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Smart Pipe: Nanosensors for Monitoring Water Quantity and Quality in Public Water Systems

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Project Significance

A 2009 study by the American Society of Civil Engineers (ASCE) showed that 7 billion gallons of clean, treated drinking water disappears every day, mostly due to old, leaky pipes and mains. The amount is enough to serve the population of California in daily water usage. The approximate dollar cost, given varied water rates in different U.S. regions, is $20 to $100 million daily. Unfortunately, America's drinking water systems face an annual shortfall of at least $11 billion to replace aging facilities that are near the end of their useful lives and to comply with existing and future federal water regulations. Moreover, leaking systems have wasted not only dollars but also priceless natural and energy resources for future generations.

This research project was initiated to develop the concept of a sensor unit to improve water supply infrastructure via a highly advanced, cost-efficient monitoring system. A research group led by the Illinois State Water Survey, in collaboration with the Department of Mechanical Engineering at Northwestern University, has developed a "Smart Pipe" prototype: a multi-sensor unit to monitor water flow and quality using state-of-the-art nanotechnology. Each 2.5 by 2.5 millimeter base unit includes sensors for pressure and temperature flow velocity. The Smart Pipe is connected with a wireless processor and antenna to transfer monitoring data to a command center in real time.

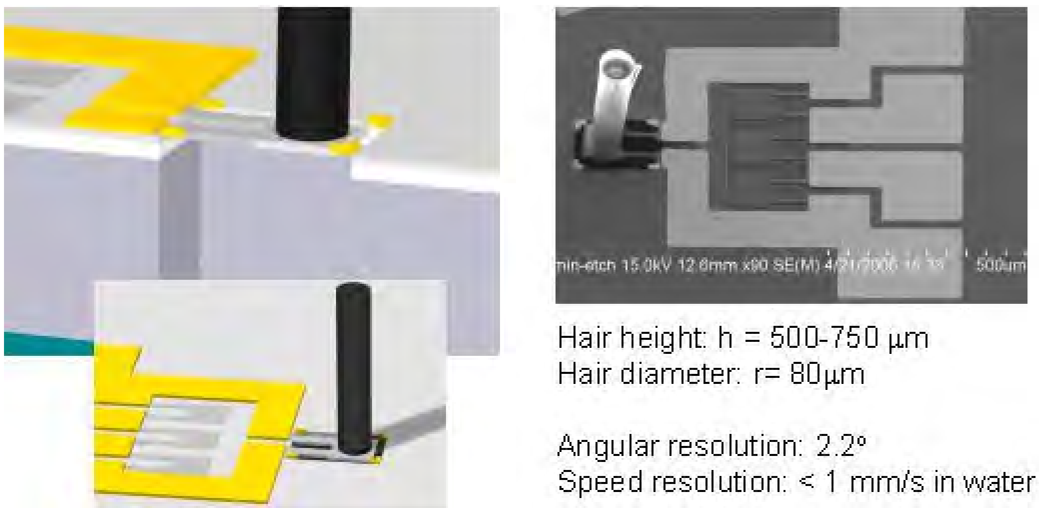
The Smart Pipe prototype has been designed as a module unit with an expandable monitoring capability for future available sensors. With several Smart Pipes installed in critical sections of a public water system, real-time monitoring will automatically detect flow rate, pipe pressure, stagnant points, slow-flow sections, pipe leakage, backflow, and water quality without altering flow conditions in the pipe. Moreover, applying this technology at an affordable cost will help small and/or rural public water systems with government water standards implementation, capacity development, and water systems operations.

Procedures

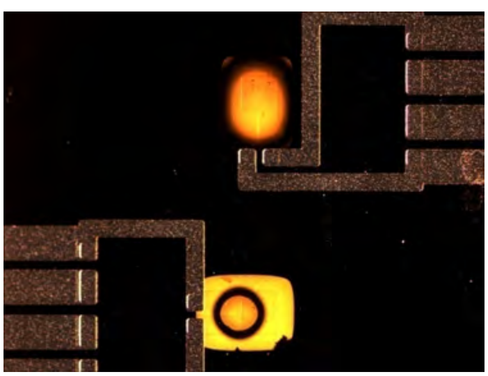
System development included hardware, software, and experiments. Each component was designed considering the feasibility of the manufacturing process, practical usage, and cost efficiency. Detailed specifications of the hardware and software are available upon request, or visit the project Web site at: http://www.isws.illinois.edu/gws/sensor/smartpipe/.

Hardware

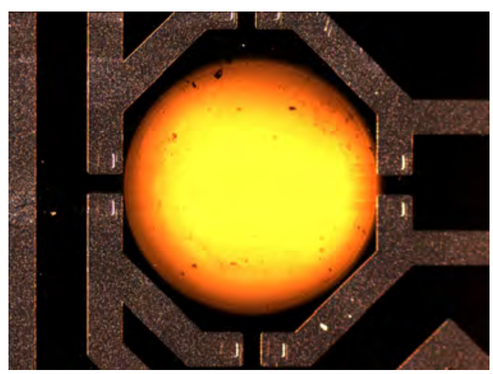
The two main hardware developments were 1) packaging individual sensors into one sensor unit, and 2) packaging the sensor unit with field material, which is a PVC pipe system used in real public water supply systems. An example of a design diagram and dimensions and photographs of an actual sensor unit taken by microscope are shown in Figure 1. The packaging process was very challenging, and involved determining the layout of the sensor position, the efficiency of the circuit design, and the optimum coating with field material. The sensor position was designed to decrease the distortion of the flow field, which will decrease the chance of false readings by individual sensors. The efficient circuit was designed to decrease the usage of power and the size of the sensor unit. The optimum coating of field material (inner wall of PVC pipe) was designed to increase the sensor durability and also provide an accurate reading without a damping effect from coating material. The latest generation of the sensor unit, G4, includes one pressure sensor, one temperature sensor, and two flow sensors (X direction and Y direction), as shown in Figure 1. The flow sensors were the most challenging aspect of the development and testing because of their complex design (Chang, 2007; Nannan et al., 2007).



(a) The design diagram and dimensions of the flow sensor (also available at: http://www.mech.northwestern.edu/medx/web/research/current/advsensors/2006-focus-intro/slide8.html)



(b) Photos of the temperature sensor (above) and the flow sensor (below) taken by microscope

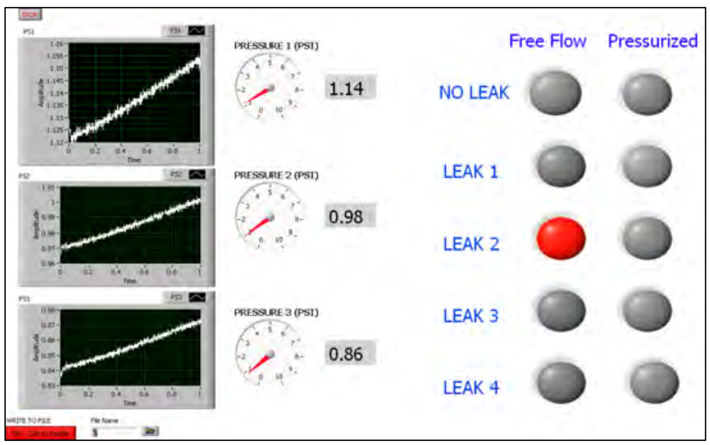


(c) Photo of the pressure sensor taken by microscope

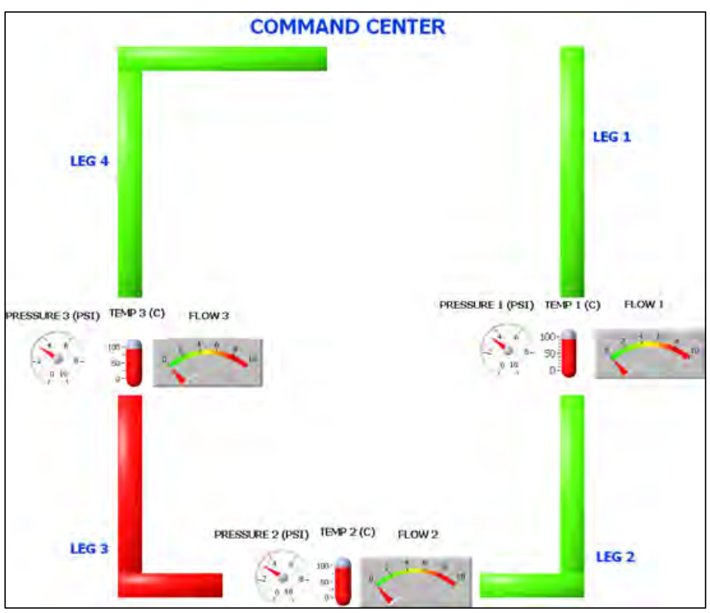
Figure 1. The latest generation of sensor unit, G4

Software

The two main software developments were 1) communication between the sensor unit and a PC, and 2) a command center console. Each sensor needed to translate the physical property that it measured (e.g., temperature, pressure, and velocity) to electrical voltage and current to start the data stream. The efficient circuit design in packaging was critical to reduce the noise that can interfere with the electrical properties. The Data Acquisition Boards (DAQ), commercially available interfaces between the signal and a PC, were applied to transform the electrical properties to a digital signal that can be recognized by the command center console on a PC. The customizable command center console was programmed using LABVIEW software, which is the emerging standard in visual programming-based instrumentation control systems. Figure 2 shows two different versions of the command center console.



(a) Command Center with panel layout



(b) Command Center with pipe layout

Figure 2. Two Command Center consoles with customized configurations programmed using LABVIEW

Experiment

Three major experiments were conducted: 1) a sensor unit strength test, 2) the proof of concept on leak detection algorithm, and 3) a live demonstration with field material. Figure 3 shows a test pipe with an earlier version of the sensor unit attached inside. Inner pipe pressure was increased by injecting water from the right end. Wires from the left end transferred the signal from the sensor unit to confirm its survival. The objective was to ensure that the sensor unit had the strength for normal performance under 100 pounds per square inch (psi), although the normal pressure for a public water supply system is approximately 55 psi.

The proof of concept on leak detection algorithm was conducted to confirm the hypothesis that pipe leaks can be detected by the algorithm that computes the fluctuation of the sensor reading due to leakage (Figures 4 and 5). The experiment used a commercial pressure sensor (Honeywell pressure sensors, part number 19C100PG5K) instead of the experimental nanosensor in order to confirm the feasibility of the algorithm. An increase in the differences between sensor readings indicated the occurrences and locations of the leaks as shown in Figure 6, although the magnitude of the increase of differences is small in this demonstration. The small magnitude is due to low resistance in a 2-inch PVC pipe for relatively low flow rates. The magnitude of the increase of pressure differences should be increased when the pipe diameter and length increased as a practical system. Moreover, the flow sensor, which was not included in this experiment, will provide more sensitive readings than using only a pressure sensor. Therefore, this experiment successfully confirmed the concept of the leak detection algorithm under the most difficult condition (small scale with a less sensitive sensor) in the laboratory. Based on the circuit design theory (Figure 7), an earlier version of simulation software for the algorithm of leak detection was developed using MS-EXCEL. The software is capable of simulating a network with various conditions such as pressure, flow rates, and leakage. It can be used to predict, analyze, and verify the measurements from a real system.

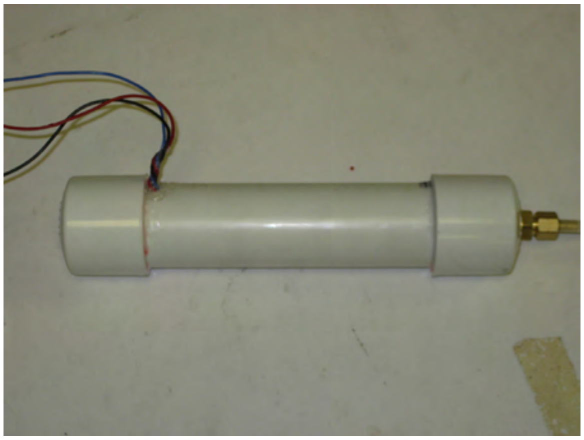


Figure 3. Test pipe for sensor unit strength (2" PVC)

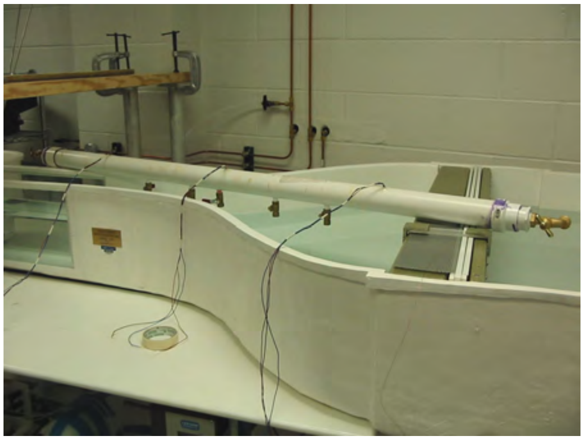


Figure 4. The test chamber for the proof of concept on leak detection algorithm

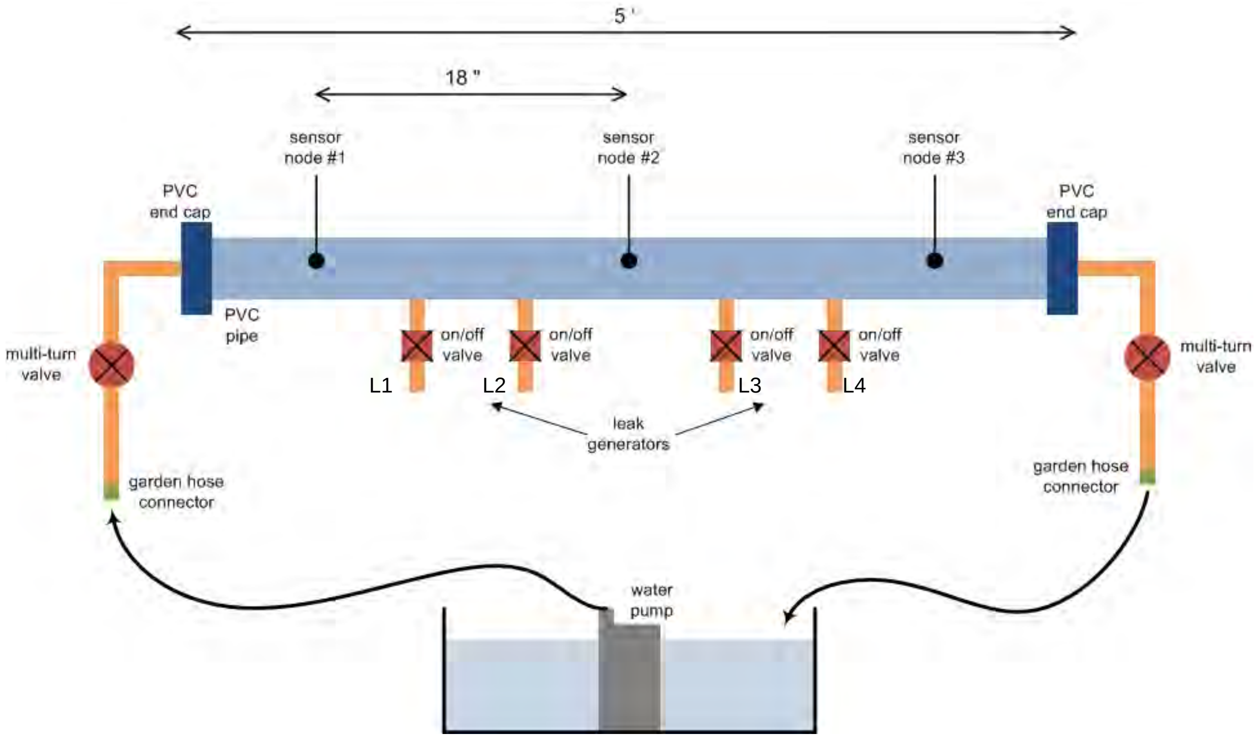


Figure 5. The design diagram of the experiment for leak detection algorithm

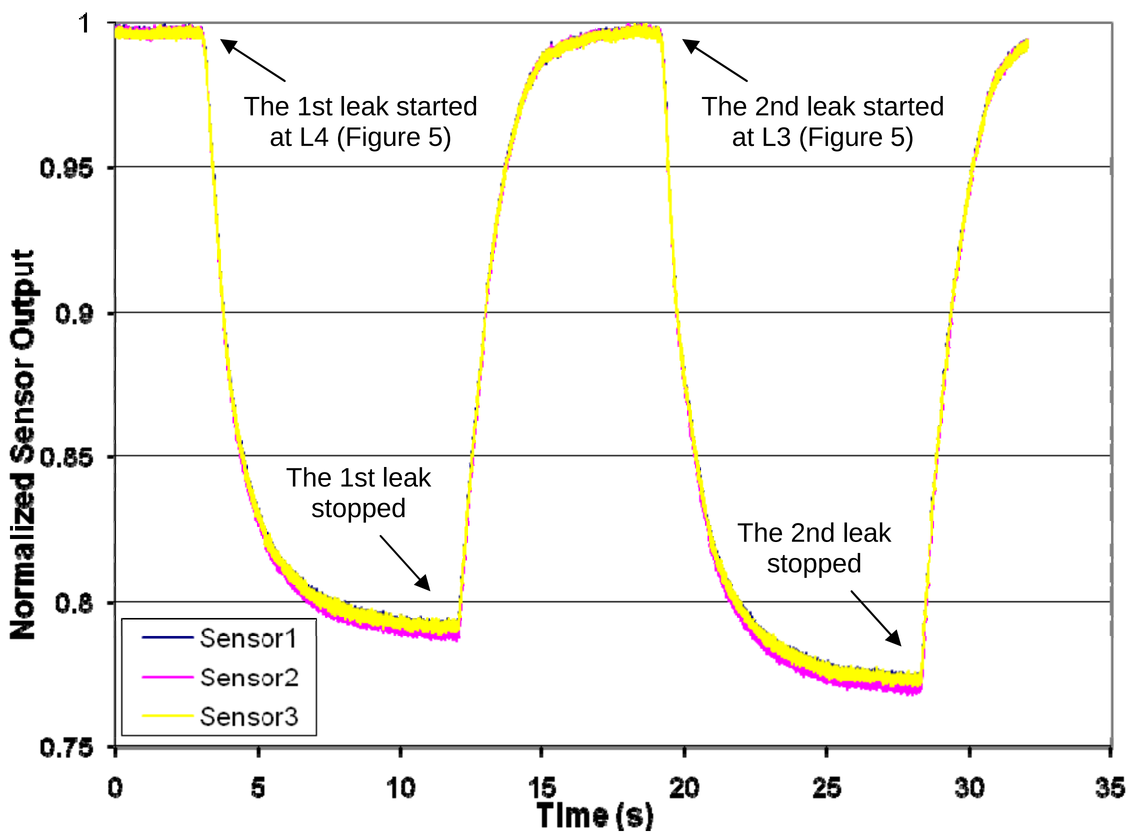


Figure 6. The 1st leak generated at leak point L4 (between sensors 2 and 3 in Figure 5), and the 2nd leak generated at leak point L3 (between sensors 2 and 3 in Figure 5)

The live demonstration with field material was conducted by embedding the sensor units inside several 2-inch PVC pipes, which were installed into a scaled-down water supply network. The video of this live demonstration is available at: http://www.youtube.com/watch?v=8xSlLCScIqw. Figure 8 shows the four controllable leaks, which were valves that could be opened or closed to simulate a leak, and the sensor units were spaced equidistant from each another. Based on the previous MS-EXCEL model, a new mathematical model was developed using MATLAB to compute the possible leak based on real-time measurements from sensors for each of the possible leak scenarios.

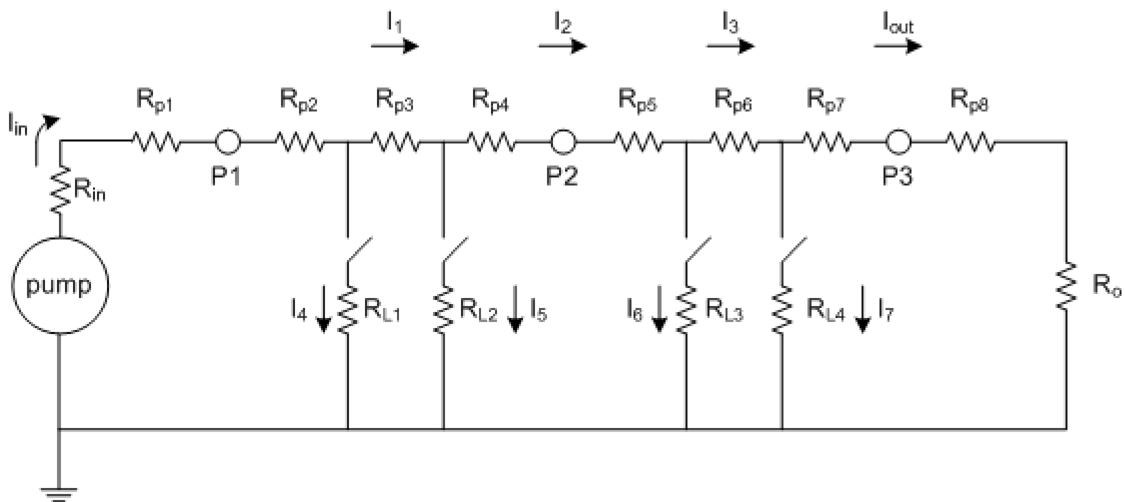


Figure 7. The design diagram of the leak detection algorithm corresponds to Figure 5. Nodes P simulate sensors with the same corresponding numbers in Figure 5. Four R_L simulate the leaking flow rates including on/off switches. Ten R_P simulate the pipe flow rates in different pipe segments. Nine I simulate the pipe pressure in different pipe segments.

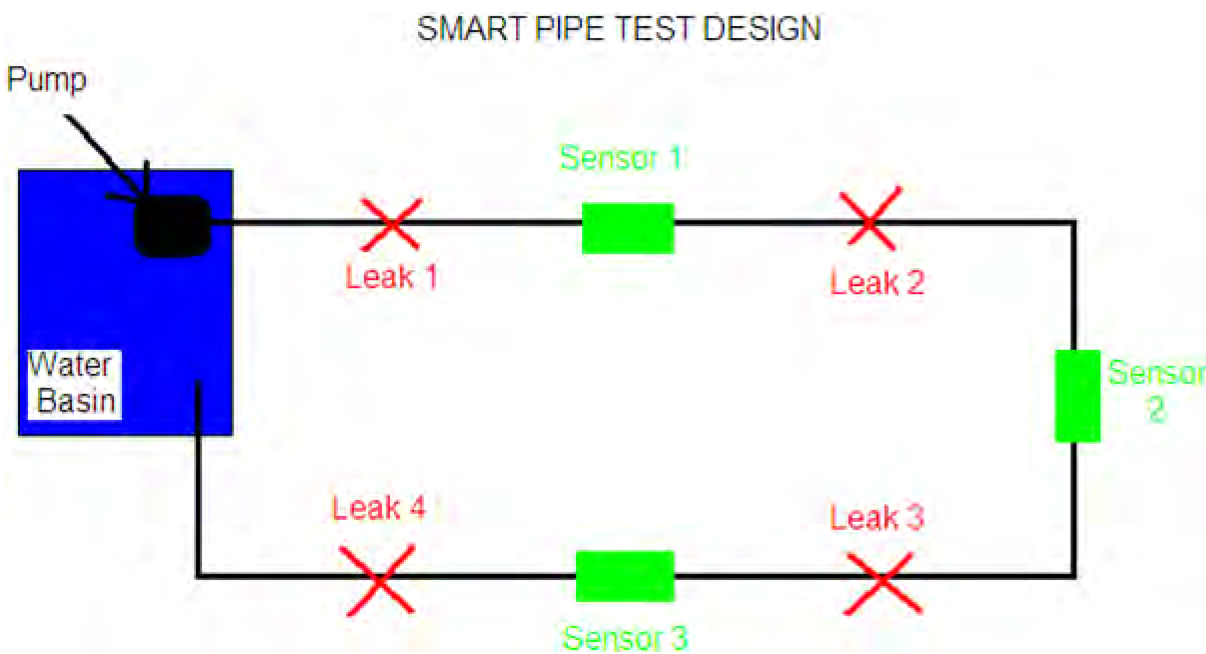


Figure 8. The design diagram of live demonstration with field material

Figures 9 shows one of the examples from this experiment (shown in Video file), which is the test data taken from the flow sensor placed in the Smart Pipe sensor. In Figure 9, the first 13 seconds of data represent free flow throughout the entire pipe system. The flow sensor outputs a relatively constant voltage representing the steady state system. At 13 seconds, the valve at the end of the pipe system is shut off, blocking the flow and allowing pressure to build up to 55 psi in the pipes. Although the pressure sensors are unable to detect the motion of the water, the flow sensor data clearly detect that the water has stopped flowing past the sensor after 13 seconds (zero flow is calibrated to -3 volts in this experiment).

In order to test leak detection, we retained the pressurized state and opened the leak at valve 2 (Figure 8) at approximately 40 seconds (Figure 9). A spike in the flow past sensor 1 (Figure 8) was immediately detected until the valve was shut off again after several seconds before it fell back down to zero flow. Since the end valve remained closed throughout the process, even with the valve at leak 2 opened, no flow was allowed to pass through sensors 2 or 3. Thus, the successful detection of flow past sensor 1 determined the existence of a leak between sensors 1 and 2.

The model results are displaced on the Command Center console, which is a Graphic User Interface (GUI) developed for data acquisition using LABVIEW software. As shown in Figure 2, there were two versions of the Command Center, and both were tested successfully for acquiring test data from a hard-wired system, continuously monitoring the sensor outputs, and notifying the user when and where a leak occurs.

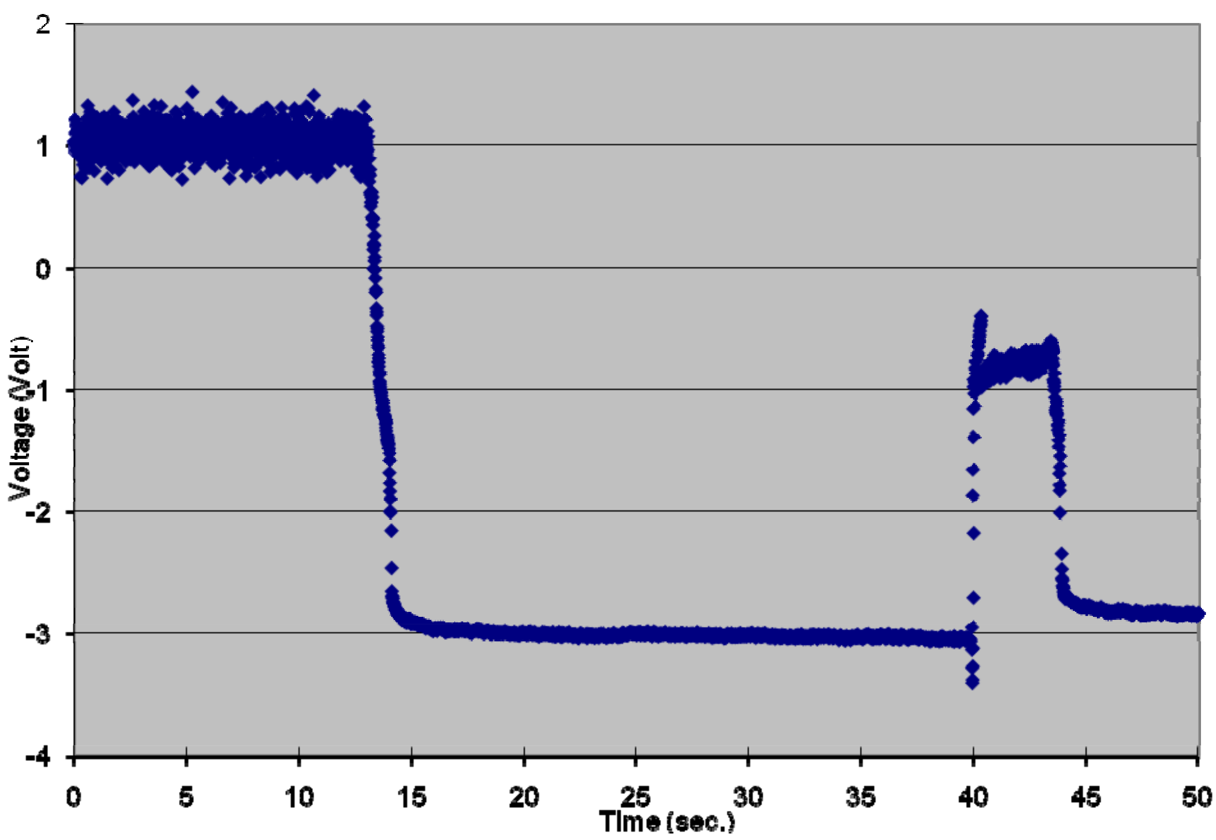


Figure 9. Flow detection and leak detection by the flow sensor (sampling frequency is 0.01 second)

After considering the economic benefits, experiments for a wireless data stream were tested using a 2.4 GHz wireless device, CROSSBOW, instead of a commercial wireless carrier. The software of the wireless system CROSSBOW is compatible with the Command Center generated by using LABVIEW. Figure 10 shows data taken from the same pressure sensor using both the LABVIEW data acquisition card and the CROSSBOW wireless data acquisition transceivers. The low pressure was used to test the sensitivity of the wireless system. The agreement of the two sets of data above shows that the CROSSBOW devices are capable of supplying the same data but without the need for the sensors to be wired to the computer.

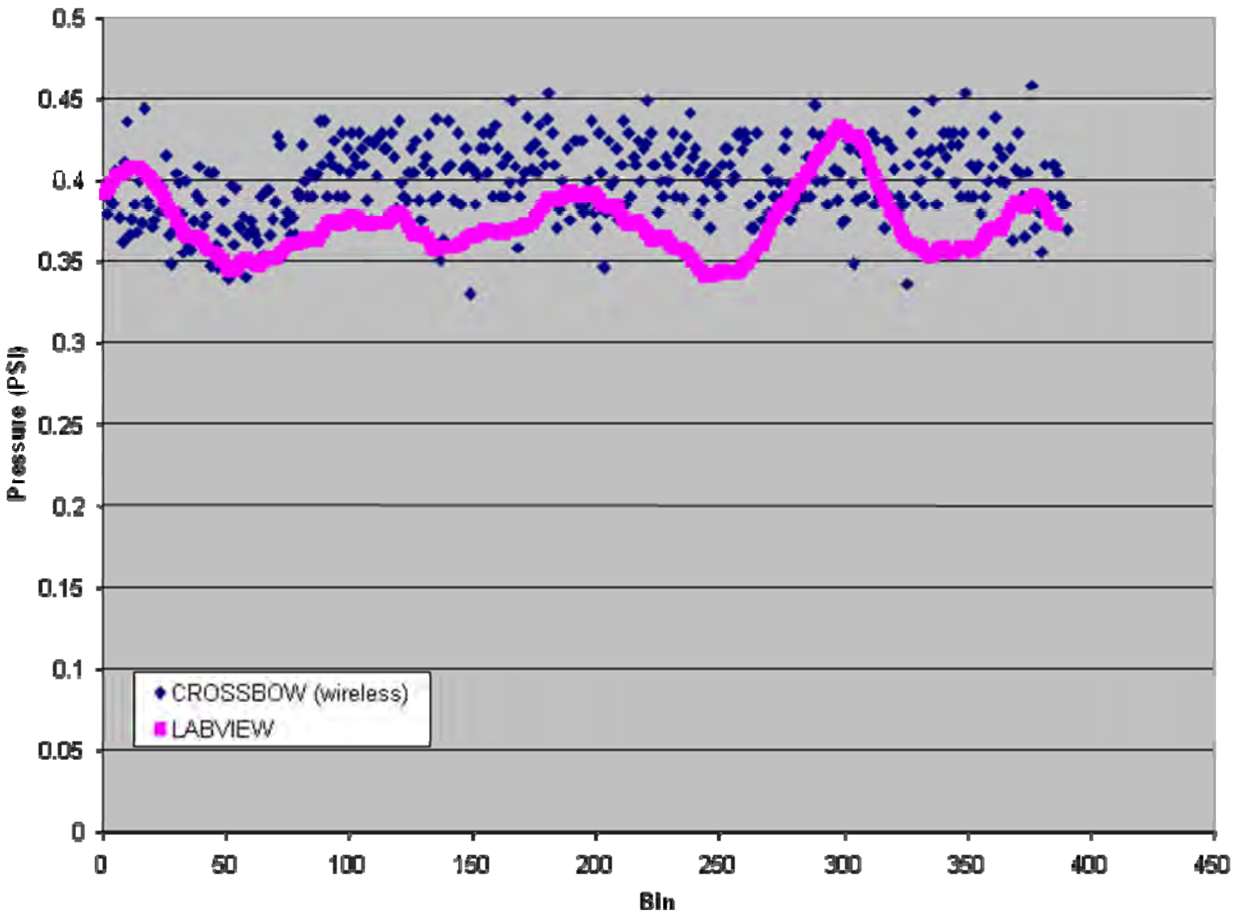


Figure 10. The comparison of data acquisition by wired device (LABVIEW) and wireless device (CROSSBOW)

Summary and Future Work

We have presented the concept for development and efficiency of nanosensors on the Smart Pipe for public water supply systems. The results from the experiments have demonstrated the efficiency of detecting pipe leakage using flow and pressure sensors as well as the feasibility of using a wireless infrastructure. Test results for multiple sensors with an advanced packaging process have shown the feasibility of using durable field material (PVC pipe) for the outdoor environment. Further study is recommended to improve this prototype via real-life application that includes the study of the frequency of required maintenance, fouling investigation, measurement calibration, real-time data communication software, manufacturing cost efficiency, long-term stability, and precision and accuracy assessment for commercial-grade products. The temperature sensor (Figure 1b) has been tested and is ready for future application in water quality detection. Since the Smart Pipe was designed as a module unit, it has an expandable capability for future available sensor units such as those for arsenic or radium. The nanosensor set has greater potential in addition to pipe leakage detection. We are currently working on a patent application with the Office of Technology Management at both the University of Illinois at Urbana-Champaign and Northwestern University in order to benefit small communities by using our research; however, this patenting process will not be completed before the end of the project. This project has developed a conceptual prototype of the Smart Pipe unit and has demonstrated its potential for benefiting water supply systems in small communities. The broader application of this new generation of nanosensor sets is dependent on future research funding.

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