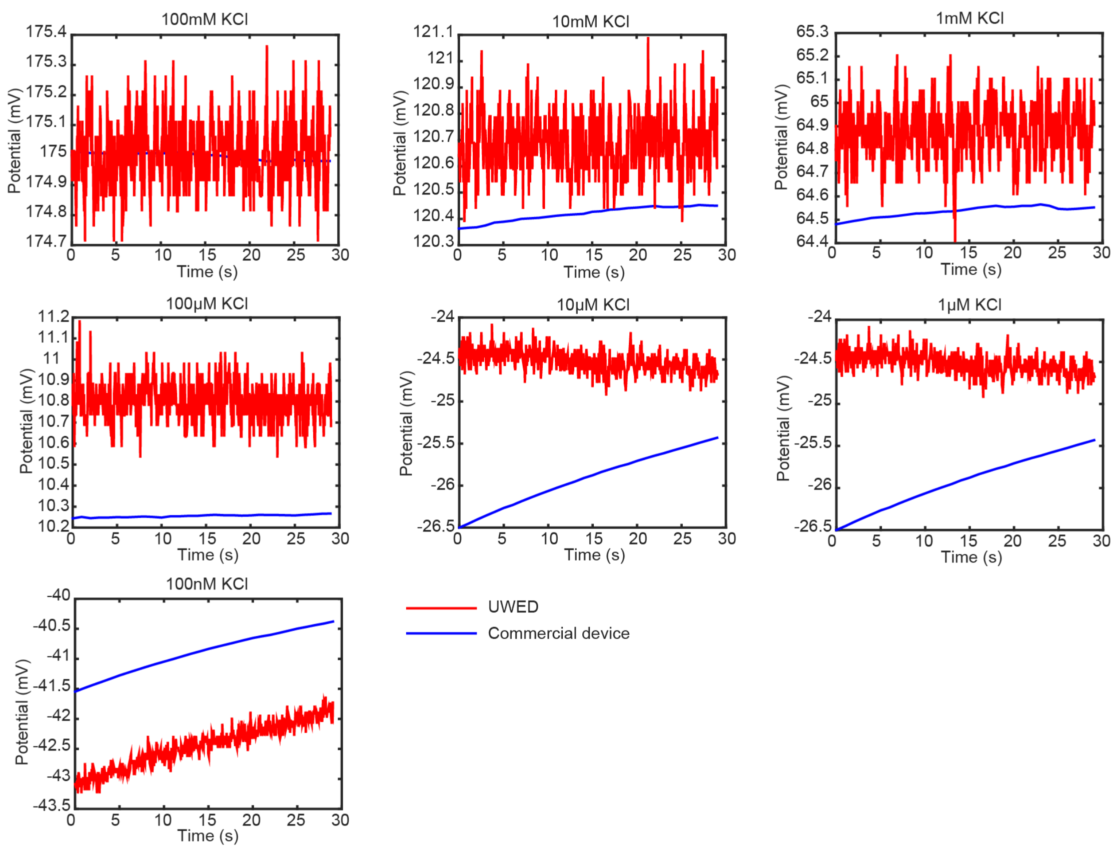

Figure S10. Drifts in electrical potential of K^+ ISE measured with UWED and a commercial potentiometer.

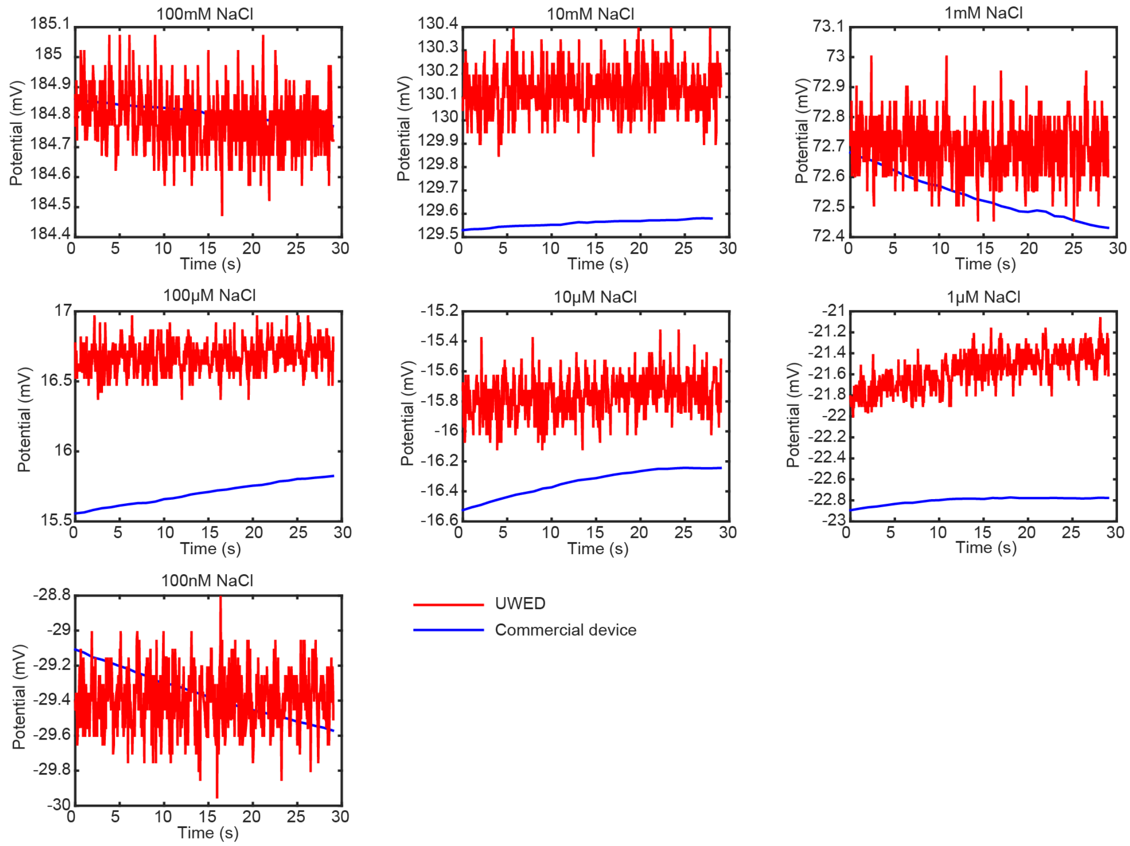

Figure S11. Drifts in electrical potential of Na^+ ISE measured with UWED and a commercial potentiometer.

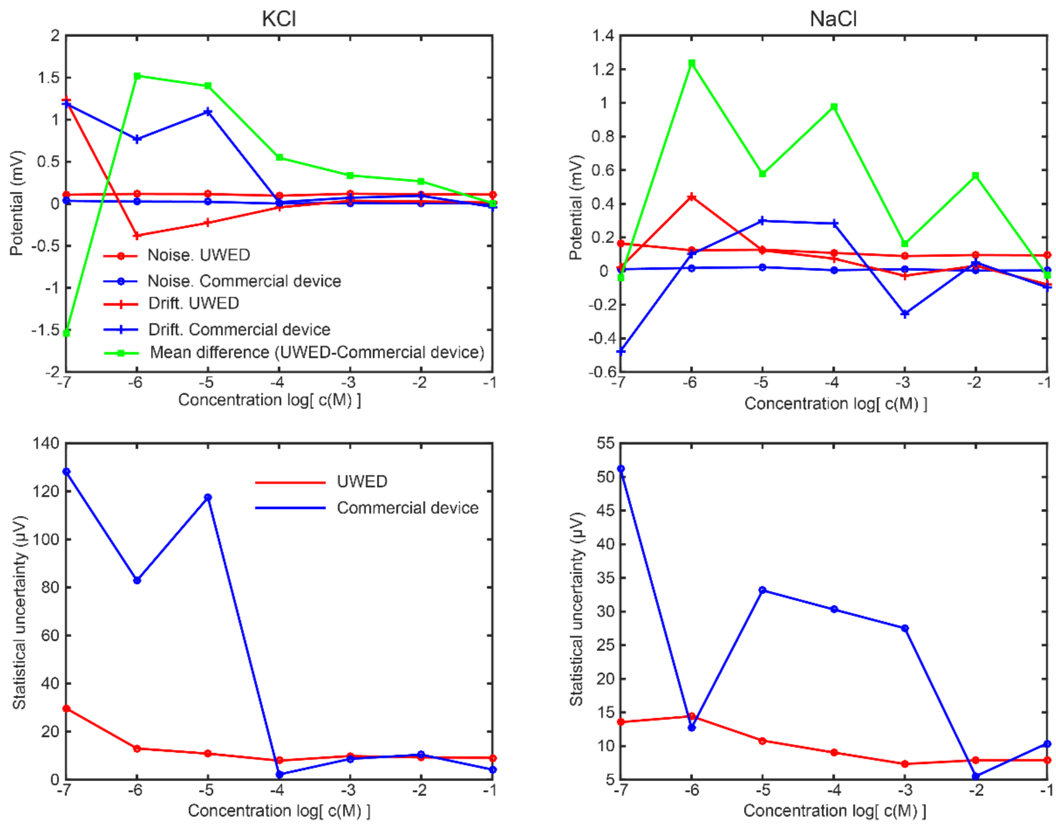

Figure S12. Comparison of noise and drift in potential of ISEs measured with UWED and the commercial potentiometer. We calculated statistical uncertainty as $std(Signal)/\sqrt{N_{datapoints}}$.

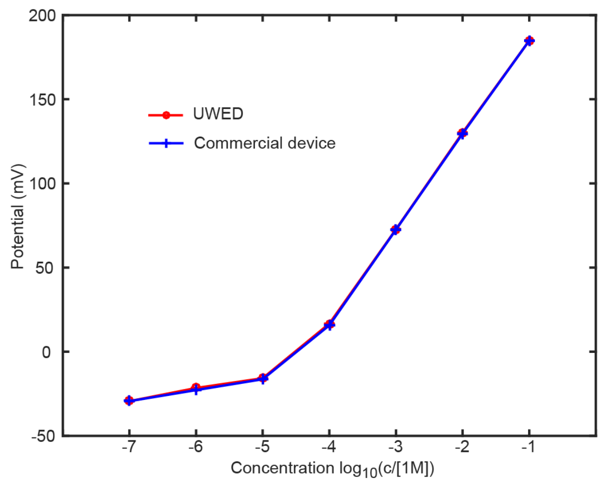

Figure S13. Potential of Na^+-ISE in Na^+ solutions with varying concentrations, measured with UWED and a commercial potentiostat. The slope of potential of ISE vs log concentration of Na^+ agreed with the theoretically expected Nernstian slope of 59.2 mV/decade. We observed a slope of 56.2 mV/decade for UWED and 56.4 mV/decade for the commercial potentiostat over a concentration range of 100–0.1 mM Na^+.

7.2 Chronoamperometry (CA)

7.2.1 Experimental Description

Measurements: We used a commercial screen-printed three-electrode cell (DRP-110CNT-GNP, DropSens, Llanera, Spain) for performing the chronoamperometry on ferricyanide. This electrode contained a carbon (modified with gold) working electrode, carbon counter electrode, and silver reference electrode. We placed 40 µL of fresh solution of ferricyanide on the working zone of the screen-printed electrode, applied a potential of 100 mV to the working electrode (vs the reference electrode), and recorded the current (from 0.5 s to 5 s) with the UWED and a benchtop commercial potentiostat (AutoLAB).

Preparation of solutions: We prepared solutions of ferricyanide (10 mM to 10 µM) in a PBS buffer (Lonza, Walkersville, MD, 1 mM KH_2PO_4, 56 mM Na_2HPO_4, 150 mM NaCl, pH 7.4).

7.2.2 Results

Figure S14 shows the chronoamperograms of ferricyanide at concentrations ranging from 10 mM to 25 µM. There is excellent agreement between data obtained by the uWED and the commercial potentiostat at concentrations of 2.5 µM–2.5 mM ferricyanide. At concentrations of 5–10 mM the current exceeds the current range of UWED (maximum 180 µA), and causes deviation between measurements of UWED and the commercial potentiostat. Figure S15 shows the theoretically expected linear relationship between the current (sampled at 1 s) and concentration of ferricyanide. There is good agreement between data obtained by UWED and the commercial potentiostat within the concentration range of 25 µM–2.5 mM, which the current is within the current range of UWED.

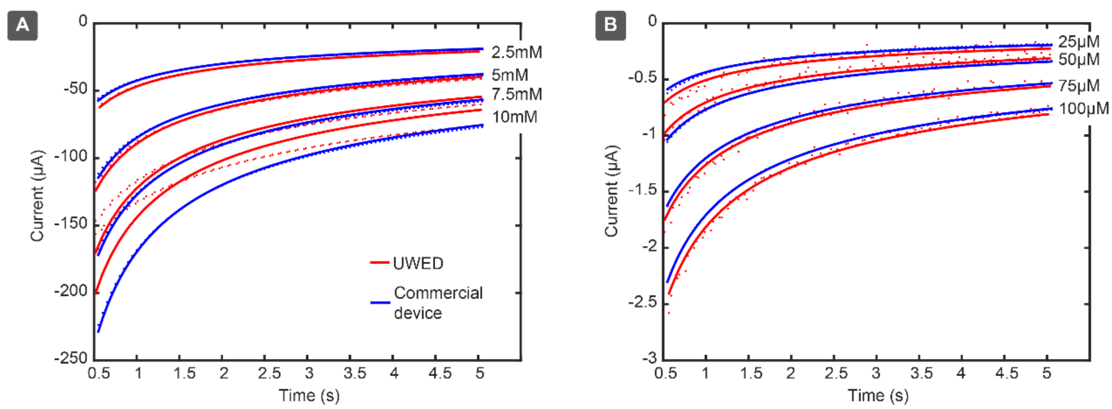

Figure S14. Chronoamperograms of ferricyanide with concentrations of 2.5–10 mM (panel A) and 25–100 µM (panel B). Potential of working electrode was 100 mV (vs Ag pseudoreference). Dots represent the measured data points (current values) and the continuous line shows the fit to the Cottrell equation.

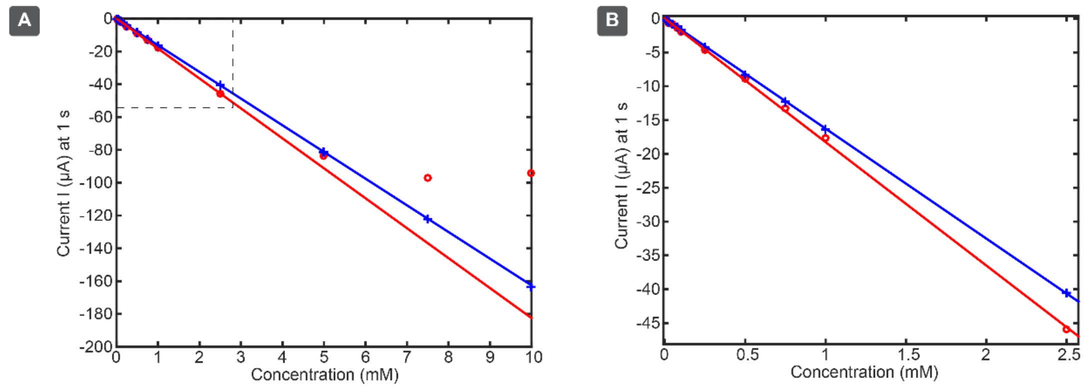

Figure S15. Linear correlation between the chronoamperometric current and the concentration of ferricyanide. (A) shows the concertation range of 0–10 mM and (B) shows the zoomed in range of 0–2.5 mM. The current measured by UWED deviates from linearity in concentrations of larger than 2.5 mM, because the current exceeds the maximum of current range of UWED.

7.3 Cyclic Voltammetry (CV)

We measured CVs using a commercial screen-printed three-electrode cell (as described in Section 7.2.1) in solutions of ferricyanide (solution preparation in Section 7.2.1), with UWED and a benchtop commercial potentiostat (AutoLAB). Figures S16 and S17 show good agreement between CVs (of ferricyanide with varying concentrations and at different scan rates) measured with UWED and the commercial potentiostat.

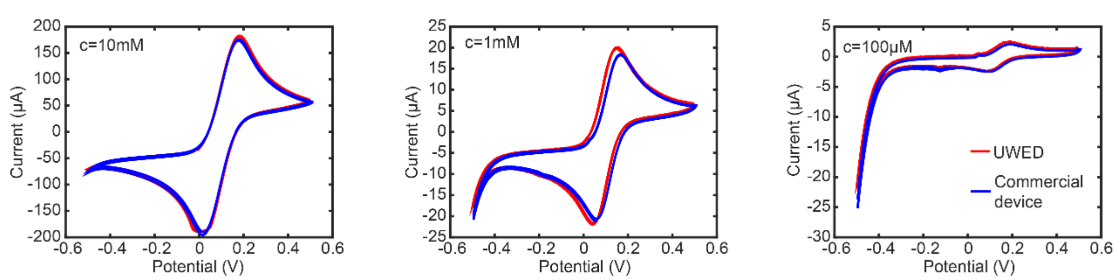

Figure S16. Cyclic voltammograms of 10 mM, 1 mM, and 0.1 mM ferricyanide (scan rate at 100 mV/s).

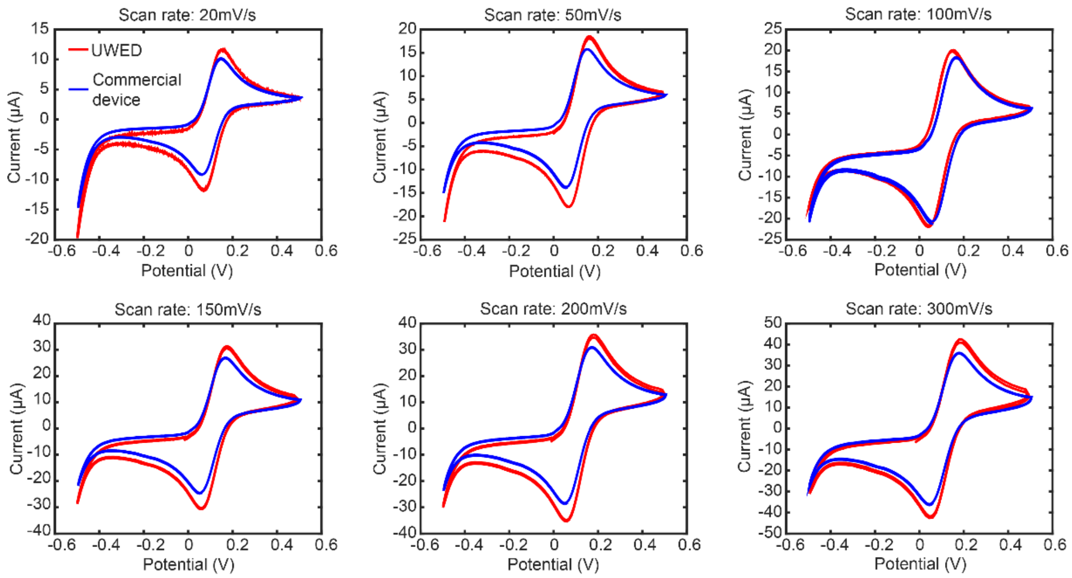

Figure S17. Cyclic voltammograms of 1 mM ferricyanide at a scan rate of 20, 50, 100, 150, 200, and 300 mV/s.

7.4 Square Wave Voltammetry (SWV)

We measured square wave voltammograms using a commercial, screen-printed, three-electrode cell (as described in Section 7.2.1) in solutions of ferricyanide (solution preparation described in Section 7.2.1), with UWED and a benchtop commercial potentiostat (AutoLAB). Figure S18 shows that at concentrations of 5 mM or less ferricyanide the peaks measured by uWED and the commercial potentiostat are in good agreement. At high concentrations (7.5 and 10 mM) the current exceeds the maximum of current range of UWED, and causes the double-peak looking artifact. Figure S19 shows that the theoretically-expected linear relationship between the peak height of the square wave voltammograms and the concentration of ferricyanide.

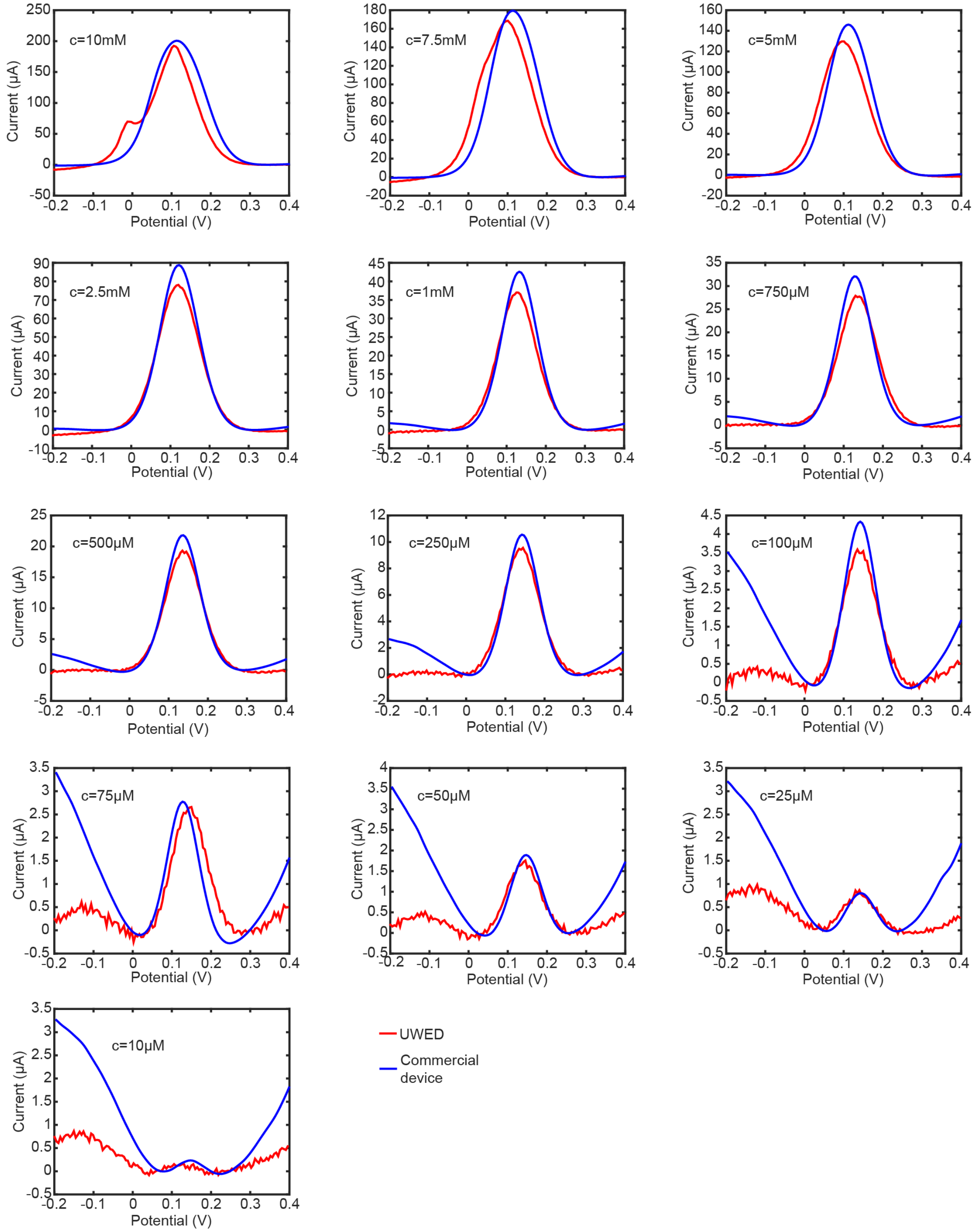

Figure S18. Square wave voltammograms of ferricyanide at concentrations ranging from 10 μM–10 mM. We scanned the potential from 0.4 to -0.2 V at a scan rate 50 mV/s (5 mV steps), with amplitude of 25 mV and frequency of 10 Hz.

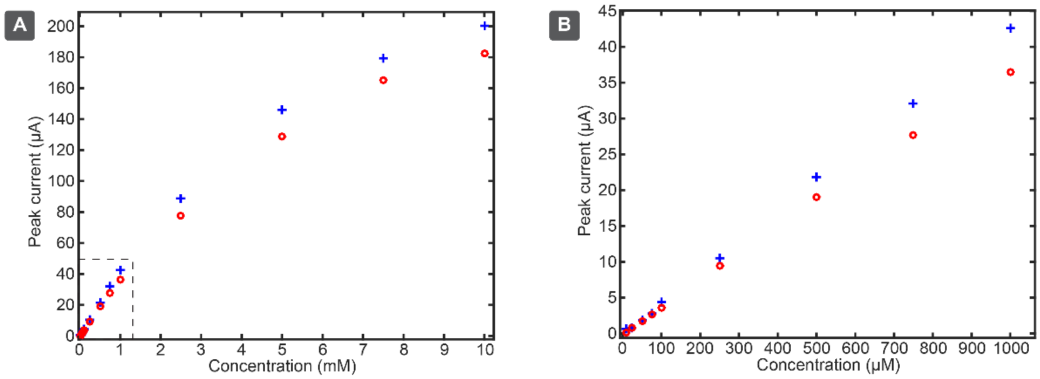

Figure S19. Linear correlation of peak height of the SWV with the concentration of ferricyanide. (A) shows the full range of 0–10 mM, and (B) shows a zoomed-in range of 0–1 mM.

8. Additional Resources

Separate .zip file contains following folders and files

- Electronics – folder is containing the electronic design (Eagle 7.6.0 free version)
  - UWED.sch – Eagle circuit diagram
  - UWED.brd – Eagle PCB board design (for manufacturing)
  - GerberFiles/ – Folder containing board design in Gerber format (used for manufacturing). This folder contains files: UWED.cmp, UWED.dpv, UWED.sol, UWED.stc, UWED.sts and Gerber files explanation.pdf describing exactly each Gerber file.
- Firmware – folder is containing the Arduino firmware
  - Firmware.ino - Firmware for onboard microcontroller RFDUINO
- Apps – folder is containing source codes of basic electrochemical test applications for iOS (in TechBASIC)
  - POT.BAS - Potentiometry
  - CA.BAS - Chronoamperometry
  - CV.BAS – Cyclic voltammetry
  - SWV.BAS – Square wave voltammetry
  - DPV.BAS – Differential pulse voltammetry
  - GUI.BAS - Graphical user interface with inputs for CV and SWV

- Code_as_pdf – folder is containing all the software code (firmware and apps) as pdf files.

Video (UWED.mov) is showing an example of device operation (CV).

References

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