A Didactic First Approach to Electrochemistry and Electronics: A Low Cost Apparatus for Conductivity Measures Based on Arduino and a Hand-Made Cell

Emanuele Dell'Aglio*, Giovanni Visco, Rita Reale, Luca Ugo Fontanella and Maria Pia Sammartino

Chemistry Department, "La Sapienza" University, p.le A. Moro 5, 00185, Rome, Italy

CGR 2019
VIII Convegno Giovani Ricercatori

Abstract

Even if aspecific, the measure of conductivity, together with pH ones, is a fundamental parameter for the characterization of aqueous solutions [1] as well as for a monitoring of water sources, water networks and waters used for warming and cooling industrial plants.

We here describe a very inexpensive prototype for such measures that only bases on Arduino UNO R3 [2], an open-source circuit board with only passive components, a handmade cell with stainless steel electrodes embedded in Poly-methyl methacrylate (PMMA) and a freeware management software.

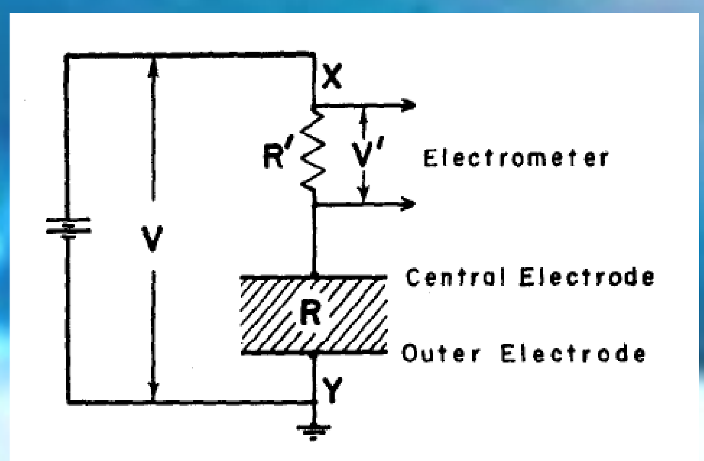


Fig.1, from an article of L.G. Smith, 1952

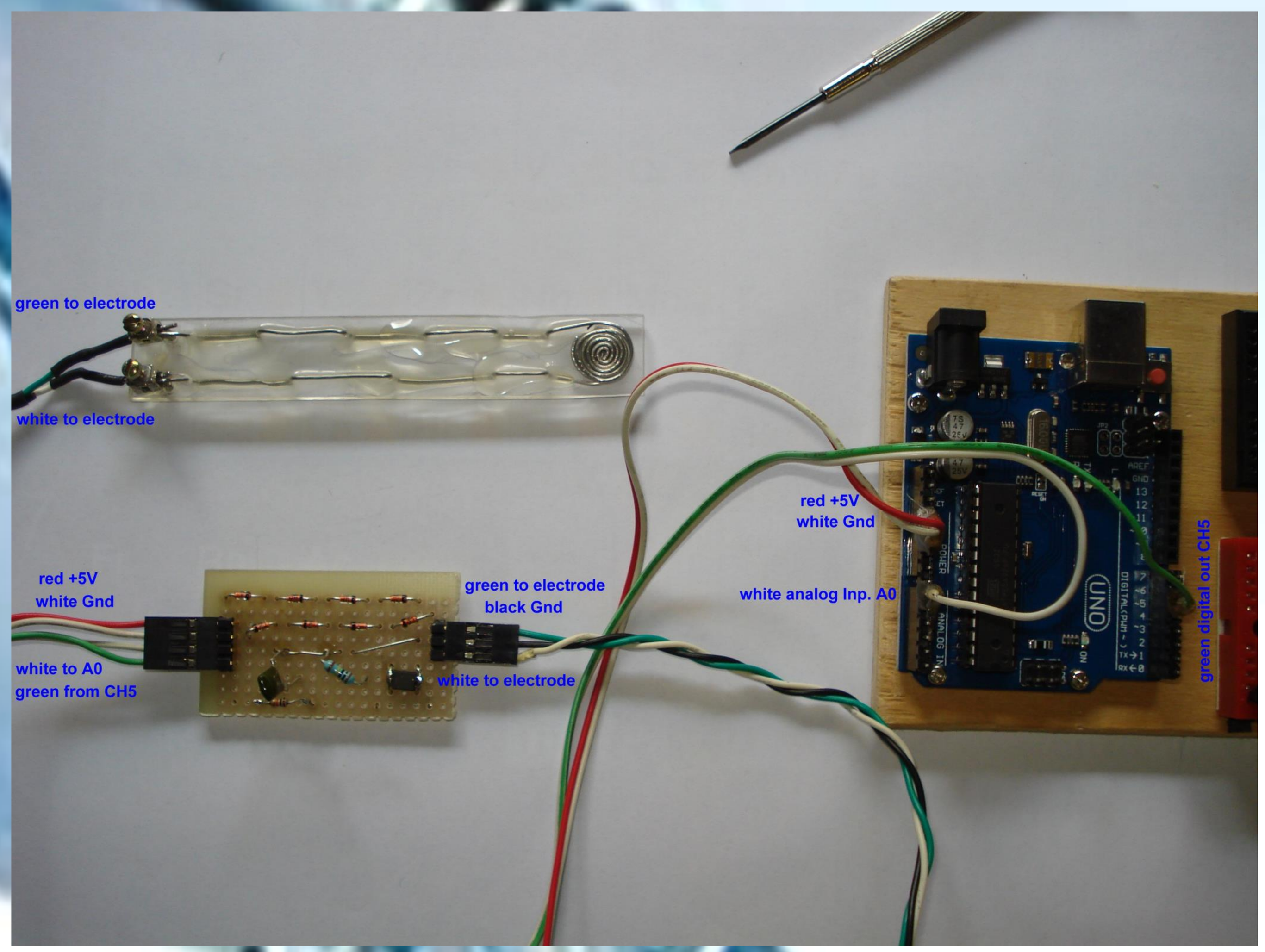


Fig.3 – Photo of the prototype and details on the connections between its three blocks

Introduction

Searching on the web with the string "arduino conductivity" we obtain 566,000 results. Unfortunately the first two (arduino.stackexchange.com and create.arduino.cc) are wrong because both use the DC current and some plugs as electrodes. The main problem of those 566,000 links are "the chemical correctness" and "the accuracy" in every aspect; from chemical resistant electrodes, passing to the signal applied to electrodes, ending with the calibration and accuracy of the measures, and finally we didn't find citation on reproducibility and reliability of the measure/instrument.

The project is Open Source and anyone can reproduce and upgrade to fit his/her need.

Aim of the project

With the aim of filling the gaps highlighted in the Introduction we decided to construct an inexpensive apparatus for measures of conductivity to be used first in a laboratory exercitation for our students, and, after some upgrade to increase accuracy and reproducibility, in routinary measures in any kind of lab or for industrial control.

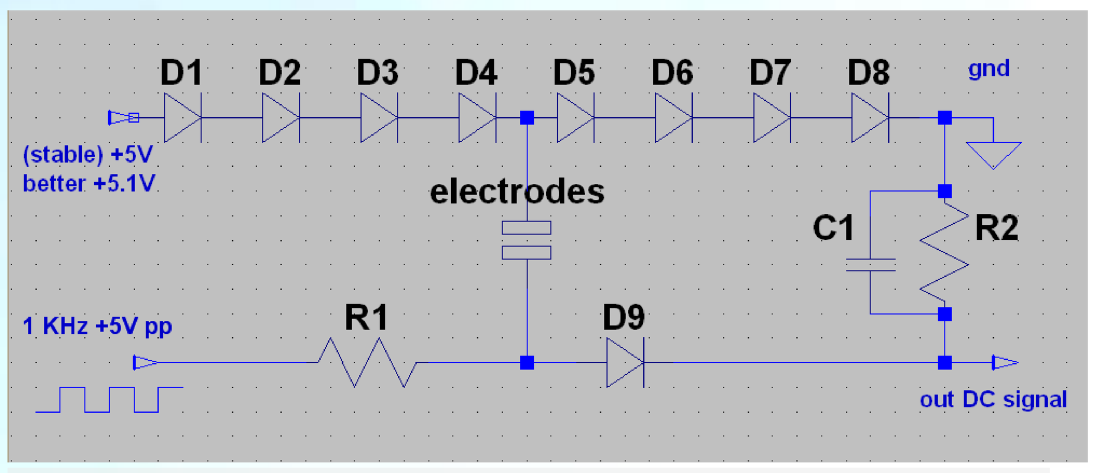


Fig.2, simplified external circuit, D1-D8=1N4448, D9=BAT60A, R1=1K0, R2=1M0, C1=10n0

Application

Using 2 standard solutions (Merck) the conductivity meter Mettler Toledo S470 Seven Excellence equipped with InLab 731 ISM cell was calibrated. Next using 9 different commercial mineral waters the "secondary measurement standard" [3] was perfomed. Distilled and tap water were also analysed. The obtaind conductivity values were used to check the response of the Arduino prototipe as show in Table 1. All measurements were carried out by immersing the cell in the water samples, maintained at 20.0 ± 0.2 °C using a Julabo UC-5B/5 thermostatic bath; as an alternative, for example for "in situ" measures, the temperature control can substituted by its measure followed by a correction of the conductivity value through apposite conversion tables [4].

The prototype

The proposed prototype and their connections are shown in Fig.3 .

Handmade cell: the conductivity cell (100x18x2 mm) consists of two 316L stainless steel wires, 0.8 mm in diameter, embedded in a PMMA sheet and ending outside, on its opposite sides, in a spiral shape, 13 mm in diameter, glued on the PMMA sheet using a two-component acrylic glue. So they result isolated each other and in a rigid structure that ensures to maintain their fixed distance even in case of accidental impacts. The spiral shape let to increase or decrease the exposed surface and, in turn, to obtain measures in different conductivity ranges (low, medium, high). The generated electric field is not equivalent to the one of common conductivity cells but equally efficient.

External circuit (simplified electrical circuit in Fig.2): the circuit, uses only passive components. The centre of the series of diodes, D1-D8 corresponds to the point Y of Fig.1 and can be considered an "invented" center tap (between 0 and +5V) Using a PWM with a 50% duty cycle (setting value equal to 127) as output on the pin 5 of Arduino a frequency of about 1 kHz, and an almost perfect square wave can be obtained (Fig.4). The current passes through the R1 resistor, acting as current limiter and let to obtain a voltage swing of 2.5 V on the B electrode with respect to the A electrode. Having 2.5V peak to peak the true root mean square (RMS) value is about 880mV that is comparable to a commercial conductimeter.

Arduino UNO R3: the board uses the 5V pin, the GND pin, analog pin A0 to input and the digital pin 5 for output, they are connected to the circuit board 3. At the opposite side of circuit board two pins allow the connection to the cell and a third, from Arduino, comes to ground for shield.

More and more cells were built before of optimize the one here presented, i.e. in order to obtain a measure range from few to 2000 µS.

Arduino is managed by IDE Release 1.8.9. The program sketch is written by scratch without library or reusing another module. The main point of the sketch is the oversampling-and-decimation routine using the circuit noise (see Fig.5) to obtain a 11 bits resolution.

Strategy

Our idea was inspired by an article of L.G. Smith, "On the Calibration of Conductivity Meters", dated 1953, a comparison of his circuit (Fig.1) with our one (Fig. 2) mainly evidences that we measure the voltage on electrodes and the V source works in AC while R' is used by us as current limiter and not for the measure. Such circuit is a bridge between Arduino and a handmade conductivity cell to solve a problem bound to a direct connection cell-Arduino. Arduino easily produces 5 and 3.3 V continue voltage and pulses from 0 to 5 V at intervals from few milliseconds up to some minutes; it also produces pulse signals with modulation (PWM) at frequency about 500 and 1000 Hz with a duty cycle up to 256 levels. Anyway, the signal is a square wave between 0 and 5 V but, unfortunately, a symmetric voltage centered on zero (as an example –1.5, 0, +1.5), needed to obtain an alternate current, cannot be instead produced.

For this we must 1) produce a swing AC voltage on 2 stainless steel electrodes, using a 1000 Hz frequency, 2) measure the voltage or the current on the electrodes 3) obtain by mean of some equation the conductivity' all is possible with Arduino R3 with aid of external circuit.

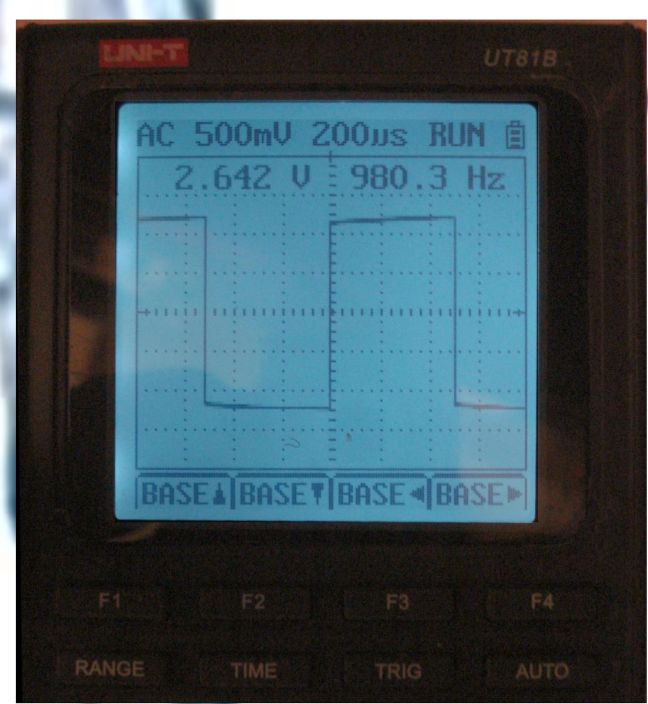


Fig.4, the waveform on the electrodes, in air measure bu handyscope UNI-T 81b. The square wave is as expected (using x1 probe with 10Mohm impedence)

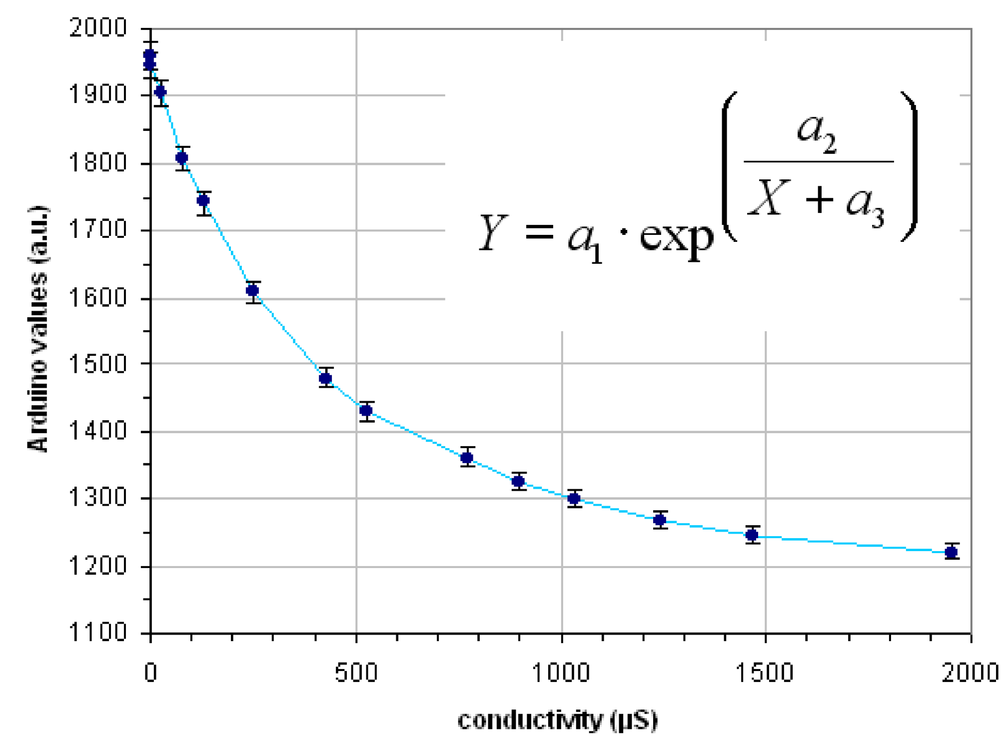
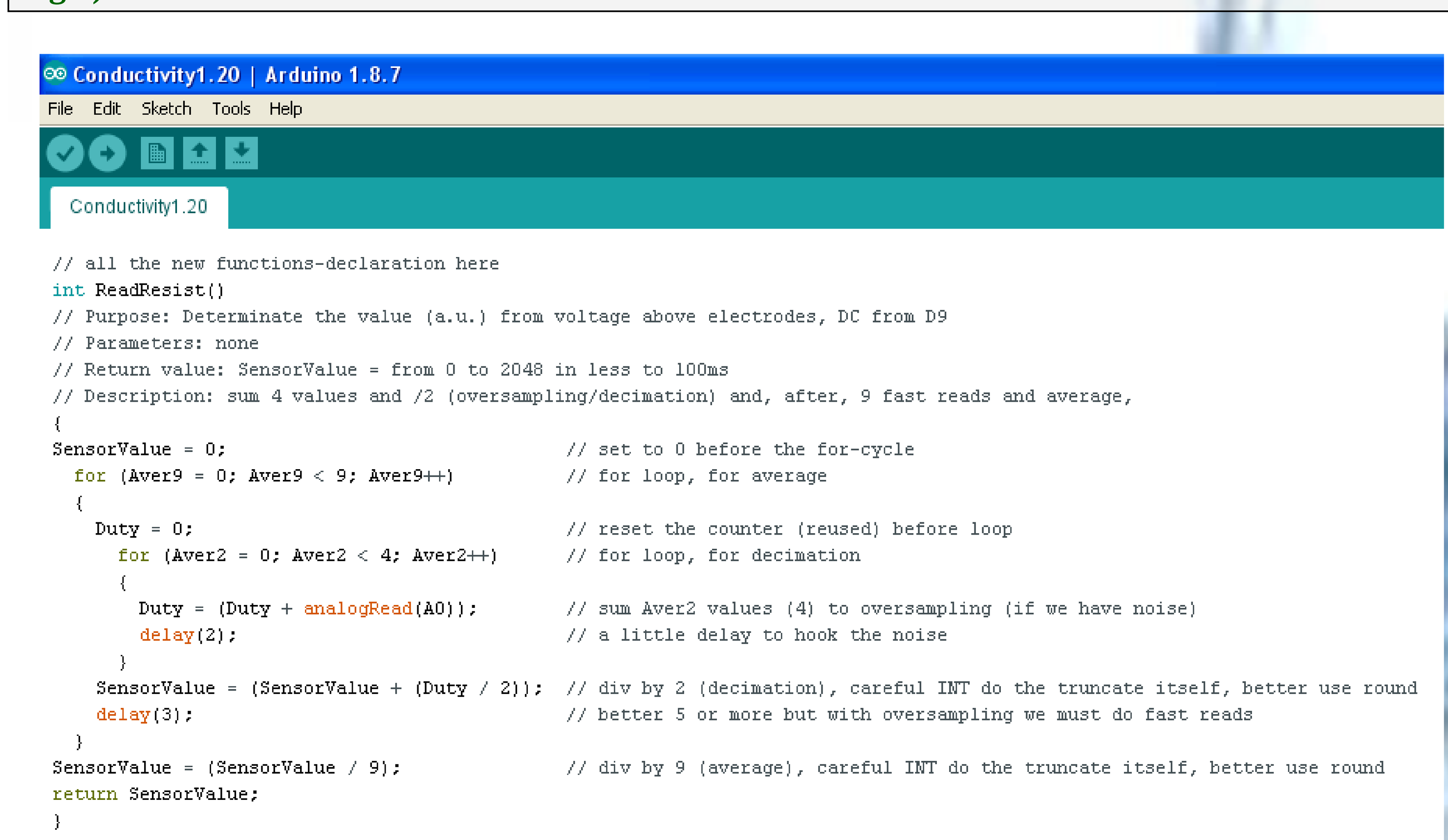


Fig.6, scatterplot of the data of Tab.1, column 2 on X and column 3 on Y and relative equation



```
// all the new functions-declaration here
int ReadResist()
// Purpose: Determinate the value (a.u.) from voltage above electrodes, DC from D9
// Parameters: none
// Return value: SensorValue = from 0 to 2048 in less to 100ms
// Description: sum 4 values and /2 (oversampling/decimation) and, after, 9 fast reads and average,
{
SensorValue = 0;                             // set to 0 before the for-cycle
  for (Aver9 = 0; Aver9 < 9; Aver9++)        // for loop, for average
  {
    Duty = 0;                                // reset the counter (reused) before loop
      for (Aver2 = 0; Aver2 < 4; Aver2++)    // for loop, for decimation
      {
        Duty = (Duty + analogRead(A0));      // sum Aver2 values (4) to oversampling (if we have noise)
        delay(2);                            // a little delay to hook the noise
      }
    SensorValue = (SensorValue + (Duty / 2)); // div by 2 (decimation), careful INT do the truncate itself, better use round
    delay(3);                                // better 5 or more but with oversampling we must do fast reads
  }
SensorValue = (SensorValue / 9);             // div by 9 (average), careful INT do the truncate itself, better use round
return SensorValue;
}
```

Fig.5, part of the main skecth, the oversampling and decimation routine to obtain a resolution of 11 bits and a more stable value passed to output routine as serial data

Table 1 - Comparison of data obtained by the classical apparatus for conductivity measurements and by the proposed prototype.

Sample	Conductivity measured by lab instrument (µS/cm)	Arduino circuit with R1 = 1Kohm	
		Adimensional Value	Voltage between the electrodes (AC-V)
Distilled water	1.3	1945	2.633
Sant'anna	25.1	1904	2.485
Standard 1	76.1	1807	2.224
Levissima	129.6	1742	2.01
Vera nestle	251.5	1610	1.606
Sorgesana	429.9	1480	1.218
Acea tap water	528.7	1430	1.188
Lete	771.9	1362	0.997
Standard 2	900.4	1325	0.935
Uliveto	1031.5	1301	0.774
Grazia	1243.5	1269	0.66
Gaudianello	1467.7	1247	0.598
Essenziale	1952.5	1222	0.472

Results

Obtain sturdy electrodes is not easy with the standard geometry so a new one is proposed. Using this circuit and our electrodes produce (as in many many instruments) a non linear response so the calibration as cited in p.28, 2.39 of BIPM [3] cannot be performed, of course the procedure of p. 48, 5.5 note 2 [3] know as "secondary measurement standard" requires to use almost 10 real different samplesas in Tab.1.

Fig.6 shows the correlation between data obtained by the lab and the prototype; it evidences an "exponential decay" trend; this is not a problem considering that such trend, as an example, is common for the respone of NTC, widely used to measure temperature. The subtended equation is also reported.

Conclusions

With a few euro, 10 in our simulation, anyone can construct a robust cell and a small passive circuit that coupled with an Arduino UNO, let to perform conductivity measures from few up to 2000 µS in water.

Since the prototype represents both the concept of the law on which the measure bases and the analytical rules, its construction and use can be considered a first approach to electrochemistry and electronics if used in didactic lab exercises.

For the next prototipe an accurate temperature sensor will be coupled to the cell and probably of the external circuit will be upgraded to obtain a more robust noise rejection but without compromise the oversampling.

References

1) J. W. Rodger, The Electric Conductivity of Pure Water, Nature, 51, 1894, 42-43
2) J.P. Grinias, J.T. Whitfield2, E.D. Guetschow, R.T. Kennedy, An Inexpensive, Open-Source USB Arduino Data Acquisition Device for Chemical Instrumentation, J Chem Educ., 93(7), 2016, 1316-1319
3) BIPM, Vocabulaire international de métrologie – Concepts fondamentaux et généraux et termes associés (VIM), JCGM/WG 2 Ed., 2008
4) ISO 7888:1985, Methods of Sampling and Test (Physical and Chemical) for Water and Waste Water, Part 14 Specific Conductance (Wheatstone Bridge, Conductance Cell), Second Revision, IS 3025 (Part 14):2013

Fig.7, All of makers and electronics users, also teachers must thank to the Team that developed the Arduino board widely used in didactics.

For background image we must thank Fonti Pineta, mineral water, Clusone, BG, Italy.

We also thank the developers (fig. 7) of Arduino for having revolutionized the field of electronics and prototyping.