An Open-Source IoT Remote Monitoring System for High-Hazard Dams.

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***Abstract*—The Internet of Things can be used to provide low-cost solutions to challenges in remote sensing. In South Carolina, high-hazard dams must be monitored manually during periods of heavy rainfall. In this work, an open-source Internet of Things remote monitoring system with integrated data filtering is presented and experimentally evaluated. The remote monitoring system measures water level using ultrasonic and pressure sensors and processes data using an ATmega2560-based microcontroller using cellular communication via the Message Queuing Telemetry Transport protocol. Field testing shows accurate data when compared to established gages and proves the viability of the sensor as a low-cost, long-term remote monitoring option for dams.**

***Index Terms*—IoT, water level, MQTT, filtering**

I. Introduction

Unexpected dam failure can result in the loss of both life and property [1]. During the period of October 1-5 in 2015, South Carolina experienced historical flooding that resulted in 19 fatalities, over 20,000 displaced citizens, and an estimated 2.2 billion USD total cost of the disaster [2]. The South Carolina Department of Natural Resources reports that 47 dams failed during this period, contributing to the damages [3]. Since 2015, the South Carolina Department of Health and Environmental Control (SC DHEC) Dams and Reservoirs Safety Program has expanded and performs routine dam inspections to prevent failure before a flooding event [4]. According to the program manager, engineers may be stationed for days at a time at high-hazard dams during periods of heavy rainfall to manually monitor water level.

The United States Geological Survey's (USGS) Rapid Deployment Gage (RDG) is meant to be installed during storm events to monitor at-risk areas in which there is no existing gage infrastructure [5]. Shown in figure 1 is an RDG from the USGS Columbia, SC office. A radar sensor is used to measure water level, which is recorded by the Sutron SatLink3 datalogger, and readings are transmitted via satellite up to every hour during a storm event. The major downside of the RDG is the price at approximately 13,000 USD per unit, as quoted by J. Shelton from the USGS Columbia office on May 12, 2022.

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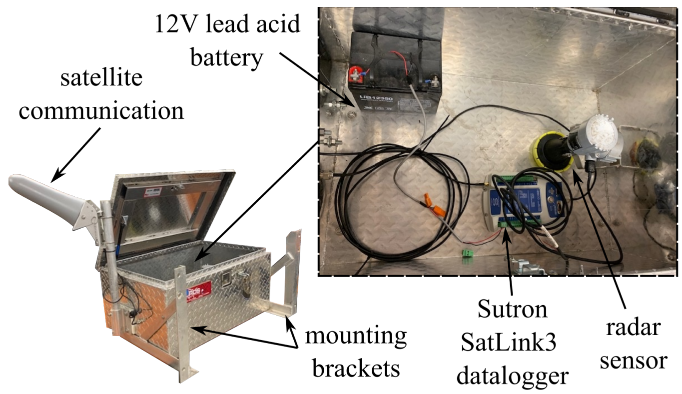

Fig. 1. USGS rapid deployment gage.

This paper presents an open-source Internet of Things (IoT) water level sensor with integrated data filtering for remote monitoring of dams. As remote monitoring solutions for dams are largely limited to permanent, costly systems [6], this work attempts to provide an economical and location-flexible alternative at less than 360 USD for dam owners and regulators that lack the funding for traditional systems. The impact of this work is increased gaging accessibility for state-run dam safety programs, which have historically been limited in monitoring capabilities. The authors hope that this experimentally-validated, open-source IoT system will increase the number of high-hazard dams being monitored, Hardware and software designs are available via a public repository [7].

II. Hardware Design

A. Overview

The water level sensor is built on the ATmega2560 microcontroller using the Arduino Mega development board. The development board is compatible with the Botletics SIM7000A LTE shield, an IoT cellular shield for real-time data monitoring and visualization. Custom printed circuit boards (PCBs) for datalogging and power control were designed to be integrated with the existing hardware. The datalogging PCB houses an MPRLS ambient pressure sensor, a JSN-SR04T ultrasonic sensor, a submersible pressure transducer, indicator LEDs, a DS3231 real-time clock, and a micro SD card module. The power control PCB uses an INA219 current sensor to monitor the voltage of the 12V battery. Figure 2 shows a block diagram of the hardware components.

A 10 Watt solar panel is used to extend the package's longevity. The solar panel is wired in parallel with the battery to both power the water level sensor and charge the battery when sufficient sunlight is available. The solar panel is the primary power source during the day until the fully-charged battery takes over at night. In one field test, the addition of the solar panel has allowed the package to be deployed for 15 days in a location with full sun.

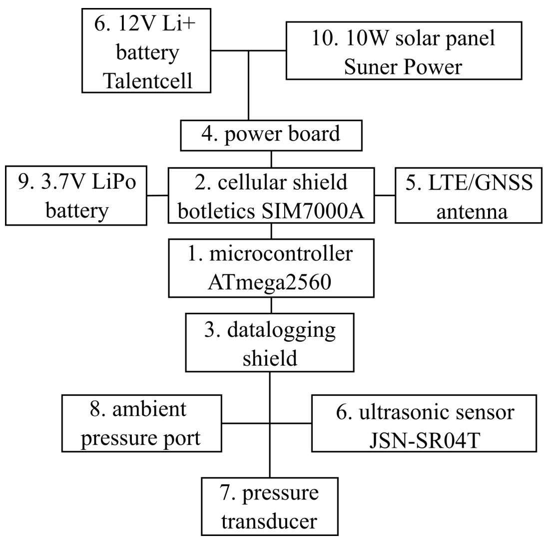

Fig. 2. Block diagram of the sensor package.

B. Sensing Technology

Water level is measured using two sensors: a contactless ultrasonic sensor and a submerged pressure transducer. The waterproof ultrasonic sensor is mounted over the water's surface and sends a burst of ultrasound that is reflected back up to the sensor. The time between transmission and reflection is converted into a distance measurement between the sensor and the surface of the water. The pressure transducer is submerged in the water body using a weight and measures the hydrostatic pressure of the water, which is converted to inches of water head above a known elevation. Two sensors are used in this system to validate each sensor's reading in case one sensor is not functioning properly.

C. Data Transmission

The botletics SIM7000A cellular LTE shield enables real-time monitoring using the LTE CAT-M1 standard via a Hologram Global IoT SIM card. LTE CAT-M1 is suitable for IoT projects with lower amounts of data transfer [8], and the Hologram SIM card is designed to switch between different carriers, allowing flexible deployment locations. The sensor uses the lightweight Message Queuing Telemetry Transport (MQTT) network protocol to publish and subscribe to messages between the sensor and Adafruit IO, which acts as the MQTT broker. Adafruit IO stores data in feeds that can be visualized in real-time with a graphic user interface (GUI) that utilizes interactive controls for subscribe functions and displays for publish functions. Figure 3 shows the sensor deployed in a field test transmitting data in real-time to the GUI. The sensor publishes data to the broker concerning battery voltage, power consumption, location, ambient pressure, internal package temperature, and stage measurements from both the ultrasonic and pressure sensors. The sensor subscribes to data from the broker concerning deployment status, sampling rate, GPS location queries, and initial elevation.

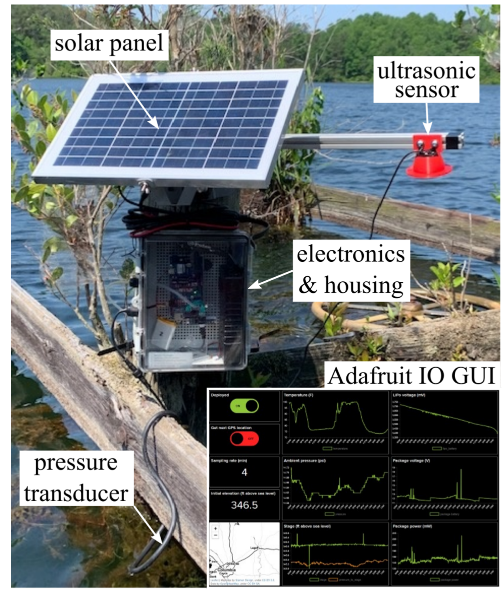

Fig. 3. Deployed remote monitoring system on the Sandhills REC Pond Dam's primary spillway showing the custom GUI visualizing data in real time-during a deployment on May 21-25, 2022.

D. Power Consumption

The system was designed to optimize power consumption during severe weather events through the addition of a 10 W solar panel and by entering into a low power sleep mode between sampling cycles. Power consumption and battery voltage are monitored remotely to ensure batteries can be changed promptly if necessary. Dams commonly provide many shade-free deployment locations that allow the 12 V battery to recharge during the day. In a field test conducted on Spring Lake Dam in Columbia, SC, the system battery lasted for the entire 15 day deployment without needing to be changed. On average, the battery voltage dropped 0.7 V overnight and would be fully charged in 4.5 hours of full sun. On very cloudy days, the system was able to partially charge, and the 6000 mAH capacity of the battery allowed the system to continue to function into the next day until sufficient sunlight permitted a full charge.

III. Software Design

A. Data Collection Process

During deployment, the sensor's sampling rate and elevation parameters are initialized using the GUI. The sensor will constantly be waiting for a subscription from the MQTT broker with each of these initial values until the deploy parameter is received as "ON". The data collection cycle begins after this, and each sensor is read and values are stored into character buffers. These character buffers are published to the broker via the cellular network, where they appear on the GUI. After all data have been published, the sensor package will go into a low power sleep mode for the specified sampling rate. If the broker sends a subscription packet during this period, the package will respond immediately, complete the data collection cycle, then return to sleep mode. Figure 4 outlines the data collection process and communication with the MQTT broker.

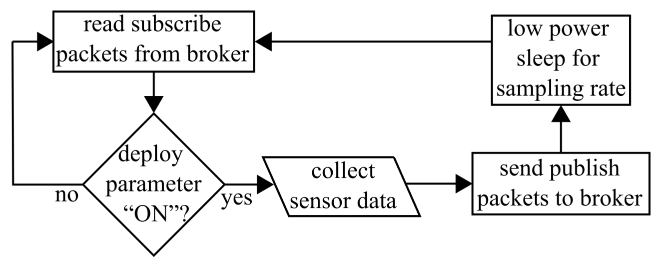

Fig. 4. Package data collection cycle with MQTT broker. Controls are subscribed to the sensor from the broker, and data is published from the sensor to the broker.

B. Filtering

Noise in the ultrasonic sensor has returned error readings of up to a 12 foot difference from the true signal in initial testing, indicating a false spike in water level. To address this, a median filter was integrated into the software to filter out these noisy readings before they are published to the broker. A median filter is applied if the next data point deviates from the previous data point stored in a sliding window array by more than a certain tolerance. If that tolerance is passed, then the data point is replaced with the median value of the data points stored in the array, making it ideal for large error spikes that typically only occur once or twice in a row.

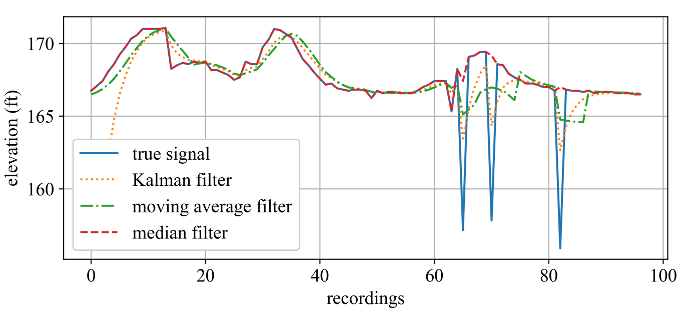

Fig. 5. Simulations of different filters applied to ultrasonic sensor data taken on April 5, 2022. Kalman, median, and moving average filters are compared.

Different filters were tested on noisy data to determine which filter was most suited to the application. The data were collected during a storm event on April 5, 2022, and simulations of that data collection with different filters are plotted in figure 5. After applying these filters to the noisy data, the median filter was chosen due to its suitability for reconstructing the true signal while filtering out the error readings. The filter has been integrated on-device during data collection.

IV. Testing and Results

To validate the sensor's ability to capture and transmit accurate water level data, the remote monitoring system was deployed at the Saluda Riverwalk next to a USGS gage in Columbia, South Carolina. Also deployed with the system was a HOBO self contained water level logger, a 1,330 USD commercial water monitoring solution [9]. The system was deployed for 21 hours and data are shown in figure 6.

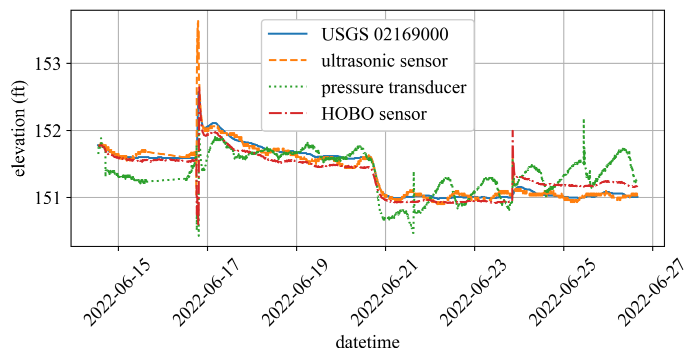

Fig. 6. Ultrasonic and pressure transducer elevation data plotted against UGSG gaging station 02169000 on April 21-22, 2022.

The plot shows that the sensor data can be transmitted consistently from the package to the Adafruit IO platform. The results are plotted with Python using data downloaded directly from the GUI rather than from any onboard storage. USGS data are retrieved from the USGS website, where all stream gage data are publicly available [10]. HOBO data are stored on-device and retrieved after the deployment. The data show relative agreement between all sensing methods, with the ultrasonic sensor data aligning closest to USGS data. The median filter effectively filters out any error spikes above a three foot tolerance. The pressure transducer experiences significant drift in the latter half of the testing period, even with ambient pressure accounted for in post-processing. This is likely due to the lower instrument quality of the sensor. The agreement of the ultrasonic and pressure sensors with the USGS gage, the consistent data transmission with the MQTT broker, and the median filter's ability to exclude any major error readings all indicate the sensor's viability for low-cost remote monitoring applications.

V. Conclusion

The water level sensor presented in this work offers a viable alternative to traditional gaging technology. IoT services like Adafruit IO and compatible hardware allow the sensor to be significantly more economical than alternatives like the USGS RDG, while still reliably transmitting accurate data during both severe and calm weather. The sensor's portability opens up new possible gaging locations, as well as quick and flexible deployments, which are not offered by most traditional gages. Future work will investigate the drift of the pressure sensor by employing filtering techniques and temperature compensation to improve the sensors' accuracy.

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