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ScienceDirect
Procedia Engineering 168 (2016) 407 – 410
Procedia Engineering
www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

Micro-USB Connector Pins as Low-Cost, Robust Electrodes for Microscale Water Conductivity Sensing in Oceanographic Research

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Abstract

Motivated by the widespread need to sense water conductivity in oceanography, as well as in other applications in fluid dynamics and environmental monitoring, we propose using the exposed gold-plated pins of readily available micro-USB connectors as miniaturized, parallel finger electrodes. Since the electrodes are 600 µm apart, they grant sub-mm spatial resolution, suitable for most applications. Standard micro-USB cables are an ideal, ready-to-use solution, since they are shielded, are preassembled in different lengths, and enable 2 and 4-wire measurements. In order to take full advantage of these USB probes, we have designed a custom, open-source 4-channel measuring circuit, named "Conduino", consisting of a low-noise (SNR = 60dB) shield board coupled to an Arduino microcontroller. Experimental results demonstrate sensing performances comparable with state-of-the-art reference instrumentation (0.1% resolution in the 0.1-15 S/m range), with significantly lower cost and increased versatility and reliability.

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
Keywords: impedance sensor; stratified flows.

1. Introduction

Accurately measuring water conductivity is pivotal in oceanography [1] and in the study of stratified flows [2], since conductivity enables calculating salinity and density (at a given temperature). In this field, the best-performing sensor, in terms of spatio-temporal resolution, is a miniaturized conductivity probe [3], featuring a glass capillary

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Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.188

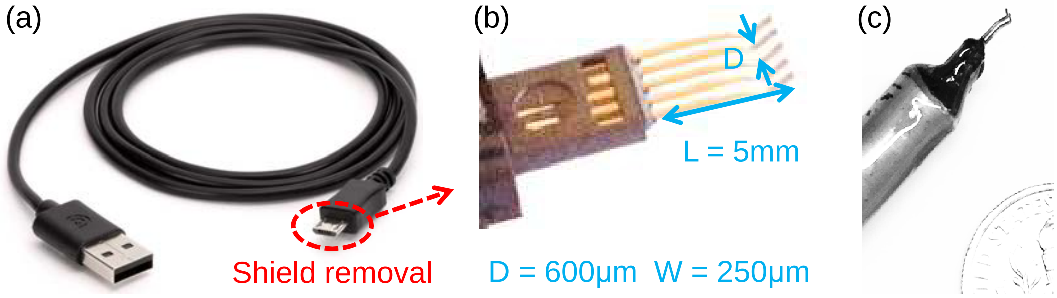

Fig. 1. Electrodes preparation by removing the shield from the standard micro-USB cable (a) to expose 5 parallel fingers (b), easily sealable with epoxy (c) and suitable for conductivity sensing with sub-mm resolution.

with a 500 μm-wide tip hosting 4 platinum microelectrodes. Despite its excellent performance, the relatively high cost and fragility of this probe have severely limited its use. In order to extend the adoption of conductivity sensing to multi-channel experimental scenarios, as well as to enable widespread research and educational use at low cost, we conceived an alternative electrode fabrication approach. Our choice of electrodes retains sub-mm resolution, while allowing, at the same, simple, robust and customizable use, as explained below.

2. USB electrodes

We propose using the metallic pins of small, standard connectors as electrodes. We tested a wide variety of high-density connector types. While all all proved suitable for mm-scale conductivity sensing, we focus here on the micro-USB connector (Fig. 1a). Beyond being readily available, it contains 5 electrodes that are directly accessible electrically from the USB-A side (differently, for instance, from the Lightning connector by Apple). The electrodes are also suitable for both 2- and 4-wire measurements and are separated by distance of just 600 μm, thereby granting sub-mm spatial resolution. Furthermore, the pins are gold-plated, allowing direct use in ionic solutions. The only required manual operation is the removal of the metallic shield around the pins (Fig. 1b). Preassembled, shielded cables of various lengths are a versatile solution for different experimental setups. We calculate that a couple of pins (length of 4.5 mm and width of 250 μm) are characterized by an intrinsic sub-ms time constant (double layer

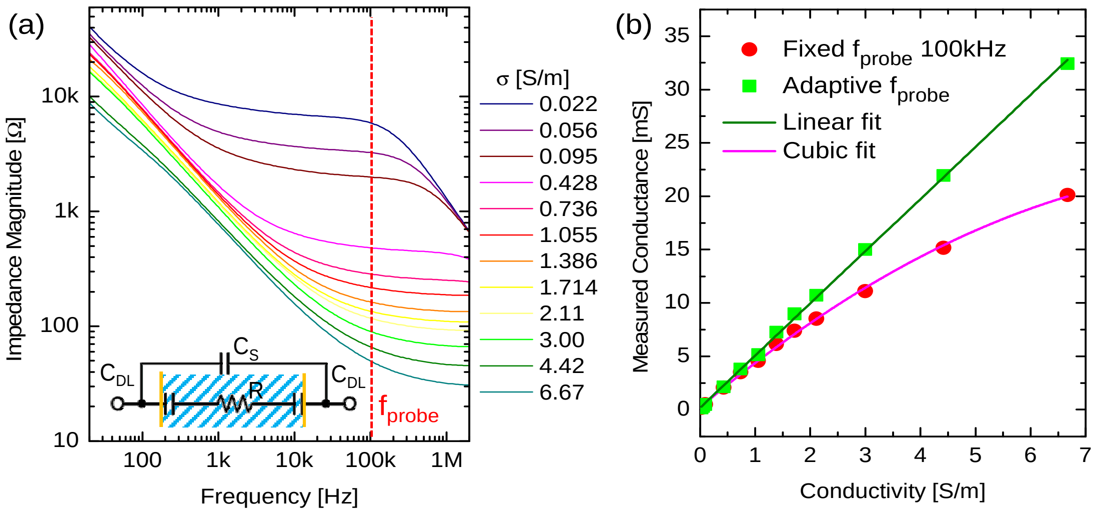

Fig. 2. (a) Impedance spectra measured with the micro-USB connector for conductivities spanning from 0.022 to 6.67 S/m showing the resistive plateau accessible with f_{probe} = 100 kHz requiring (b) a cubic calibration.

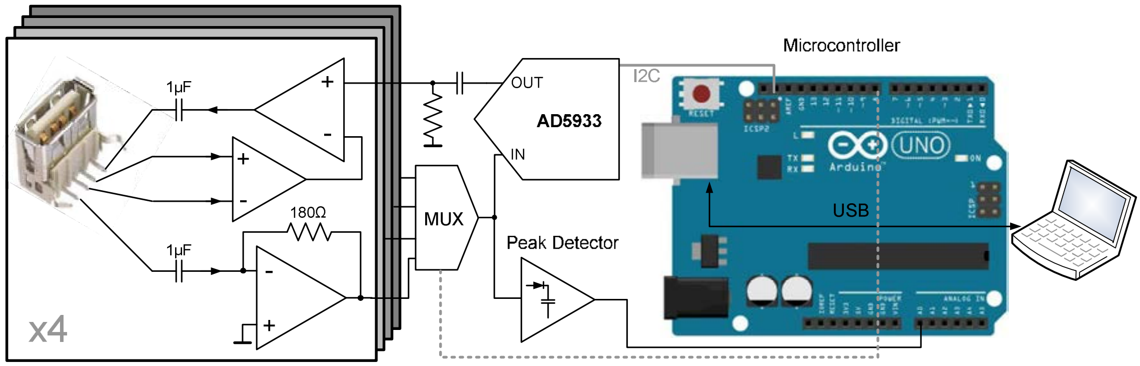

Fig. 3. Block scheme of Conduino featuring four multiplexed channels.

capacitance C_{DL} ~200 pF), cell constant of k = 130 m^{-1} and thermal noise below 30 pA/√Hz. Impedance spectra (Fig. 2a) performed in the 20 Hz-2 MHz range (with the Agilent E4980A LCR meter) demonstrate that water conductivity can be straightforwardly sensed in the range from 0.02 S/m to 6.6 S/m with a single sensing frequency f_{probe} = 100 kHz. A shown in Fig. 2b, calibration is necessary. Since a cubic polynomial is adequate, this calibration is combined with the three-point fit routinely used to approximate the non-linear relation between conductivity and water density [4]. After three days of continuous salinity measurement (with an applied AC voltage of 100 mV), no signal degradation has been observed.

3. Conduino board

To take full advantage of these off-the shelf and extremely low-cost electrodes, we have designed the Conduino board (Fig. 2), an open-source companion circuit tailored for measuring conductivity σ with these electrodes. It has a compact credit-card-size form-factor and features four channels connected with a multiplexer to a single-chip impedance detector (AD5933 operating at 100 kHz) adapted to measure low resistance (σ from 0.1 to 15 S/m, typical values in this application) with an input transimpedance amplifier (R_F = 180 Ω, stable with electrode double layer capacitance up to 500 nF) and with a precision output buffer. It supports also 4-wire operation (with an additional feedback loop to compensate the ohmic drop of a cable long up to a few meters). A peak detector allows saturation avoidance and auto gain adjustment. Single +5 V power supply is provided from the USB connection of the Arduino board used for data acquisition (every 11 ms) and transmission to a PC running Matlab for analysis and calibration.

4. Experimental results

The prototype has been extensively experimentally characterized; here we show two brief examples. At a conductivity of 10 S/m, the noise level is 2.2 mS/m rms, giving a SNR = 60 dB, i.e. a resolution of 0.1%, far exceeding the 1% resolution normally required in these flows [2]. Thanks to power supply from the laptop, battery operation grants complete decoupling from noisy power lines, as well as portable operation in the field.

Fig. 4 shows a validation of the Conduino with a handheld conductivity meter (PCE-PHD 1 by PCE Instruments): as reported in Fig. 4a, after performing a three-point calibration, the values of the measured conductivity, (changed in steps) are consistent with an accuracy of a few percent in the range from 0.3 to 3.5 S/m. Focusing on a single step, (Fig. 4b) the higher temporal resolution of the Conduino (11 ms) with respect to 2 s for the PCE, with similar size and complexity, is evident.

Fig. 5 shows the comparison of the Conduino and the state-of-the-art instrument (MSCTI by PME) in a classical stratified flow experiment. Both probes are mounted on the same crossbeam, moved by a PC-controlled stepper motor to vertically scan a salt-stratified solution and thus measure the vertical density profile (from 1.002 to 1.04 g/cm^3) across a depth of 14 cm. The Conduino signal accurately matches the result achieved with state-of-the-art microelectrodes and commercial instrument. In addition, the micro-USB electrodes can be arranged in custom-

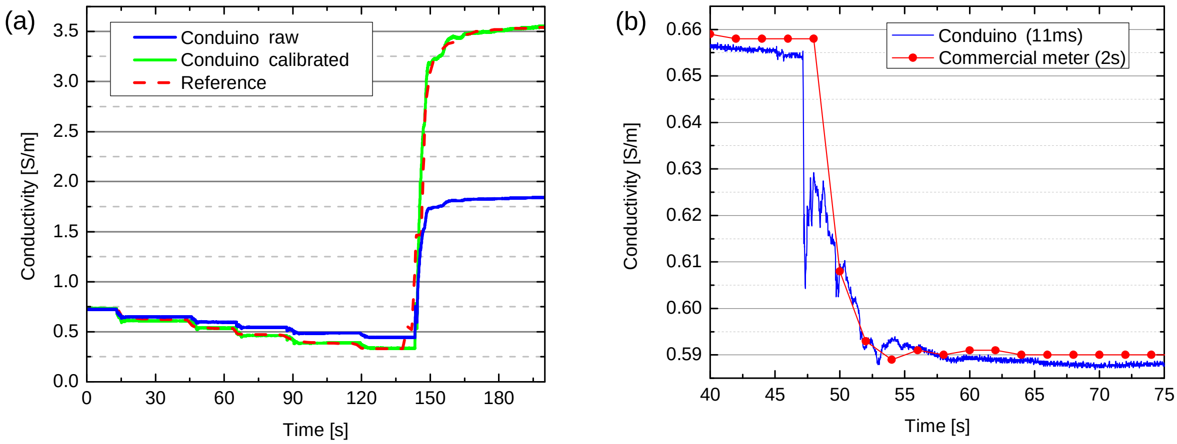

Fig. 4. Time tracking of conductivity comparing Conduino with a handheld laboratory conductimeter: (a) effectiveness of calibration and (b) comparison of temporal resolutions in tracking a single step.

shaped arrays to reconstruct the spatial density structure in dynamic flow environments, which we have demonstrated in experiments involving internal waves.

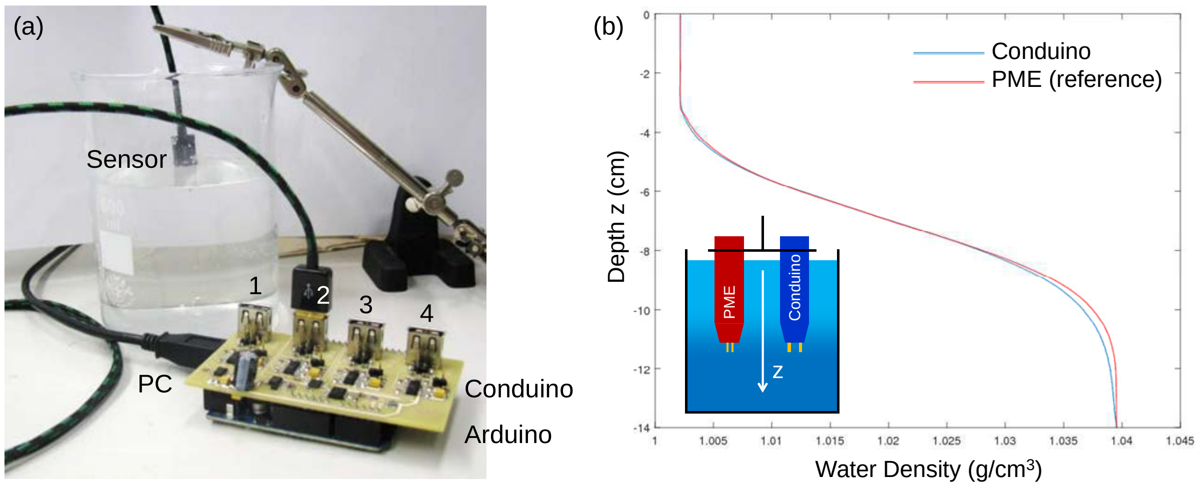

Fig. 5. (a) Conduino prototype and (b) comparison with MSCTI by PME reference probe in a simultaneous density profiling experiment in a 0.2 m tank, showing excellent agreement (within the uncertainty of the calibration).

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