Wireless sensor network for calibration and deployment of low-cost fluid flow-rate sensors

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Abstract—**This report focuses on low-cost networked fluid flow rate sensors for use in environmental studies and other applications requiring automated fluid flow rate measurements with high spatial density. The sensors are based on deflection of a flexible printed resistive element immersed in the stream. A wireless network is used for mass calibration of multiple sensors in a test flume. After individual sensor calibrations are obtained, the same wireless network can be used to collect flow rate data in the sensor application. A modular connection system enables the user to quickly reconfigure the system's physical layout for calibration or deployment purposes.**

Keywords-calibration, distributed measurement systems, environmental sensors, wireless sensor networks

I. INTRODUCTION

Fluid flow rate sensors are needed for monitoring stream flows in fundamental studies of erosion (the research area targeted by the sensors in this report), and in more applied areas such as closed-loop control in chemical processing. Because these sensors are generally deployed in harsh environments, a low-cost rugged transducer is desirable. An inexpensive flexible printed resistive element can work as a flow sensor, but individual calibration is needed to match the sensor's output voltage to a particular flow speed in meters per second.

This report describes the construction of flow sensor circuits based on deflection of a flexible resistive element, the Flexpoint "Bend Sensor." The performance of these flow sensors is compared to that of a Sontek acoustic Doppler velocity sensor. A wireless sensor network is used for simultaneous calibration of multiple sensors in a test flume, producing individual calibration coefficients for storage in a database alongside the sensor's serial number. Finally, the sensor network is reconfigured for deployment and visualization of the flow rate data.

The flow sensor here is one element of a multiparameter sensing system for aquatic environmental measurements described in previous work [1]. This article provides more detail on the flow sensor and particularly, a mass calibration method that takes advantage of the built-in sensor serial number and wireless network interface.

II. FLOW SENSOR SPECIFICATIONS

In this application, expected flow speeds range up to a few meters/s during storms, with typical flows at ~0.5 m/s or less. The flow is turbulent, with Reynolds numbers in the range of 10,000 when the Bend Sensor's 2-inch length is used as the characteristic length. A flow-rate uncertainty of 1.5 cm/s (~3% of the flow rate) is acceptable, and a measurement rate of 1 sample per minute is adequate. The sensors need to be low-cost ($20 US) so they can be installed densely—in some cases, 20 cm apart to monitor the flow over a cross-section of a small stream near the origin of a watershed.

The devices will stay in the stream for approximately 3 weeks between maintenance visits, and their readings will complement periodical point measurements from a higher-resolution ADV sensor. The temperature ranges from -20 C to 40C, and they are typically under at most 3 m of water (hydrostatic pressure ~ 30 kPa). Because power is supplied to multiple sensors by a 4-AA battery pack, the sensors need to consume on average <1 mW of power for the supply to last the entire 3 weeks. This is largely achieved by turning the sensors off between measurements. Finally, sensors need to be protected from debris and insensitive to fouling by algae.

Besides the environmental and cost requirements, the specifications include some usability requirements. The long-term goal is a system that can be installed by users without a measurement or engineering background (for instance, K-12 students), yet can upload reliable data for global environmental studies. It should be possible to deploy the system with minimal programming, hardware modification, and record-keeping, and the resulting data should be stored in a standard format compatible with online databases. Therefore, we include error-checking methods, timestamping, and automatic recognition of individual sensor spatial location

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and orientation in the specification list and discuss methods for accomplishing these aims.

III. Flow Sensor Circuit

There are numerous established flow sensing methods including acoustic Doppler velocimetry (ADV) and rate-counting of a propeller immersed in the flow. ADV provides high-quality, high speed (50 Hz) data, but is relatively expensive. Propellers are a low-cost alternative but are subject to fouling by algae, which could slow or stop their rotation. A bendable element is expected to be less sensitive to fouling. The flow sensor in this report consists of a voltage divider with a fixed (10 K) resistor and a variable resistor (the Bend Sensor) with a resistance that increases from ~4K to ~20K when deflected from a straight configuration to a 90-degree bend configuration. We found that of the varieties of available BendSensors, the two-inch polyester-coated type had a good dynamic range over the typical flow speeds expected in the environmental sensor application. For basic performance testing, we used a wired data acquisition system to monitor the analog signal at the output of the voltage divider, while for mass calibration and deployment, the voltage divider was interfaced to a 16-bit A/D converter (DS2450) that also provides multidrop addressability over a 1-Wire interface, and assigns a unique serial number to each sensor. A complete flow sensor with waterproof housing is shown in Fig. 1 alongside its voltage divider circuit.

The unique serial number is important for calibration purposes. Application of a waterproof epoxy between the base of the flexible element and the electrical circuit produces slight differences in mechanical properties between each sensor assembly. Calibrating and assigning individual calibration coefficients to each sensor therefore becomes necessary, and the serial number provides a link between an individual sensor and its calibration data in a central database.

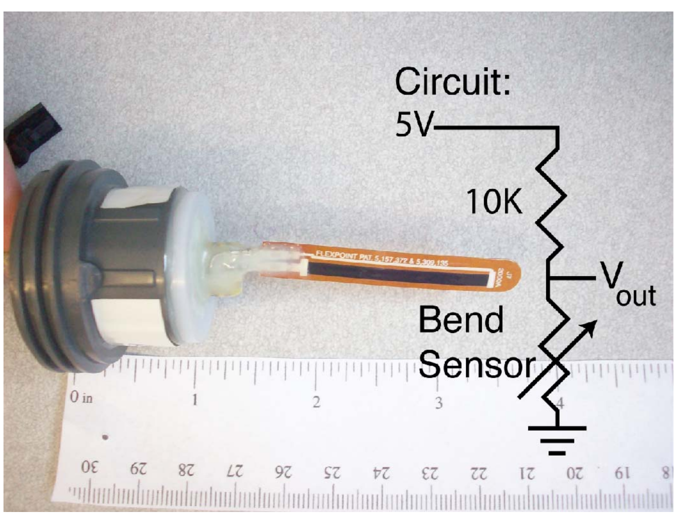

Fig. 1: A waterproofed Bend Sensor installed in a PVC pipe union and interfaced with a voltage divider and analog-to-digital converter chip.

IV. High Speed Analog Sensor Tests

To compare the flexible sensors with a standard flow velocity measurement, the sensors were installed in a test flume alongside the ADV sensor. The system used to generate fluid flow in these experiments was a 50-foot long, two-foot wide flume with a variable water flow rate controlled by a pump and valve. The flow sensors were attached to PVC pipes clamped to the top of the flume. The PVC pipes provided mechanical anchoring and also a sealed dry conduit for the voltage divider circuit and wires connecting the ground, signal, and power to the sensors.

For high-speed data acquisition (50 Hz) a LabView interface was used to sample the analog voltage output from three flexible flow sensors. The 50 Hz sampling rate is fast enough to capture ~0.1 second duration peaks and troughs that are observable by ADV. These features are attributed to turbulence in the flume, and their amplitude increases with flow speed. Fig. 2 shows sample data from both the ADV in Fig. 2(a), and from the three flexible sensors in Fig. 2(d), then compares the noise seen in the ADV sensor with a typical flexible sensor. Both sensor types have noise that drops off with frequency but is otherwise distributed evenly across the spectrum, without any notable peaks at frequencies up to half the 50 Hz sampling frequency. The noise spectrum is shown in Fig. 2(b) for the ADV and figure 2(e) for the flexible sensor. The noise is a combination of turbulent velocity fluctuations and random noise from sensor components such as resistors.

At a given steady flow rate, both the ADV and flexible sensors produce a constant output value with relatively large random fluctuations on either side. The amplitude of the fluctuations grows as the flow rate increases. Fig. 2 (c) shows the distribution of fluctuations above and below the mean value of the ADV signal for a large sample set collected at a flow rate of 60 cm/s. The fluctuations are tens of cm/s, but the distribution is symmetric, so the precision is greatly improved by averaging dozens or hundreds of successive measurements. Specifications for this type of sensor list a flow speed uncertainty of 0.5 cm/s.

A similar situation was observed for the velocity signal from the flexible sensors in the analog tests. Fig. 2 (f) shows a symmetric noise distribution for the flexible sensor at two flow rates, and also for static deflection where the sensor has been removed from the flume. The fluctuation amplitude is larger for the higher flow rate, and extremely narrow when the sensor is not experiencing turbulent flow. In the last case, the fluctuations were on the scale of the quantization levels of the 12-bit voltage signal ($5V/2^{12}$)=1.2 mV. Analyzing deviations from the mean is a simple process that can be carried out by the processor on a wireless node. A suddenly narrow set of deviations could indicate that a sensor is exposed above the water line during a drought. Even more interesting, if a flexible sensor becomes jammed into a static position by debris, or covered in sediment, it might still be bent and would indicate flow. However, the small deviations could indicate that the flow data should be disregarded.

During the flume tests, the average sensor voltage output increased with flow rate as expected due to increased resistance of the bend sensor as it experienced greater deflection. During

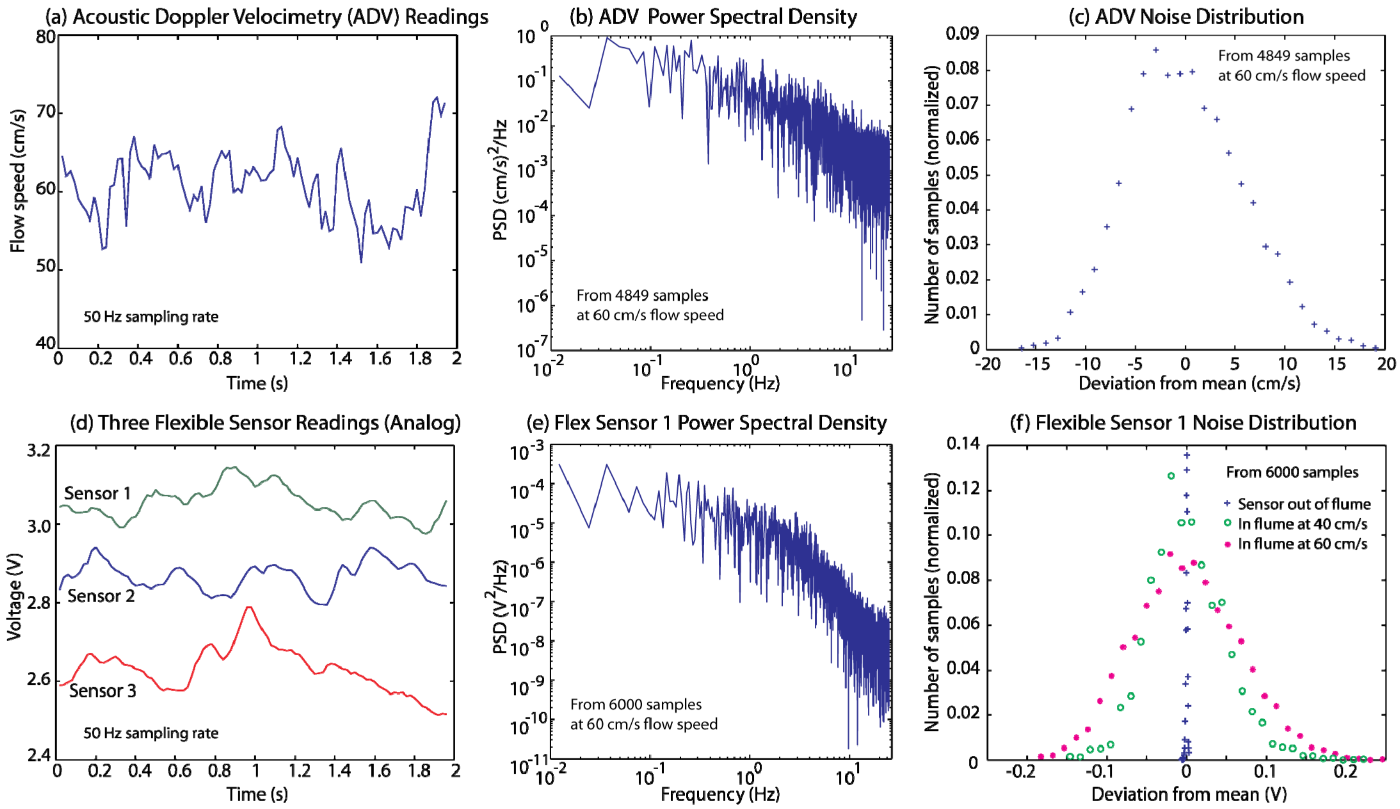

Fig. 2: Comparison of Acoustic Doppler Velocimeter and flexible flow sensors. (a)ADV time series, (b) ADV noise spectrum, (c) ADV fluctuation statistics, (d) time series for three flex sensors, (e) flex sensor noise spectrum, (f) flex sensor fluctuation statistics for two flow speeds and zero static deflection.

sensor deployment, the sensors will be switched on at intervals of 1 minute or even greater in order to conserve battery power in the field. It will be important to collect several samples during this sampling time so that the turbulent fluctuations can be averaged out. It is also important to consider the impact of the fluctuations upon sensor calibration. While battery conservation is less important during lab-based use of the wireless sensor network, meaning that it is possible to sample more often than once per minute, the maximum sampling rate of the combined wired/wireless network is approximately 3 Hz per sensor. This means the flume should be kept at a constant flow rate during collection of several minutes of voltage data from the batch of sensors during calibration. Analysis of the calibration results will enable an estimate of the minimum number of samples required to reach the specified 3% uncertainty at each flow speed.

V. Mass Calibration via Wireless Sensor Network

For calibration of multiple sensors, the sensors were each interfaced to an onboard A/D chip (the DS2450) which was connected to a wireless sensor node (Crossbow TelosB) programmed to communicate with the DS2450s using the 1-Wire protocol. Voltage data from two sensors on each of six wireless nodes was collected on a PC equipped with another TelosB node programmed as a receiver. In Fig. 3, the installed flow sensors and ADV sensor are visible at the base of the flume before filling.

Several PVC test stands were installed to anchor the sensors and protect circuitry and wires from the water. At the top of each PVC structure, the TelosB wireless node was housed in a plastic water-tight capsule with a 4-AA battery pack. Even when the dielectric capsule was sealed with a threaded lid, the signals could readily travel ~100 feet from the nodes' printed circuit antenna to the data collection computer.

Twelve sensors were calibrated simultaneously by setting the flume at each of nine volumetric flow rates for several minutes, and collecting a data file during that time. Each wireless sensor can address upwards of 100 sensors [2], so the calibration system can potentially handle many more sensors at once. With fewer sensors per node, however, each sensor is sampled more frequently for faster overall calibration.

VI. Collection and Visualization of Data From Wireless Sensor Network

The incoming sensor data were stored as text files with each data line listing the sensor's serial number, radio node number, and sensor voltage along with packet count and related radio packet information in hexadecimal format. Because individual nodes were switched on at different times, the data from different flow sensors appeared in a random sequence and had to be kept together with the serial number for individual calibration. A Perl script identified the voltage series associated with each sensor, and converted the bytes to decimal values in

Fig. 3: Multiple sensors connected to wireless nodes before filling the flume. Sensors are oriented perpendicular to the flow at the base of the flume. The acoustic Doppler velocimeter appears at right after the row of sensors.

a comma-delimited text format for data-fitting and visualization in software packages such as MATLAB or Excel. Each sensor reported its voltage 40 to 400 times for each flow rate, depending upon the length of the test, and these data were averaged to produce points for fitting. A small fraction (<1%) of the values were at the minimum or maximum ends of the voltage range (0V or 5V). These were attributed to faulty data packets and were discarded.

Fig. 4 shows this data for four different flexible sensors over a range of flow speeds from 0.3 m/s to 0.6 m/s. Flow speeds were calculated at the location of individual sensors by considering the total volumetric flow rate, the local cross-sectional area of the flow at that sensor's position along the flume, and the sensor's distance from the flume floor. The ADV data were used to calibrate the resulting linear flow speeds. Over this relatively small range, the sensor voltages increased from 1.5 to 3V. The sensor voltage follows a linear trend over this range. Over a larger range a higher order polynomial fit better captures the data, as the voltage divider output asymptotically approaches the maximum of 5V.

A linear fit to this data produced results with a consistent slope (approximately 7 Vs/m) but with different intercepts that

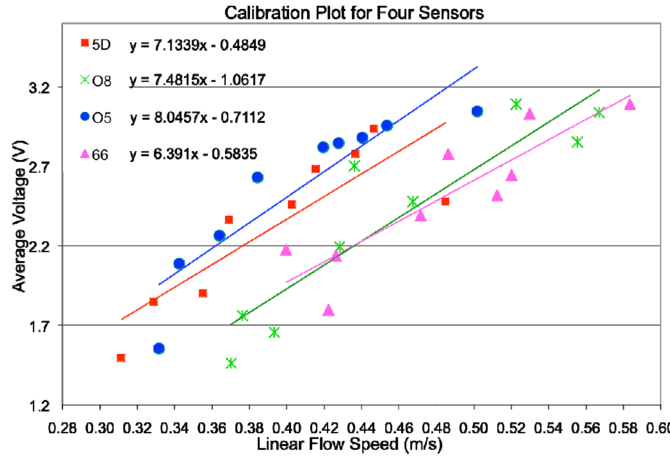

Fig. 4: Calibration plot for four different flexible sensors from flume tests. Calibration coefficients are obtained for each sensor by inverting the plots (speed-vs-voltage) and fitting the data.

depended upon the stiffness and initial electrical resistance of each BendSensor. Therefore, individual calibration coefficients were collected for each sensor.

A more detailed analysis was carried out to estimate the minimum number of voltage measurements needed for the flexible sensors to achieve a 3% uncertainty in the flow rate. The voltage-vs-flow speed relationship was inverted in MATLAB, then fit with a higher-order polynomial. Figure 5 shows this data and fit for Sensor 05, along with error bars designating the ADV's specified 0.5 cm/s uncertainty. The polynomial fit was then differentiated to calculate the effect of voltage uncertainty ΔV on flow speed uncertainty Δu:

$$\Delta u = \frac{\partial u}{\partial V} \Delta V \,. \tag{1}$$

For the voltage uncertainty, the standard deviation σ was computed from at least 40 voltage samples collected at each flow rate. For a quantity with random fluctuations like those in Fig. 2(f), the standard deviation of the average of N measurements is $\sigma / \sqrt{N}$:

$$\Delta u = \frac{\partial u}{\partial V} \frac{\sigma}{\sqrt{N}} . \tag{2}$$

Solving equation (2) for N, the maximum required values of N occur at the high end of the flow speed range. For 3% uncertainty at 0.5 m/s (Δu=1.5 cm/s), 30 or more samples need to be collected and averaged. This means at least a 10-second data acquisition time at 3 Hz. This is acceptable in the environmental sensor application where the flow pattern varies over a long time scale.

For other applications, however, a higher data rate is desirable at fast flow speeds. The number of required samples increases near the higher end of the flow rate range not only because the turbulent fluctuations (σ) are larger at higher speeds, but also because the slope (du/dV) of the flow-rate-vs-voltage curve in Fig. 5 steepens. This is where the bend sensor starts to reach its maximum deflection and the voltage divider its maximum voltage. A possible solution is a set of flexible

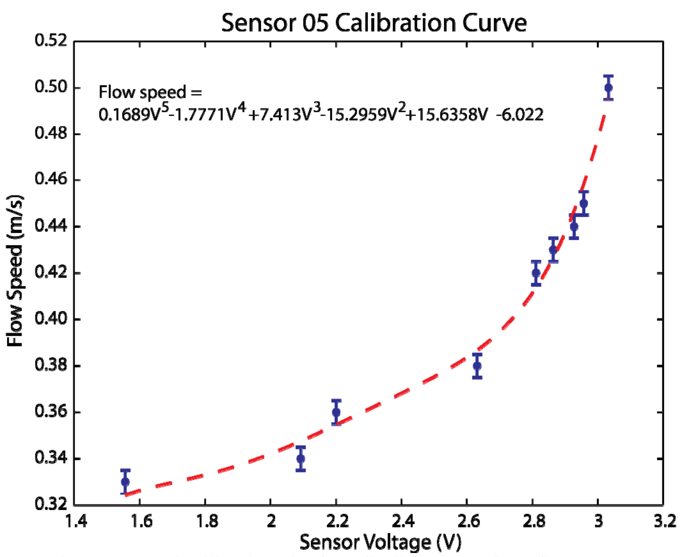

Fig. 5: Inverted calibration plot for a flexible sensor from flume tests. Calibration coefficients were obtained by a least-squares polynomial fit.

sensors having different mechanical properties and resistance values, so that for the flow rates of interest, at least one of the sensors is just in the beginning of its deflection curve.

VII. Conclusions And Future Work

Wireless sensors were chosen over wired sensors for their practical advantages in the field, but they also offered many unanticipated benefits for sensor development and calibration during this project. The wireless data acquisition system made setup and calibration run smoothly, especially for tests where it was desirable to move sensors around in the flume between tests (for instance, determining whether a sensor's position in the flume had a strong effect on the calibration results). The lack of signal and power wires reduced setup time and resulted in fewer errors due to disconnected or shorted wires, even compared to the relatively simple three-sensor LabView setup used for high-speed data collection. Because the sensor nodes were continually broadcasting data throughout the lab, two researchers were able to independently collect a calibration data series on individual laptops equipped with a TelosB receiver mote. This type of redundant data collection may be useful for noisy situations where dropped radio packets are expected, or in sensor laboratory classes where there is one system under test, but several students are interested in gathering and plotting data.

In an application where rapid flow rate swings are expected, it will be important to consider the relaxation and any hysteresis of the sensor. These sensors took some time (seconds to minutes) to fall back to their original resistance values after being removed from the flows. This is acceptable only if the flow history is known. The sampling rate must be matched to the experiment so that sudden flow changes do not go unobserved between samplings. Otherwise, a smaller sensor made of a stiffer material could be considered [3].

For data visualization, the end user needs a set of spatial coordinates, sensor orientations, and timestamps to go with the sensor data and the calibration coefficients. It is the project goal to automate the spatial data reporting as much as possible. The location problem breaks down into discovering the sensors' position in the plane, and locating each sensor's depth beneath the water. Wireless sensor network locationing is an active field of research, with popular trilateration methods based on time-of-flight of an acoustic signal vs a radio signal, or on the received signal strength of a radio signal from a beacon. However, radio-based methods do not work well under water due to signal attenuation. We take advantage of the existing wiring to find the linear sequence of the sensors on a cable underwater [4], while the above radio methods will work to locate the planar coordinates of the above-water radio nodes.

Sensor spatial orientation remains to be automated. In some cases (temperature, hydrostatic pressure) sensor orientation is relatively unimportant, but for the flow sensor it matters a great deal. A multi-axis flexible sensor might be able to determine its orientation based on the axis that experiences the most deflection.

The calibration setup shown in Fig. 3 was designed to put all sensors at equivalent locations with respect to their distance from the bottom and sides of the flume because these distances determine linear flow speed at the sensor's position. However, when using the sensors to carry out environmental research, one goal is to measure the total flux of sediment at a point along a stream. This requires sensors to be placed in a vertical grid over a cross-section of the streambed. The sensors were designed with a modular electrical and mechanical interface for easy adaptation to field sites having a wide variety of configurations. Work continues in the area of user configurability, because a major aim of the project is a multiparameter sensor system for education and environmental research that does not need extensive programming by engineers. In the next stage of the project, the wireless platform will be used to test micro and nanomaterial-based devices for chemical sensing [5-7].

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