Instructions for building a potentiostat using through-hole components

and the TI LaunchPad development board.

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**Introduction:** This manuscript describes steps used to build a low cost potentiostat. While this is not the first microcontroller driven potentiostat to be described, we feel that earlier instruments were not well suited for construction and use by do-it-yourself peeps in the public. Programming of one early instrument was not described completely[[1]](#endnote-1) and another did not lend itself to single copy fabrication.[[2]](#endnote-2) Neither had a GUI described. The instrument we describe was intended to be built by people with limited electronics experience using through-hole components. The instrument is appropriate for use by people with limited chemistry lab experience for environmental monitoring and chemical education. The design is appropriate for quantifying metal ions in water by differential pulse anodic stripping voltammetry (ASV). In addition to quantifying metal ions, the instrument can be used to characterize electron transfer by cyclic voltammetry (CV) and chronoamerometry (CA).

The lower limit of detection for different metals will depend on a number of factors, including the electrodes used, their condition, and various experimental parameters such as the plating time. For quantitative measurements it is important to calibrate the experiments using standard solutions.

While this is a reasonably advanced electronics project, it should take less than two days to assemble and test.

**Materials and equipment**: The instrument requires a computer, Texas Instruments’ LaunchPad development board, an analog instrument board, graphic user interface (GUI), microcontroller code, and a set of electrodes. The LaunchPad was chosen to provide a low cost interface between a computer and the microcontroller that runs the analog section of the potentiostat. A list of components is provided in Table () at the end of this manuscript. These can be purchased from any electronics supply company (Digikey, Jameco, Mouser). You will also need a permanent (Sharpie) marker, soldering iron, wire cutters, wire strippers, etching solution, acetone, a multi-meter and a drill. Holes in the PCB are bored using very small carbide drill bits. We use 0.035” bits purchased from T-Tech. A set of 10 cost $45. Since these bits are easily broken, using a drill press is recommended. If you do not have a drill press available, we recommend using a rotary tool like a Dremmel rather than a hand drill. In addition to this manuscript, you will need the program Energia (energia.nu), the code to program the microprocessor (found at --), and the GUI program (found at --). While the hardware and software works as presented, those who wish to modify the hardware can do so. A schematic for the potentiostat board is provided in Figure () at the end of the manuscript. Eagle files for the hardware can be found at\_\_. The GUI was written using Processing and the source code can be found at \_\_.

**Safety:** It is strongly recommended that you wear appropriate eye protection when cutting and drilling PCB boards. Chemical hazards are minimal. Be aware of that organic solvents like acetone are flammable and take sensible precautions. Nitrile gloves are recommended since acetone will dissolve latex.

**Fabricating the printed circuit board (PCB):**

**Quality control**. We strongly recommend testing the board, component placement and solder joints during the process of building the potentiostat. Testing early and often can simplify troubleshooting dramatically. In this manuscript, we provide notes in *italics* preceded by a bold **QC** where we recommend checking to assure the quality of the device.

**Preparing the Launchpad board:** The circuit board is wired to the LaunchPad development board in seven places: A the +5 volt connection is made to a connection at the mini-usb port. The remaining connections are made via the headers provided with the LaunchPad. Solder the provided female headers to the LaunchPad.

You will need to replace the microprocessor chip (MSP430g) that comes with the development board. Pry the chip that comes with the launchpad out of the socket and replace with a MSP430g2553 chip. You will also need to exchange the connections between the transmit and receive pins. For some reason, the folks at TI failed to standardize which pin their chips use to transmit and which they use to receive communications. The procedure for establishing the correct connectivitiy depends on the version of the Launchpad you have.

**Version 1.5:** If you have version 1.5 or later, you simply need to remove the jumpers for the transmit and receive pins at J3 (connects the emulation side of the board to the microcontroller, see Figure 11, page 17 of the user’s guide; SLAU318), turn them ninety degrees so that they are perpendicular to the remaining jumpers.

**Version 1.4:** As described earlier, we recommend making a com board if you have the early version of the LaunchPad. The com board has four holes in a 0.1” by 0.1” square pattern with two of the holes connected across the diagonal. The other two connected by a line of copper that loops around the outside. The com board is finished by soldering either a 2 x 2 female header or two 1 x 2 headers to the board. Pressing the female headers of the com board onto the male headers of the LaunchPad establishes the connectivity needed to communicate with the MSP430g2553 microcontroller.

**Fabricating printed circuit boards (pcbs):** While the electronics for the potentiostat fit on a single board, you may want two additional smaller boards, depending on the version of the LaunchPad you have and your intended use. If you have LaunchPad version 1.4 or earlier, we recommend you make the Com Pin Jumper board to re-route the connections pins. If you have version 1.5 or later you will not need this board. If you intend to measure very low concentrations of metal ions, we recommend you make the stirring paddle. While the paddle can be made from any solvent impervious material, making it from a copper clad pcb board will allow you to solder electrical leads to the stirring motor.

The drilling and masking patterns for the PCB board are presented in Figure 1. Figure 2 shows how the components are attached to the board. Note that the drilling pattern shows the view of the board from the top (plastic side) while the masking pattern shows the view from the bottom (the side with the copper on it). The flat side of the 1.8 volt ldo faces away from the capacitor it is next to (C3).

PDIP-drill-C.TIF Figure 1. Drilling and masking pattern for PCB boards.

*Drilling:* The board was designed to use components having pins on 0.1” centers, and to connect with the LaunchPad via headers. Thus, it is important that the scale is correct. To check the scale, locate the holes on the drilling diagram that correspond to pins labeled VCC and GND in Figure 2. On Figure 1, these holes should be 1.8” apart. If you cannot get the scale right, a pdf file of the drilling diagram is available at (). Cut the drilling pattern out of Figure 1 and tape it to the plastic side of a blank circuit board. Drill holes through the circuit board at each circle on the pattern.

*Masking:* Remove the paper drilling pattern from the circuit board. At this point, it is important that the board be clean of any grease / oil / grubby-finger-prints. Clean the board with acetone or something alkaline like ammonia and allow it to dry thoroughly. Use a “Sharpie” type permanent marker to draw lines on the copper connecting the appropriate holes as drawn in the masking diagram (right side of Figure 1). Broadening the lines to fill as much space as possible will maximize the life of your etching solution. If you inadvertently connect lines that should not connect, you can either use acetone to remove the ink and start over, or you can resign yourself to scratching off undesired copper with a sharp tool (I use the latter method).

*Etching:* A variety of good videos are available to show the process of etching the circuit board (one example at http://www.instructables.com/id/DIY-Printed-circuit-board/). Cut the circuit board from the blank using either a paper cutter (preferable) or a pair of metal shears. Place the board in the bottom of a glass or plastic container with the copper side up. Pour etching solution (weakly acidic aqueous FeCl3) in the beaker until the board is about 0.25” below the surface. Heat water in a second, larger container until it is warm to the touch (like a cup of hot coffee) and place the container containing the board in the warm water. Periodically, rock the beakers back and forth to agitate the solution. During this process, the copper showing through the mask will be etched off the board and the copper beneath the mask will remain. Reheat the water in the outer beaker periodically. Watch the board during this process. It should not take more than 15 min for all the copper to be removed from the un-masked areas. When all the visible copper is gone, you will be able to see the plastic on the back side of the board. At this point, remove the board and rinse with cool water. Remove the marker-ink mask using acetone and a paper towel (wear nitrile gloves during this step, acetone will dissolve latex).

**QC1!!!** *Check the board for electrical continuity across the pads using a multimeter set to measure resistance. The resistance from one end of the pad to the other should not exceed 2 ohms. If it does, look for scratches in the pad. If a scratch breaks the continuity of the pad, solder the scratch and check the continuity again.*

**QC2!!!** *Check to make sure that all adjacent pads are separated. If two adjacent pads show continuity, grind a path between them using a rotary (Dremmel type) tool or by scratching with a sharp tool*.

**VCC C4 P- R10 GND**

**L2 MH**

**L3 1.0 Mot1 R5**

**R9 P+ 1 M1**

**D1 R6 C5**

**D2 C7 P1 WE M2**

**C8 1.5 L4**

**2.0 R8 RE**

**C6 +5 V**

**2.1 R4**

**MH 2.2 R7 C9**

**7 8 L5**

**R2 CE C3 LDO**

**R1 C1 C2 R3**

**Mot2**

+/- 12 V conv

Quad op amp

PDIP-Potentiostat-12C.TIFFigure 2. Assembly diagram. Components labeled in yellow boxes should be attached early to allow testing of the power supply. Op amp pin labels (1, 7 and 8) and pin labels for LaunchPad connections (VCC, 1.0, 1.52.0, 2.1, 2.2, and GND) are consistent with the numbering scheme in Table 1. Circles labeled MH represent 1/8” mounting holes. Wires are connected to electrodes at points labeled WE, CE, and RE. Wire connections labeled M1, M2, P1, P+, and P- connect the board to the multiplexer and potentiometer.

*Assembly:* The assembly diagram is provided in Figure 2.All components are attached by pushing their pins (or wires) through the board from the top (plastic side) and soldering them to the copper pads on the bottom. The large rectangles are the socket that accepts the quad op amp and the +/-12 volt DC converter. While the order of assembly will not affect performance, we recommend attaching the amp socket and all the components of the power supply first. Once the components labeled in the yellow boxes are attached, the board can be attached to the LaunchPad and powered up to test the power supply circuit. The op amp socket is attached with the notch facing in the direction indicated in Figure 4. Electrolytic capacitors have directionality, make sure the marked side (the one with the shorter wire) is soldered to the lower voltage (usually ground) position. The one exception is C6, where the shorter wire is attached to the -12 volt pad.

**Headers on the potentiostat board.** We make the connections between the two boards using male headers on the potentiostat board and female headers on the LaunchPad. Male headers for the potentiostat board can be made from the headers that accompany the LaunchPad. These will be modified by cutting them with wire cutters to give 1 x 2 and 1 x 4 headers. The pins should be pused through the plastic housing until they are nearly flush. The 1x2 header is used to make connections to the +3.6 volt (VCC) and P1.0 pins on the LaunchPad. The 1 x 4 header is used to connect to pins P1.4, P1.5, P2.0 and P2.1. Solder a thick bare wire into in the ground position on the upper right of Figure 4. This wire will plug into the ground position on the female header on the Launchpad. It is useful to have the ground wire extend both above and below the board. This allows you to connect to ground from either the top or bottom and will provide a ground for your multimeter. Connect the +5 volt wire to the LaunchPad board. The +5 volt pin on the LaunchPad is found on the side of the mini-USB socket.

**QC3!!!** *Plug the LaunchPad into a usb port and measure the voltages at the pins of the op amp socket. They should give the readings in Table 1.*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Table 1. | |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| Pin | voltage |  | pin | pin | resistance |  |  |
| 4 | >+12 v |  |  |  |  |  |  |
| 10 | +1.8 |  |  |  |  |  |  |
| 11 | <-12 |  |  |  |  |  |  |
| 12 | +1.8 |  |  |  |  |  |  |

Electrodes connect to the points on the diagram labeled CE, RE, and WE. The points labeled M1 and M2 connect to a rotary switch (multiplexer) used to select one of several resistors (ranging from \_ to \_ ohms). The point labeled P1 attaches to the wiper (center terminal) of a 10 kohm potentiometer. The other potentiometer terminals are attached to the high and low voltage points labeled P+ and P-. The two diodes keep input to the microcontroller ADC between GND and VCC. Without these diodes, output from op amp 4 (far right in the schematic) can spike to +/- 12 volts (not good for the electronics).

**Multiplexer:** A rotory switch allows the user to chose one of twelve resistors that define the sensitivity of the instrument.

**Enclosure:** We use standard VHS tape boxes for enclosures. We purchased them in bulk for $0.50 each. The holes for the potentiometer and rotary switch are 3/8” diameter. The hole for the usb cable is 11/64” and those for mounting the board using 1” #4 machine screws are 1/8”.

**Software**: While Texas Instruments “Code Composer Studio” environment for programming the MSP430 is provided free of charge, we have found it difficult to use (but then, we are relatively inexperienced programmers) and have switched to Energia IDE (also freely available). Their home page describes Energia as “a rapid electronics prototyping platform for the Texas Instruments msp430 LaunchPad. Energia is based on Wiring and Arduino and uses the Processing IDE.” Energia is available for Windows, Mac, and Linux, and can be downloaded for free from <http://energia.nu/>. Programming the MSP430 with Energia is similar to programming an Arduio. The Energia code for the potentiostat microcontroller can be downloaded from \_\_.

The graphic user interface for the potentiostat was written using Processing software (Processing is available for download from [www.processing.org](http://www.processing.org)). The GUI can be downloaded from --. Libraries must be downloaded as well.

**Stirring motor and paddle:** To maximize mass transfer of material from solution to the working electrode during the ASV experiment, the solution is stirred by a vibrating paddle during the platting time. We use a vibrating coin motor that runs off the 3.6 volt VCC. The motor is switched on and off by pin P1.0. The coin motor we used requires little power, allowing us to run the thing directly from the launchpad. We make the stirring paddle from PCB material and remove all copper except for two pads where the connections are made. The motor leads are soldered to the pads, as are the wires that will lead to pins Mot1 and Mot2 on the potentiostat board. The vibrating motor is then attached to the paddle using hot melt glue.

**Electrodes:**

Three electrodes are usually used for electrochemical measurements. They are the working, counter, and reference electrodes.

One simple and relatively inexpensive option is to purchase printed electrodes from a commercial source. Pine Instruments (<http://www.pineinst.com/echem/products.asp?categoryID=31>) offers three electrode printed cell with electrodes made of either carbon, gold or platinum. Carbon electrode cost $30 for a ten pack. The gold and platinum electrodes will cost $200 for a pack of 6. While Pine has an adapter available for sale, we have had good results soldering wires directly to the printed electrodes and connect those wires to the potentiostat using alligator clips.

If you chose not to go with the printed electrodes, you will need to have separate working, counter and reference electrodes.

Reference electrodes: we use a silver wire in saturated KCl solution. The reference electrode is separated from the test solution by a junction composed of a 4A molecular sieve glued to a glass tube.[[3]](#endnote-3) It is important that the sieve be saturated with the KCl solution. Reference electrodes are stored in saturated KCl solution when not in use. While it is recommended procedure to oxidize the surface of the silver, stable electrodes can be made without doing so (ref).[[4]](#endnote-4)

Electrochemists have used a variety of materials as working electrodes over time. The choice of material is governed by factors such as reactivity and cost. Platinum and gold are popular choices due to their stability toward oxidation. One down side to these are limitations in useful potential due to hydrogen production by reducing water. Another point is cost. In 2011, 1” squares of 0.001” thick foil cost ~$100 US each. Note that these electrodes do not need to be large. Using 0.2” squares of foil would put the unit cost of platinum at about $4. Much of the early work in the field used mercury drops or pools as working electrodes. Today you don’t hear about this due to the toxicity of mercury. Another popular material is carbon.

**Theory (not necessary for building and operating the potentiostat):** Potentiostats are used to measure the electrical current that passes through an electrode at a given voltage. A three electrode configuration is typically used for electrochemical measurements at solution / electrode interfaces. The three electrodes are the counter electrode (CE), reference electrode (RE) and working electrode (WE). The microcontroller builds an output voltage versus time profile based on user determined parameters and outputs a pulse width modulated (pwm) signal reflecting the voltage profile on pin 2.1. The pwm signal is converted to an analog voltage by a two phase low pass filter comprised of resistors R1, R2, and capacitors C1 and C2. Output from the low pass filter is input into the inverting terminal of op amp 1 (see schematic, Figure 1 in the accompanying pdf file). Since the low pass filter limits the rate at which the applied voltage can change, a second input (labeled ‘pulse’ on the figures) is used to introduce a square wave for pulsed experiments. The non-inverting terminal is held at a reference voltage (Vref = 1.8 v) which is established using a low dropout oscillator (+1.8 v ldo). The output from op amp 1 is attached to the counter electrode (CE in Figures 1 and 4). The voltage of the reference electrode (RE in the figures) is established by feedback from op amp 1 and is connected to an A to D converting pin on the microcontroller (Vread). The voltage at Vread should be equal to 2 Vref – pwm. Since the pwm output of the launchpad can vary from 0 to 3.6 volts, and since Vref = 1.8 v, values of Vread can vary between 3.6 and 0 volts as well. Since Vref is attached to the non-inverting pin on op amp 3 as well as op amp 1, the voltage on the working electrode (WE in the figures) is Vref, and the voltage difference between the working and reference electrodes (pwm – Vref) can vary between +1.8 and -1.8 volts. The current that passes through the working electrode is proportional to the output voltage from op amp 3: V = -iRm where Rm is the resistance between points M1 and M2 in the figures. Points M1 and M2 are attached to a rotary switch that allows selection of different resistors to define the sensitivity of the measurement. Since currents at the working electrode can be either positive or negative, and since the lauchpad can only read positive analog voltages, it is necessary to offset the voltage output from op amp 3 prior to reading. The current offset is established using a potentiometer and connecting the wiper to the non-inverting pin of op amp 4. The offset voltage can be read by connecting the Oread pin to one of the A to D converting pins on the LaunchPad device. Output voltage from op amp 4 should equal Iread = i\*Rm + Oread. To prevent inappropriately positive or negative voltages from frying the launchpad, diodes bridge the output to the +3.6 and GND.

Power to the op amps comes from a +/- 12 volt DC converter that runs off the +5 volts supplied by a usb connection. We recommend putting a toggle switch between the +5 volt source and the input to the DC converter. This allows the voltage to the electrodes to be turned off when they are not in use (changing solutions, cleaning electrodes, etc).

Parts List:

Figure c. Schematic diagram of potentiostat board.

|  |  |  |  |
| --- | --- | --- | --- |
| Item | cat no | cost | vendor |
| LaunchPad board | MSP430g | 4.30 | Jameco |
| microcontroller | MSP430g2553 | 2.76 | Digikey |
| DC converter | DCH010512D | 10.10 | Digikey |
| op amp | LM148J | 7.79 | Digikey |
| 1.8 volt LDO | MCP1700 | 0.44 | Digikey |
| rotory switch |  | 0.95 | Jameco |
| potentiometer |  | 2.60 | Jameco |
| toggle switch |  | 1.49 | Jameco |
| pcb board |  |  |  |
| aligator clips |  | 0.35 | Jameco |
| knobs |  | 0.89 | Jameco |
| resisters | R1,2,5, 6 = 1 k ohm | 0.24 |  |
|  | R3 = 200 ohm |  |  |
|  | R4 = 2.2 k ohm |  |  |
|  | R7 = 160 k ohm |  |  |
| Course current adjust | Rm = |  |  |
| capacitors | C1 = 4.7 uF | 0.27 |  |
|  | C2 = C3 = 10 uF |  |  |
| 0.2" x 0.2" gold foil | from 1" square | 4.00 | alfa aesar |
| wire |  |  |  |
| diodes |  |  |  |
| total cost |  | 36.18 |  |
|  |  |  |  |

**Potentiostat Circuit Components and Pin Numbers**

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Value | Digikey (through hole) | Surface mount |
| Circuit | | |  |
| R1 | 1 KOhm |  |  |
| R2 | 200 Ohm |  |  |
| R3 | 1 KOhm |  |  |
| R4 | 2.2 KOhm |  |  |
| R5 | 10 KOhm |  |  |
| R6 | 10 KOhm |  |  |
| R7 | 160 KOhm |  |  |
| R8 | 1 KOhm |  |  |
| R9 | 6 MOhms |  |  |
|  |  |  |  |
| C1 | 4.7uFarad |  |  |
| C2 | 10.0 uFarad |  |  |
| C3 | 4.7 uFarad |  |  |
| C4 | 4.7 uFarad |  |  |
| C5 | 4.7 uFarad |  |  |
| C6 | 4.7 uFarad |  |  |
| C7 | 0.01 uFarad |  |  |
| C8 | 0.1 uFarad |  |  |
| C9 | 4.7 uFarad |  |  |
|  |  |  |  |
| L1-L5 | 10 uH |  |  |
|  |  |  |  |
| Multiplexer | | |  |
| R1 | 1 KOhm |  |  |
| R2 | 2 KOhm |  |  |
| R3 | 5 KOhm |  |  |
| R4 | 10 KOhm |  |  |
| R5 | 20 KOhm |  |  |
| R6 | 50 KOhm |  |  |
| R7 | 100 KOhm |  |  |

|  |  |
| --- | --- |
| Wire | LaunchPad Pin Number |
| VCC | VCC |
| Ground | Ground |
| PWM | 2.1 |
| Pulse | 2.2 (2.0) |
| Current Read | 1.4 |
| Voltage Read | 1.5 |
| DC motor on/off | 2.4 |

1. Gopinath, A. V., Russell, D., Chem. Educator, 2006, 11, [↑](#endnote-ref-1)
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