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A SALINITY SENSOR SYSTEM FOR ESTUARY STUDIES

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Abstract. In this paper, we present the design, development and testing of a salinity sensor system for estuary studies. The salinity sensor was designed keeping size, cost and functionality in mind. The target market for this sensor is in hydrology where many salinity sensors are needed at low cost. Our sensor can be submersed in water for up to two weeks (all electronics are completely sealed) while salinity is recorded on-board at user-defined intervals. The data is then downloaded to a computer in the laboratory, after which the sensor is recharged, cleaned for biofouling and ready to be used again. The system uses a software program to download, display and analyze the sensor data. Our initial laboratory testing shows the salinity sensor system is functional. The novelty of this work is in the use of toroidal (inductive) conductivity sensors, the resulting low cost and simple design.

1. **Introduction.** The border between land and ocean harbors sites of dramatic variation in environmental conditions. Precipitation, which changes daily, seasonally and inter-annually, leaves its mark in temporal fluctuations in coastal salinity. Similarly, spatial variation in salinity emerges as a function of distance to rivers and upwelled deep ocean water. Salinity is the fundamental way in which freshwater and ocean water differ and provides a direct measure of the local contribution from each source. Salinity also serves as a marker for many other environmental properties that vary along an estuarine gradient, including temperature, nutrients and the composition of planktonic (free-floating) organisms [1].

Salinity varies on small scales of space and time and this variation has important biological implications: organisms respond to extreme events, not simply the mean. In general, long-term conditions define zones (e.g., saline, mesohaline, oligohaline, or acidic, neutral, basic, or anoxic, hypoxic, or upper, mid, low intertidal). Mortality, however, is frequently associated with transient anomalous conditions, like a freeze, or a heavy rain or a tsunami. These anomalies are impossible to predict and nearly impossible to record with conventional instrumentation. The prime reason for this is cost, which necessarily limits the number of data samples (in space and time). Precise measures of salinity are less important than broad sampling, given large-magnitude variation. Therefore, the traditional way of measuring salinity is no longer applicable.

The salinity sensor system presented in this paper will greatly enhance our understanding of coastal marine ecology, including distributions of organisms, ocean-estuary coupling and zonation. Biologists have known for years how to perform salinity measurements. Taking one measurement in one place at one time is easy.

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FIGURE 1. Map of Willapa Bay, WA (map from NOAA Coastal Services Center).

They also know how to take such measurements continuously over time with large and complex instruments that cost thousands of dollars. The goal of our project is to use salinity sensors to evaluate environmental issues in Willapa Bay (see Fig. 1), which is an estuary in south-western Washington state (USA). To get the data we need, however, will require dozens of relatively small and inexpensive, autonomous, robust devices that can simultaneously record data in a harsh marine environment.

University of Washington (UW) biologists on our team hope to use monitors to establish clear environmental benchmarks by providing an accurate description of conditions and processes in this special estuarine environment. Willapa Bay is the last major estuary in the USA that remains as healthy as it was a century ago: it has no major human settlement along its shores, no factories, no major agricultural nutrient sources. Moreover, it is home to a vibrant shellfish aquaculture industry. If we can gather data needed to understand this productive marine environment, all of those who are struggling to restore other bodies of water from Puget Sound to Chesapeake Bay to estuaries all over the world will have a clearer idea of what theyre working toward.

In addition to marine ecological research, we see broad applicability for inexpensive, data-logging salinity sensors in aquaculture and the aquarium trade. In both cases, people need to know the environmental conditions experienced by their animals, particularly if they appear stressed or diseased. Extremely high or low salinity can cause mortality, depending on organism-specific tolerances, but it also has sub-lethal effects in terms of reduced growth rate, unseasonable reproduction, or susceptibility to pathogens [5]. Simple salinity sensors would aid in the diagnosis of problems before the onset of massive financial loss. Today, coastal aquaculture in the U.S. produces hundreds of millions of dollars worth of food annually and aquaculture worldwide is increasing by more than 10% annually [3]. Much of this aquaculture occurs on small family farms that could never afford expensive environmental monitoring equipment.

Sensor Type	Log Data?	Submersible?	Price
Oregon Scientific ST228	no	no	30
YSI Datasonde 6600	yes	yes	1500
Falmouth Scientific NXIC	yes	yes	6600
Vernie SAL-BTA	yes	no	88
Aandera 3919A	yes	yes	1900

Table 1. Comparison of commercial salinity sensors.

Many commercial sensors currently exist for measuring salinity in liquids, however, most are expensive and few run autonomously with logging capability or are submersible. See Table 1 for a sample of existing salinity sensors.

The salinity sensor we have developed tackles realistic issues of low power, low cost and environmental constraints. The sensor takes and stores measurements at set intervals that are defined by the user. In addition to the sensing capabilities, the sensor requires a battery life of at least two weeks and uses inductive battery charging.

To make sense of all of the salinity data taken in the estuaries over time, we have developed a software mapping tool using LabVIEW [7] for viewing and analyzing data in the laboratory. This software tool gives a color-coded map and movie of the salinity in Willapa Bay over the time period of observation.

This paper is organized as follows. In Section II, we describe the salinity sensor design in detail, focusing on the theory behind the design, the sensor mechanism, the microprocessor design, packaging and initial biofouling experimental results. In Section III, we describe the LabVIEW mapping tool. In Section IV, we discuss the initial testing and results. In Sections V and VI, we give ideas for future work and conclusions.

2. **Sensor design.** In this section, we present our design for the data-logging salinity sensor.

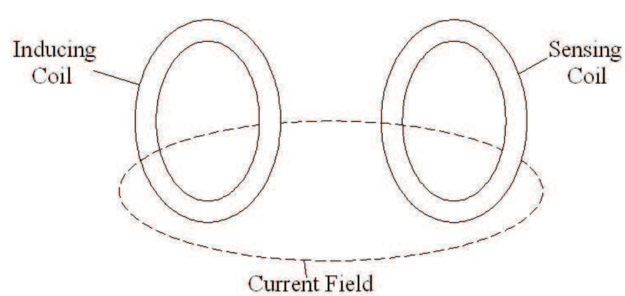

Figure 2. The current field around the sensor coils.

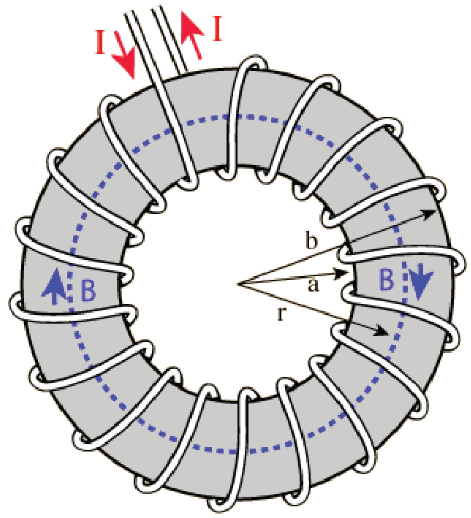

FIGURE 3. The sensing coil genertes an AC voltage.

2.1. **Theory behind the sensor mechanism.** A common method for measuring salinity uses two closely spaced, conductive tipped probes dipped into water. An electric current passing between the tips measures the conductivity of the ionized water. While this design is simple and effective, it cannot be left in the water over an extended period; the ferrous probes can oxidize and having them so close together increases the chance for biofouling rendering the instrument useless.

The motivation for our salinity sensor design was the requirement of long-term submersion, data-logging capability and resistance to biofouling. The sensors conceptual design models a common AC transformer.

When the two toroidal coils are immersed in a conductive liquid and a square wave signal is applied to the inducing coil by the microcontroller, a voltage is induced in the liquid surrounding the coil. The voltage causes an ionic current flow in the liquid loop which is proportional to the conductance of the liquid (see Fig. 2). The ionic current induces a current in the sensing coil; the induced current is directly proportional to the conductivity of the solution. The sensing coil generates an AC voltage (see Fig. 3). A rectifier and an analog-to-digital (A/D) converter are used to measure the magnitude of the voltage output. This measurement is effectively the conductance of the water, which can be converted to salinity by the microprocessor. See also the paper [4] for a similar concept in another sensor.

Conductivity varies as a function of both temperature and dissolved ions. Therefore, measurements of both temperature and conductivity are necessary to calculate salinity. Standard conversions generate unit-less values in reference to the conductivity of standard seawater at 15° C. With conductivity and temperature, salinity is calculated from the conductivity ratio [2]:

$$R = \frac{C(S,T,P)}{C(35,15,0)} \tag{1}$$

where C is conductivity, S is salinity (parts per thousand), T is temperature (Celsius) and P is pressure (decibars). C(35,15,0) is the conductivity of standard seawater (35 ppt, 15° C and atmospheric pressure). Salinity (S, in practical salinity units) is derived from this conductivity ratio. This algorithm is widely accepted in the field and has been proven accurate.

With the temperature and conductivity ratio, we can use the equations (2) and (3) below to calculate salinity, S up to 0.001 (see [6] for more background on this equation and salinity in general). The principle of calibrating standard seawater in electrical conductivity is given in [2].

$$\begin{aligned} S = {} & 0.0080 - 0.1692R^{1/2} + 25.3851R + 14.0941R^{3/2} \\ & - 7.0261R^2 + 2.7081R^{5/2} + X \end{aligned} \tag{2}$$

where R is the ratio taken from equation (1) and X is derived from the following equation:

$$\begin{aligned} X = {} & \frac{t-15}{1+0.0162(t-15)}(0.0005 - 0.0056R^{1/2} \\ & - 0.0066R - 0.0375R^{3/2} + 0.636R^2 - 0.0144R^{5/2}) \end{aligned} \tag{3}$$

2.2. **Sensing mechanism.** The hardware block diagram for our salinity sensor is shown in Fig. 4. The salinity of the water is calculated using the measured conductivity and temperature of the water. In the hardware, the microprocessor sends a square wave to the inducing coil. The current flowing through the inducing coil creates a magnetic field through the water channel. The sensing coil generates an AC voltage depending on the conductivity of the water. A rectifier and an analog-to-digital (A/D) converter are used to measure the magnitude of the output. The reading corresponds to the conductance of the water. It is converted into salinity by the microprocessor.

A temperature sensor is also needed to compute the salinity. A LM355 precision temperature sensor was used in our design. This device can be considered as a Zener diode as its reverse breakdown voltage is proportional to the absolute temperature. In order to measure a specific temperature, the part was calibrated. The allowable range of current is 400uA 5mA. We decided to supply 2mA considering that the device can get hotter as the bias current increases. This sensor was encased in shrink wrap for waterproofing.

A photograph of our prototype salinity sensors coils is shown in Fig. 5. Due to the fact that each set of coils reacts best at a different input frequency, the microprocessor is designed such that the user enters the input frequency.

We also tried several different coil orientations and epoxy filling techniques. The best coil arrangement was side-by-side. One of the epoxy-coated prototypes is shown in Fig. 6.

2.3. **Microprocessor design.** The core brain of the salinity sensor is the microprocessor controller that is embedded inside the sensor. A microprocessor controls the state in which the sensing mechanism is operating.

Four states exist, as illustrated in Fig. 7: the user interface state, transport state, data collection state and idle sleep state. By default, the sensing mechanism is in the idle sleep state, which utilizes a sleep function that reduces microprocessor power usage as low as 100nA. At the base station, by pressing the right command

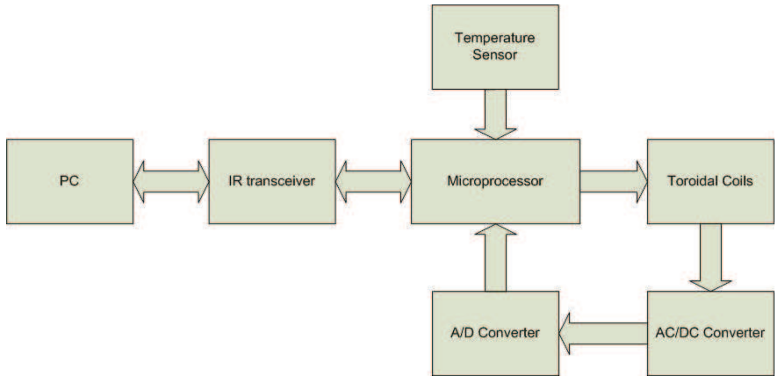

FIGURE 4. The high-level hardware block diagram of the salinity sensor embedded system. The sensor will be connected to a PC.

FIGURE 5. Salinity sensor coil arrangement.

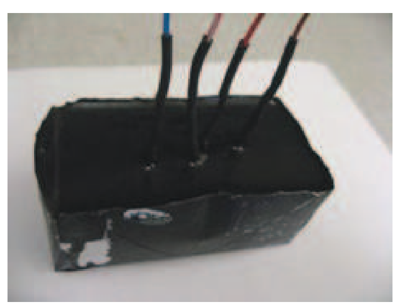

FIGURE 6. Epoxy coated sensor

key, the user can move the device to the user interface state, in which the user has the ability to enter the sensor number, set the frequency of the square wave sent to the coil, enter the measurement time interval, report sensor information, transfer data or reset data. From the user interface state, the sensing mechanism is sent to the transport state and will remain so until the user has transported the device to

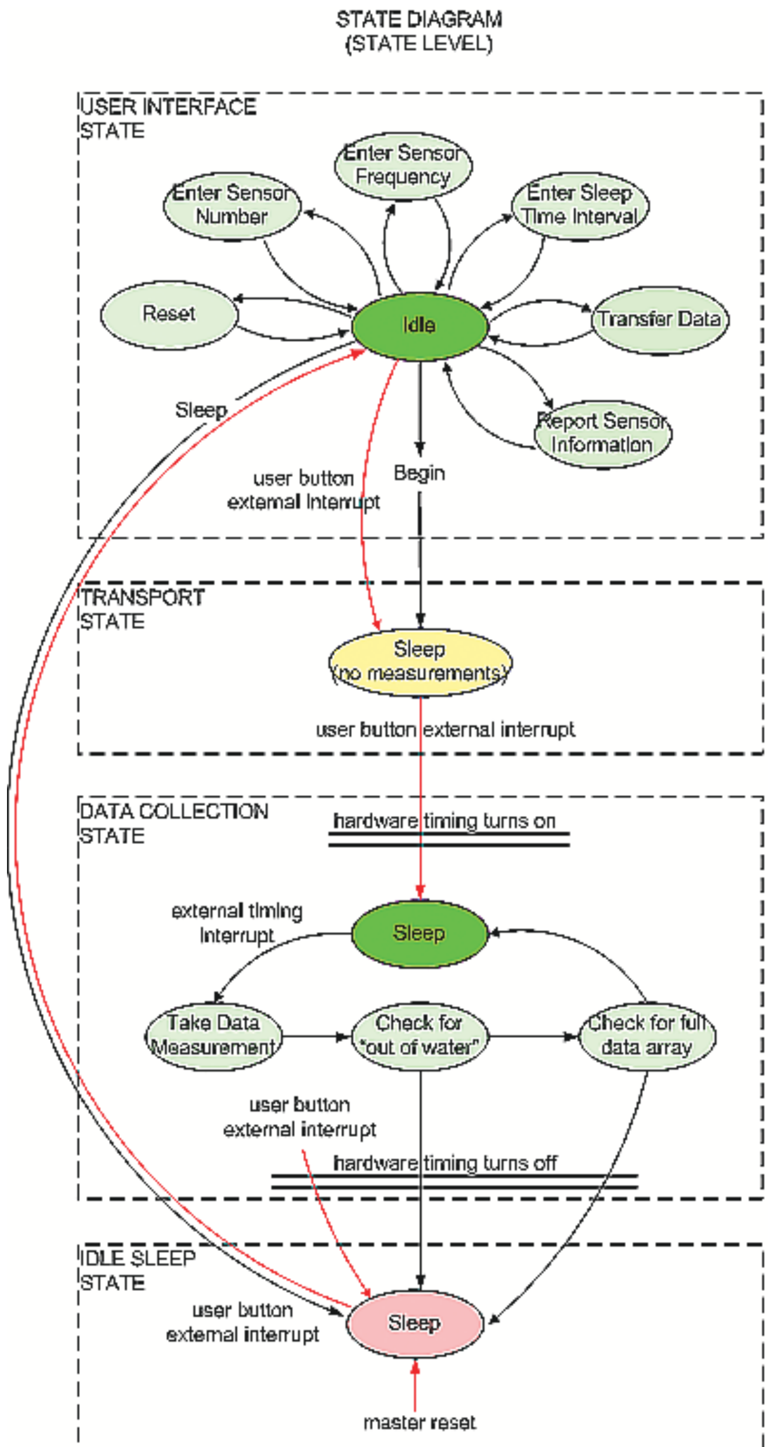

Figure 7. State diagram of salinity sensor.

its desired data-acquisition location. Again using the right command, the sensing mechanism is sent to the data collection state and the timing hardware that dictates the passage of time is powered on. The timing hardware interrupts the microprocessor every minute that elapses and once the desired time interval is reached, the sensing mechanism records the salinity. Upon completing its salinity measurements, the microprocessor powers off the timing hardware (to conserve battery life) and is sent back into the idle sleep state. The device remains in this state until the user retrieves it from the water, returns it to be processed, and presses the button, sending it to the user interface state.

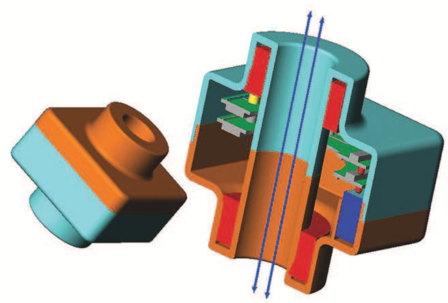

FIGURE 8. The concept chassis design for the salinity sensor.

2.4. **Packaging.** The desired chassis design for the sensor prototype is shown in Fig. 8. There will be no external metal parts or non-smooth features. The casing will be designed to be airtight, protecting the internal electronics and prevent environmental hazard if the sensor is lost. After two weeks, the sensor will be removed from the water for data retrieval, cleaning and recharging. The unique toroidal design allows water to flow through an inner channel, which is a key difference from the probe-based sensors. This design allows the water to travel through the inner part of the coils.

An additional set of induction coils will be used to recharge the sensor back in the laboratory. Again, since the sensor is hermetically sealed, all three main operations of the sensor interacting with the outside world, namely, taking measurement, charging battery and accessing data, will be done without opening the casing.

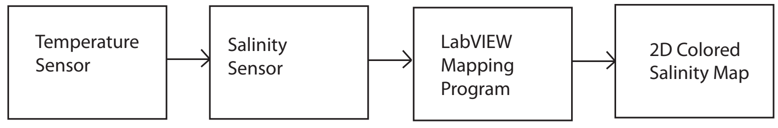

FIGURE 9. High-level block diagram of LabVIEW mapping tool.

3. **LabVIEW mapping tool.** The state of the art in data analysis in similar biological surveys is Microsoft Excel. We decided to make a new analysis tool,

which includes showing the sensor values on a map and also showing a movie of how the sensor value changes over time. This will be more useful, especially when the number of sensors is increased in the estuary.

The goal of the mapping tool is have an easy way to view and analyze the information collected by the sensors in the estuary. The program allows detailed analysis on the salinity of the estuary. Users will be able to monitor the salinity for the entire period of observation, and study how the marine organism responses to different levels of salinity. Fig. 9 shows a high level block diagram for LabVIEW Salinity Mapping Program.

A GPS device will be used to record the locations of the sensors when they are placed in the water. The sensors will be hooked onto fixed posts dug into the edges of the estuary. The data will be entered into the LabVIEW mapping program according to the recorded coordinates on the pre-programmed map of the estuary. The salinity sensor will be taking measurements and storing data every 15 minute-intervals for two weeks. After two weeks, the sensors are brought back to the laboratory and download data from the sensors to the mapping program.

Data from the sensors is organized by the LabVIEW program according to the pre-recorded sensor number. The program then produces a color-coded salinity map of the test area. The map shows the shoreline and the salinity is interpolated between measure points using the known GPS coordinates of the map corners and the sensor locations.

The salinity mapping program consists of five main modules, a data acquisition module, a planning tool module, a data analysis module, a movie generating module and spreadsheet generating module. Five modules work cooperatively to create a salinity movie and a data spreadsheet that allows one to see the changes in salinity over a period of time.

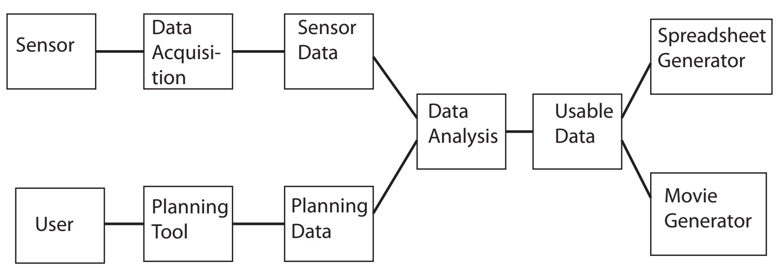

FIGURE 10. Block Diagram of the LabVIEW Salinity Mapping Program.

Fig. 10 shows a block diagram of the software program. The sensor data is being acquired by the data acquisition module and stored into a binary file. The binary data is integrated with the planning tool data by matching the sensor number by executing the data analysis module. After the analysis is done, the file is stored into a binary file that is used to generate a salinity movie and a salinity data spreadsheet.

The LabVIEW mapping program conducts sensors deployment planning, data modification, and generates movie and spreadsheet data all in one program. The desired sensor location can be planned by clicking on the map shown in Fig. 11 and the program will provide an estimate GPS value. This enables biologist to map the salinity sensor on the computer and stored the data electronically. The program also allows one to select the color that pertains to different salinity degrees to be

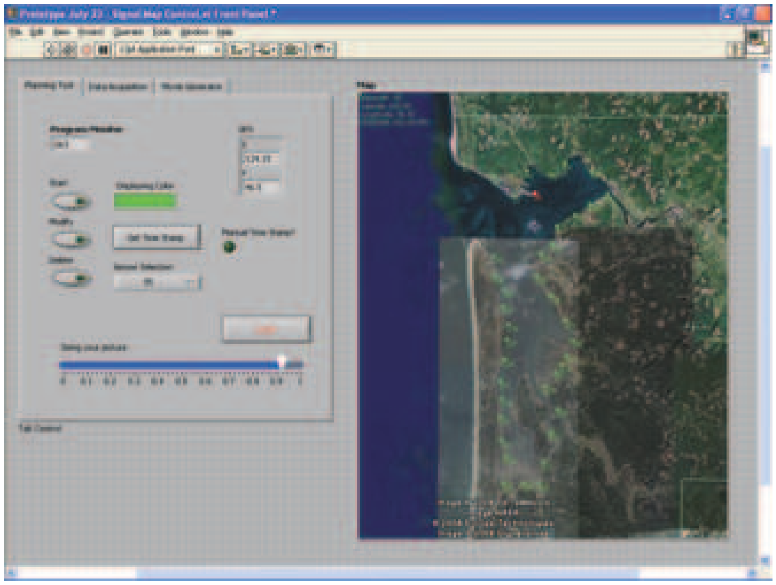

FIGURE 11. LabVIEW GUI for salinity mapping program.

displayed in the salinity movie. This gives flexibility to create the salinity movie in their desired representation.

4. **Testing and results.** In our laboratory, we calibrated the salinity sensor with solutions of known salt concentration. Using the calibration data, we compared our sensors value against the value of a commercially available sensor, the YSI Datasonde 6600 sensor.

Our sensor is based on the conductivity of the water, so in the following experiments, we focused only on recording the conductivity. For our initial experiment in testing the salinity sensor, we used one bucket of sea water at conductivity 63.5 mS. We then added distilled water in measured units over eleven more readings. We measured each concentration using the YSI Datasonde 6600 and our data-logging salinity sensor. One reading was done with the YSI sensor and four readings were done with our salinity sensor.

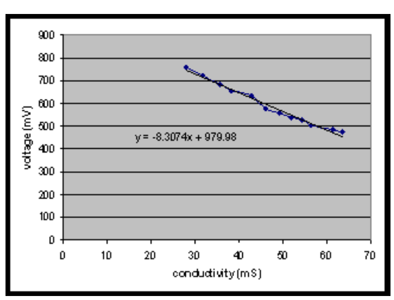

FIGURE 12. Average conductivity reading vs. voltage from the AC/DC converter in the salinity sensor.

We observed, in a very simple analysis, that as the conductivity decreased (as measured by the YSI sensor), our salinity sensor recorded an increase in the voltage (mV), which was measured from the output at the AC/DC converter voltage. Fig. 12 shows the results from our testing.

Once we have the conductivity and the temperature readings, we can plug all of the variables into the standard salinity equation to calculate salinity. This standard conductivity equation, however, requires variables to be recorded at certain exact settings such as a 35 salinity unit and 15° C and zero pressure. Using this method, the sensors can be calibrated to produce accurate salinity readings at any saline concentration. Fig. 13 shows the prototype testbed in our laboratory.

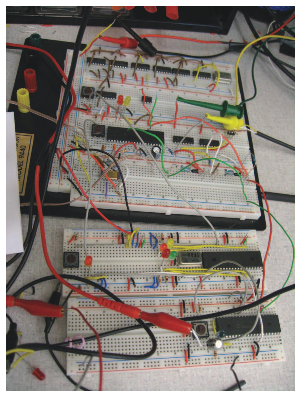

FIGURE 13. Salinity sensor testbed.

5. **Future work.** Our future plans are to deploy sensors in the Willapa Bay estuary, collect data, and use the LabVIEW mapping program to compare with known data collected using a commercially available sensor. This will also give us the variability in temperature.

We are also considering adding RF communications and GPS to our sensor. RF communications may be implemented to address two considerations that affect the devices data collection speed and physical integrity. The first consideration would be to transmit salinity data from the device directly to the user, allowing for easy device number identification, quicker data collection and status reports. The second consideration, to simplify of the apparatus, will increase its lifespan, as the number of avenues for water leakage is reduced.

6. **Conclusions.** We have reported on a new low-cost, data-logging salinity sensor system. This system consists of a salinity sensor and a GUI mapping tool. The salinity sensor is unique due to its simplicity, low cost and ease of use. The goal price range for the commercial version of the sensor is less than 100 USD (cost based on electronics only). The sensor has many applications in hydrology, marine ecology and aquaculture. The driving motivation for the development of such a sensor was the biology research field, where current sensor technology is financially out of reach for many researchers. The user-friendly graphical user interface (GUI) using LabVIEW will allow users to easily download and analyze data from multiple sensors, vastly improving current analysis practices.

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