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A miniature, low cost CTD system for coastal salinity measurements

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Abstract
In this work we describe a small, low cost conductivity, temperature and depth (CTD) system for measurements of salinity in coastal waters. The system incorporates three low cost expendable sensors, a novel planar four-electrode conductivity cell, a planar resistive temperature device and a piezoelectric pressure sensor. The conductivity cell and the resistive temperature device were fabricated using novel printed circuit board (PCB) microelectromechanical (MEMS) techniques combined with a new thin-film material, liquid crystal polymer (LCP). Printed circuit board techniques allow for mass production of the sensors, thereby lowering the cost of the system. The three sensors are packaged so that they are independent of one another and can be quickly replaced if bio-fouled or damaged. Deployments in Bayboro Harbor, St Petersburg, FL demonstrate that the novel CTD systems are capable of obtaining highly resolved *in situ* salinity measurements comparable to measurements obtained using commercially available instruments. The estimated accuracies for the conductivity, temperature and pressure sensors are ±1.47%, ±0.546 °C and ±0.02 bar, respectively. This work indicates that a small, low cost CTD system with expendable/replaceable sensors can be used to provide accurate, precise and highly resolved conductivity, temperature and pressure measurements in a coastal environment.

Keywords: PCB MEMS, environmental sensors, salinity, liquid crystal polymer, coastal measurements

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Salinity is widely perceived as a fundamental variable in the regulation of natural marine systems. It is a key parameter in determining many of seawater's physical characteristics, such as density, conservative element concentrations and solubility of gases [1]. In addition, as a conservative water mass tracer, it is critical to descriptive modeling of oceanic circulation, mixing and climate processes. Salinity is an important ecological factor, inasmuch as it influences functional and structural properties of organisms through changes in total osmotic concentration, relative proportions of solutes, coefficients of absorption and saturation of dissolved gases, density and viscosity [2]. Because of the global significance of salinity in marine systems, oceanographic researchers are exploring various new tools, such as instrumented animals, in order to study the physical, chemical and biological structure of the oceans [3], thus increasing the need for small, low cost, highly resolved *in situ* instruments.

Salinity is determined by a conductivity, temperature and depth (CTD) instrument that measures the electrical conductivity, temperature and pressure of seawater respectively [4]. Normally, these sensors are fabricated using costly multi-layer screening or traditional micromachining/MEMS techniques [5, 6]. We have described the design, fabrication and characteristics of liquid crystalline polymer (LCP)-based conductivity cells and resistive temperature devices using novel PCB MEMS fabrication techniques [7].

LCP is a thermoplastic material which has a very low moisture absorption and permeability, thus making it an ideal substrate for environmental sensors [8]. These novel techniques allow for the rapid fabrication and potential mass production of these devices, thus lowering their cost. We have proven the suitability of using PCB MEMS-based sensors for conductivity and temperature measurements in the laboratory via comparisons with commercial instruments. The conductivity sensor fabricated was a planar, thin-film (LCP), four-electrode cell, consisting of electroless nickel, gold and platinum metals. The temperature sensor was a resistive temperature device (RTD) fabricated using copper-clad LCP material. The conductivity and temperature sensors were combined with a piezoresistive pressure sensor package to create a total analysis salinity system which can enable distributed salinity sensor networks for large area measurements and science.

Harsh corrosive conditions and a plethora of micro-organisms make *in situ* salinity measurements a very challenging task. Bio-fouling, or the undesired deposition of microbial layers or biofilms on surfaces, occurs immediately in natural marine waters [9]. Bio-fouling and corrosion can lead to sensor drift, thus requiring recalibration or maintenance performed on the instrument by the manufacturer, resulting in inconvenient down-time. This problem could be avoided with the use of expendable/replaceable conductivity, temperature and pressure sensors for the determination and monitoring of salinity in natural waters. Among the PCB MEMS fabrication technologies, low cost expendable sensors have demonstrated their suitability as environmental monitoring tools for several chemical and physical parameters [10, 11].

Current commercially available CTD instruments range in cost from 1000s to 10 000s dollars depending on the application. Instruments that are packaged for deep deployments (1000 + *m*) are costlier than others due to the titanium housings used, where as the average cost of a coastal water system is 5500 dollars. Another expense associated with commercial instruments is the maintenance and recalibrations, which is typically performed by the manufacturer. This not only costs 100s of dollars, but contributes to instrument down-time, whereas the PCB MEMS system has replaceable sensors with minimal down-time. An approximate cost of the PCB MEMS CTD system is 1000 dollars with the cost of replacement sensors in the 10s of dollars based on price of materials utilized for construction.

In this work we demonstrate the suitability of a low cost, expendable sensor PCB MEMS-based CTD system for coastal salinity surveys. We present the expendable sensor design and characterizations along with good correlation of the systems' performance in coastal waters compared to a commercial CTD (AML, LLC model micro-CTD). Application-based measurements are also reported in this work.

2. System configuration

The CTD system integrated the PCB MEMS-based conductivity cell and RTD with a commercially available pressure module (Intersema MS5535 14 bar Pressure Sensor Module), which includes a piezoresistive pressure sensor and an ADC-interface IC. MS5535A is a low-power, low-voltage device with automatic power down (ON/OFF) switching that provides pressure and temperature measurements. The approximate size of the CTD sensors were 10 mm diameter, 13 mm × 10 mm and 7.3 mm diameter, respectively. The three distinct sensors were packaged in independent plugs machined out of Delrin material and the sensors were mounted using a permanent urethane resin (Scotchcast 2130, 3M). Flexible printed circuitry connectors and cables were attached to the fingers of the conductivity and temperature sensors and placed through a slit in a plug for electrical interfacing. The pressure sensor was mounted to a small circuit board and placed in a plug with connecting wires. The sensor plugs were fitted with an O-ring and mounted in the top end cap of the underwater housing of the system. The watertight acrylic canister housed the circuit boards and internal battery and the bottom end cap contained an underwater connector for communications and power. The overall CTD system measured approximately 10 cm in diameter by 10 cm in length. A schematic of the CTD system with individual sensor plugs is shown in figure 1.

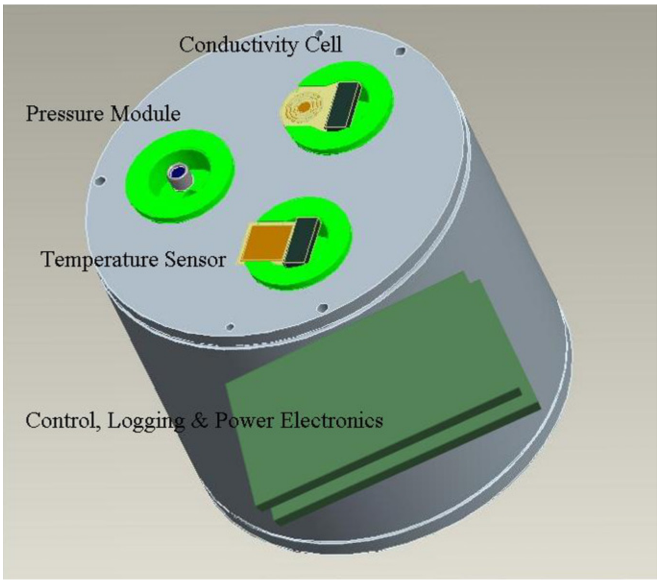

Figure 1. Scheme of the PCB MEMS-based CTD showing the independent expendable sensor plugs and environmentally protected circuit boards.

The CTD system electronics were comprised of two stacked circuit boards that control the sensors, microprocessor and power. Sensors were controlled by a low-power MSP430 microcontroller device containing a 16 bit RISC processor with 64 bit floating point calculations (Texas Instrument). The highly integrated microcontroller incorporated internal accessible flash, D/A, A/D, references and timing capabilities. A MAX3221 low-power RS232 level converter handled communications and ADC1241 performed a 24 bit A/D conversion with a 60 Hz digital filter and self-calibration. Sensor biases were handled by the microcontroller's internally self-calibrated 12 bit D/A converter.

The CTD system required 3 mA for the RS-232, 800 μA average quiescent, 10 mA sampling deionized water, 22 mA sampling water at 70 mS cm^{-1} at 6 to 12 volts dc power. Internal power was supplied by a 9 volt alkaline battery and provided 22 days of operation with a sampling rate of every

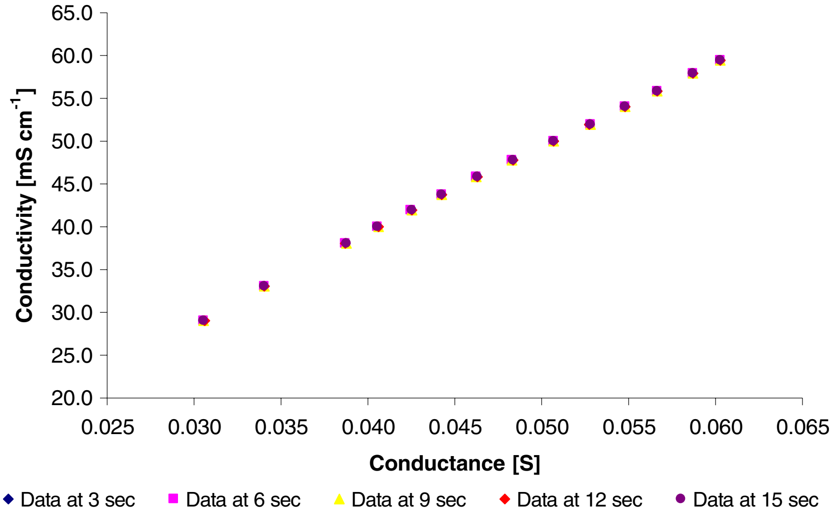

Figure 2. The conductance versus conductivity of the PCB MEMS conductivity cell for five replicate measurements.

15 min. Endurance can be doubled when two batteries are connected in parallel.

The CTD software was a comprehensive program, which allowed the user to communicate with the system through the serial port. The software was a menu-driven program that allowed the user to set the system clock, sampling start/stop times, sensor bias and calibration curves, memory format and sampling rate. Data displayed included date, time, temperature (°C), conductivity (mS cm^{-1}), pressure (mbars) and pressure module temperature (°C).

3. CTD sensor characterizations

3.1. Conductivity cell

The conductivity cell was calibrated using International Association for the Physical Sciences of the Oceans (IAPSO) standard seawater samples (Ocean Scientific International Limited, Hamshire, UK). The conductivity calibration procedure entailed taking five repeated measurements with a 3 s interval of one standard conductivity solution at various temperatures. The conductivity (mS cm^{-1}) of the standard seawater sample (34.995) per temperature was calculated using the electrical conductivity method formula [12].

Q1 The conductance (Siemens) of the conductivity cell was plotted against the calculated conductivity (mS cm^{-1}) for all replicates, as shown in figure 2. The calculated R^2 value (0.9997) of the conductivity cell indicated very good linear correlation with a 95% confidence limits, ranging from ±0.28 to 0.59 mS cm^{-1}. The average standard deviation multiplied by two of the five repeated measurements or estimated precision of the sensor was calculated as 0.0320 mS cm^{-1}, thus showing good sensor repeatability for conductivity values 30 to 60 mS cm^{-1}, which is the average range of most coastal environments.

In [7] a comparison was shown between our sensors' response and that obtained using a commercially available benchtop environmental probe (Mettler Toledo Inlab 730) [7]. The PCB MEMS conductivity cell exhibited good linear correlation with an R^2 value of 0.9999 from 0 to 60 mS cm^{-1} when compared to the commercial probe. To estimate the accuracy of the PCB MEMS conductivity cell, the mean absolute percentage error (MAPE) was calculated by summing the absolute difference between the two sensors, dividing by the sum of the reference readings and multiplying by 100%. This method highlights errors attributed to the fact that the initial calibration method is susceptible to errors in the gain of the linear regression used to calculate conductivity from conductance; this is observed in the linear regression between the two probes as a small offset, but a non-unity gain term in figure 2. The accuracy for the commercial probe was stated as ±0.005 mS cm^{-1}, whereas the estimated accuracy of the PCB MEMS conductivity cell was ±1.47% (MAPE) from 0 to 60 mS cm^{-1}. This translates to a calculated error of ±0.882 mS cm^{-1} at the high end (60) and ±0.0294 mS cm^{-1} at the low end (2), which corresponds to the actual data. The % RMS error method was not used because of the large error terms generated near 0 mS (fresh water).

3.2. Resistive temperature device

The resistive temperature device was calibrated against a calibrated platinum resistive temperature device with an accuracy of ±0.0012 at 0 °C (Minco Thermal Tab, platinum 385). Five resistance measurements were averaged to obtain a stable reading at each temperature. The linear regression equation was entered into the CTD software program to calculate the calibrated temperature (°C) data from the measured resistance (Ω). The calculated R^2 value (0.9998) indicates good linear correlation between the measured (resistance) and predicted variables (temperature). The 95% confidence limits were calculated and had a range of ±0.141 to 0.586 °C. The resistance (Ω) of the RTD was plotted against the temperature (°C) for all replicates, as shown in figure 3. The average standard deviation multiplied by two or estimated precision of the PCB MEMS RTD was calculated as 0.0066 °C for the range of 2 to 50 °C.

Experiments have verified that the PCB MEMS RTD was comparable with a conventional temperature probe (and Fluke 80T-150U temperature adapter) and exhibited good linear correlation with an R^2 value of 0.9997 [7]. To estimate the accuracy of the PCB MEMS RTD, the RMS_{error} was

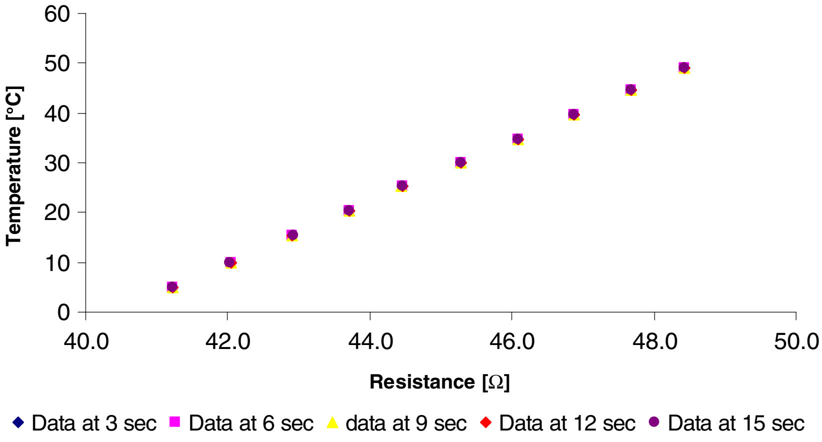

Figure 3. The resistance versus temperature of the PCB MEMS RTD for five replicate measurements.

calculated by taking square root of the average of the squared differences between the two sensors. This method highlights errors attributed to the fact that the initial calibration method is susceptible to errors in the offset of the linear regression used to calculate temperature from resistance; this is observed in the linear regression between the two probes as a near unity gain, but a significant offset term in figure. The accuracy for the commercial probe is ±1 °C and the estimated accuracy based on the $\mathrm{RMS}_{\mathrm{error}}$ value of the PCB MEMS RTD is ±0.546 °C for the range of 0 to 50 °C.

The calibration error source for both the conductivity and temperature sensors realized in PCB MEMS is the slow heat transfer from the water bath to each sensor. Since each sensor is calibrated by varying the temperature of the bath over time, the offset between the Minco probe reading and the true temperature of the sensors affects each sensor differently. However, since each calibration point is generated by the same temperature jump and the same time delay, the temperature offset remains constant at each point. The conductivity of the IAPSO water sample changes 1.19% per 1 °C from 15 °C; therefore a constant temperature offset represents a larger conductivity offset at higher temperatures. Since the RTD responds linearly to offsets, the offset in the reading is the same at any temperature.

3.3. *Piezoresistive pressure module*

The Intersema MS5535A pressure module (140 dbar) was tested and compared to another discrete pressure sensor (Keller PA-10), in order to insure that the appropriate results were obtained from the integration of the pressure module to the sensor circuit board. The Keller PA-10 was a semiconductor bridge strain gauge with a maximum range of 500 dbar and was used on the commercial CTD instrument. Both sensors were mounted into a pressure vessel and then the vessel was pressurized and depressurized several times. Pressure measurements were recorded for both sensors simultaneously. The data were plotted and the sample regression and R^2 values were calculated. The R^2 value (0.9999) shows excellent linear correlation between the Intersema pressure module and the Keller pressure sensor. The reported accuracy was 0.020 bar with a resolution of 0.0012 bar. The internal temperature sensor had an accuracy of 0.8 °C and a resolution of 0.015 °C.

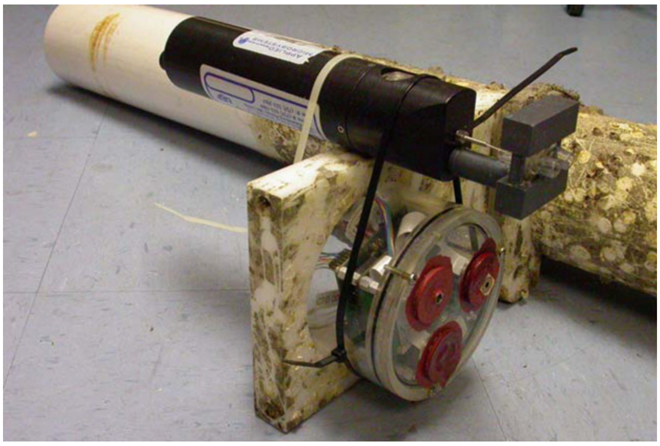

Figure 4. Photograph of the experimental setup for the comparison of the PCB MEMS-based CTD system with the commercial CTD instrument.

4. Experimental results and discussion

4.1. *Comparison field test*

We have tested the CTD system in natural seawaters for *in situ* conductivity, temperature and depth measurements. The tests were performed in Bayboro Harbor, St Petersburg, FL, USA (27°45′38.50″ N, 82°38′01.47″ W) to evaluate the field performance of the PCB MEMS-based CTD in comparison to a conventional CTD instrument (Applied Microsystems Micro-CTD).

The CTD instruments were mounted to and affixed to a floating platform within the harbor and then submerged approximately 0.50 m in depth (shown in figure 4). The CTD instruments were programmed to take simultaneous conductivity, temperature and depth measurements every 15 min for an 8 h period. Wireless data were transmitted real time for both instruments. The wireless system was a field 802.11b-type transceiver unit derived from a Lantronix embedded 802.11b system.

The results are shown in figures 5(*a*)–(*d*); the solid lines correspond to the PCB MEMS-based CTD and the dashed lines represent measurements acquired from the correlating commercial CTD. In figure 5(*b*), the small dotted line represents the temperature values obtained from the pressure

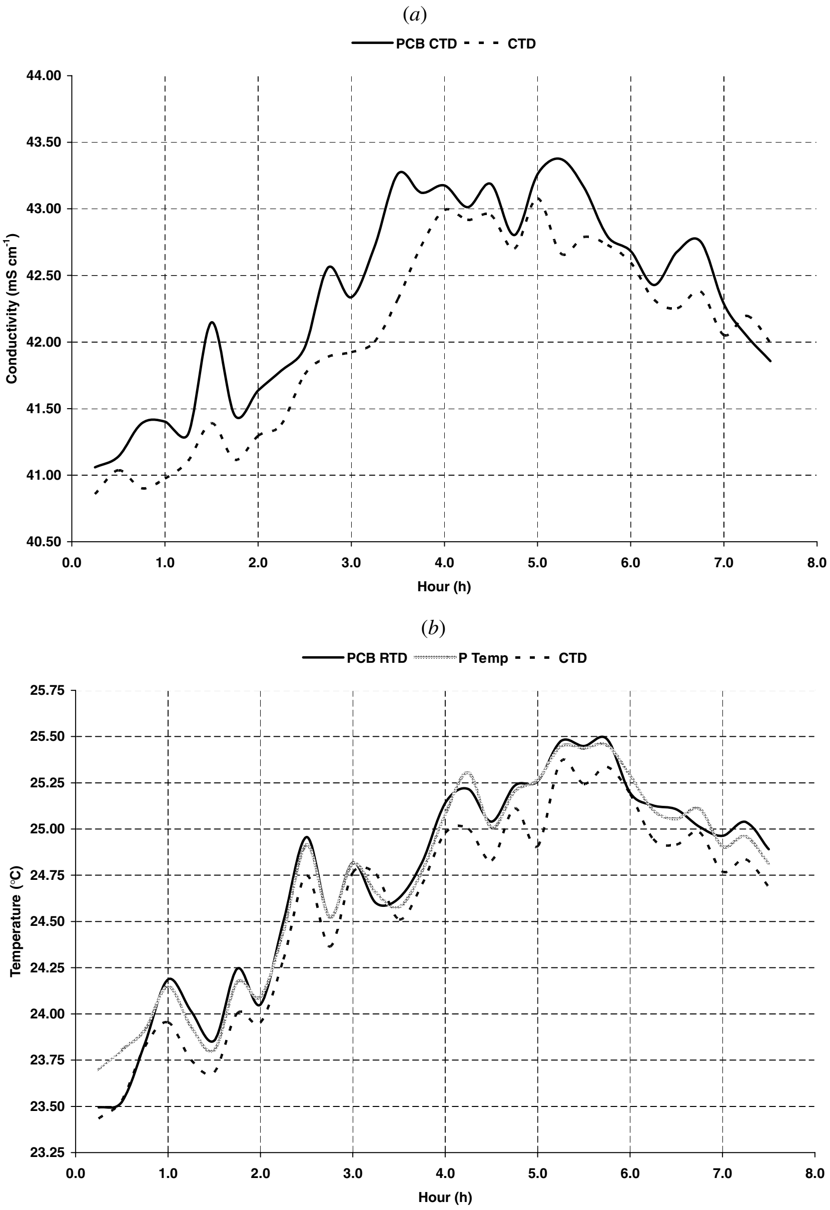

Figure 5. Results obtained in the field test at Bayboro Harbor. The solid lines correspond to the measurements acquired from the PCB MEMS-based CTD and the dashed lines represent the correlating commercial CTD. (*a*) Conductivity (mS cm^{-1}) values obtained. (*b*) Temperature (°C) values obtained for the three temperature sensors. The dotted line corresponds to the temperature sensor on the pressure module of the PCB MEMS CTD. (*c*) Depth (*m*) measurements recorded. (*d*) Calculated salinity values.

module for additional comparison. Figure 5(*a*) shows that the PCB MEMS conductivity cell corresponds well with the benchmark CTD instrument, where the standard deviation is 0.2307 mS cm^{-1}. Figure 5(*b*) shows the standard deviation of the PCB MEMS RTD and the commercial CTD temperature sensors as 0.0818 °C. The standard deviation between the PCB MEMS RTD and the pressure module temperature sensor is 0.0559 °C. Figure 5(*c*) shows the output difference observed between the pressure sensors, where the standard deviation is 0.0117 m. The average difference of 0.167 m could be due to the proximity of the instruments to one another and the location of the sensors on the instruments. As shown in figure 6, the pressure sensor of the commercial CTD is approximately 0.09 m above the other two sensors, whereas the pressure module on the reported CTD system is planar with the other sensors. The two CTD instruments were positioned so that the conductivity sensors were in close proximity of each other. Salinity measurements were independently calculated using the temperature and conductivity data with the Practical Salinity Scale 1978 formula for both CTD systems and shown in figure 5(*d*) [13]. Good correlation between the two salinity measurements can be seen in the calculated values where the standard deviation is 0.170 psu (practical salinity units). The output difference observed could be due to the dissimilar sensor configurations between the two conductivity transducers. The PCB MEMS-based conductivity cell is an open-electrode cell, where the commercial CTD has a short conductivity sensor within a quartz sensor cavity, which may reduce the background noise. The slightly different depths of the measurement points may also affect the salinity within an estuary, where density layers are highly stratified due to freshwater advection, flow rate and salt diffusion [14].

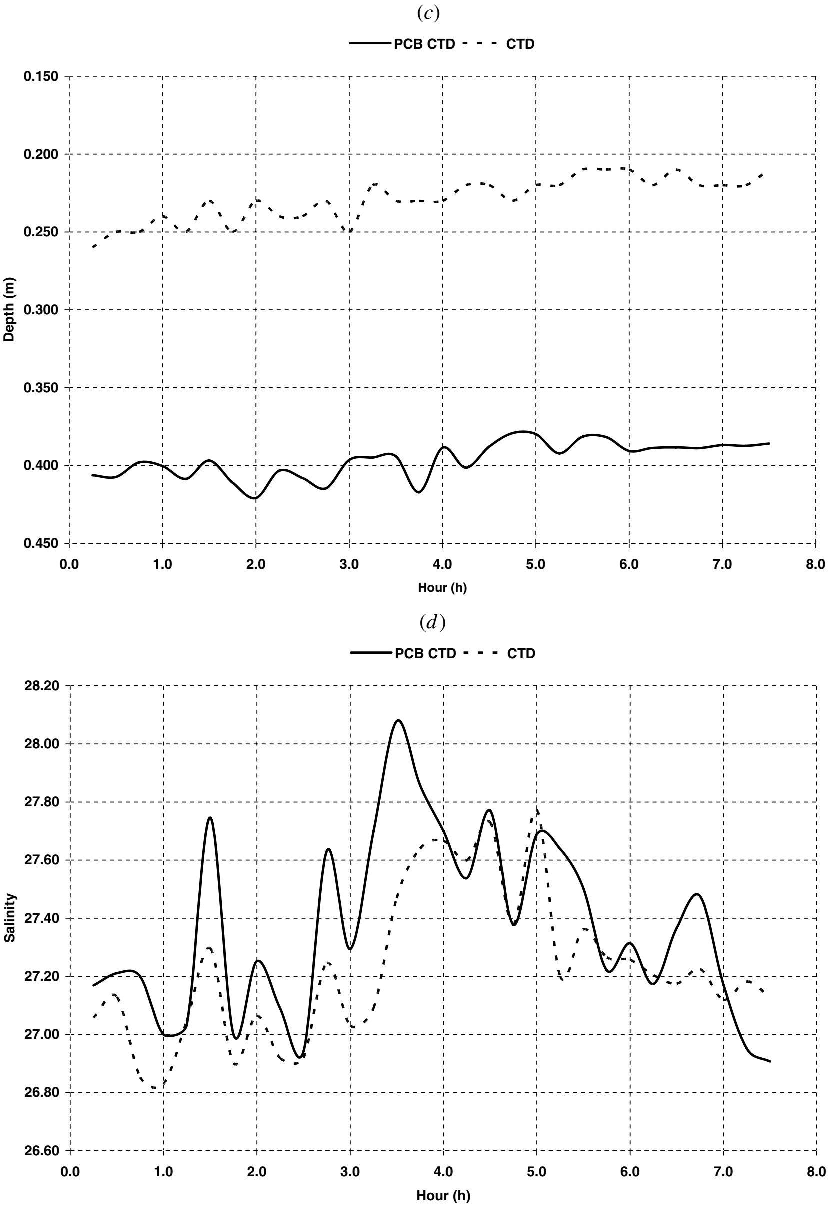

Figure 5. (Continued.)

Figure 6. (*a*) Photograph of the raceway filled with seawater from Bayboro Harbor. (*b*) Photograph of the PCB MEMS CTD submerged in the raceway. The black extension is a communication connector plug.

4.2. Coastal application

The PCB MEMS-based CTD system was deployed in an open-air natural water flow-through tank system, which holds 1550 l of seawater. Seawater from Bayboro Harbor was continuously pumped into the holding tank and will be referred to herein as the raceway (figure 6(*a*)). The raceway is designed to cultivate and study scallops and oysters in a confined natural

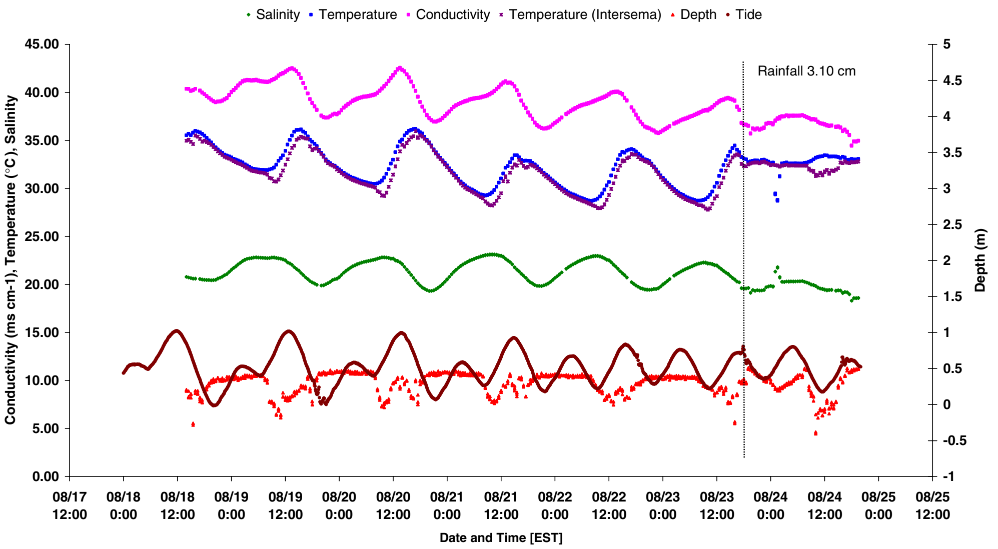

Figure 7. Results obtained in the raceway field experiment. Conductivity (mS cm^{-1}), temperature (°C) and salinity values correspond to the primary *y*-axis. The depth and tidal values correspond to the secondary *y*-axis. Rainfall is depicted by the dotted vertical line.

setting. The CTD was used to monitor the salinity conditions of the raceway for a 7 day period prior to the introduction of bay scallop (*Argopecten irradians*) juveniles. The CTD system was programmed to acquire conductivity, temperature and depth at a rate of three measurements every 30 min and logged internally. The power source for the CTD system was an internal 9 volt battery.

After the 7 day period, the CTD system was removed from the tank and the measurements were obtained as shown in figure 7. Conductivity, temperature, depth and salinity results were obtained along with temperature measurements for the thermometer incorporated within the pressure module and the water level (tide) data. Tidal data were collected by National Ocean Services (NOS) and stored in the Center for Operational Oceanographic Products and Services (CO-OPS) database[1]. Rainfall data were also acquired for the deployment location (Albert Whitted Airport, St Petersburg, FL) and period (17–24 August) from NOAA (see footnote 1). A significant rainfall event (3.10 cm) occurred on 23 August between 19:00 and 20:00 hours and is represented by a vertical dashed line in figure 7. This event was captured by the CTD system, which measured a noticeable change in the conductivity and temperature of the seawater.

Figure 7 demonstrates the variations of conductivity, temperature and depth measurements versus time for the period of 1 week. The PCB MEMS RTD was observed to be consistent with the commercially manufactured temperature sensor of the pressure module. Temperature data reflected elevated temperatures during the day and lower temperatures at night. Conductivity measurements fluctuated with temperature, but once parameters were incorporated into the salinity equation and temperature was compensated, the data were normalized. Bayboro Harbor has a mixed tidal pattern, where successive high tides or low tides are of significantly different heights through the cycle, which causes fluctuations in salinity [15]. These fluctuations were measured with the CTD system and were calculated using the Practical Salinity Scale 1978 [13].

5. Conclusions

The experiments performed have demonstrated a prototype of a novel PCB MEMS-based CTD system suitable of monitoring conductivity, temperature and depth in coastal waters. The research presented includes the novel design and integration of the system as well as the PCB MEMS sensors' characterizations and specifications. The conductivity cell performed well with an estimated precision of 0.0320 mS cm^{-1}, an estimated accuracy of ±1.47% and a range of 0 to 60 mS cm^{-1}. The RTD performed well with an estimated precision 0.0066 °C, an estimated accuracy of ±0.546 °C and a range of 0 to 50 °C. The piezoresistive pressure module performed well with an accuracy of ±0.02 bar and a range of 0 to 140 m.

Field evaluation tests verified that all measurement principles essentially worked as intended *in situ*. All results obtained with the PCB MEMS CTD showed good correlation with those acquired by a benchmarking commercial CTD instrument. Salinity data were acquired for a 7 day application-based deployment of the CTD system and showed parametric fluctuations which corresponded well with the environmental conditions. Further experimentation of this system will include depth profiles, towed measurements of GPS transects and long-term deployments.

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[1] http://140.90.121.76/data_retrieve.shtml?input_code=011011111pwl&station=8726520+St.+Petersburg,+FL.

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Queries

(1) Author: Please check if sentence ‘The conductance (Siemens) . . . from ±0.28 to 0.59 mS cm^{-1}’ retains the intended sense after the change made to it.
(2) Author: Please check if reference [5] is okay as set.
(3) Author: Please check if reference [12] is okay as set. Do you mean page numbers when you mention ‘2–44 to 2–50’? Please specify.
(4) Author: There is a mismatch between the source file and the PDF file. We have followed the source file as it seemed to be the updated one.
(5) Author: Please be aware that the colour figures in this article will only appear in colour in the Web version. If you require colour in the printed journal and have not previously arranged it, please contact the Production Editor now.
