Automated Scour Detection Arrays using Bio-Inspired Magnetostrictive Flow Sensors

Deliverable 5A
Report: Results of Laboratory Study
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Executive Summary

The laboratory study is a vital component of the scour detection experimental program providing a proof-of-concept study under controlled conditions. It will also allow the project team to identify the limits of the proposed technology under challenging conditions, specifically low-flow conditions where signals appear similar to static conditions. The signals recorded in the laboratory study will be vital for development of signal processing algorithms to be developed in Task 8. The laboratory study setup will also serve as the initial proving ground for the embedded data acquisition and processing components before they are tested in the field. The laboratory validation study will focus on quantifying the effects of both flow and scour rates on the performance of the system. Five levels of water depth as well as five levels of water velocity will be studied. In addition, performance in sand and silt conditions will be studied for sediments of varying size. Finally, a small-scale demonstration of the application of the smart scour-sensing posts for riverbank monitoring will be conducted in the scour flume located at Michigan Technological University (MTU).

Outputs:

- Proof-of-concept in a controlled environment.
- Understanding of the role flow and scour rates play in the ability of the scour detection arrays to detect scour.
- A library of candidate signals to be used for classification (static versus dynamic sensors) in the signal processing activities of Task 8.
- Controlled environment to validate and debug embedded data interrogation system (Task 6) and interface with decision support engine of Task 9.
- Small-scale validation of river bank monitoring using the smart scour sensing posts.

Contents

Introduction

To confirm the capability of the system a robust program of validation has been conducted to define the limits of the approach in the laboratory. The proof-of concept laboratory experiments were conducted to validate the ability of the system to monitor and measure scour and to check the ability of the network of wireless sensors to successfully process data. The results of the laboratory validation experiments have been presented here. The tests conducted were all clear water tests.

The laboratory experiment were conducted under controlled environment which allows a simulation of scour conditions at various water velocities and act as a test of the scour detection and monitoring system. Scour primarily affects the foundation, abutments and piers of the bridge. The effect of scour on abutments and piers was studied in the laboratory experiments. During the laboratory experiments, the water velocity varied to develop scour.

The laboratory experiments were performed in the Civil Engineering Hydrology Laboratory located at Michigan Technological University.

Objectives

Under two laboratory conditions, a flat river bed and a 45-degree river-bank, the proof-of-concept scour detection arrays were studied to meet the following objectives:

- Understand the role flow and scour rates play in the ability of the scour detection arrays to detect scour.
- Quantify which flow conditions create false indications based on low flow conditions.
- Evaluate new scour monitoring technology under study and identify improvements.
- Explore possible problems that might be encountered in field.
- Obtain a library of signals collected in a controlled environment to correlate outputs to transduce condition (*e.g.*, static vs dynamic, or nominal sensor condition vs fault condition).
- Calibrate thresholds for various transducer geometries to classify signals.
- Test autonomous data collection and interrogation systems for the field validation study and assess the scour prediction method.

Laboratory Facility

Flume (Water channel)

The water channel in the hydrodynamics lab is a rectangular, cement experimental tank. The inner walls were coated with epoxy spray to allow for a non-leaking tank. The dimensions of the flume were an inside width of 0.92m, a total height of 1.04m, and an inside length of 10.18m. It consisted of an inlet and outlet at the head and end of the tank, respectively. A pump was used to move the water from the outlet to the inlet through a 0.245m diameter pipe. The pipe had 27 1.588mm diameter holes facing in the downward position, which allow water to empty into the head tank. There was a wall that separated the inlet area and the main experimental tank. This internal wall was constructed of 20mm diameter PVC pipes, which were stacked parallel to allow for flow straightening into the main water channel.

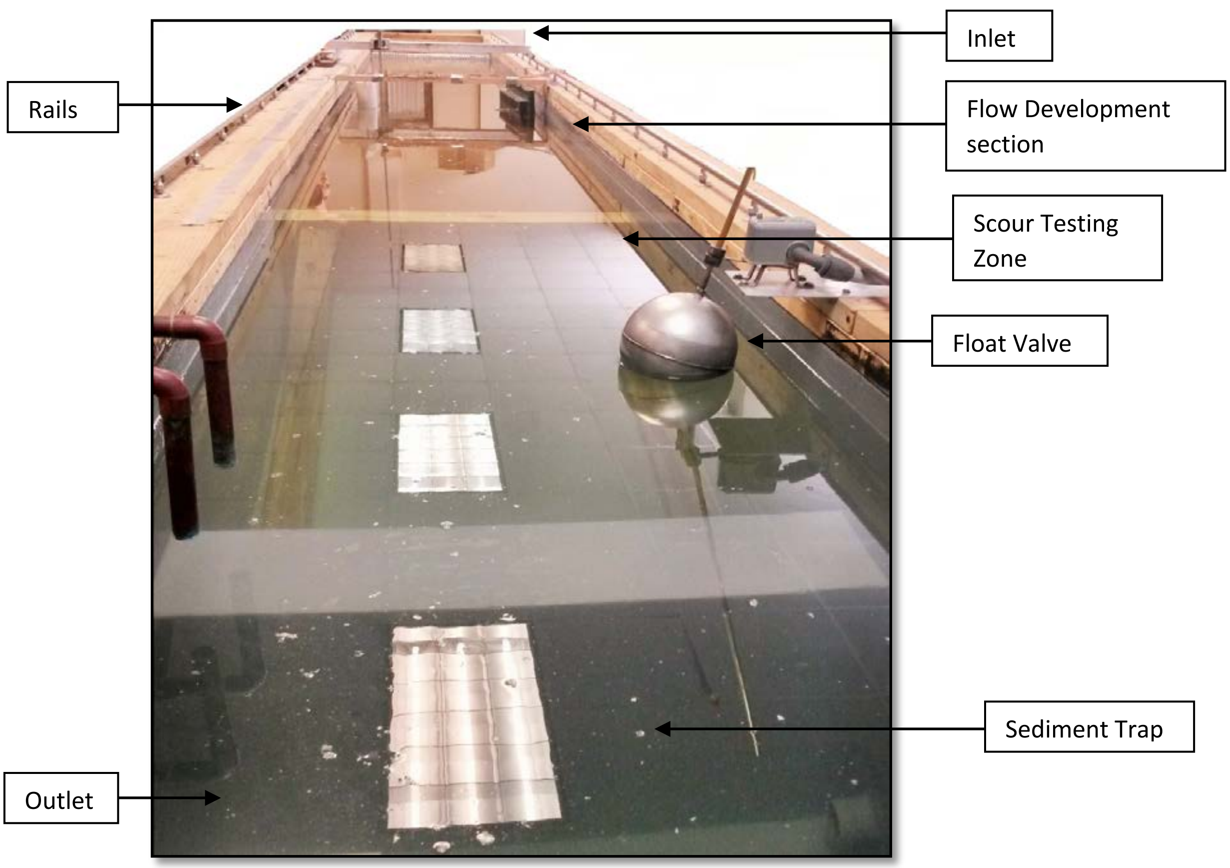


Figure 1 Flume Structure

Water channel setup for first experiment

For the first case in the set of experiments, a flat bed was constructed following the flow straighteners section. This approach area was approximately 1m in height and 3m in length. This bed was made of plywood and had an epoxy varnish overlay for waterproofing purposes. Soil was then placed on top of the flat bed. The next area was the scour section, which was filled with fine sand. The sand was filled from the bottom of the water channel, level with the soil in the preceding section. The bottom of the water channel was the cement floor of the laboratory. A wooden wall standing 630 mm tall from the flume floor was constructed near the end of the scour chamber for sediment trapping. The sand, in the scour chamber, was level with the soil in the flat bed section and ended at the wooden wall. The water height was made to be just above the top sensor of the pier.

Figure 2 Flume setup for first experiment

Water channel setup for second experiment

For the second case in the set of experiments, the flat bed was removed. It was replaced with an angled embankment bed that was positioned 45 degrees from floor of the flume. The flow straighteners were repositioned to accommodate for the embankment slant. The approach area had dimensions of 3m length and 0.5m height. It was constructed of plywood and had a coarse sand paper overlay. The scour section was filled with the same fine sand from the first case. The sand was angled at a 45 degree position, which lined up with the bed. This exposed a portion of the flume floor from the angled bed section through the scour section. The wooden standing wall was removed and the scour chamber tapered off before it reached the sediment trap area.

Figure 3 Flume setup for second experiment

Scour experiment structure

Model Pier and Abutment

To conduct the proof-of concept laboratory experiment a pier and an abutment were assembled using PVC board and pipes for the laboratory test. The pier was made using a 4 inch diameter Poly vinyl chloride (PVC) pipe attached to a box made up of rigid form of PVC board. Also a simple abutment was constructed using PVC boards and 2 inch PVC pipe was used make piles. Waterproof glue and quick setting super glue was used to hold the assembly together.

The dimensions of the pier and abutment were to scale with the flume being used for the experiment. The models were made to closely match a similar structure in the field. The total height of the pier was 2 ft 10 inch and it was made to be 4 inch wide and the abutment was approximately 2 ft 10 inches in height and 2 ft wide. Both the pier and abutment were coated with waterproofing silicon and was spray painted white to make it waterproof and weather proof. The transducers were attached to the pier and abutment assembly itself for the experiment. Holes that fit the sensors were drilled into the abutment and pier using a drill and sensors were mounted on the models. The hole was then coated using silicon for waterproofing. Four whisker type transducers each was mounted on both pier and abutment models. The transducers were spaced 6 inches from each other. Figure 1 shows the model pier and abutment used for the laboratory experiment.

Figure 4 Pier and Abutment

Posts

For the river bank experiment two simple posts, one with bio inspired whisker type sensors and other with airfoil sensors were made. PVC strips two feet in length and one inch in width were used as posts. The sensors were mounted on the posts using waterproof glue. Three sensors each were mounted 3 inches apart in each post. Figure 2 shows an example of the post used.

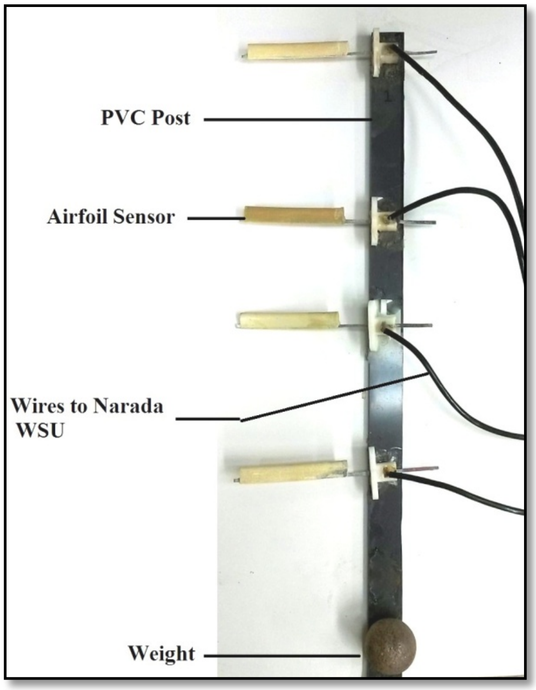


Figure 5 Sample Airfoil posts

Proposed Scour Detection System

For the purpose of lab validation tests two Narada WSU were used. The transducers were mounted on the model pier and abutment and PVC posts. The sensors were connected to each Narada WSU using wire setup. Power was provided to the Narada's using an AA battery pack. In the test the Narada wireless sensors was setup to send the data to a laptop computer in the first case and to a single board computer in the second case for analysis. While this function is not strictly necessary for wireless systems with full embedded data processing abilities, it is necessary to validate the functionality of the sensors.

Equipment for scour monitoring and detection

Transducers

In the proof-of concept laboratory tests two different sensors were used. The sensors used in the laboratory study are 1) Bio-inspired magnetostrictive whisker sensors and 2) Magnetostrictive Airfoil sensors.

Bio-inspired magnetostrictive whisker sensors

The whisker shaped sensors are inspired by the whiskers of marine animals which provide the marine animals with important sensory information of the environment around them. The whisker sensors are made of Galfenol wire, which is an alloy of iron and gallium. Galfenol is magnetostrictive in nature and has corrosion properties that are similar to those of steel, and four times less that iron. The whisker sensor consists of five main components 1) Galfenol whisker 2) GMR sensor 3) clamping fixture 4) Small permanent magnet and 5) Low power operational amplifier. Figure 3 shows an example of whisker sensor.

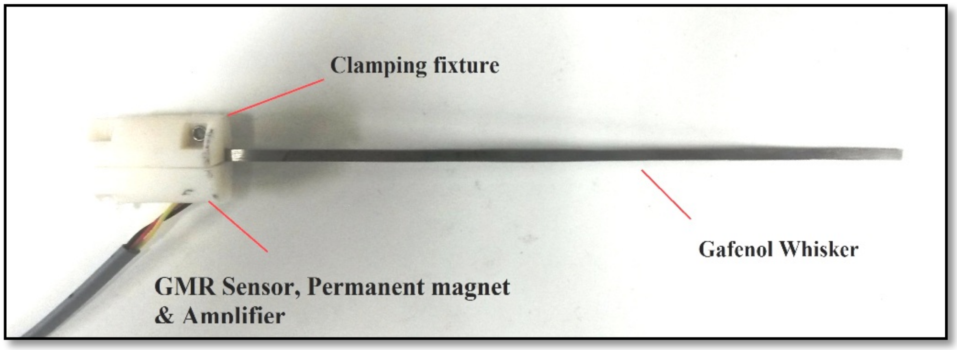


Figure 6 Whisker Sensor

Magnetostrictive Airfoil sensors

The Airfoil sensors are an improved version of whisker inspired magnetostrictive Galfenol sensors. Airfoil sensors work on the exact same concept as the bio-inspired whisker flow sensors. However, the airfoil sensors are much more robust compared to the whisker inspired sensors. A wax layer in a shape of airfoil was added in the sensors to improve its sensitivity Figure 4 shows an example of airfoil sensor.

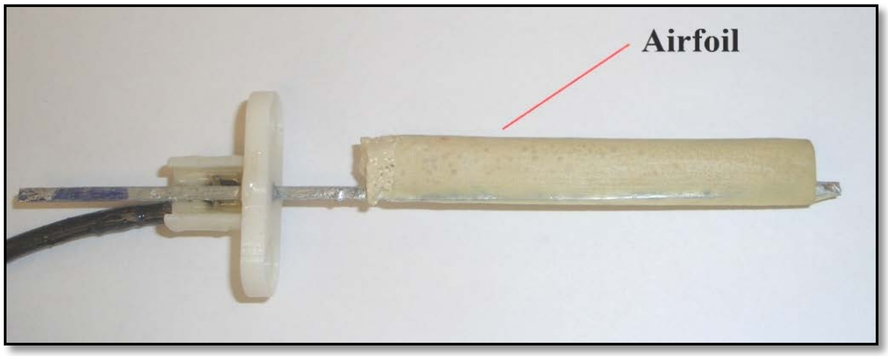


Figure 7 Airfoil Sensor

Wireless sensing unit

Low power *Narada* wireless sensing unit was used in the laboratory study as the wireless sensing interface. The *Narada* WSU is developed by Swartz *et al* (2005) and is produced by Civionics Inc.

Narada Wireless sensing unit

The Narada is a low-power wireless sensor node designed explicitly for the monitoring of civil infrastructure systems and has been successfully used in many types of structures in the past. It has been designed for applications requiring high resolution data collection, and/or real-time

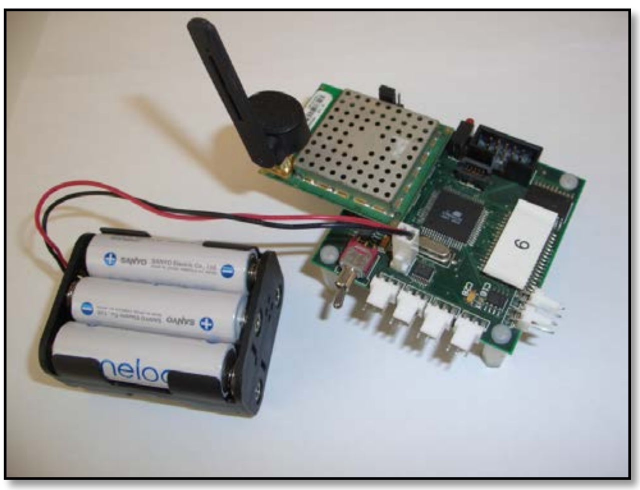


Figure 8 Narada WSU with battery pack

control (Civionics). The Narada consists of ADS8341 16-bit sensing interface to digitize and sample analog transducer signals with four analog input channels that can read analog signals ranging from 0 to 5Volts. The computational core of Narada is 8-bit ATmega128 microcontrollers that is responsible for managing sensor operation and perform analysis, including the storage of sensor data. The ATmega128 is an 8 bit, low power microcontroller that has 128 kB of flash memory to for temporary data storage, and 4 kB of electrically erasable programmable read only memory (EEPROM). It also features IEEE 802.15.4 compliant wireless modem, the Chipcon CC2420 that adopts the 2.4 GHz IEEE 802.15.4 radio standard, which acts as a communications interface and serves as WSU's link to the world. The Narada wireless sensing unit contains an inbuilt actuation interface to allow the sensor to command actuators. The actuation interface consists of a Texas Instruments DAC7612 2 channel 12-bit DAC capable of outputting analog signals from 0 to 4.1 V with a resolution of 1mV.

Base Station

The base station aggregates the data from multiple wireless sensing units in use and it creates a decision file in accordance to the data received from the wireless sensing units. The base station assembly used for the laboratory experiment composed of Narada Base Station, centralized PC laptop or Single Board computer (SBC), and a power supply.

Narada Base Station

The Narada Base Station is produced by Civionics Inc. The Narada Base station is a wireless data acquisition hub built around the Atmel ATmega128 microcontroller. The ATmega128 is an 8 bit, low power microcontroller. The Narada Base station connects to the PC through an available USB port and can facilitate data collection, real-time control, and network maintenance tasks (Civionics).

Figure 9 Narada Base Station

Centralized PC Laptop / Single Board Computer

A normal laptop was attached to the Narada base station using a USB port to for the laboratory experiment. A single board computer was also utilized for the river bank experiment. The single board computer used for this study is PPM-LX800-G manufactured by WinSystems Linux (Ubuntu 11.10) operating system.

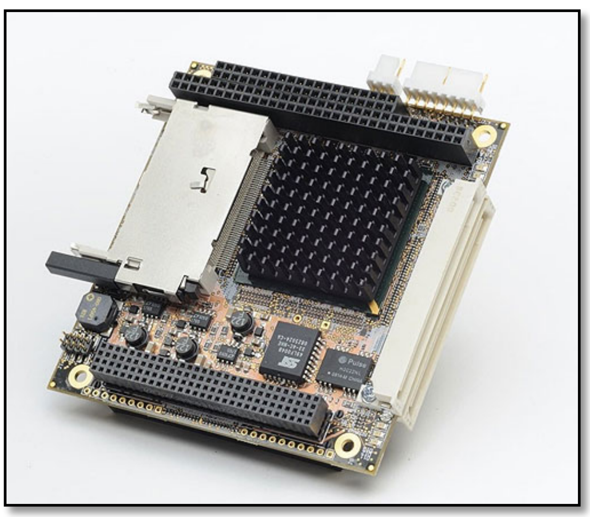


Figure 10 Single Board Computer

Equipment

Scour Measurement (Hydrology)

Scour was measured using a point gage. Before the initial pump speed, the bed elevation was measured as 77.3 cm. This measurement was a baseline for calculating all scour depths.

Change in pressure (Δh, measured in ft) for each pump speed was recorded from the manometer. In order to convert pump speed to channel flow, Q (cfs), the following equation was used:

$$Q = 0.203\sqrt{\Delta h}$$

Experimental Setup

Pier and abutment experiment

The first case, the flat bed was filled with a layer of soil. There were three divisions of soil types laid on the flat bed. The first section was about 1m in length and was filled with gravel about 25.4mm deep. This gravel section transitioned into a gravel/sand mixture of about 25.4mm deep and 1m in length. The final transition was filled with fine sand to about 25.4mm deep and spilling into the scour sector. The sand had a d50 of 0.56mm. The same sand was filled to this height in the scour section of the flume. Placed in the sand, was a replica of a bridge pier and abutment. These models were scaled 1/30th of the size of a bridge pier and abutment. The pier was made of a 30mm PVC tube and was placed perpendicular to the flow and channel bed. It had a height of 0.3m above the sand bed. The abutment was placed in contact with the east wall of the flume and the pier was placed 1 ft away from the west wall of the flume. The distance between the abutment and pier was 1.6 ft. The height of the abutment above the sand bed was 0.3m. It had a width of 20 mm and a length of 40 mm. The width of the abutment faced the oncoming flow, while the length of the abutment was parallel to flow. For laboratory testing purpose, to make the installation easy, the bio inspired whisker type sensors were mounted on the model abutment and pier itself for scour detection and monitoring. Four sensors each was mounted on both pier and abutment models. For the purpose of lab validation tests two Narada WSU were used. The transducers that were mounted on the model pier and abutment were connected to each Narada WSU. Power was provided to the Narada's using an AA battery pack. In this test the Narada wireless sensors was setup to send the data to a laptop computer for analysis.

Figure 11 Flume setup for Pier and abutment experiment

River bank experiment

The second case, two posts were used. The flume was setup to match a river bank for this experiment. The flow development zone which was a wooden structure from the previous setup was removed and replaced by an inclined wooden structure to create a riverbank. Fine and clean sand was used to create a river bank on one side of the flume. The posts were then buried in the river bank so that the sensors were aligned perpendicular to the flow of water. To make the posts stable, weights were attached to the ends of the posts. The transducer on the top of the post was left unburied, the bottom two transducers were fully buried in the sand and one of the transducer was partially buried when placed in the flume. For the purpose of lab validation tests two Narada WSU were used. The transducers that were mounted on the posts were connected to the Narada WSU. Power was provided to the Narada's using AA battery pack. In this test the similar to the previous setup the Narada wireless sensors was setup to send the data to a laptop computer for analysis.

Figure 12 River bank experiment

Experimental Procedure

In an effort to understand the impacts of flow and scour on the ability of the detection sensor to detect scour, a model of a bridge pier and abutment were installed in a laboratory flume. In both laboratory set-ups, the proof-of-concept sensors were tested and associated scour was measured.

In order to generate a database of signals to be used for classification (static versus dynamic signals) multiple pump speeds were used. Pump speeds started at 9.06 hertz, and were increased in 1.0 increment, up to a maximum pump speed of 30 hertz.

Scour was measured for each pump speed at multiple time intervals. Once equilibrium was reached, scour was measured and recorded as "worst scour" for each pump speed. Equilibrium is defined as less than 1% change in scour over a 3-hour period. The worst scour location, either upstream or downstream of each structure, was also documented.

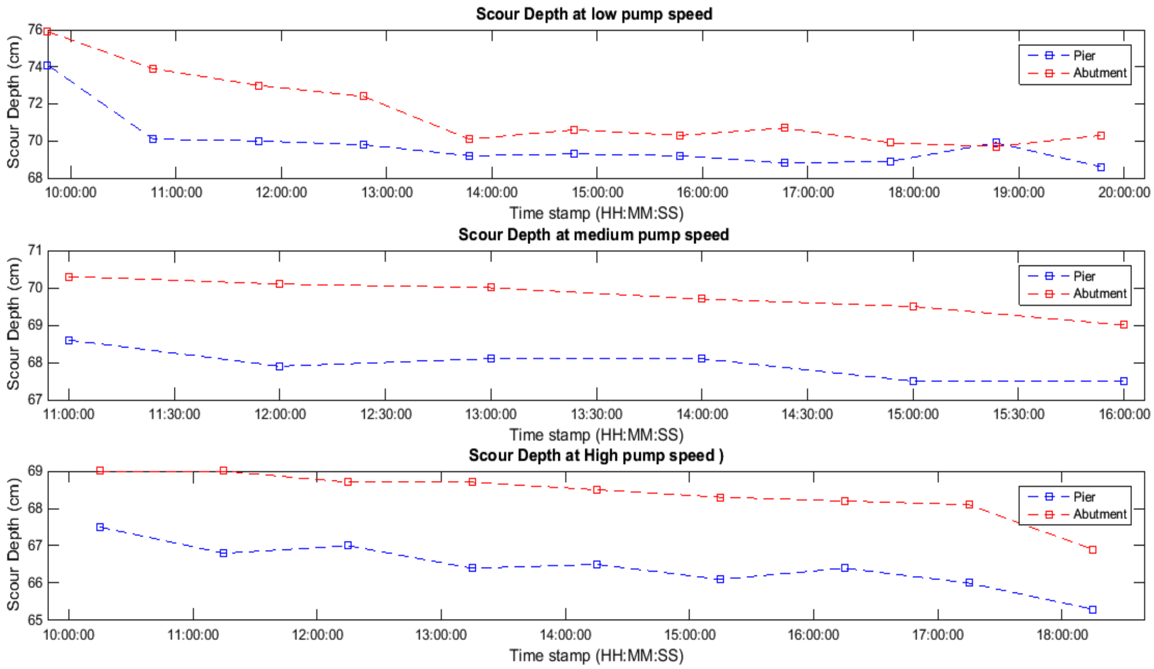
The data was collected periodically for the entire duration of the experiment using two Narada sensor units powered by battery pack for detecting scour. The data collected was processed to determine the dynamic and static states of the sensors.

The sand used for the experiment had sediment of mean size, d_{50}, of 0.56mm (0.0018ft) and geometric standard deviation = σ_{sed}, $(d_{84} / d_{16})^{1/2} = 1.25$.

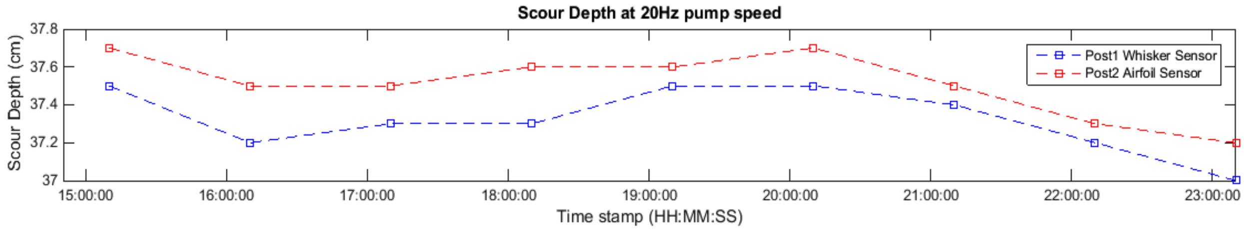
Figure 13 Scour hole developed

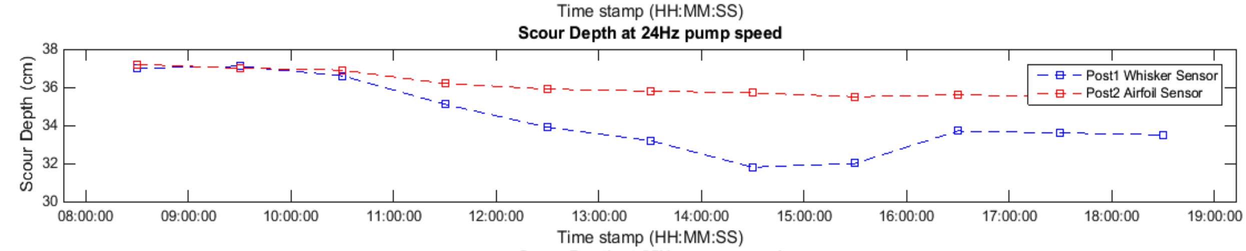
The following plots show the depth of scour developed during various velocities during the experiment. The first plot shows the depth of scour hole generated during the experiment using model pier and abutment. The next figure shows the plot of depth versus time for the river bank experiment.

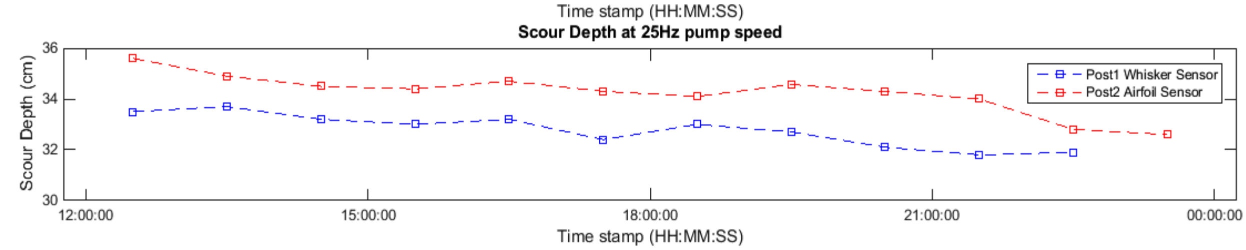
Scour Depth Plot Pier and abutment experiment



Scour Depth Plot River bank experiment







Results

Figure through shows time domain plot of sensors when they are buried (static) and unburied (dynamic).

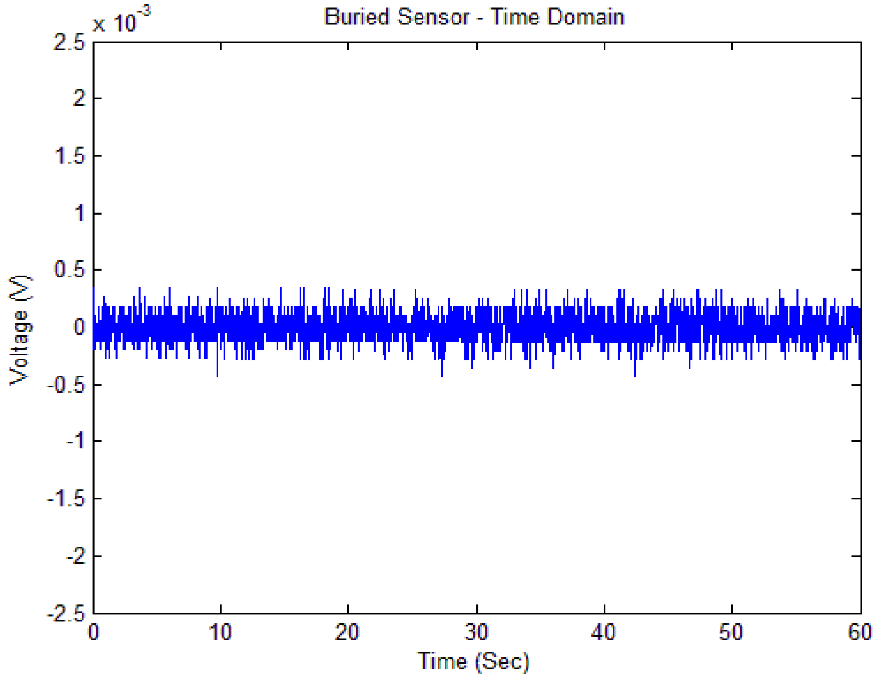


Figure 14 Time domain plot of Buried Sensor (Static State)

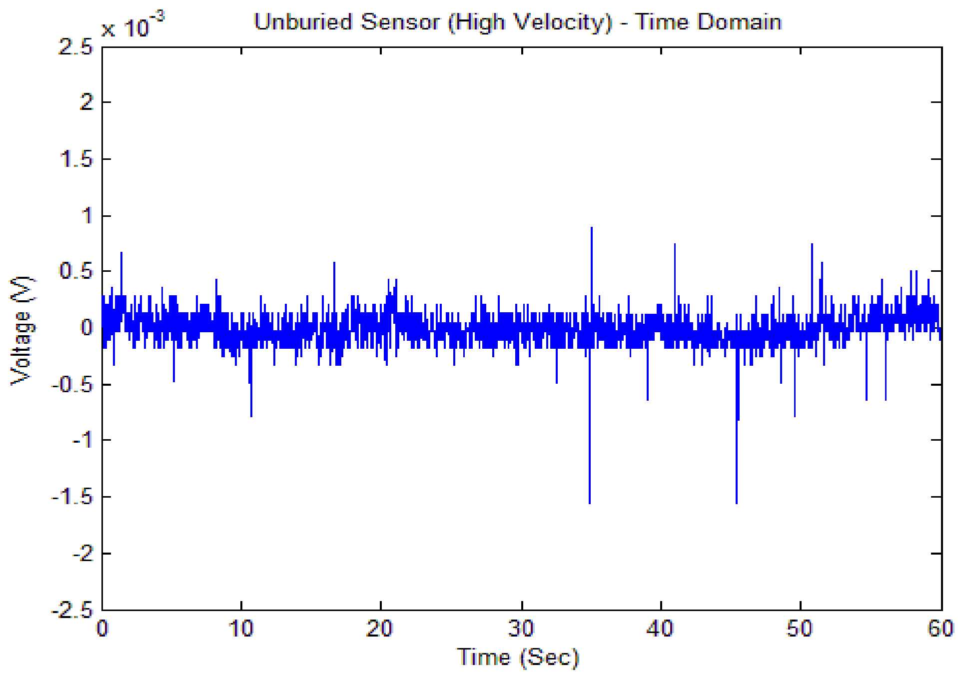


Figure 15 Time domain plot of Unburied Senor (Dynamic State)

Data collection analysis of laboratory experiment: model pier and abutment

In this laboratory experiment the data were collected the monitoring system every hour and transmitted to the server which in this case was a laptop. Scour hole developed was measured at regular intervals. The plots below show the time domain plot of the data.

Test Parameters:

Sampling frequency (Hz) = 100 Hz

Sampling time (sec) = 30 Seconds

Samples per polling cycle = 3000 samples

No of Units = 2

Unit ID (s) = 77 WSU (Whisker) (Abutment)

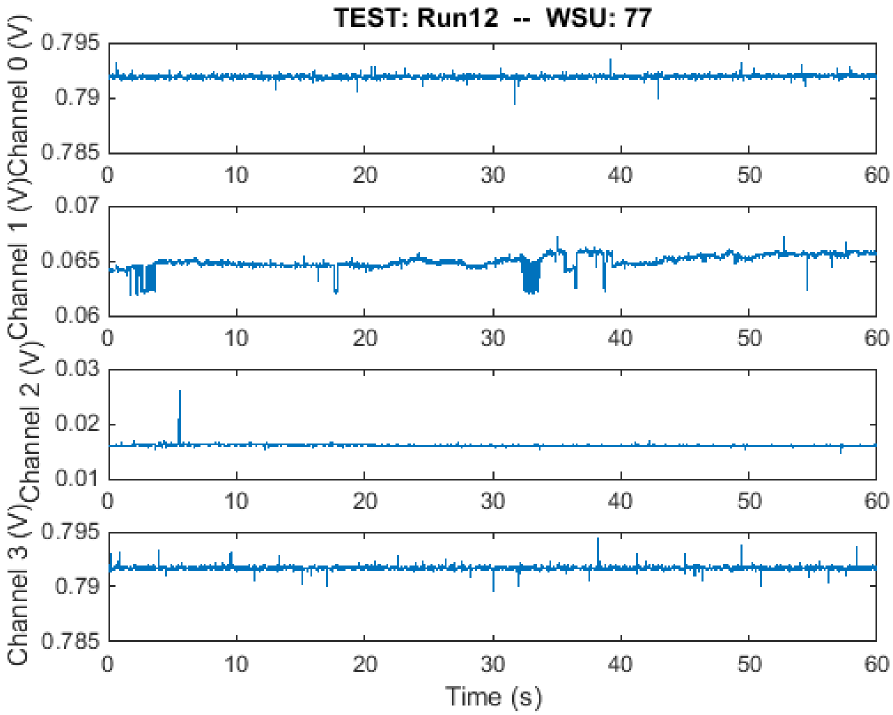
Channel(s) LEGACY_CH0, LEGACY_CH1, LEGACY_CH2, LEGACY_CH2

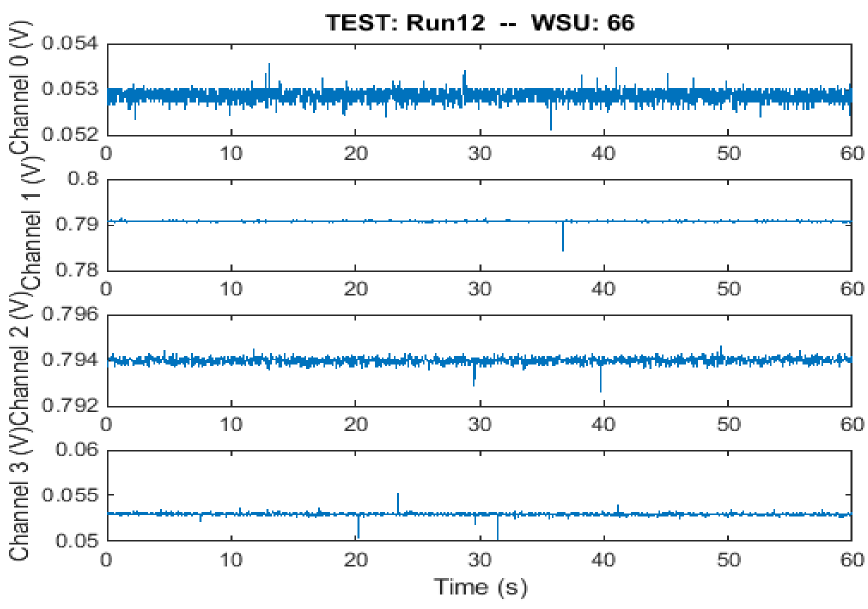
Unit ID (s) = 66 WSU (Whisker) (Pier)

Channel(s) LEGACY_CH0, LEGACY_CH1, LEGACY_CH2, LEGACY_CH2

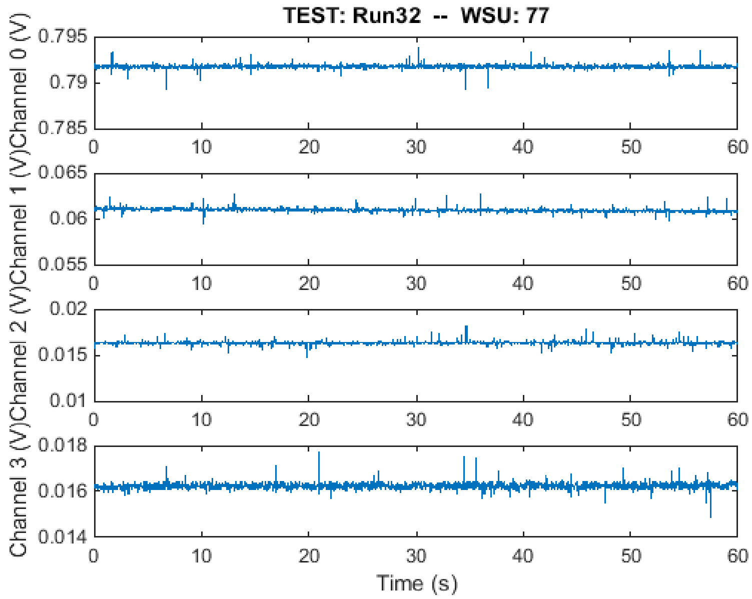
Sample time histories are shown below.

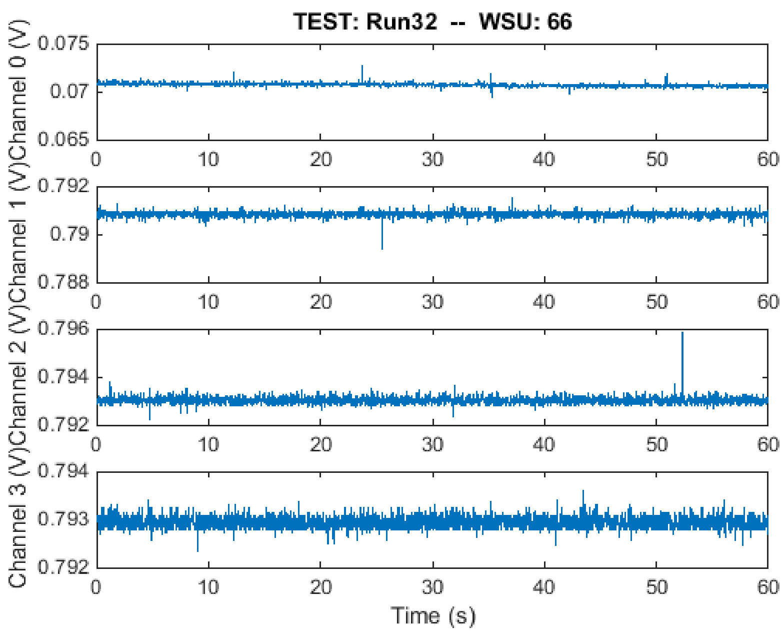
Time domain plot at low water velocity (Time stamp 12:03:08):



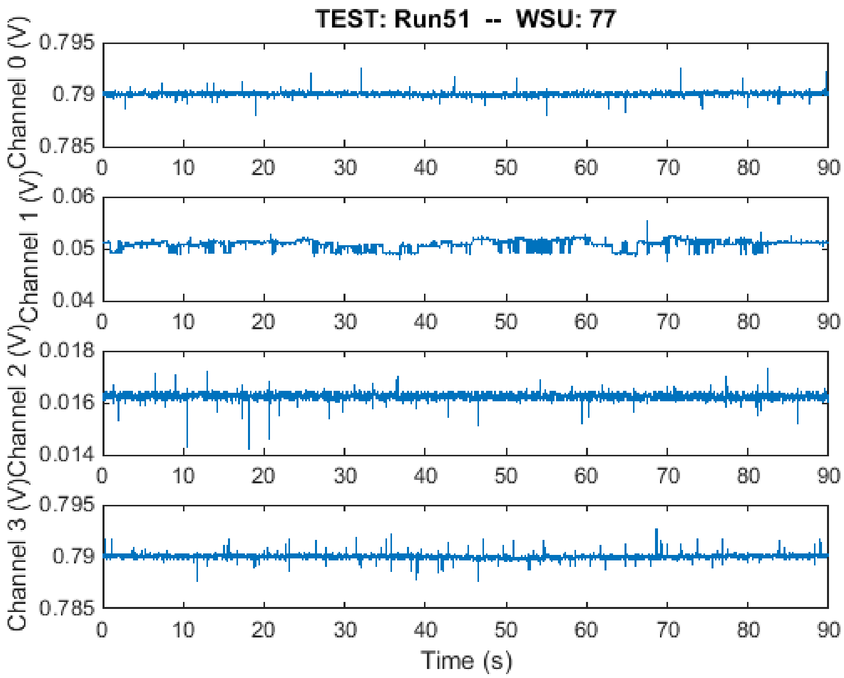


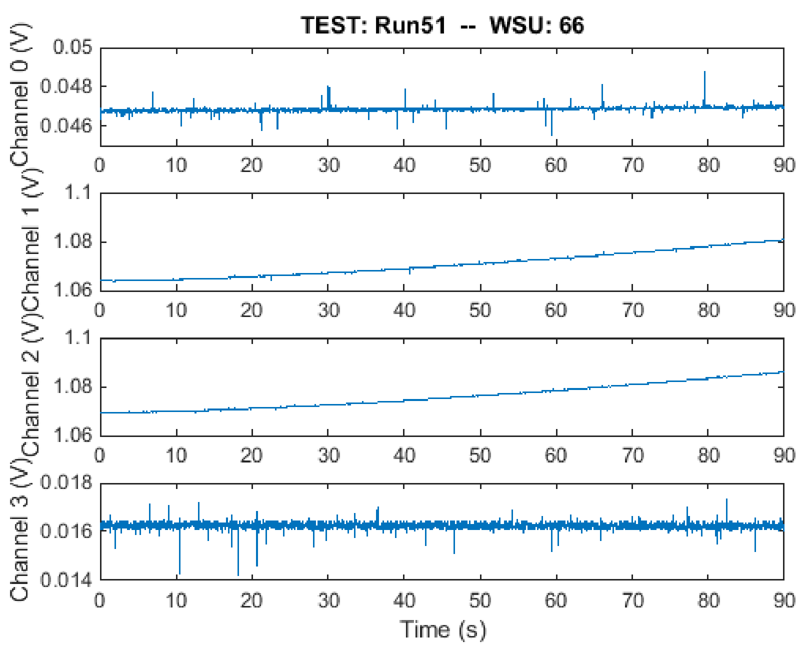
Time domain plot at medium water velocity (Time stamp 13:29:12):





Time domain plot at high water velocity (Time stamp 15:09:28):





In some cases, minor mean drift was observed on one or more channels in the outputs from the Hall sensors. In these cases it becomes clear that detrending algorithms will be necessary as part of the autonomous data interrogation algorithms.

Data collection analysis of laboratory experiment: model post

In the laboratory experiment the data were collected the monitoring system every hour and transmitted to the server which in this case was the Single board computer. Scour hole developed. The plots below show the time domain plot during different velocities.

Sampling frequency (Hz) = 50 Hz

Sampling time (sec) = 60 Seconds

Samples per polling cycle = 3000 samples

No of Units = 2

Unit ID (s) = WSU 7 Post 1 (Whisker)

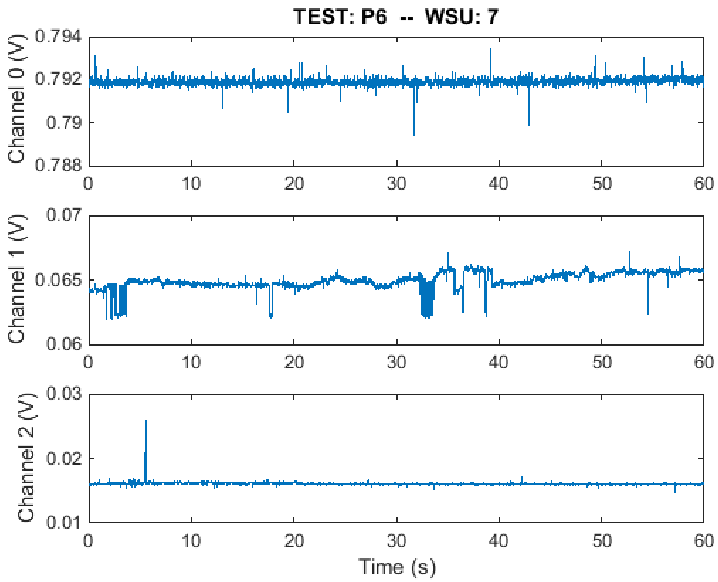
Channel(s) LEGACY_CH0, LEGACY_CH1, LEGACY_CH2

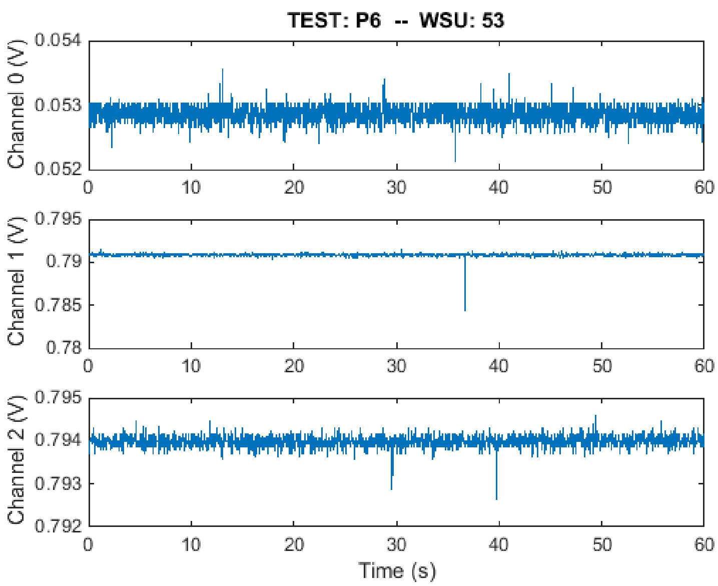
Unit ID (s) = WSU 53 (Airfoil)

Channel(s) LEGACY_CH0, LEGACY_CH1, LEGACY_CH2

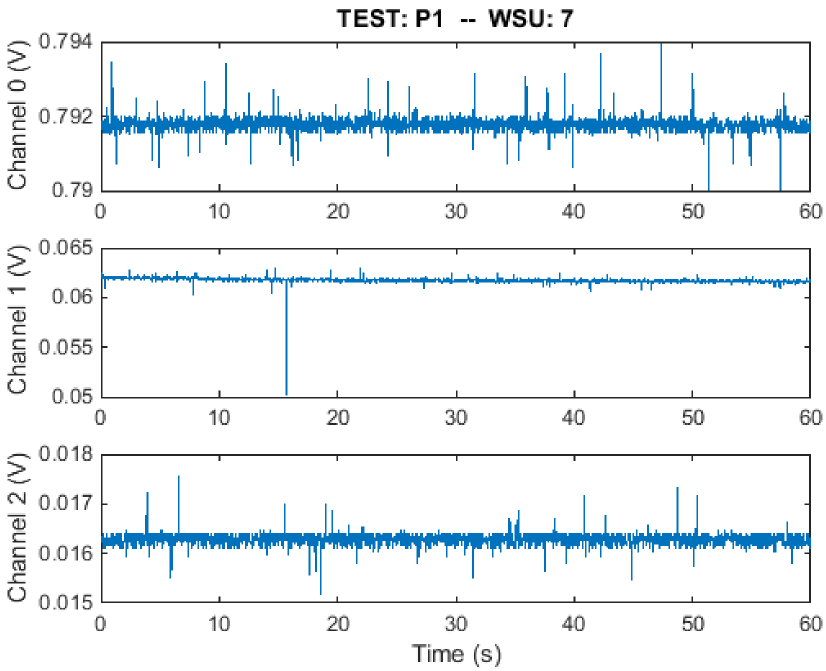
Sample time histories are shown below.

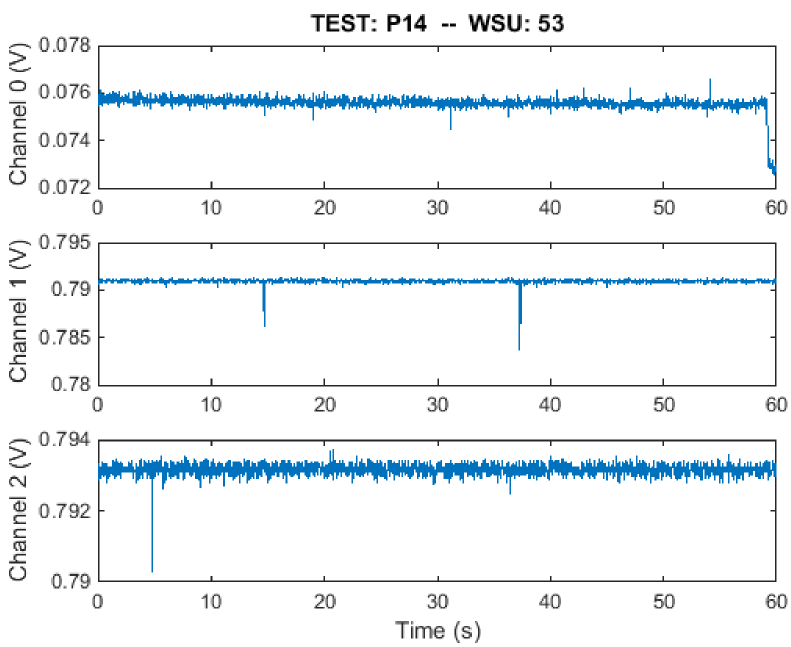
Time domain plot at low water velocity (Time stamp 15:03:32):



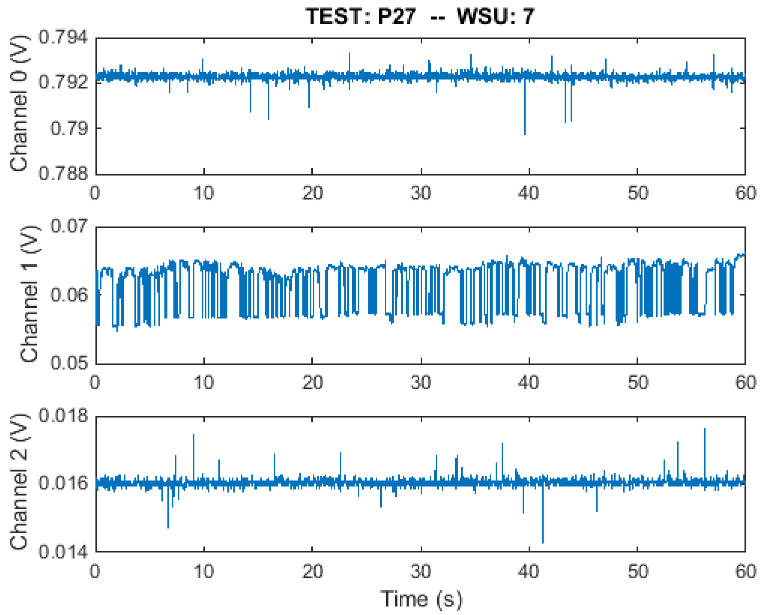


Time domain plot at medium water velocity (Time stamp 14:01:25):

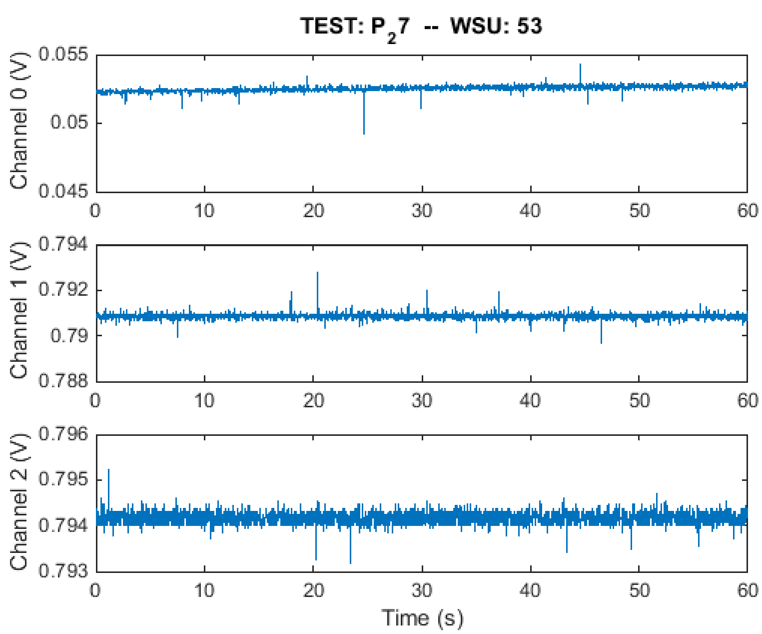




Time domain plot at medium water velocity (Time stamp 18:06:52):



Here, on Channel 1, a sensor fault condition (poor connectivity of the sensor to the data acquisition devise) was observed. This signal, and others like it will be useful to establish a library of fault signals for later classification algorithm development.



The plot below shows the success rate of the sensors (whisker and airfoil type) in correctly stating the state of the sensors at different velocities of water in the flume.

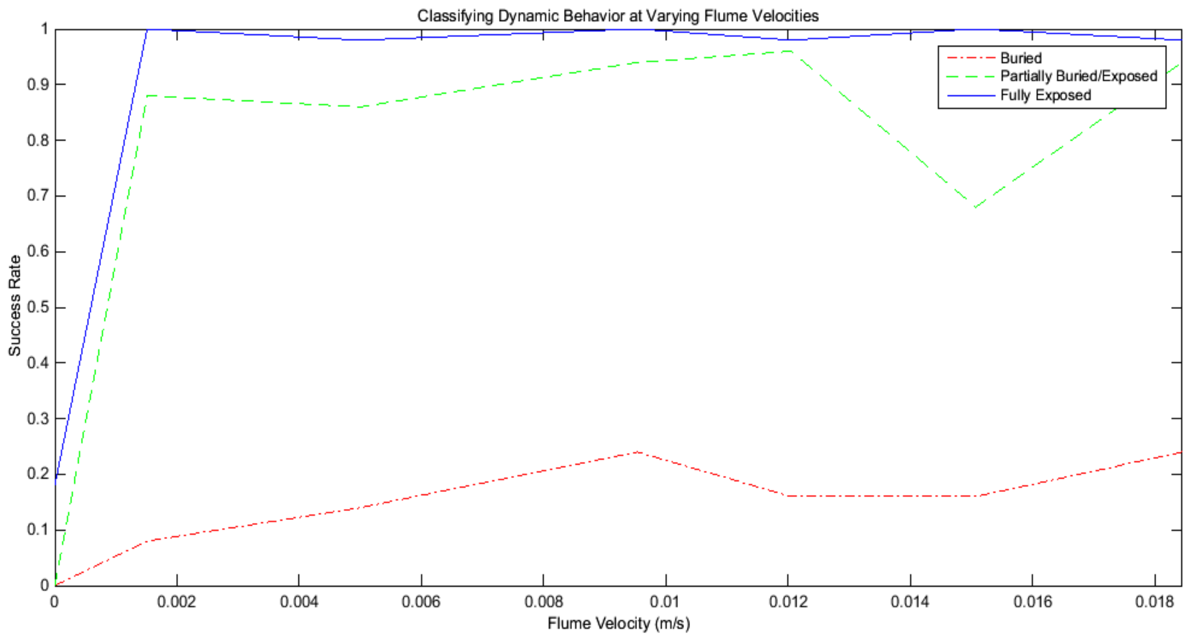


Figure 16 Success rates of sensors

Conclusion

The proof-of-concept experiments were performed in the laboratory to validate the ability of automated scour detection and monitoring system that is based on bio-inspired magnetostrictive flow sensing sensors to successfully monitor scour. The laboratory results demonstrated that distinction between static sensor and a dynamic signal can be made, and with the knowledge of the depth of the sensor scour can be measured and monitored up to the spatial resolution of the transducer sensor locations. The laboratory tests established the automated characteristic of the system and displayed the ability of the system to give a warning of impending bridge failure successfully. The ability of the system under study to automatically capture and log peak scour events was shown. Laboratory tests also yielded a useful library of signals characterizing dynamic water-borne sensor data for the various transducer geometries used in the study. This data will be used in later phases of the study to develop interrogation algorithms that will autonomously classify the condition of the transducer and identify the presence or absence of scour.

Acknowledgements and Disclaimer

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