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SALAMANDER: A Distributed Sensor System for Aquatic Environmental Measurements

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Abstract *– This report details a new distributed measurement system, "SALAMANDER," which stands for Serial Amphibious Linear Arrays of Micro And Nano Devices for Environmental Research. The SALAMANDER platform is designed for a wide range of users, from students to environmental researchers. Modular construction allows users to customize a high spatial density sensor array for fundamental and applied studies of sediment transport. We demonstrate integration of temperature, pressure, flow rate and optical turbidity sensors into a data collection system designed for a two-week battery life. Specifications are given for integrating new sensor types such as sample collectors and chemical sensors for determining the composition of sediment in this multi-year project.*

Keywords *– Distributed measurement systems, environmental sensors, wireless sensor networks, educational sensor systems*

I. INTRODUCTION

We describe a modular software and hardware platform called "SALAMANDER," for Serial Amphibious Linear Arrays of Micro And Nano Devices for Environmental Research. The SALAMANDER platform enables environmental researchers and students to assemble an array of aquatic sensors at high spatial density, for studies of water quality and sediment transport. Within this distributed system, flow rate sensors are coupled with sensors that can identify sediment density and ambient conditions over a stream cross-section, to produce a detailed spatiotemporal profile of sediment flux in watersheds. This effort will quantify the effects of local sediment mitigation projects [1], provide a new platform for monitoring water quality at the resolution of individual watersheds, and improve our ability to model and understand the origin and fate of sediment in the streams.

Because they are robust with respect to damage or disruption of individual devices, wireless sensor networks are ideal communication systems for this type of distributed sampling project. However, radio waves do not propagate far in water, moist soil, and similar conductive media. A local wired network can instead sample conditions in the medium and broadcast it out through an above-water wireless circuit, as in groundwater-sampling "javelins" or "pylons" [2,3]. We combine this general approach, shown in Fig. 1, with a modular sensor attachment system that lets end users customize the network to their own experiments.

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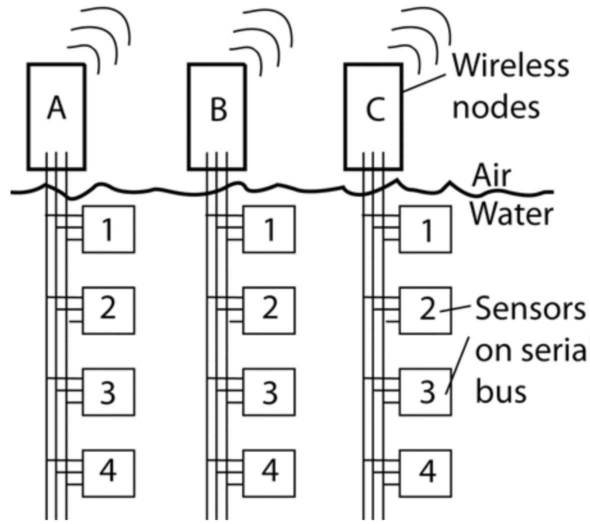

Figure 0: Set of wireless nodes with local wired networks of underwater sensors.

II. SYSTEM OVERVIEW

An individual SALAMANDER consists of an above-water wireless node and battery in a waterproof housing, connected to a vertical array of sockets for underwater sensor attachment. A group of SALAMANDERS is deployed along a streamline or over a cross-section of streambed. Each wireless node is programmed to poll every attached sensor in turn and send the data to a central computer via an 802.15.4 wireless link, with a range of approximately 300 feet. Each node broadcasts sensor data once per second, or at longer intervals to preserve battery life; a two-week or longer battery lifespan is desired in this application. These independent wireless nodes enable the rest of the network to continue collecting data if some SALAMANDERs become lost or disabled by waterborne debris.

The overall system is designed for simple assembly and data collection by users with a wide range of research experience. All sensor modules therefore use the same watertight connector (a ½-inch plastic pipe union) and the same serial interface (1-Wire serial bus). Sensor types and calibration coefficients are stored alongside sensor serial numbers on local EEPROM chips or on a central datalogging computer. An important project objective is to have environmental researchers customize sensor arrays for their own experiments without needing to modify sensor housings or software.

A second user group consists of researchers who produce new types of sensors, for instance resistive sensors that respond to water headspace vapors adsorbing onto nanomaterials [4]. These groups can incorporate new sensor types into the network by providing a 0-5 V analog output, a set of calibration coefficients, and electrical contacts to power the sensor on and off.

Because high spatial density sampling is a prime goal of the SALAMANDER project, small size and low cost ($20) sensor designs are emphasized. Initial sensor types include pressure, temperature, optical turbidity and flow rate, followed by automated sample archivers and online chemical analyzers.

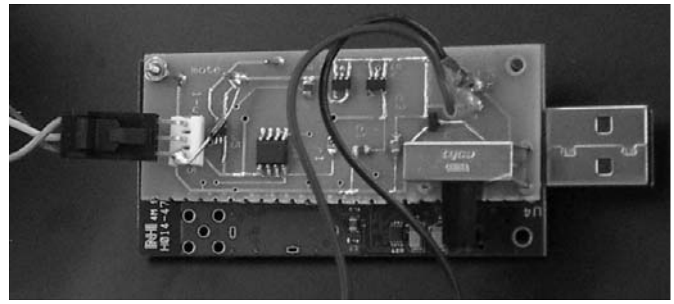

Figure 0: Power conversion board enables Tmote Sky module to interface with 1-Wire sensors. Three wires at left carry 5V, data, and ground to the sensor chain; wires at right go to a 6V battery pack.

III. RESULTS

For the wireless nodes, Moteiv Tmote Sky modules were chosen because of their low power consumption and the wide availability of open-source code within the TinyOS community [5]. The motes' onboard Texas Instruments MSP430 microcontrollers were programmed to communicate with DS2450 Quad Analog-to-Digital converters (Maxim Integrated Products) using a single GPIO pin via the 1-Wire protocol. The DS2450 chips form an interface between all analog sensors and the digital data line, except for temperature sensors, which are available with a built-in 1-Wire communication interface (DS1820 family, Maxim Integrated Products). Because the Tmote modules operate on 3V while the sensors and A/D chips typically require 5V for power and digital signals, a custom power conversion board was built for the Tmote modules (Fig. 2). Onboard low-power 3V and 5V regulators produce the necessary DC voltages from 4 AA batteries, while a bidirectional level translator (MAX3371, Maxim Integrated Products) connects the 3V data signal at the Tmote's GPIO pin to the 5V sensor communication line.

The power boards also include a power switch, reverse battery protection circuitry, wire connectors for the three outputs to the sensor line (data, 5VDC and ground) and a battery monitor (DS2438, Maxim Integrated Products). Modules can be programmed via a USB port with or without the power conversion board attached and powered up.

For data collection over the 802.15.4 radio link, a single Tmote can be connected to a laptop or desktop PC. However, because a system with longer battery life is required for fieldwork, the data collection software was compiled for the ARM processor and installed on a small, low-power (0.25 W) single-board computer (TS-7260, Technologic Systems). One Tmote attaches to the single-board computer's USB port and collects data from the other motes. A 12V, 18 A-h rechargeable sealed lead acid battery contains enough capacity to run the data collection system for over two weeks.

Software on each node cycles through a list of sensor serial numbers at 1 Hz, using the "Match ROM" method to address each individual sensor in turn. While we programmed in the serial numbers for each node, it is also possible to discover unknown sensors by implementing the "SearchROM" algorithm [6]. Three wires (power, data and ground) are used to interface up to 12 sensors, with an upper limit of nearly 100 sensors [7]. Spare A/D inputs on the DS2450 chips are programmed as switches to turn sensors on only while sampling, an important consideration for power saving in resistive and optical sensors that draw current during a measurement. The data stream arrives in the following format, which shows successive readings from DS2450-based sensors on three different nodes:

```
0C 01 08 93 FF FF FF FF 82 7D 07 00 20 01 D4 09 00 00 00 0A 20 50
0C 01 08 69 FF FF FF FF 82 7D 08 00 20 39 D3 09 00 00 00 17 2A 40
0C 01 08 26 FF FF FF FF 82 7D 09 00 20 1F CD 09 00 00 00 CD 1B 90
Packet info: header, length   Node ID   Sensor serial number   Data
```

Besides sensor data, the packet indicates the node number and the sensor type, for interpretation of the received data. Four sensor types plus a battery monitor signal appear in the data stream. Currently, a lookup table on the data-collection PC stores all serial numbers alongside sensor type and individual sensor calibration coefficients for correct interpretation of the data.

Fig. 3 shows a SALAMANDER with six attached sensors of four different types.

Temperature sensors (DS1820) are indicated by family code 28, while all other sensors interface through the DS2450 (family code 20).

Flow sensors use the DS2450 to read an analog signal from a voltage divider constructed with a flexible resistive BendSensor (Flexpoint, Inc). Fig. 3 shows a close-up image of a flow sensor. The bend sensor resistance and the output voltage increase when the flexible element is deflected by the flow, as measured in Fig. 4; for this style of sensor, the undeflected resistance was approximately 5 kΩ and maximum deflected resistance was 15 kΩ. Calibration experiments in a test flume or trough provide a set of three coefficients for each flow sensor, enabling the user to track linear flow velocity in meters per second based on the sensor voltage. When combined with chemical sensors and optical sediment density detectors, these flow velocity sensors enable

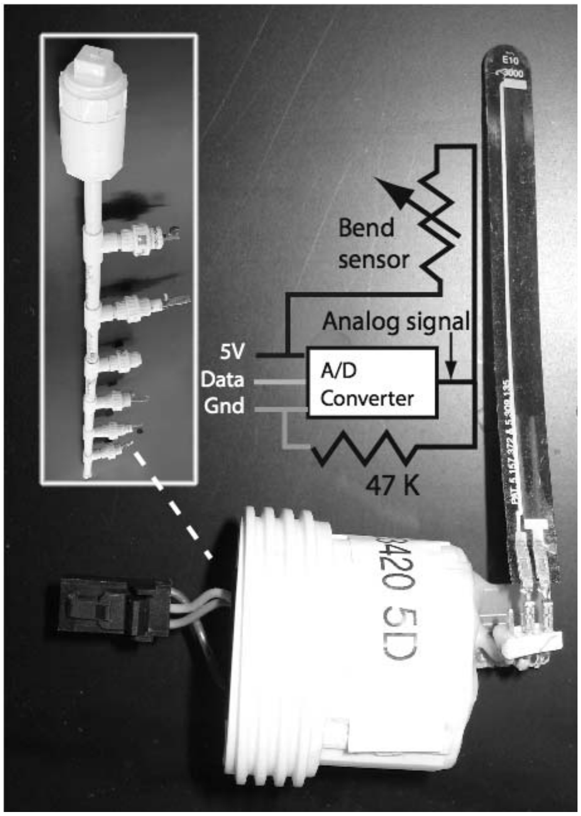

Figure 3: Inset: SALAMANDER with turbidity, pressure, temperature, and flow sensors (flow sensor shown enlarged with schematic of DS2450 A/D interface). Tmote Sky radio node and 4AA battery pack fit in top capsule. All sensors attach via ½-inch PVC pipe unions.

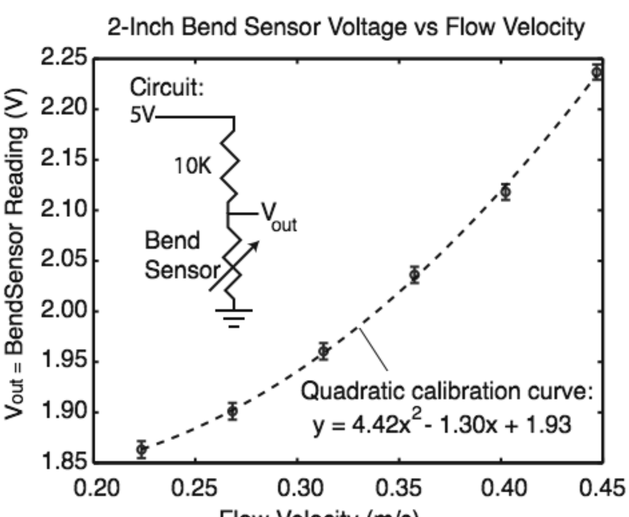

Figure 4: Measured voltage and resulting calibration curve for a water flow rate sensor based on the 2-inch long polyester-coated BendSensor. Flow velocity is determined from the voltage data by inverting the calibration curve, using the processor on the Tmote Sky or on the data collection computer.

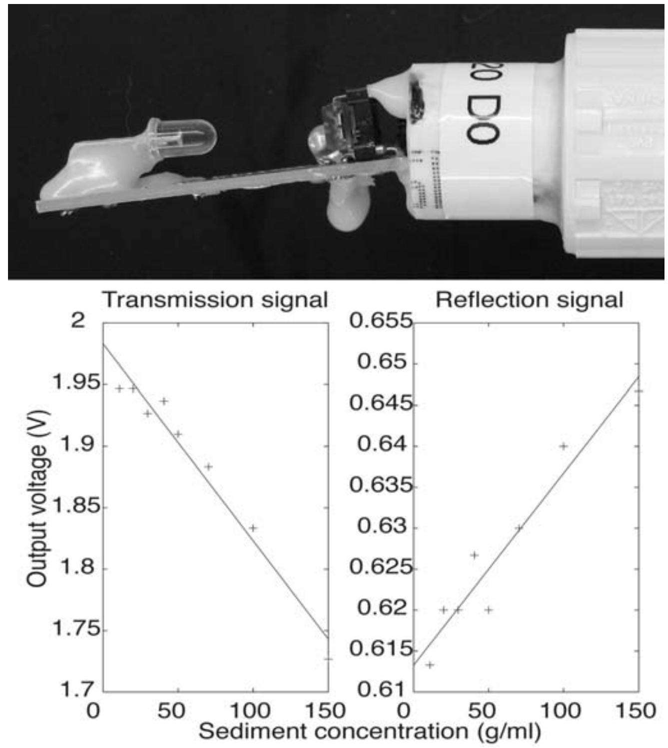

Figure 5: Low-power turbidity sensor uses red LEDs and an optical sensor to measure reflection and transmission through 1 to 3 cm of water. The sensor components are waterproofed by a vapor-deposited parylene coating.

researchers to map out the flux of dissolved chemicals and solids over a cross-section of streambed.

Pressure sensors based on the MPX5700A MEMS silicon-membrane sensor (Motorola) were installed on small boards with a temperature sensor. They produced a linearly-scaled analog voltage output (5V at 100 psi) which was interfaced to a DS2450. Waterproofing the entire pressure sensor with a 10-micron conformal parylene coating was not observed to significantly change the pressure reading. Underwater pressure readings indicate the stream depth, which can fluctuate dramatically during rainstorms.

Turbidity sensors (Fig. 5) were built around the OPT-101 light sensor (Burr-Brown) which produces a linearly-scaled 0-5V output vs light intensity [8]. For conditions of varying light intensity, the OPT-101's gain is scalable by adjusting an external RC network which can be constructed from fixed-value components or, for adapting to a variety of conditions, from digitally-adjusted potentiometers. The DS2450 1-Wire analog-to-digital chip was used to read the output and to independently control power to the OPT-101 and two LEDs at short distances from the front and side of the light sensor. This technique saves power and provides a means to subtract the ambient light signal with both LEDs off. Fig. 6 is a schematic illustrating how the four analog-to-digital inputs of the DS2450 are used in output mode (for powering the sensor and LEDs) and input mode (for collecting the analog voltage signal from the photosensor.)

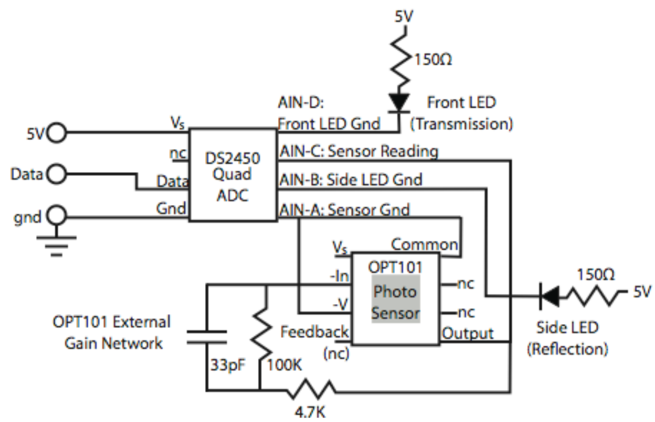

Figure 6: Circuit schematic for optical turbidity sensor based on OPT-101 photosensor and DS2450 analog-to-digital converter.

Calibration in sediment solutions of known concentration showed a linear relationship between density and light intensity, with intensity falling for transmission through solutions of increasing density (front LED in line with the sensor) and rising for reflection from particles in solution (side LED at 90 degrees to the sensor).

Fouling compensation: During warm months, the turbidity sensors' LED and detector surfaces can become fouled with algae before the two-week battery lifetime is finished. Even though light still reaches the sensor, it is attenuated by the coating and its intensity no longer provides a direct measurement of turbidity in the stream. Some commercial systems use a mechanical wiper to alleviate this problem. However, motorized wipers are expensive and consume excessive battery power for our application, especially in high-density installations where numerous turbidity sensors are attached to one battery pack.

A passive, low-power approach involving two LEDs at different distances can compensate for fouling that occurs between service visits. In this method, two LEDs are placed at different distances from the OPT101 sensor. The coating on each LED and sensor surface attenuates some fraction *f* of the transmitted light, which is assumed the same for each of the two LEDs due to similar algae growth conditions. The total attenuation of light through the bulk of the water depends exponentially upon distance *z* of the light source from the sensor, as well as the fouling attenuation fraction *f*, producing an intensity measurement at the sensor as follows:

$$I_{sensor} = I_0 f e^{-\alpha z} \quad (1)$$

In equation (1), I_0 is the original intensity at the light source, and α is the attenuation constant of the sediment-laden solution, which contains all the available information about the sediment density. If two LEDs are placed at the same viewing angle, but at different distances z_1 and z_2 from the sensor, it is possible to cancel out the fouling fraction *f*, and determine α by taking the ratio of two intensity measurements I_1 and I_2 collected by activating each of the two LEDs in turn:

$$\alpha = \frac{ln(\frac{I_1}{I_2})}{z_2 - z_1} \quad (2)$$

Using this method with a second sensor as well as two light sources further increases the system's ability to produce reliable turbidity data, since the additional sensor can detect the case of non-uniform fouling (for instance, when floating debris has completely blocked one of the LEDs). In this case, the turbidity data can be flagged as unreliable until the next service visit.

While these optical turbidity measurements do not detect the chemical composition of sediment, a sudden change in turbidity provides a useful triggering event for automated sample collection in solenoid-actuated traps, or trace metal sample archiving by plating dissolved metal ions onto an electrode. Under such conditions, the sediment density is increased, enabling a usable sample to be concentrated in a shorter time, and the samples themselves are highly likely to be correlated with a notable event such as a storm or chemical spill.

Rapid increases in turbidity are also valuable as triggers for efficiently scheduling online chemical sensors [9]. These and other sensors may require lengthy preconcentration times or more power than the turbidity sensors, making such a hybrid sensor approach very practical in this battery-powered system.

Figure 7: Clockwise from top left, leak checking a SALAMANDER in the laboratory; SALAMANDERS installed outdoors in protective cages with wireless nodes above water; determining individual serial numbers of attached sensors for programming a Tmote Sky wireless node.

IV. SETUP AND DATA COLLECTION

To set up a SALAMANDER under the current system, users select a batch of sensors and enter the serial numbers as constants into microcontroller software, along with a lookup table that associates each sensor with its type (temperature, pressure, turbidity or flow). The DS2450 and other 1-Wire chips' unique serial numbers are readily accessed using the free 1-Wire Viewer utility (Maxim Integrated Products). After serial numbers are loaded, the microcontroller software is then compiled for the MSP430 processor using a PC and downloaded to the Tmote Sky node via USB. At this point, the node is disconnected from the computer and provided with a battery pack.

Sensors are attached to the device in any order, and the system is leak-checked in the laboratory (Fig. 7). In a typical stream installation, where storms may wash objects into the water, the SALAMANDERs are protected from branches and other waterborne debris by wire cages (also shown in Fig. 7).

The programmed nodes are self-sufficient, cyclically polling each of their sensors at approximately 1 sensor per second and broadcasting the data back to the PC or single board computer, which collects data from the sensor nodes using another Tmote Sky module running a data-gathering program. While the software is capable of routing a message across multiple nodes, the internode distances in the high spatial density stream-monitoring application are generally only a few meters, so each node is within range to broadcast its information directly to the datalogger. The datalogger saves the incoming hexadecimal datastream into a file for subsequent analysis by a Perl script or MATLAB program, which connects the sensor serial numbers to a database of calibration coefficients stored on the host PC. The script pulls out a time series of data from each sensor for visualization as shown in Fig. 8, a plot of data from two SALAMANDERS installed in a local stream (shown in Fig. 7). Readings from turbidity sensors at two different depths, flow sensors at three different depths, a submerged temperature sensor, and a submerged pressure sensor, were collected onto the datalogging PC via the 802.15.4 wireless link.

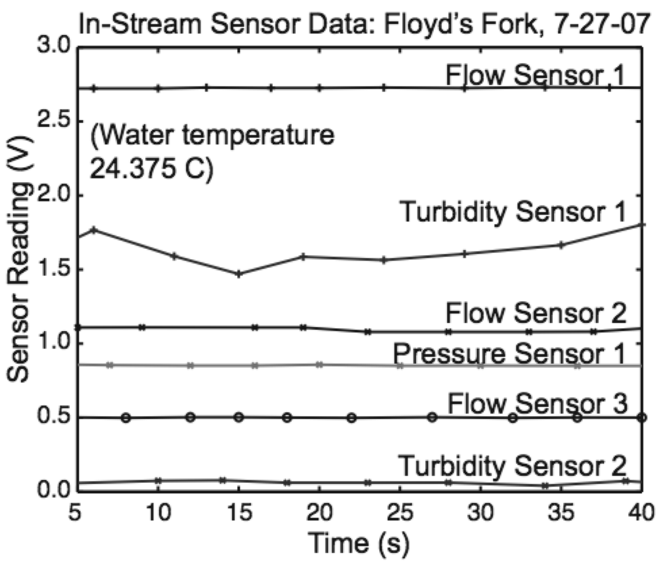

Figure 8: Time series of in-stream sensor data collected from four sensor types, at different depths, using two SALAMANDERS.

V. CONCLUSIONS AND FUTURE WORK

Results reported in this manuscript are from the first year of the project. During this period, we have constructed a modular system for aquatic environmental measurements which uses an inexpensive electrical and mechanical interface, along with open-source software. Future work on the system architecture focuses on improving the user interface and adding chemical sensors.

Because the current system requires users to compile code, automated sensor recognition based on the 1-Wire Search Algorithm, or assisted configuration through a menu-driven configuration utility, is highly desirable. For three-dimensional data mapping, users also must manually keep track of the spatial location of sensors installed at various depths on each SALAMANDER, because the addressing algorithm provides no information about their physical sequence. We have recently developed a method to automatically detect spatial position along a sensor array [10] which is compatible with the processing resources available on these wireless nodes. Other improvements to the user interface include storing calibration information in onboard sensor memory, so that users will be able to purchase a sensor, install it and immediately receive calibrated, position-mapped data from the environment.

New sensor types to be developed for the system include automated sample archivers and resistive chemical sensors. The SALAMANDER system described here is expandable to both chemical sensors which collect trace metals dissolved in the water, and those which collect and analyze its headspace vapors through a vapor-permeable membrane.

These developments in usability, combined with incorporation of new sensor types, are directed at an easily reconfigurable system for mapping the nature and quantity of sediments transported in watersheds.

ACKNOWLEDGMENTS

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