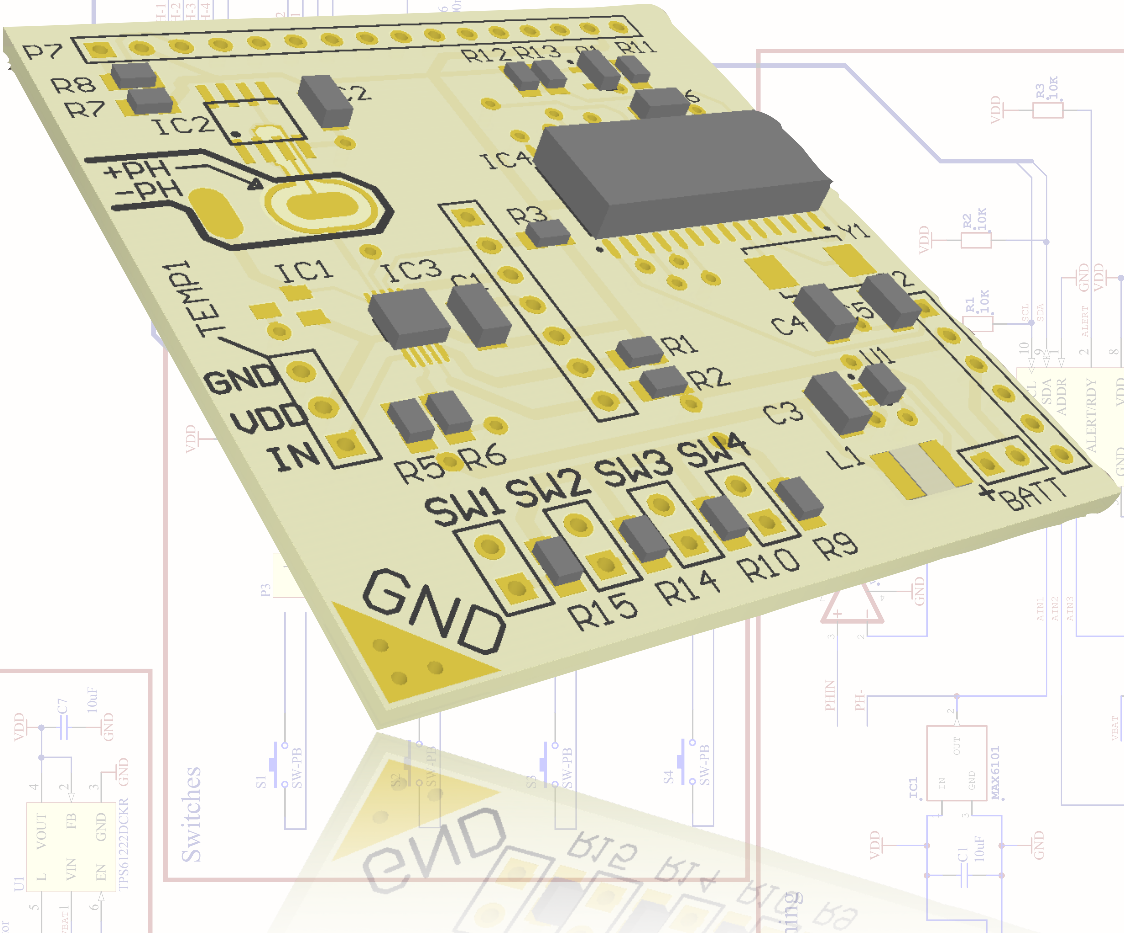
Design and Construction of a Modern pH-meter in SMT Technology

Final year thesis by Davide Bortolami



INDICE

Project goals and description

Description:

The purpose of this project is to creare a pH-meter with specifications similar to marketed products.

During development it has been chosen to kept the hardware as modern and concise as possible. When available, modern ICs have been chosen over legacy alternatives, giving space to a state-of-the-art software configurable ADC and ultra-high specs op-amp. [more info in the general hardware description].

The goals of the project were chosen at it’s genesis, and nearly no compromise has been taken during development and design.

An handheld shape has been chosen for the instrument. While a wooden case (CNC machined) is preferred, a 3d printed PLA case is also an available and acceptable solution.

Technical specifications:

- Shape: Handheld tool
- Power source: AA/AAA battery
- Concurrent measurement and display of both pH and temperature
- Standard BNC connection for brand-less pH probes
- Temperature resolution better than 0.1°C
- pH resolution of at least 0.1pH
- Easily readable LCD display with firmware control
- Differential measurement mode (delta - Δ)

Why English?

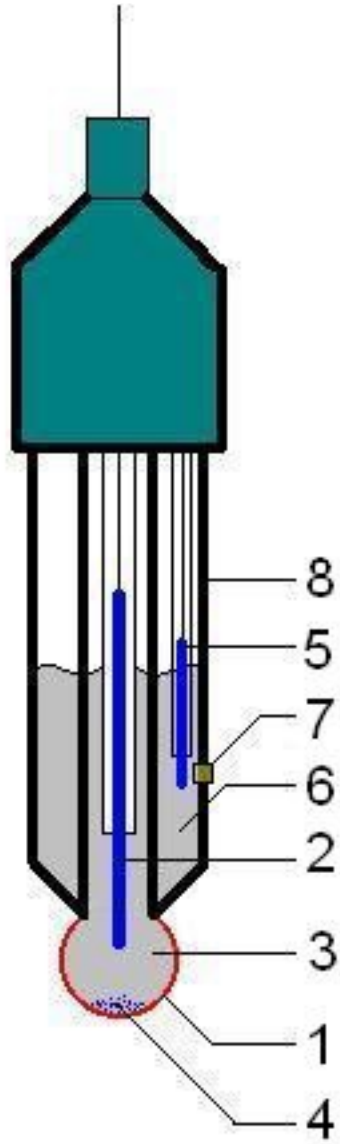
Both the code and this thesis itself are written in English. While my mother language is Italian I found many obstacles in using it. It’s despicably common to find untranslatable terminology in the electronic field, and i find no point in using convoluted sentences to convoy meanings that are simpler to explain in English. During early stage development and the feasibility study every document found on the internet was in English. The code was also commented in english from the start, while this thesis was completely rewritten from scratch.

The pH probe - theory

A pH probe (technically called a glass electrode) is a type of ion-sensitive electrode made with doped glass. The most common is sensitive to H+ ions (the pH probe) but version for Na+ and Ag+ are available.

In the figure[1] on the side the following element are highlighted:

1. Doped glass bulb
2. Internal electrode, coated in silver chloride
3. Internal solution, generally of 0.1mol/l of KCL. The pH of this solution determines the offset of the probe, so it must be as close to pH 7 as possible
4. AgCl precipitated from the electrode
5. External electrode
6. Reference solution, not present in cheap probes
7. Junction made from ceramics or quartz fiber, not present in cheap probes
8. Non conductive glass insulation



Typical pH probe construction diagram

The manufacturer provide us with a 200MΩ specs as equivalent DC impedance of the probe.

In order to measure with precision we need a very low measurement current. The current generated by the probe can be easily calculated by ohm's law:
Presuming +-300mv@14pH for 0.1pH the voltage will be

$300mV * \frac{0.1° ph}{14-7} = 4.2mV$ and thus the current will be

$$I = \frac{V}{R} = \frac{4.2mV}{200M\Omega} = 21.43pA$$

A measurement current of two orders of magnitude inferior to the probe current is suggested.

$I_{max} = \frac{21.43pA}{100} \approx 200fA$ (maximum).

Similarly a suggested input impedance can be calculated:

$$R_{MIN} = 100 * R_{PROBE} = 100 * 200M\Omega = 25G\Omega$$

[1] https://en.wikipedia.org/wiki/Glass_electrode

Hardware - Analog:

General hardware description:

The analog stage of the pH-meter is the part of the circuit wired to the temperature and pH probe. It is comprehensive of both signal amplification and analog-to-digital conversion.

As with any other part of the design the KISS principle has been applied (keep it simple, stupid) to keep both complexity and price low.

Everything in this stage is built around the ADS1015 ADC, that features a integrated voltage reference, programmable gain amplifier and 4 input channel that can be used in differential or single-ended mode. Everything software configurable via the i2c interface.

To avoid a more complex design a major goal was to keep everything powered up from a single supply line (0-5V) in common with the micro controller. The ADC with this power supply cannot measure negative voltages (<GND).

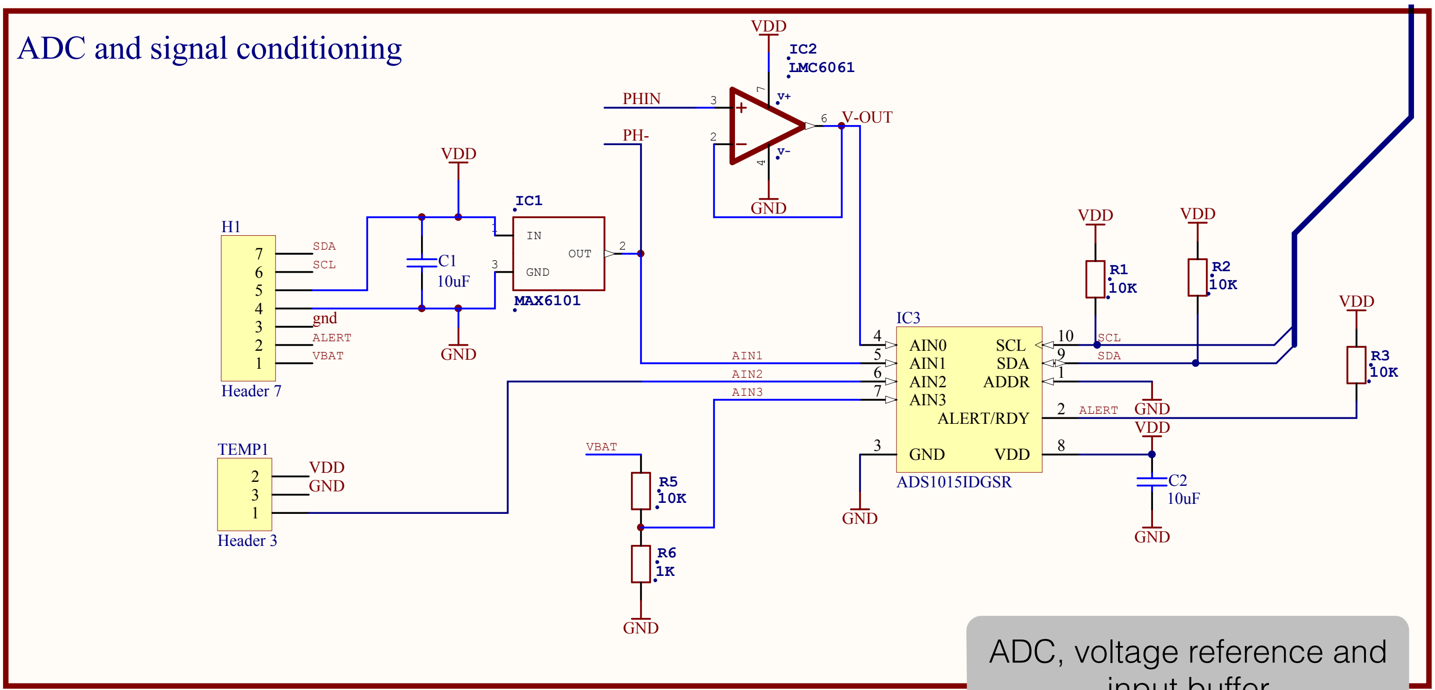
Since as previously explained the pH probe output can range from about -250mV to 250mV, is fundamental to raise his reference ground in order to keep the output >GND. This is achieved with a MAX6101 voltage reference, which provide 1.25V at the probe ground, thus allowing the pH probe output to always be between $1.250V \pm 250mV = 1.0 \div 1.50V$ and consequently never go below GND.

The output is buffered by the LMC6061 operational amplifier in a simple follower configuration.
The LMC6061 feature an absurdly low input bias current of 10fA, many order of magnitude less than the one flowing in the pH probe in the worst case scenario. It also has a very low input offset, ideal for such small voltages.

The use of an instrumentation operational amplifier (featuring a differential high input impedance) was considered but their cost can easily reach 20€@1pc for one that meets the desired specification.

Other voltages measured by the ADC includes the battery trough a resistive voltage divider $V_{out} = V_{batt} * \frac{R_2}{R_1 + R_2} = V_{batt} * \frac{1}{10+1} == 0.9V_{batt}$ and the voltage output from an LM35 temperature sensor (10mV/°C).

Schematic:



ADC, voltage reference and input buffer

Virtual ground with MAX6101:

To generate the virtual ground for the pH probe a MAX6101[2] precision voltage reference has been used. Its output of 1.250V is perfect for our application.

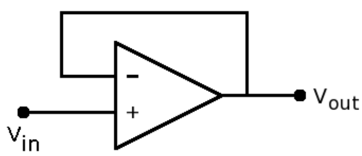
Even though it is a precision device [3] it has been chosen for the following reasons:

- 3-pin SOT23 package
- No feedbacks or external resistors needed
- Stable with capacitive loads (like a pH probe) up to 200uA
- 5mA source and 2mA sink

The ability to sink current is fundamental because the pH probe can provide both a positive or a negative voltage.

Voltage follower with LCM6061 op-amp :

The LMC6061 is a precision operational amplifier that feature an extremely low input bias current of 10fA.



Typical follower configuration

To understand how incredibly small 10fA=1*10^-14A (as in 1>milli>micro>nano>pico>femto !) are we can calculate the average time between every single

[2] Maxim Integrated max6101 voltage reference - http://goo.gl/wuKk8c

[3] low temperature coefficient of 75ppm/°C (max) and an initial accuracy of ±0.4% (max) [source: datasheet]

electron flows in the conductor.

$$I_{avg} = \frac{\Delta Q}{\Delta t} \qquad \Delta t = \frac{\Delta Q}{I_{avg}} = \frac{e}{I_{avg}} = \frac{1.60217657 \times 10^{-19} Coulomb}{1*10^{-14} Ampere} \approx 1.60*10^{-5} s \approx 16 \mu s$$

where e is the elementary charge of a single electron/proton.

16μs is not a long interval at all, for comparison the relative frequency is only 62KHz, about 30% more than the sample rate of a common audio CD. In the same time one electron flows into the LMC6061 input, a modern oscilloscope is able to acquire 80kbits of data.

While a low input bias current is a fundamental parameter in choosing the operational amplifier is not the only one. The op-amp with the lowest input current on the market is the LMC662 (2fA) [4] and while it's fairly cheap and in a practical package [5] it has an offset voltage of 3mV. Assuming a 500mV range the error would be greater than 0.5%: totally unacceptable.

The LMC6061 has emerged as a reasonable compromise between input bias current (10fA), low offset voltage (100uV) and price (1.75€@1pc).

The typical input impedance is >10TΩ, far above the required 25GΩ as previously explained.

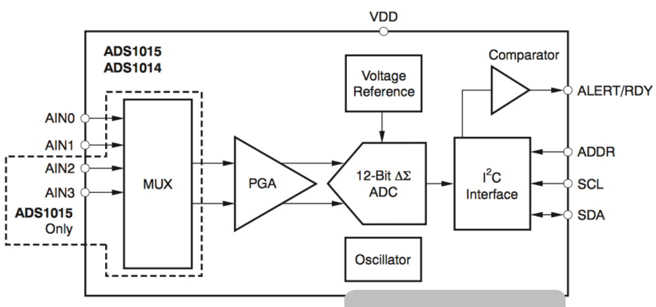
Since the input impedance is so high, a guard trace (connected to Vout) is necessary to avoid errors induced by surface currents on the PCB board.

Analog to digital conversion with ADS1015 :

The ADS1015[6] is a modern ADC, with the following features:

- 4 single ended channel or two differential channel inputs
- 12 bit
- From 128 up to p to 3300 samples per second
- Internal precision voltage reference
- Internal precision programmable gain amplifier with less than 0.05% gain error
- Supply range from 2.0V to 5.5V
- i2c interface
- Typical offset error of just ±0.5LSB

Those specifications are perfect for pur application. An Arduino library[7] is available from Adafruit, a popular open hardware company, providing good and tested examples for software development.



ADS1015

The channels AIN0 and AIN1 have been used in differential mode to measure the probe voltage,

[4] http://www.ti.com/lit/ds/symlink/lmc662.pdf [LMC662 CMOS Dual Operational Amplifier]

[5] http://goo.gl/YS67tY [LMC662 on digikey]

[6] http://www.ti.com/product/ads1015 [12-Bit ADC with Integrated MUX, PGA, Comparator, Oscillator, and Reference]

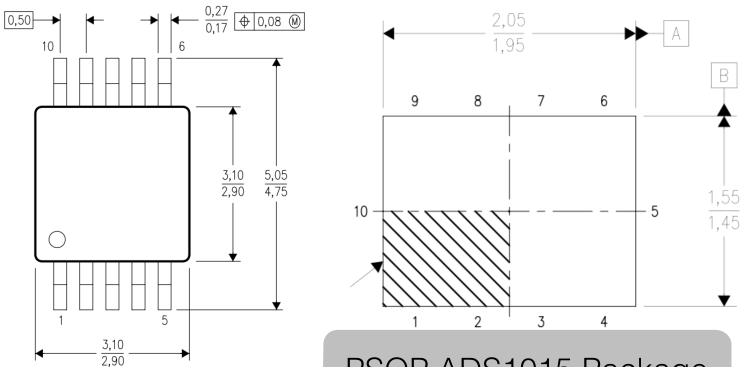
[7] https://github.com/adafruit/Adafruit_ADS1X15 [ADS1015 Arduino library from Adafruit Industries]

AIN2 has been used for the LM35 temperature sensor and AIN3 for battery voltage measurement.

Pull-ups of 10KΩ on SDA and CLK do not seem to offer good reliability, so 4.7KΩ pull-ups have been used instead.

The ADS1015 is manufactured in [8] PQFP or PSOP packages, both are very small and both required professional PCB with soldermask and small traces.

The PSOP package has been chosen, with its 10 pin in a flat package of just 2.45x1.95mm.



PSOP ADS1015 Package

[8] http://en.wikipedia.org/wiki/List_of_integrated_circuit_packaging_types

Hardware - Digital:

The core of the system is, a usual, a microcontroller. The PIC16f876a has been chosen because it's easily available, well documented and has hardware i2c.

The availability of a free development suite (MPLAB X) able to run on mac was a necessity since most of the development was made on this platform.

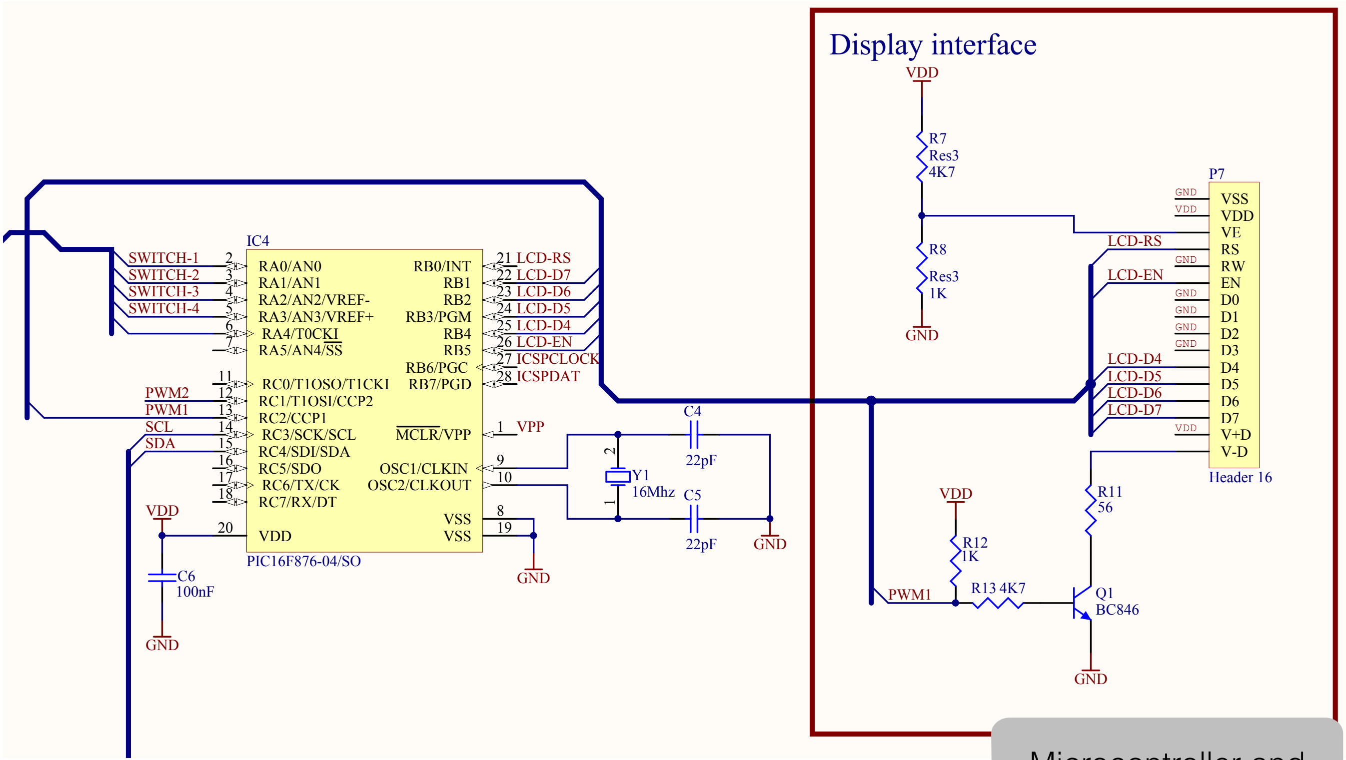
91% of the available program memory and 68% of the available ram was is used.

A 16x2 LCD display has revealed to be the simplest and most practical solution, allowing to display multiple values.

To control the LCD backlight a simple transistor switch based on a BC846[9] NPN transistor has been used. The resistor value are industry standard[10] for this type of application and works in a wide range of supply voltages.

The following schematic covers the micro controller and display interface.

Schematic:



Microcontroller and display interface

[9] http://www.nxp.com/documents/data_sheet/BC846_SER.pdf [BC846 65 V, 100 mA NPN general-purpose transistors datasheet]

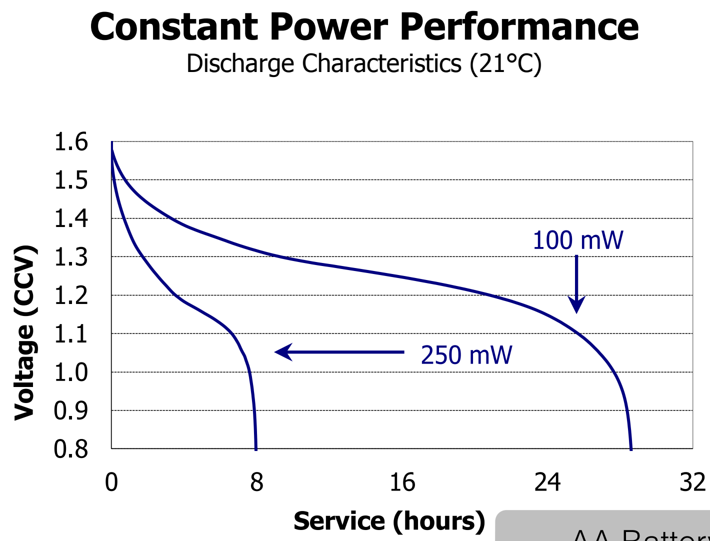
[10] http://www.mikroe.com/downloads/get/1709/easypic_v7_schematic_v104c.pdf [EasyPic v7 development board schematic]

Hardware - Power supply:

In order to make the instruments as portable as possible, one of the goal was to power it from a single AA battery. To do so, a TPS61222[11] boost converter has been used, allowing the board to be powered from 0.7V up to 5V.

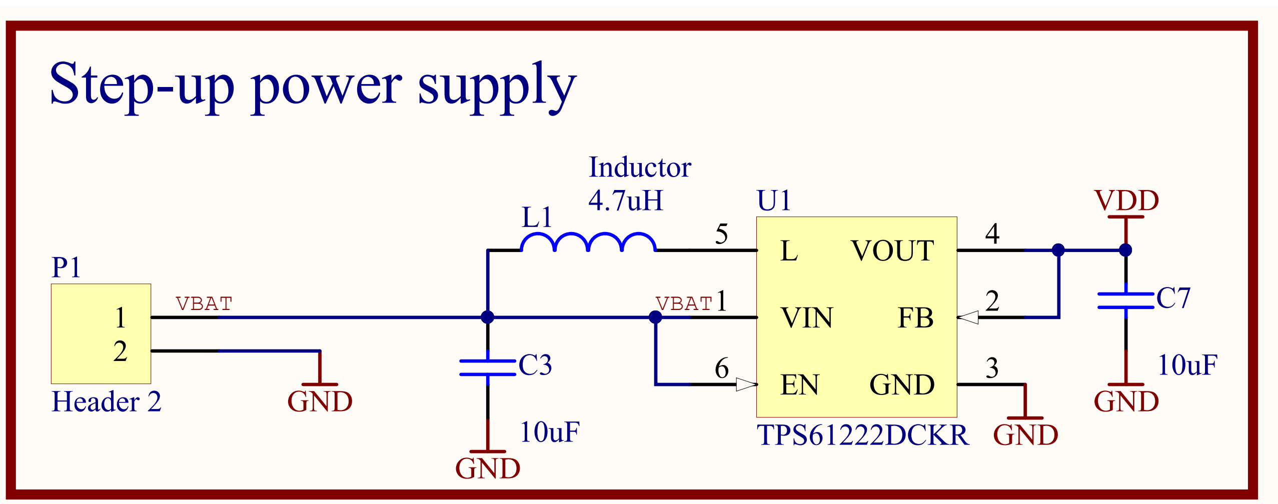
The circuit has been implemented as per data datasheet specification. While this IC can supply only 60mA, the required current never go above 25mA RMS even with backlight at full power.

Looking at a AA standard (Zinc-Manganese Dioxide) battery data sheet[12], we can notice that the battery hold an effective charge just until 1V is reached, allowing the power supply circuit to drain every joule possible out of it.



AA Battery

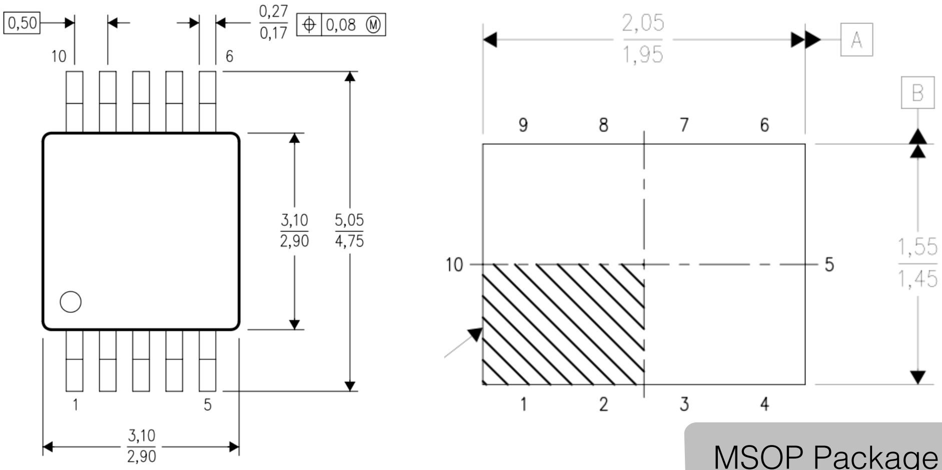
Schematic:



[11] http://www.ti.com/lit/ds/symlink/tps61222-ep.pdf [TPS61222 boost converter datasheet]
[12] http://data.energizer.com/PDFs/E91.pdf [Energizer AA cell E91 datasheet]

Printed circuit board development:

One of the design goal was to use mainly SMD components. The ADC and the Power supply controller are available only in very small packages, such a MSOP.

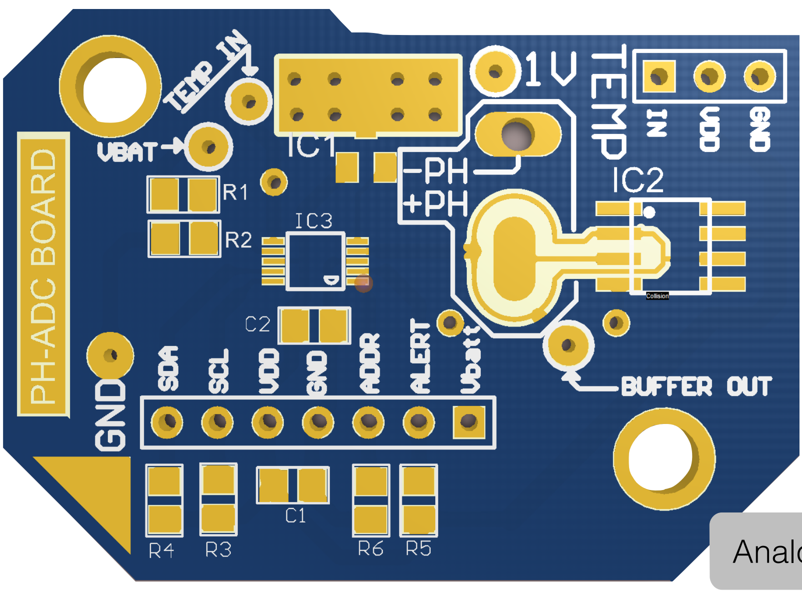


MSOP Package

Such small packages require a professionally made PCB, with soldermask and very thin traces and pads. Since no similar service is available in Italy at a reasonable price, the boards were custom made in China.

Altium Designer[13] software was used to create both schematic and pcb design.
The first step was to develop and analog board (comprehensive of ADC and input buffer) to be used with a separate development board with the pic microcontroller. After testing and software development a more complicated board, featuring also the power supply, a PIC micro controller and the LCD interface was made.

The analog board has many test point and a few small traces to test the quality of the manufactured pcb. Many of those features has been removed in the latest version.



Analog board

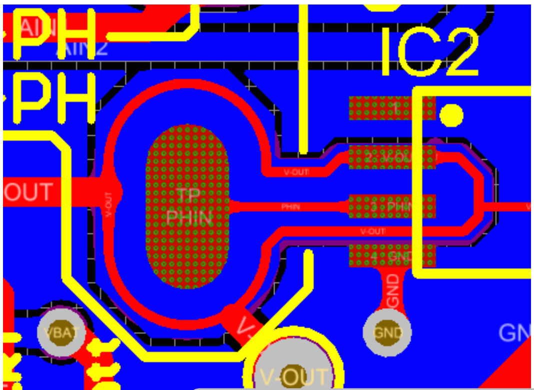
[13] http://www.altium.com [Altium main company website]

Guard traces and routing for high impedance sources:

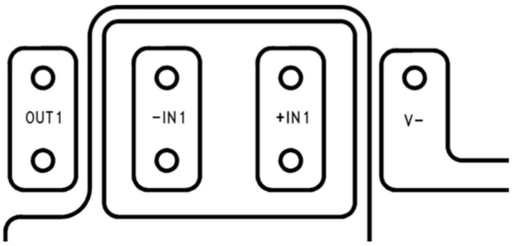
Since the input current of the op-amp buffer is incredibly small, a guard trace is needed around the input path to prevent surface currents to disturb the delicate measurement.

Information on guard traces and high impedance design can be found in Texas Instruments, Microchip and Analog Devices notes[14].

The soldermask need to be removed on the guard trace. The trace itself must be connected to a low impedance source with a voltage as close as possible to the one of the high impedance source. Since the Op-amp implement a simple follower circuit where the output voltage is equal to te input one, the trace was connected to Vout and the inverting input.



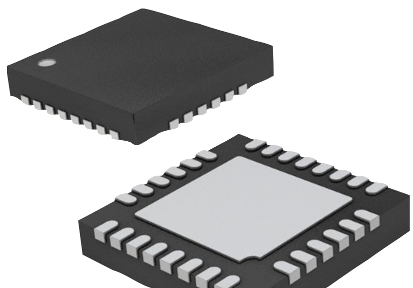
Guard ring implemented on the board



Guard ring as illustrated in the data sheet

SMD Soldering:

All the components were hand soldered without using solderpaste. Only no-clean flux for SMD soldering has been used. It's extremely important to clean the board with isopropyl alcool to avoid surface currents near the input stage due to flux contamination.

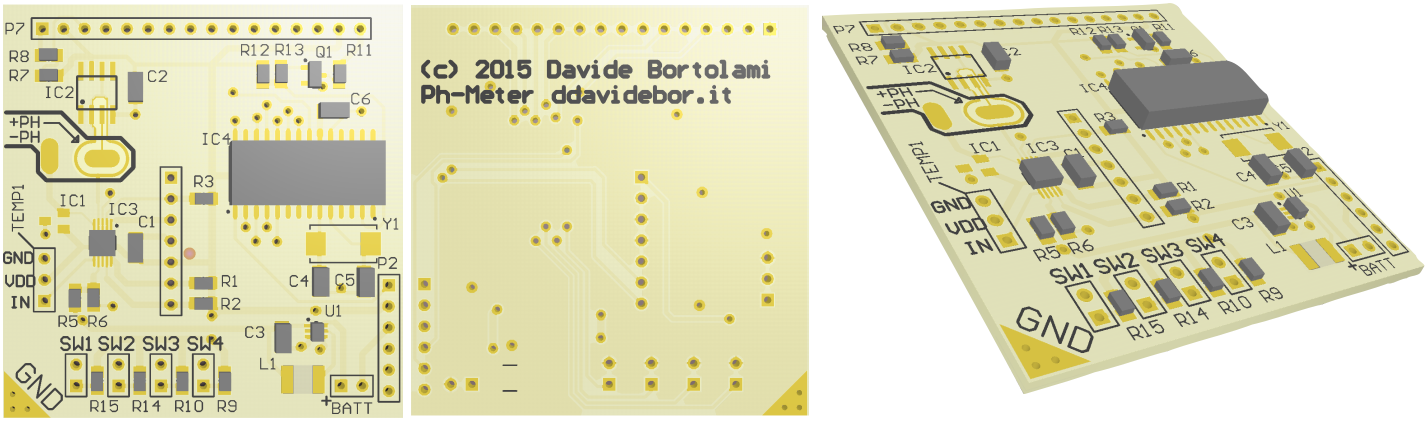

QFN package

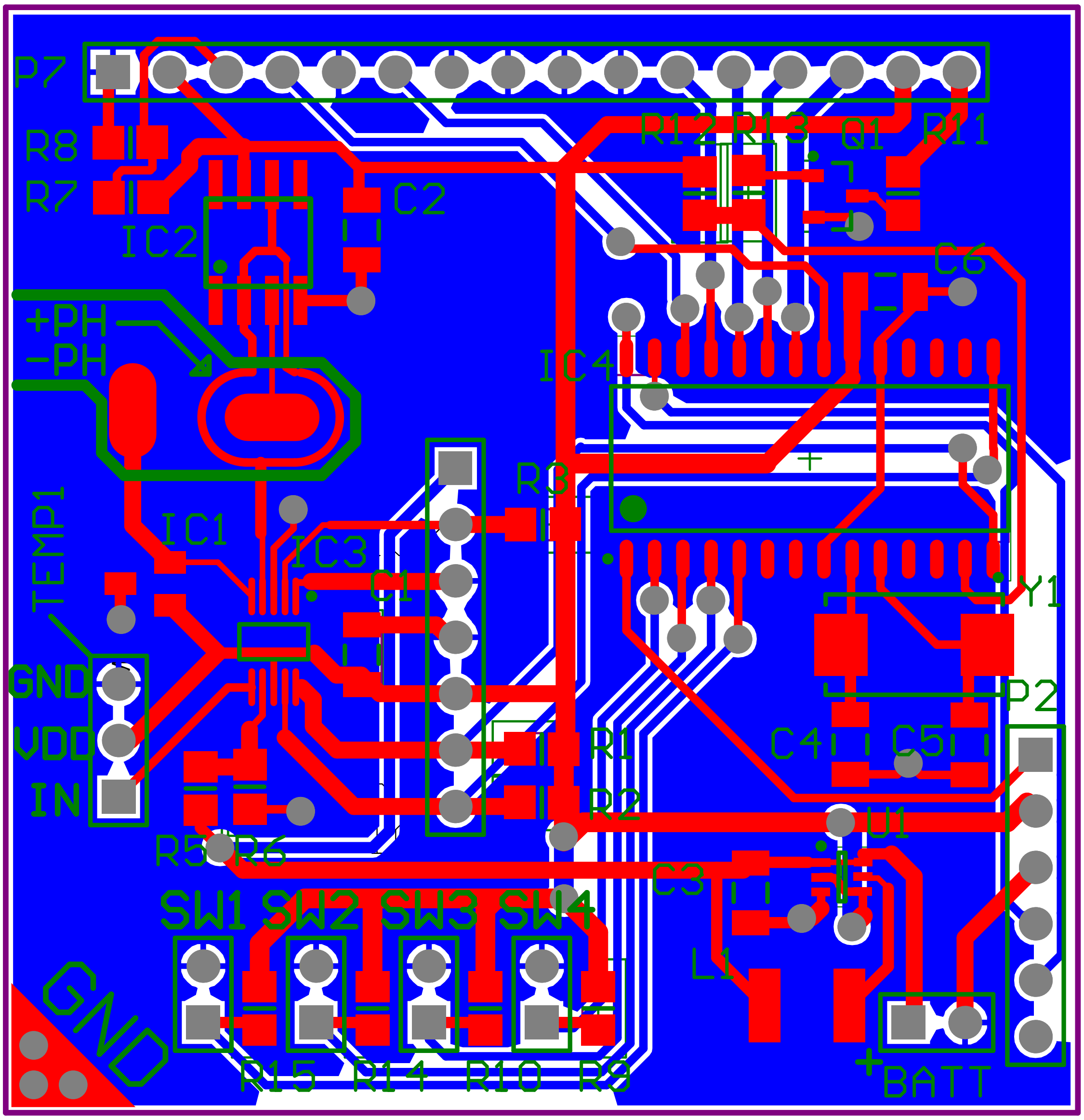
Since no QFN packages have been used a hot air gun was not necessary in order to reflow the pins.

[14] http://www.analog.com/library/analogDialogue/archives/43-09/EDch%2012%20pc%20issues.pdf [Printed Circuit Board Issue training material from Analog Devices]
http://ww1.microchip.com/downloads/en/AppNotes/01258B.pdf [AN1258 - Op Amp Precision Design: PCB Layout Techniques]
http://www.ti.com/lit/ml/slyp173/slyp173.pdf [High Speed PCB Layout Techniques from "High Speed Analog Design and Application Seminar" by Texas Instruments]

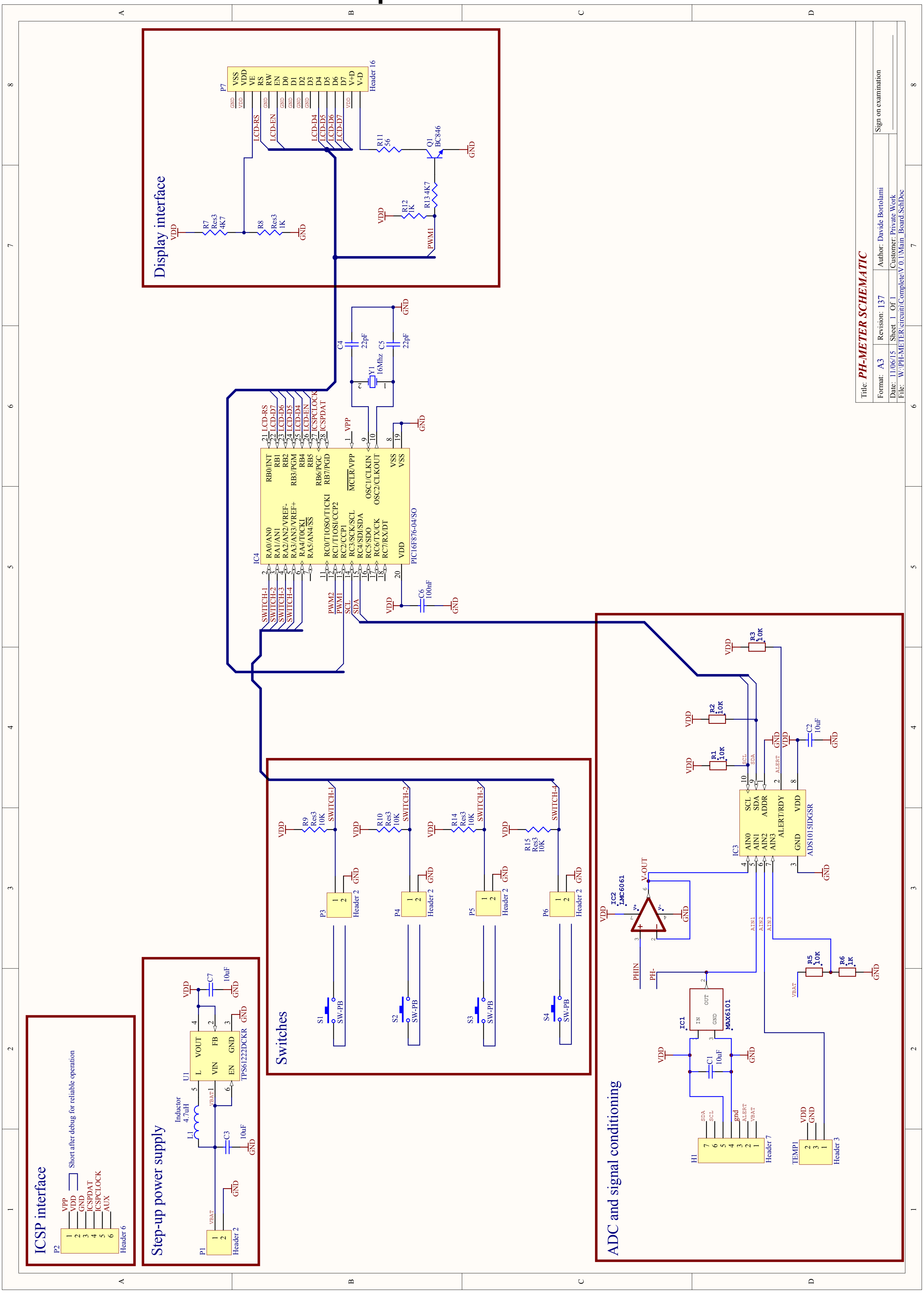
Complete board:

The following renders and drawing are of the complete board





Complete schematic:



Firmware development:

Description:

The firmware has been written on Microchip MPLAB X running on Mac/Windows/linux with XC8 compiler version 3.32. Various libraries have been written or ported from the older HITECH compiler or other platforms.

main.c / setup():

This routine sets TRIS and PORT registers, initialize the lcd and wpm libraries.
If enabled it also print a boot screen for a couple of second and flashes the lcd backlight for a nice power-up effect.

main.c / PhCalc():

This routine calculate the pH based on the voltage from the probe and the temperature measured.

The equation used is the following:

$$pH = 7 + \frac{V * F}{R * T * \ln 10}$$

Where F is the Faraday[15] constant , R the gas[16] constant, V the voltage on the probe and T the temperature in Kelvin degrees.

The equation was derived from the AN-1851[17] guide of Texas Instrument.

main.c / GetTemperature_celsius():

Return the temperature in celsius degree from a single ended measurement of the LM35 temperature sensor.

Since the LM35[18] output 10mV/°C the conversion is elementary:

$$T[°C] = LM35_{out} * 100$$

main.c / print_float() , print_main() and print_delta() :

Those subroutines print various value on the lcd, correctly formatted.
They make large use of the LCD_printf library.

15 http://en.wikipedia.org/wiki/Faraday_constant [Faraday constant, 9.64853399(24) x 104 C mol–1]

16 http://en.wikipedia.org/wiki/Gas_constant [gas constant , 8.3144621(75) J K^{-1} mol^{-1}]

17 http://goo.gl/iORk6V [AN-1852 Designing With pH Electrodes]

18 http://www.ti.com/lit/ds/symlink/lm35.pdf [LM35 Precision Centigrade Temperature Sensors datasheet]

main.c / error_diagnostics_ph_probe_overload() , error_diagnostics_temperature_overload():

Since the pH probe or the temperature sensor could be disconnected from the instrument or overloaded, is necessary to check if the temperature and the pH probe voltages are within limits.
Those limits are set to 100°c for the LM35 and +-250mV for the pH probe. If those value are off limit the subroutine will take control of the instrument and output a error message on the LCD screen.

main.c / MODE_Main() , MODE_Delta , MODE_Debug_Voltage():

Those subroutines are called from main() and they require a cycle counter in input. The first time they're called (cycle counter = 0) the lcd is cleared and the zero value is reset for the delta mode.

The main mode shows pH, temperature and battery levels.
The delta mode shows a differential measurement of the pH (where the initial value is re-acquired when cycle counter = 0) featuring both actual and initial value and the battery percentage.
The voltage debug mode print differential and single ended measurement of the pH probe for manual calculation, probe test and debug purposes.

main.c / Backlight_Setup();

Every time this subroutine is called the lcd backlight slowly change level (off-25%-50%-75%-100%-off). The subroutine work by changing the PWM1 duty cycle using the PWM library.

Initially the backlight is off, since the led is fairly power-consuming for a instrument powered up by just one battery.

main.c / main();

This is the main routine, called when the pick powers up and always active. The first time it's started it calls setup() and then enter an infinite while(1) cycle. In this cycle a polling on the input buttons is executed, and the cycle counter is kept updated.

A simple debounce algorithm is implemented, by waiting for the button release and for an extra 50ms.

the main mode has priority over all other modes if more than one button is pressed.

ads1015-config.h

The masks for the ads1015 config registers are kept in this file. Most of them are from the Adafruit ADS1015[19] library, with the exclusion of the ones controlling the voltage ranges.

ads1015_routines.h:

GetProbe_voltage() return the voltage from the pH probe, measured in differential mode. The range can be changed inside the subroutine code if needed.

VoltageReadSingleEnded() allows for single ended measurement of every channel and range.

The sequence of byte that needs to be sent can be found on the ADS1015 datasheet[20].

configuration.h:

Configuration.h contains defines for pins, configuration pins, buttons and a few constants that are practical to kept in a single place.

A set of macro allows for an easy selection of the development board from the main.c file.

constants.h

This file contain a few constants for the pH equation, such as the faraday constant, the molar gas constant and ln10.

The source are WolframlalpHa, wikipedia and the GNU scientific library

i2cb.h

This library implement the i2c protocol using pic dedicated hardware module. It's a ported version of the PIC18 PLIB library, but the author is unknown.

i2c stands for "Inter Integrated Circuit", a popular protocol for communication between ICs.

Legacy register names have been added by including pic16f87_legacy.h

A very important function, not found in similar libraries is the acknoledge function, necessary in order to comunicate correctly with the ADS1015.

includes.h:

This very short header files include the following libraries:

- xc.h (basic pic library)

---

[19] https://github.com/adafruit/Adafruit_ADS1X15 [ADS1015 Arduino library from Adafruit Industries]

[20] http://www.ti.com/lit/gpn/ads1014 [Ultra-Small, Low-Power, 12-Bit Analog-to-Digital Converter with Internal Reference from Texas Instruments]

- stdio.h
- stdarg.h
- stdlib.h
- stdbool.h (true and false definitions)
- math.h (advanced math, used for trunc())

LCD.h:

This library allow for an easy control of the LCD display. It's a heavily modified version from previous works and a complete port to the new XC8 compiler. It's a joint work of both me and Benato Denis[21].

This library is fairly simple to use:
How to use:
1. Include the library
2. call LCD_Init(); once
3. Move the cursor on the lcd with LCD_Set_Cursor(Line, Column);
4. Write something with LCD_printf("num: %d char: %c", 1, 'A');
5. Write a char with LCD_Write_Char('a');
6. Clear the LCD with LCD_Clear();
7. if you want to use custom symbols:
   7.1. Generate an array with this tool http://www.quinapalus.com/hd44780udg.html
   7.2. Save the array with "const unsigned char MyCustomChar[8] = {…,…}"
   7.3. Move the array into the lcd controller memory with LCD_Custom_Char(array, position) with a position from
   7.4. Write the custom char on the lcd with LCD_Write_Char(position)

LCD_printf.h

This file is part of the LCD.h library and should be in the same folder.

It implement a similar but lighter function to the c printf(), allowing to easily printf formatted text on the LCD display.

It's possible to deactivate this function by commenting out "#define activate_printf"

The original work is copyrighted Kustaa Nyholm of SpareTimeLabs[22] and it was initially designed to run on the HC08[23], a old Motorola/Freescale family of micro controller based on the venerable Motorola 6800 microprocessor[24]
Thanks to the excellent quality of the code the library compiles flawlessly on XC8, and only minor adjustment have been made to print the output character with LCD_Write_Char(…)

[21] https://github.com/NeroReflex [Benato Denis public repository on github.com]

[22] http://www.sparetimelabs.com/printfrevisited/printfrevisited.php ["A tiny printf revisited"]

[23] http://www.freescale.com/webapp/sps/site/taxonomy.jsp?code=HC08FAMILY [HC08 microcontrollery family by Freescale]

[24] http://en.wikipedia.org/wiki/Motorola_6800 [Motorola 6800 microprocessor]

pwm.h:

This library allows for an easy control of the PWM duty cycle and proper initialization of the PWM module. It has been ported from work by previous authors.

1. Be sure to define _XTAL_FREQ, see XC8 manual for more informations
2. In your setup routine launch PWM_Init(desired frequency). Note that the frequency will be approximated to the nearest available, as specified in the source code.
3. Change the PWM duty cycle with PWM1_Duty(); or PWM2_Duty(); using any value from 0 to 1023
4. Start the PWM signal with PWM1_Start(); or PWM2_Start();
5. Stop the PWM signal with PWM1_Stop(); or PWM2_Stop();

On PIC16F876A PWM1 is available on pin RC2 and PWM2 is on pin RC1.

PWM1 has been used to control the LCD backlight through a transistor.

temperature_conv.h:

The following subroutines convert between Celsius, Kelvin and Fahrenheit degrees.

- float CelsiusToKelvin(float Celsius)
- float KelvinToCelsius(float Kelvin)
- float KelvinToFarenheit(float Kelvin)
- float FarenheitToKelvin(float Farenheit)

Conversion equations can be found on wikipedia[25].

[25] http://en.wikipedia.org/wiki/Conversion_of_units_of_temperature [Conversion of units of temperature]

Attachment list:

Source code:

The following files are part of the source code of this project:

- main.c
- includes.h
- ads1015-config.h
- ads1015_routines.h
- configuration.h
- constants.h
- i2cb.h
- LCD.h
- LCD_printf.h
- pwm.h
- temperature_conv.h

Schematics and pcb:

- Complete schematic, A3
- PCB layout, A3

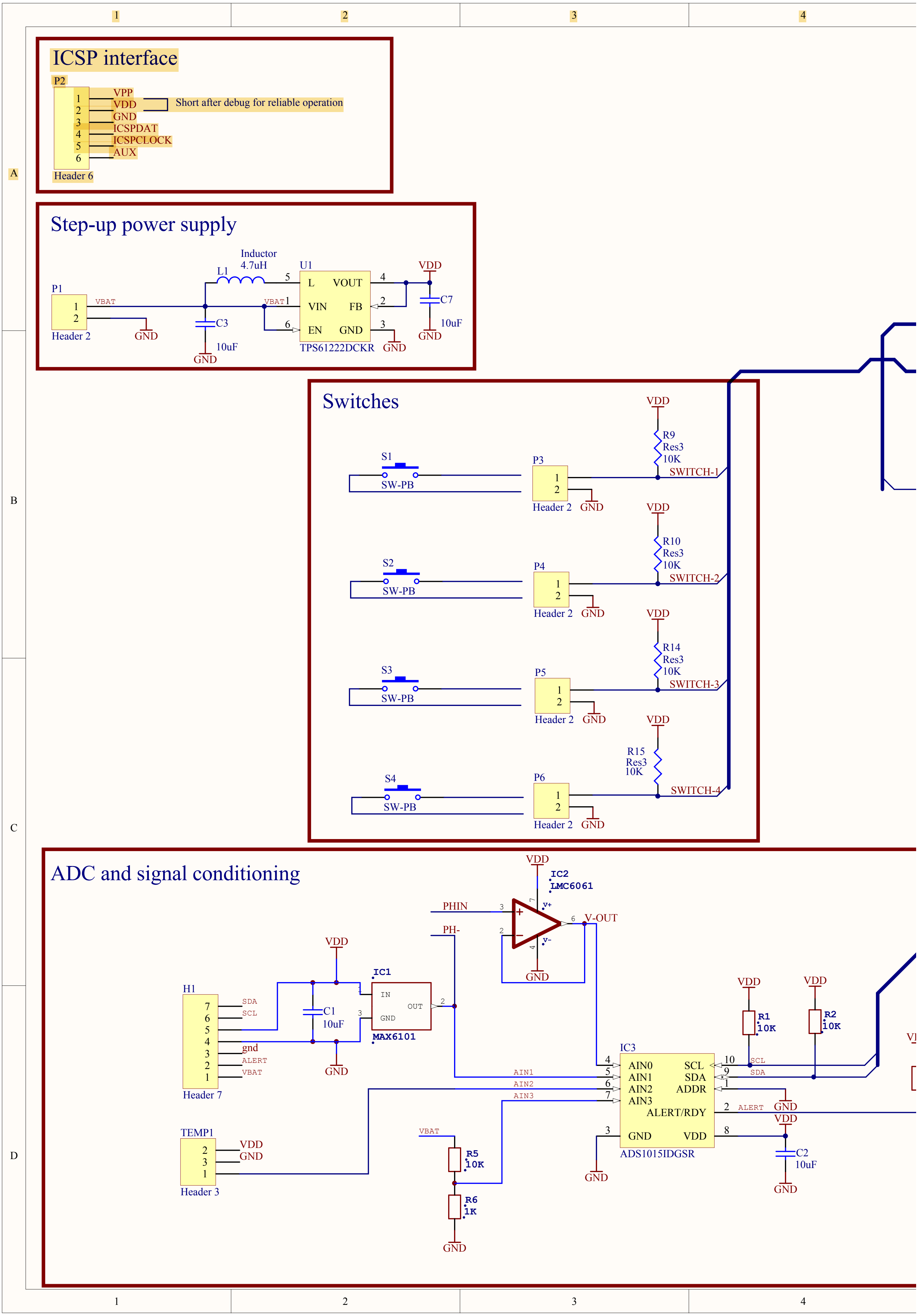
A copy of this thesis can be found on http://static.ddavidebor.it/ph-meter_thesis/ or on ddavidebor.it for future reference.

Copyright note:

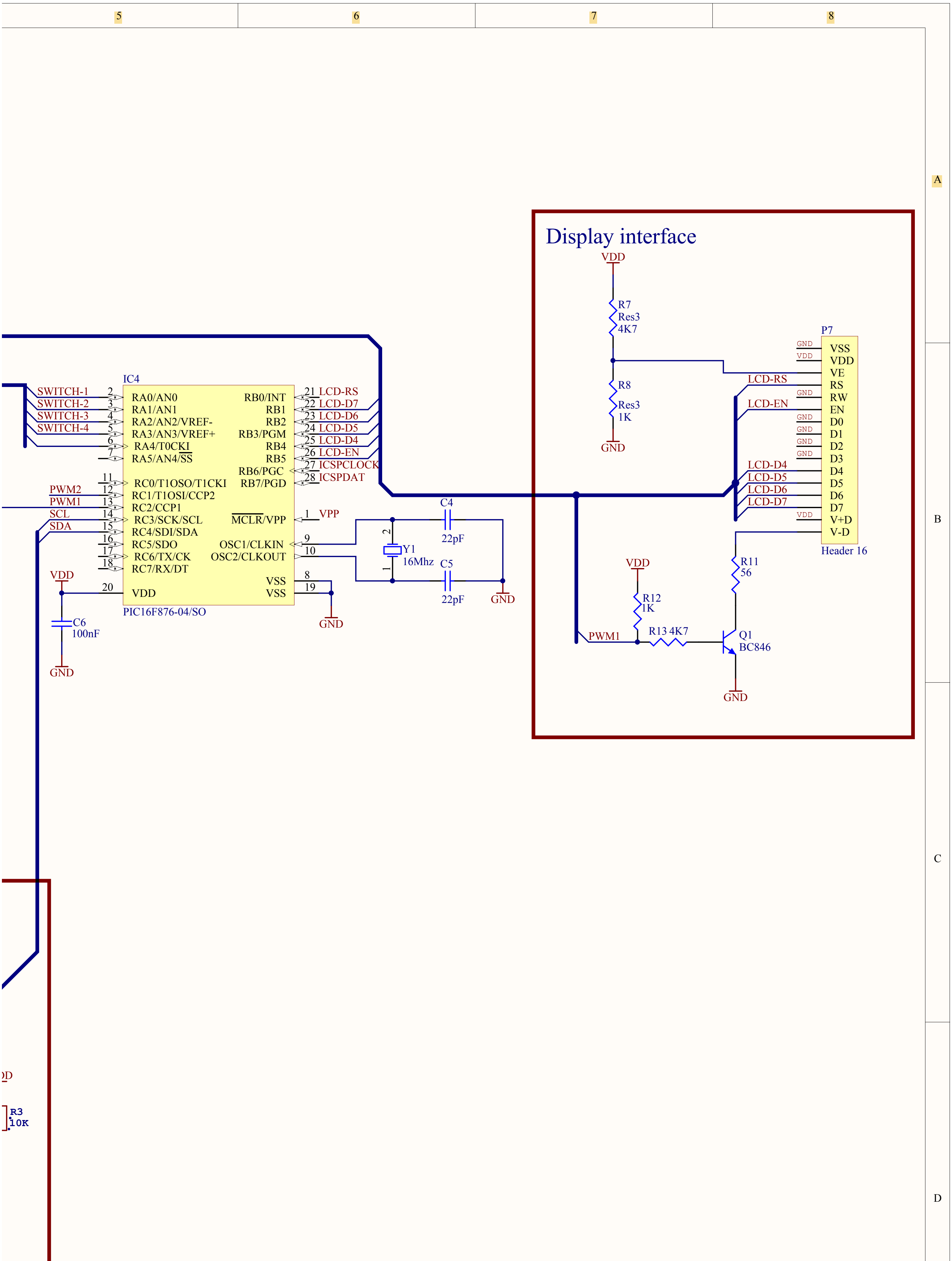
Acknowledgements:

My heartfelt thanks to the following peoples and companies, who have directly or indirectly contributed to the project or otherwise supported me while developing it:
- Prof. Giorgio Tombola
- Prof. Rosario Mangano
- David L. Jones
- Dr. Daniel Shalev
- Talentlab a.p.s.

[26] https://creativecommons.org/licenses/by-nc-nd/3.0/it/deed.en [CC-BY-NC-ND Creative Commons Licence]

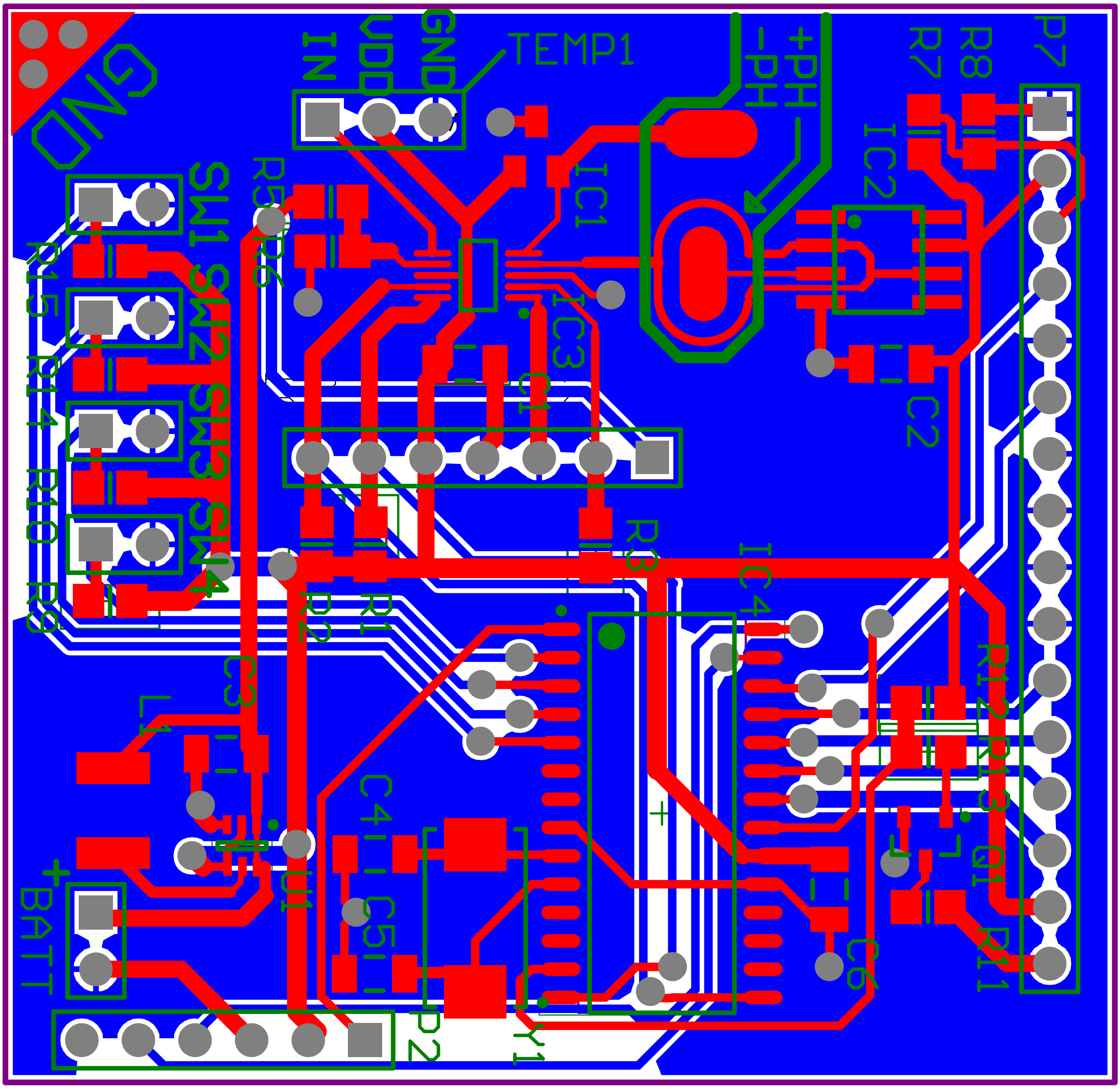


ICSP interface
P2
VPP
VDD
GND
ICSPDAT
ICSPCLOCK
AUX
Short after debug for reliable operation
Header 6
Step-up power supply
P1
VBAT
Header 2
GND
Inductor
4.7uH
L1
U1
L
VOUT
VIN
FB
EN
GND
TPS61222DCKR
VDD
C7
10uF
C3
10uF
Switches
S1
SW-PB
P3
Header 2
R9
Res3
10K
SWITCH-1
S2
P4
R10
SWITCH-2
S3
P5
R14
SWITCH-3
S4
P6
R15
SWITCH-4
ADC and signal conditioning
IC2
LMC6061
PHIN
PH-
V-OUT
V+
V-
H1
SDA
SCL
gnd
ALERT
Header 7
IC1
IN
OUT
GND
MAX6101
C1
10uF
TEMP1
Header 3
AIN1
AIN2
AIN3
R5
10K
R6
1K
IC3
AIN0
AIN1
AIN2
AIN3
SCL
SDA
ADDR
ALERT/RDY
VDD
ADS1015IDGSR
R1
10K
R2
10K
C2
10uF



Title: *PH-METER SCHEMATIC*			
Format: A3	Revision: 137	Author: Davide Bortolami	Sign on examination
Date: 11/06/15	Sheet 1 Of 1	Customer: Private Work	
File: W:\PH-METER\circuiti\Complete\V 0.1\Main_Board.SchDoc			

PCB Layout



GND
IN
VDD
GND
TEMP1
+PH
-PH
R7
R8
P7
IC1
IC2
IC3
IC4
C1
C2
C3
C4
C5
C6
R1
R2
R3
R5
R6
R9
R10
R11
R12
R13
R14
R15
SW1
SW2
SW3
SW4
L1
U1
Q1
BATT
P2
Y1