Automated Scour Detection Arrays using Bio-Inspired Magnetostrictive Flow Sensors

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Report: Signal Processing for Scour Detection
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Executive Summary

This report details the signal processing approach taken to detect flow at whisker sensors for autonomous remote sensing of bridge scour using magnetostrictive scour sensing posts. Static flow indicates a sensor buried in sediment while dynamic flow signals indicate a lack of sediment and potential scour. Autonomous algorithms to detect these conditions are required to free the bridge owner from data interrogation duties allowing them to focus on bridge management instead. A number of approaches are investigated, but a frequency-domain approach is ultimately selected for signal detection to increase sensitivity, reduce computational effort, as well as reduce the false alarms caused by sensor failure and noise.

Outputs:

- Autonomous embedded algorithm for bed detection.

Contents

Introduction

This report presents the implementation details of the river bed detection algorithm, showing how it has been executed. The riverbed detection algorithm analyzes the raw sensor data from each buried whisker transducer and classifies the output as corresponding to either static, dynamic, or some sensor fault behavior. Those sensors that are static are assumed to be buried in sediment while those that are dynamic are considered to be above the riverbed or located in a scour hole. In this effort, simple algorithms that give good sensitivity even in low-flow conditions are preferred in order to allow for more reliable autonomous operation as well as reduce the computation effort required to classify the data (which will save battery energy within the post). The algorithm must also have minimal memory requirements to allow it to be executed, embedded in resource-constrained, low-power wireless sensor units (WSUs) that form the computational core of the smart scour-sensing posts developed for this study. Direct data interrogation within the post will eliminate the need to communicate copious amounts of raw data wirelessly at bridge sites improving network and system resilience and reducing energy consumption. In addition to the low-power WSUs, the algorithm will be implemented on single board computers (SBCs) at some sites where wireless operation is not an objective. In these implementations, energy and computational resources are less limited.

Objectives for autonomous detection algorithm

The design of the algorithm had several objectives:

- Simplicity
- Minimal memory utilization
- Fast execution time
- High sensitivity
- Repeatability
- Error detection

Platforms

The project will use both low-power WSUs as well as more capable SBCs as data acquisition and processing platforms. The WSUs employed are Narada wireless sensing and control devices with 8-bit fixed-point microcontrollers and a scant 128kB of SRAM provided for data storage. Narada wireless sensor node comes with a custom written embedded operating system. The operating system simplifies the process of the wireless sensor for the user and serves as an intermediary software layer between hardware and software written for data interrogation. Within the custom operating system, additional engineering algorithms for data interrogation may be used with a number of algorithms already developed in an existing library. Some of the algorithms that were utilized for this project included computation of basic statistical measures, the fast Fourier transform (FFT), as well as least-squares approximations of time-series models for input/output data (*e.g.*, AR, ARX, ARMA, *etc*.).

To support additional platforms (and for debugging purposes), these algorithms were ported to Linux as well as Windows. Since, for implementation in the SBCs selected for this study, the Linux operating system (Ubuntu 11.10) is being utilized, the final integrated detection algorithm was ported to Linux.

Operation

In this study, a central based station (composed primarily of a SBC) was used to coordinate the activities of the wireless monitoring system and to serve as storage of network measurement data of the system. To initialize the Narada WSUs and execute the riverbank detection algorithm, three server setup files are used. The first file default_settings.dat is a text file containing DAQ parameters is created by the user, processed by an executable server program running on the PC, and wirelessly transmitted to the network over Narada IEEE802.15.4 receiver board connected to the SBC USB port. This file default_settings.dat allows the user to modify the IEEE802.15.4 network settings defined for the wireless sensor network including the communication channel, personal area network (PAN) ID, and the server node ID. A second file, called DAQ_settings.dat, is used to set data acquisition parameters including the sampling frequency, total sampling time for a test, the number and ID of the WSUs participating in a test, and the WSU data channels to be used. A final setup file, analysis_settings.dat, is defined to establish the thresholds to apply to each sensor channel that help the algorithm to differentiate between static and dynamic signals (these thresholds will vary according to the transducer used).

The base station initiates data acquisition from all WSUs within the local network at the beginning of a scour detection cycle. WSUs within scour posts collect and store time history data from all transducers on the posts. At the end of the test, the base station ensures that the test has completed and then requests that the WSUs perform data processing on their locally collected data including finding basic statistical measures as well as frequency-domain analysis using an FFT and rudimentary digital filtering. The results of these algorithms are reported to the base station which then classifies each signal according to the rules defined in the setup file. The results from each channel are then uploaded via cellular data modem to a central server to be presented to the user. An overview of this process is shown in Figure 1. Additional details of the individual steps are provided in subsequent sections of this report.

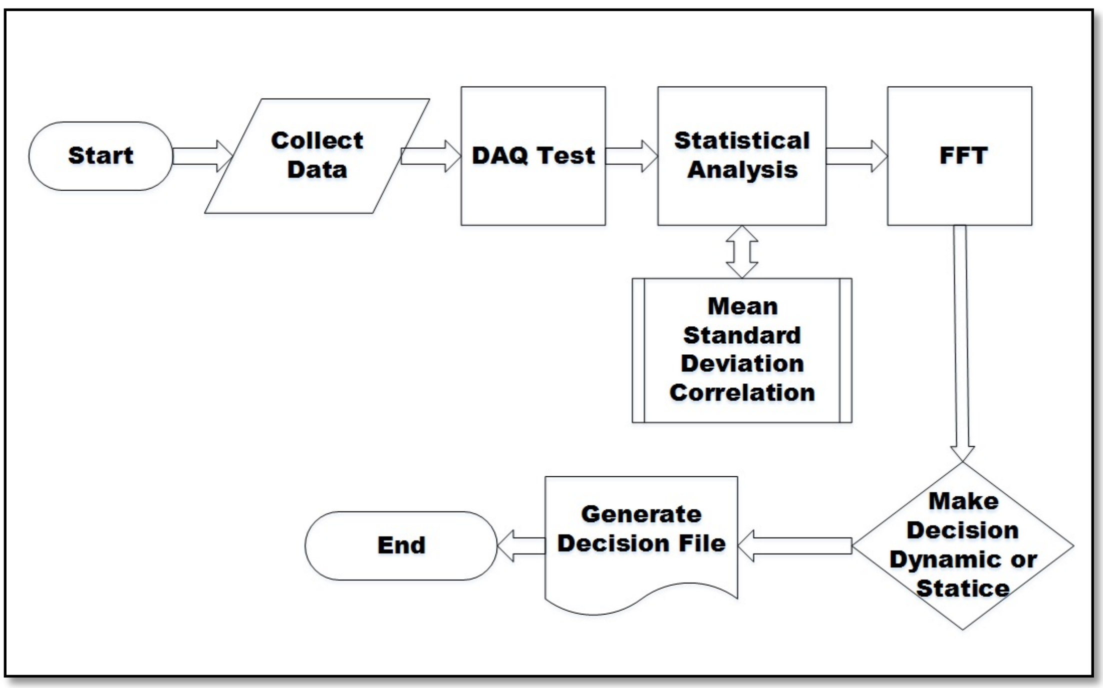

Figure 1 Basic Algorithm Steps

Data acquisition (DAQ)

Data acquisition (DAQ) module written for the embedded operating system provides the Narada wireless sensing unit with the ability to collect and store data or of real-time continuous data streaming to a server, the former being most useful in this application. The DAQ collects data from the node analog-to-digital converter (ADC) and stores it in SRAM. Data processing activities take place within the sensor node and only processed results are reported to the base station. Bridge managers may make a request from the remote visualization client to view raw sensor data from the sensors in upcoming detection cycles. In this case, the base station will request raw data from the WSUs as well, collecting it and uploading it to the remote server via cellular data link.

Statistical computation

Statistical modules have been added to allow the Narada to perform statistical analysis of the data collected. The algorithm is written so that the Narada can calculate the mean, standard deviation, correlation and the cross correlation between the sensors. Normal or Gaussian distribution is used to calculate the mean, standard deviation, correlation and the cross correlation. These measures (particularly standard deviation) can be compared to a threshold to determine whether the transducer is measuring static or dynamic signals. In addition, cross correlation measurements can be helpful in identifying cross-talk and other indications of faulty sensor channels.

Calculate the mean for all channels (for n samples):

$$\mu x = \left(\frac{1}{n}\right) \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Xi}$$

Calculate the Gaussian standard deviation for all channels:

$$Var = \left(\frac{1}{n-1}\right) \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{Xi})^2$$

$$\sigma = \sqrt{\mathrm{Variance}}$$

Calculate covariance between all channels:

$$cov(X,Y) = \frac{\sum_{i=1}^{n}(X_i - \mu_X)(Y_i - \mu_Y)}{n-1}$$

Calculate correlation coefficients:

$$r_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y}$$

Fast Fourier transform and frequency-domain analysis

The fast Fourier transform (FFT) modules have been written for the embedded operating system to provide Narada with the capability to perform frequency-domain analysis of the data. The FFT previously included has been altered to make it able to compute FFT for channels ranging from one to four. It also calculates the magnitude and phase angle of the FFT which is used to define the static/dynamic signal threshold. To conserve memory within the WSU, only the lower half of the FFT is stored in memory (*i.e.*, those values below the Nyquist frequency) owing the the lack of independent information contained in the remaining portion of the FFT results. For dynamic signal detection, only low-frequency values of the FFT are owing to the limited bandwidth of the fluid-coupled transducer output. Laboratory studies revealed that frequencies above 10 Hz generally did not contain signals corresponding to the vibrations of the whisker sensors in their submerged state. Rudimentary digital filtering of the signal above 10Hz was performed and the sum of the remaining FFT magnitude is used as the primary indicator of the presence of dynamic signals with large sums indicating dynamic behavior. High levels of signals in frequencies above 10 Hz and poor signal-to-noise ratios measure in the frequency domain were used as indicators of sensor faults.

Decision file and application of thresholds

A decision file ALGOTEST in "csv" format is created by the base station at the end of every scour monitoring test. The file informs the end user the time test was conducted, the unit numbers of the sensing units, used and the states of each transducer. Table 1 shows the states defined. The decision on whether the sensor is dynamic or static is made after comparing the mean, standard deviation and the magnitude of the frequency-domain analysis to a certain pre-assigned. These thresholds were determined for each transducer type after carefully studying the data collected in the laboratory tests. Decision integer is assigned to each sensor which informs the user about the state of the sensor. Figure 2 shows an example of the decision file created. In addition, sensor fault states including excessive noise and inconclusive (intermediary) flow states are also defined.

Table 1. Decision states

Decision Integers	**State**
0	Static State
2	Dilatory State
3	Transitional State
4	Dynamic State
5	Noise

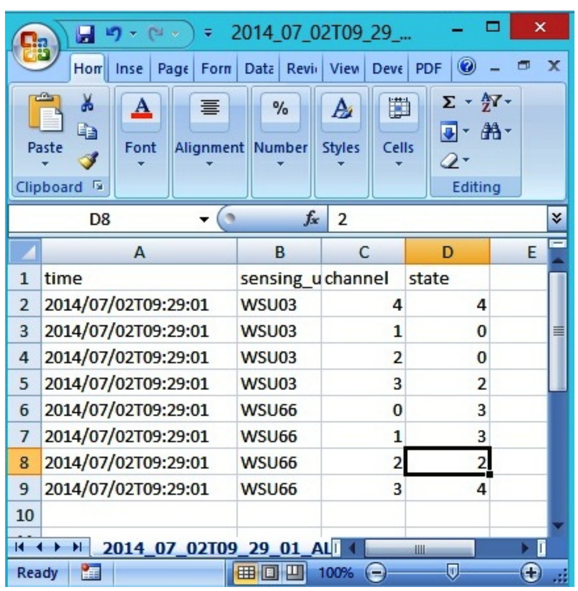

Figure 2. Decision File

This data is uploaded to the remote decision support client to be interpreted and presented to the end user. A summary of the entire test algorithm is depicted in Figure 3.

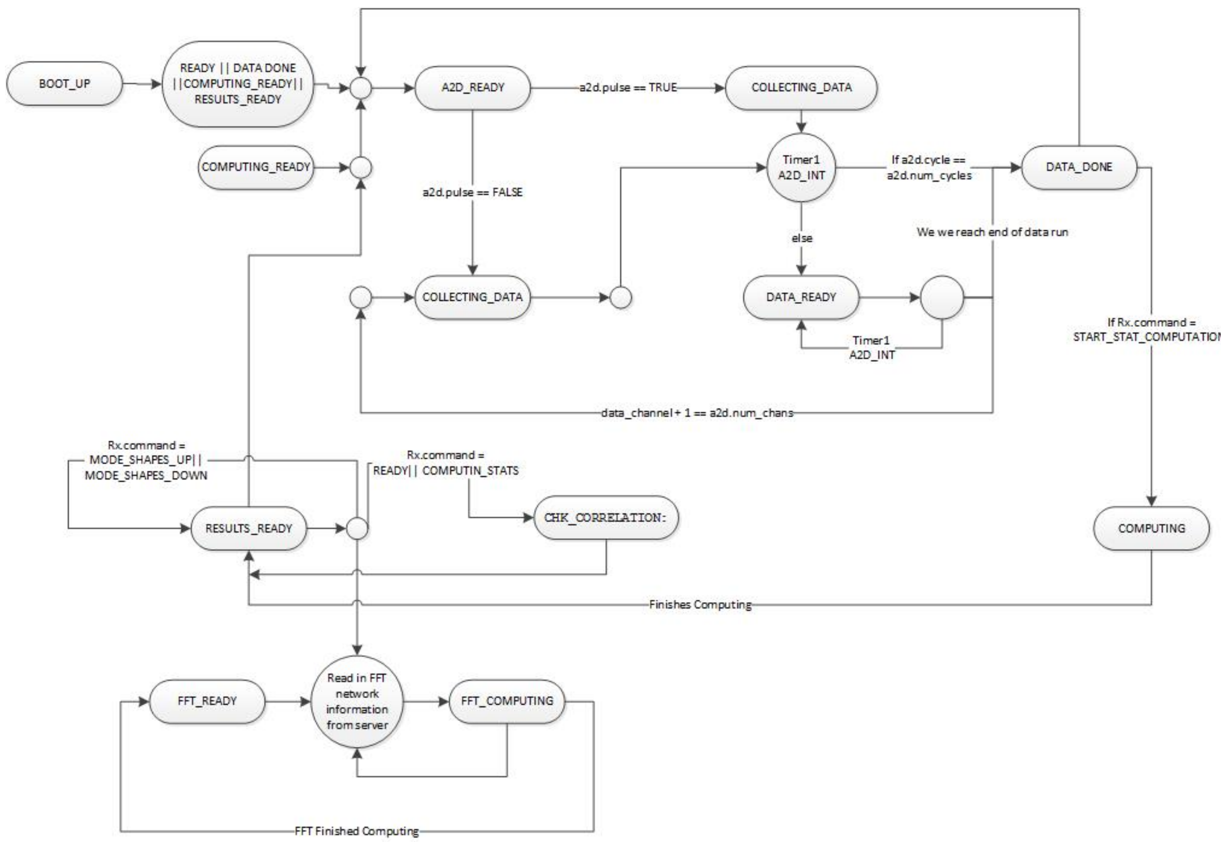

Figure 3. Flow chart depicting Narada WSU algorithm in scour sensing post

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