Automated Scour Monitoring Using Magnetostrictive Whisker Sensor Arrays

Presenter:

R. Andrew Swartz Michigan Technological University

Project sponsor:

Commercial Remote Sensing and Spatial Information Technologies program of the U.S. Department of Transportation (USDOT)
Office of the Assistant Secretary for Research and Technology

Project team:

Baibhav Rajbhandari, Benjamin D. Winter,

Brian Barkdoll, Jennie Tyrrell, Megan Mc Neil Michigan Technological University

Colin Brooks, K. Arthur Endsley Michigan Technological Research Institute

Alison Flatau, Suok-Min Na, Steven Day University of Maryland

Andrew T. Zimmerman, Civionics Inc.

Vital In-Kind Support:

MDOT

MDSHA

Michigan Tech
Michigan Technological University

Project Motivation

- Bridge scour is a major concern:
  - Most common historical cause of bridge collapse.
  - Difficult to detect underwater problems.
- State of scour in constant flux:
  - Large storms create high-velocity flows that carry away sediment.
  - Subsequent slower flows often redeposit sediment back around the bridge piers.
  - Annual measurements may miss peak scour events.
  - Embedded monitoring system required.
- Characteristics of scour detection system:
  - Automated, continuous measurements.
  - Measure, log, and report multiple transient events.
  - Unaffected by turbulent, icy, or sediment filled waterways.
  - Robust and long-lived.
  - Self diagnostics/failure detection.
  - Inexpensive to own and operate.

Thruway Bridge: Scour failure, New York.
(*Source: Associated Press, 1987*)

Extreme scour.
(*Source: Melville and Coleman*)

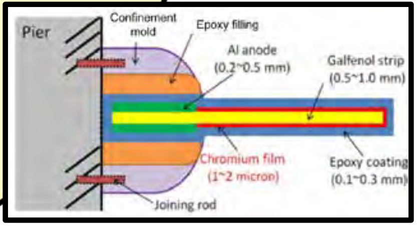
Ideal Scour Detection System

Permanent

- Always active:
  - Capture peak events
  - Issue warnings
- Automated operation

Robust

- Difficult to damage
- Works in many conditions:
  - Turbulent water
  - Suspended sediment
  - Debris and ice
- Long design life

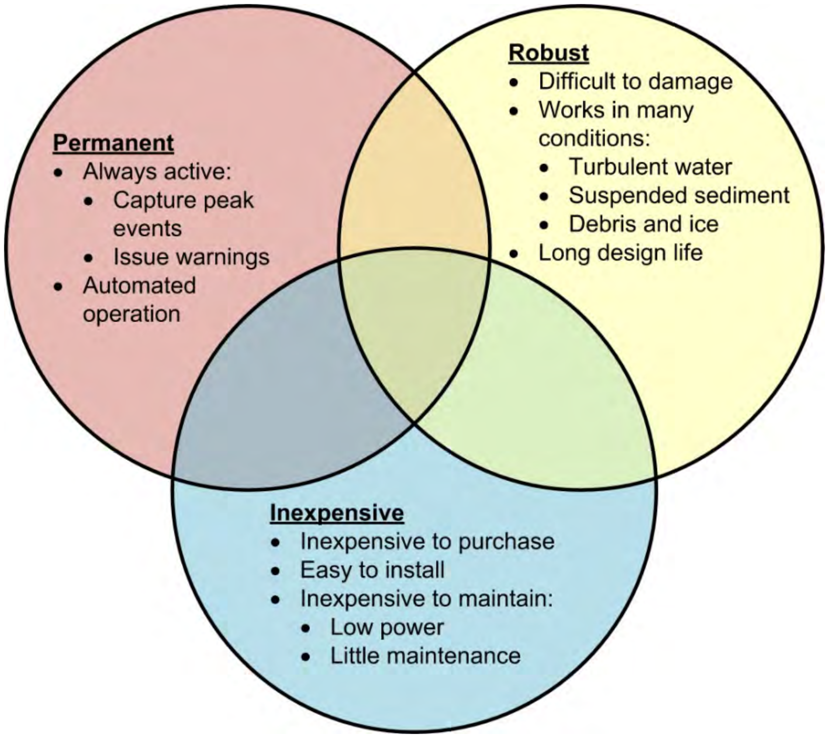


Inexpensive

- Inexpensive to purchase
- Easy to install
- Inexpensive to maintain:
  - Low power
  - Little maintenance

State-of-the-Art for Scour Detection

- Manual inspection:
  - Sounding rods/weights.
  - Divers.
- Embedded instrumentation:
  - Sonic depth sounder.
  - Sliding collar devices.
  - Subsurface geophysical methods:
    - Continuous seismic-reflection profiling (CSP).
    - Ground penetrating radar (GPR).
  - Broadband acoustic Doppler current profiler (BB-ADCP).
  - Time-domain reflectometry.
  - Tilt-meters/accelerometers.
  - Buried radio-frequency (RF) sensor “fish”.
  - Buried-rod instrumentation systems.



Magnetostrictive Scour Sensor Array

- Array of magnetostrictive flow sensors mounted to pier:
  - Galfenol whiskers bend in river current.
  - Higher flow rates result in greater bending of whisker sensor.
  - Small perturbations in flow rate are natural.
- Buried sensors will appear to indicate static flow rates:
  - Channel bed line can be inferred from positions of sensors returning static versus dynamic flow readings.
  - Detects scour or channel aggradation.
  - Overtopping alerts possible too.
- Sensor failure detection:
  - Sensor array provides redundancy.
  - System must detect faulty sensors.

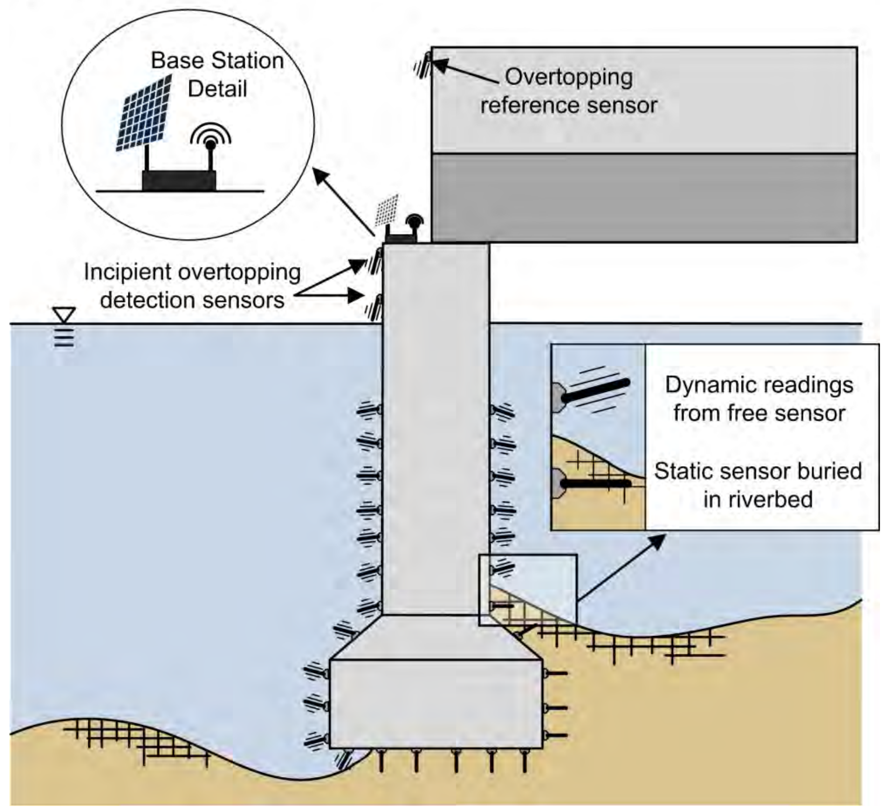
Monitoring:
- Array of bio-inspired flow sensors
- Riverbed depth estimation

Detection:
- Pier undermining
- Channel aggradation
- Abutment erosion or outflanking

Computation:
- Scour forecasting from flow data
- Sensor fault detection

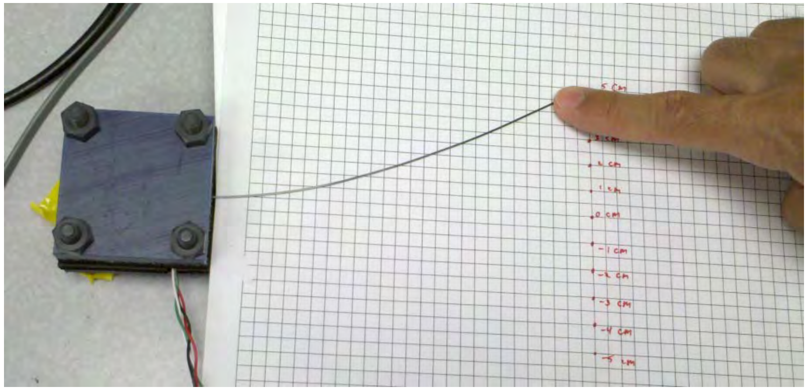
Communications:
- Issue warnings to DOT or police via cellular data network link
- Close gates to stop traffic if severe scour conditions present

Power:
- System to be solar powered where utility grid connection is unavailable



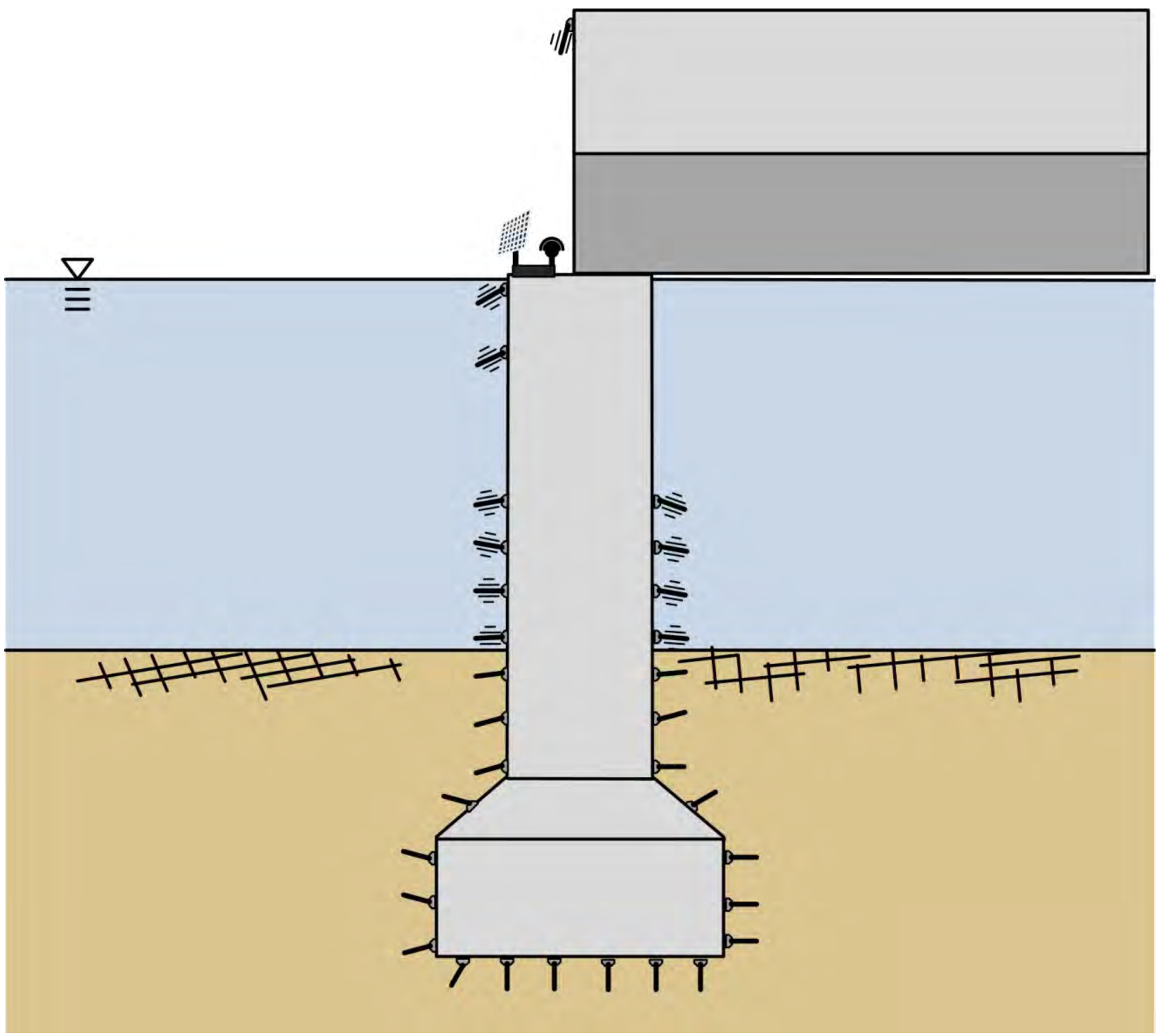
Magnetostrictive Flow Sensor

- Biologically-inspired flow sensor:
  - Galfenol/alfenol cantilevered beam (whisker).
  - Strain and magnetic field are coupled.
  - Fluid flow bends the beam.
- Developed as an airflow sensor:
  - Very effective in water.
  - Rugged and durable transducer:
    - As compared to PZT.
    - Coated to protect from corrosion.
  - Inexpensive sensors:
    - Galfenol wire is inexpensive to produce.
    - Hall effect sensor from computer hard-disk drive.
- Calibration requirements for proposed application are minimal:
  - Need to discern between static and dynamic signals, not between differing complicated signal patterns.



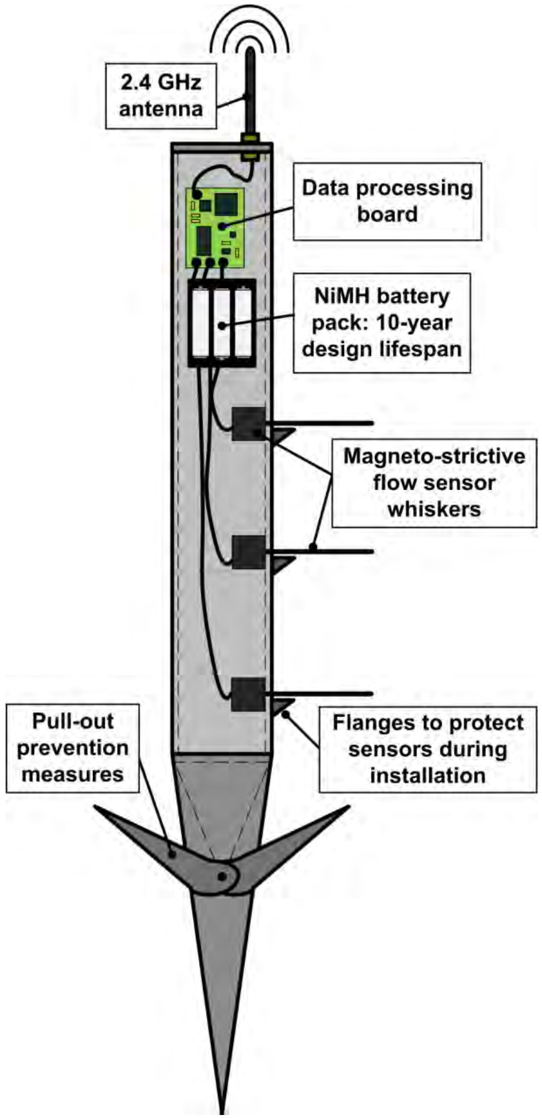
Large operational range of Galfenol flow sensor.

Operation of Sensor Array



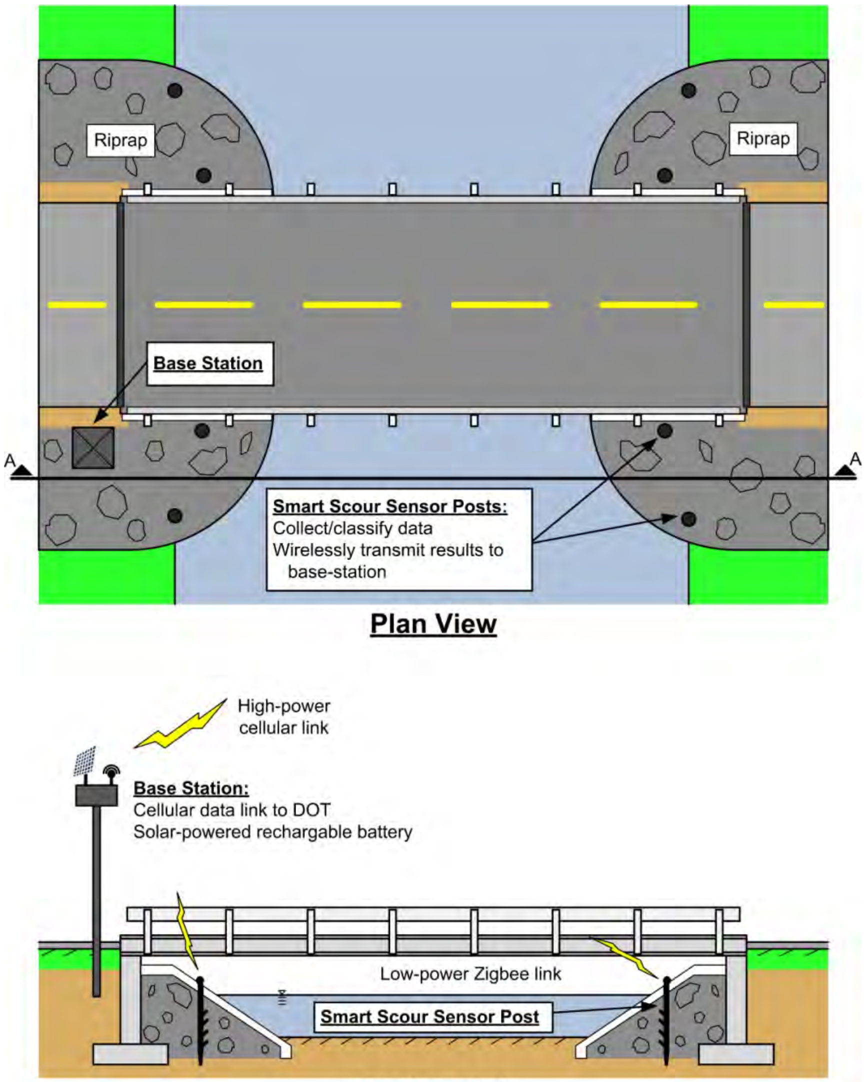
Incipient Overtopping

Smart Scour Sensor Post



- Modular sensor posts for scour detection:
  - Contains magnetostrictive flow sensor whisker array:
    - Number of transducers may be variable.
  - Driven into the ground in scour sensitive areas.
  - On-board electronics interrogate raw data.
  - Battery powered; desired design life = 10 years.
  - Low-power wireless transmitter sends processed results to base station:
    - External antenna for best results.
    - Internal antenna with reduced range.
- Base station:
  - Aggregates data from multiple sensor posts.
  - Contains cellular data link.
  - Solar power cells to recharge batteries.

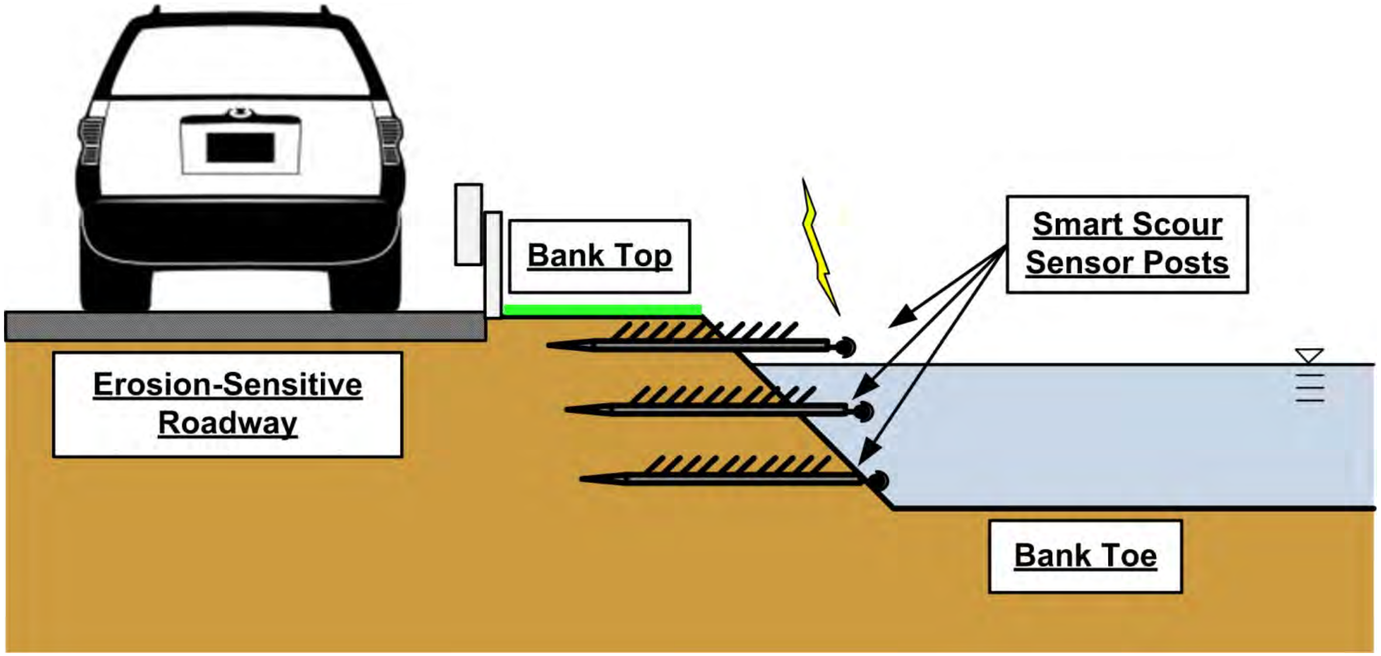
Smart Scour Sensor Post: Abutments



Plan View

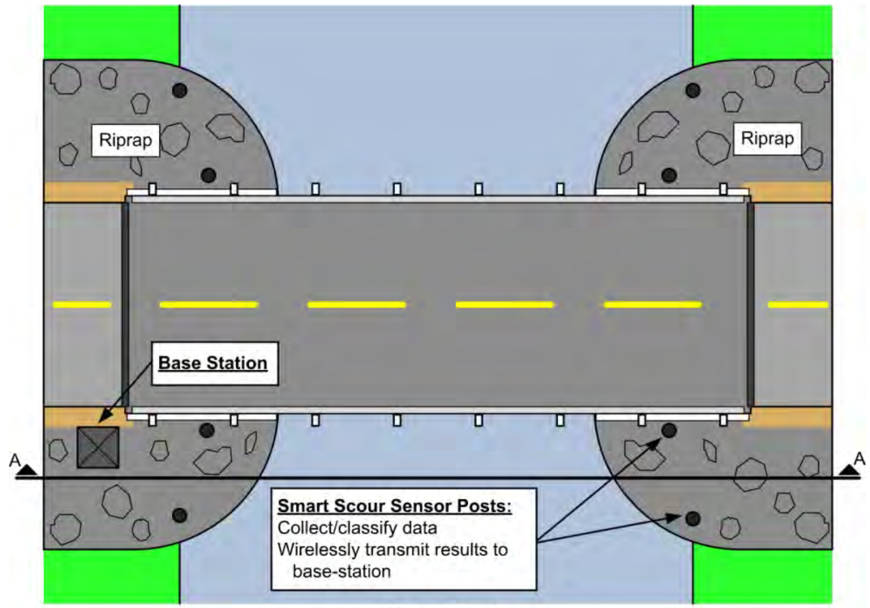
Section A-A

Smart Scour Sensor Post: Banks

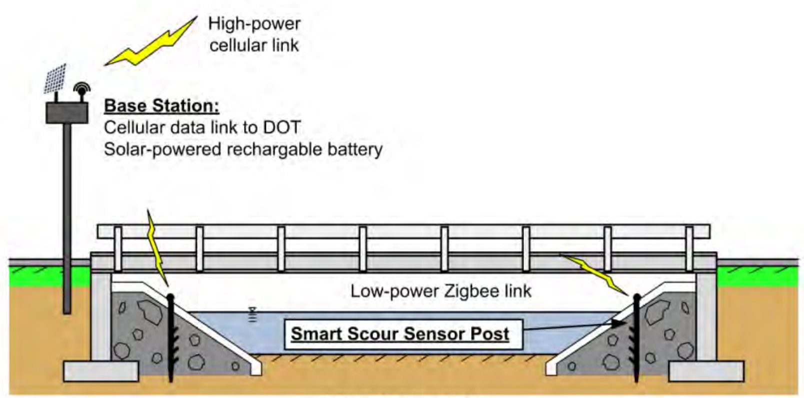


Advantages of Proposed System

- Permanent:
  - Always on – captures transient events.
  - Can always issue warnings.
  - Can capture multiple scour cycles.
- Simple data analysis:
  - Can be automated with great accuracy.
- Inexpensive:
  - System composed of inexpensive components.
  - Transducers are self-powered.
- Highly robust:
  - Galfenol whisker sensor significantly more robust than piezoelectrics and fiber-optics.



Plan View



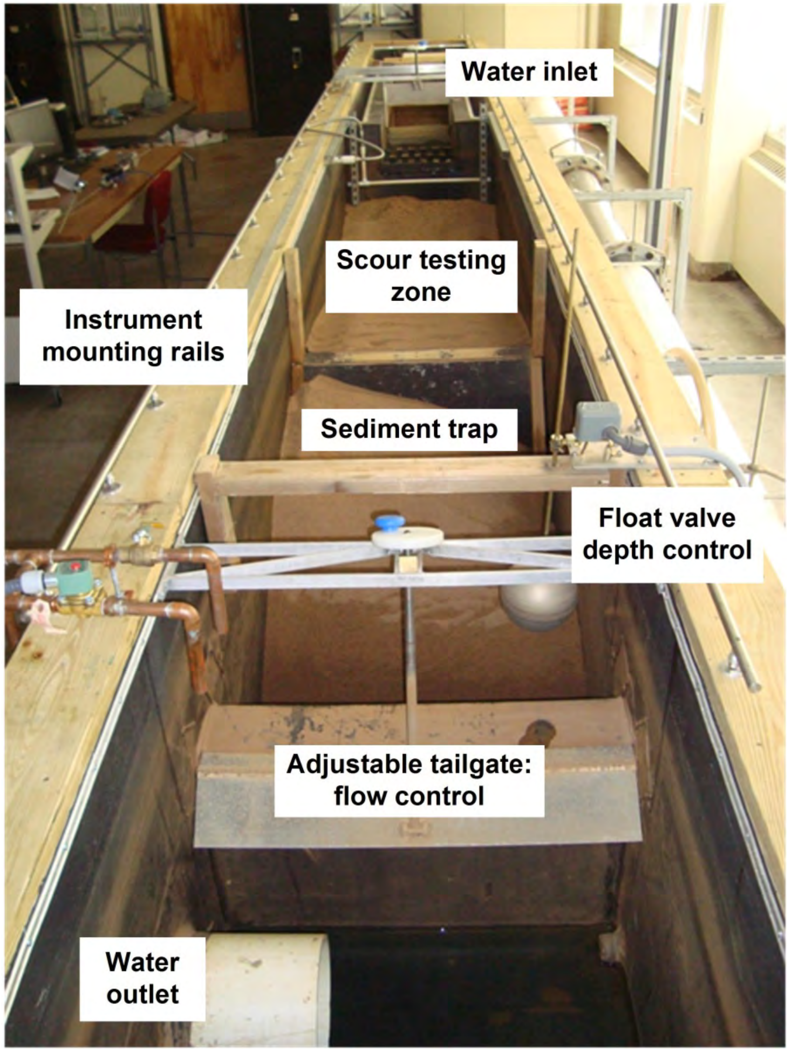
Section A-A

Laboratory Validation Study

- Perform proof-of-concept experiments in controlled environment.

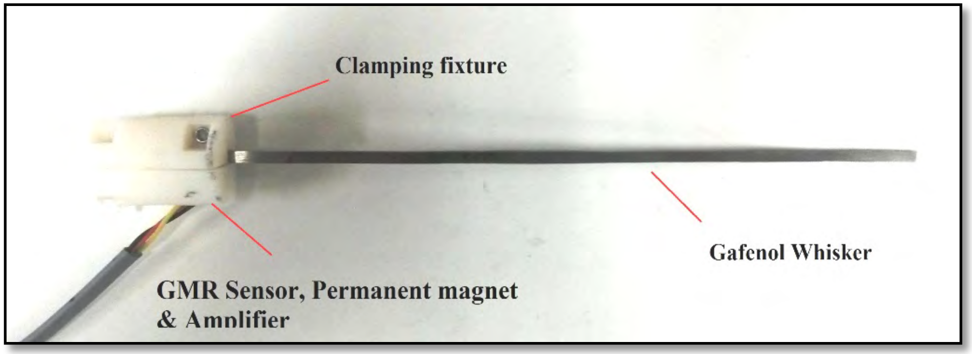
- Characterize typical dynamic signatures for varying conditions:
  - Fast and slow velocities.
  - Turbulent and low-turbulence flows.

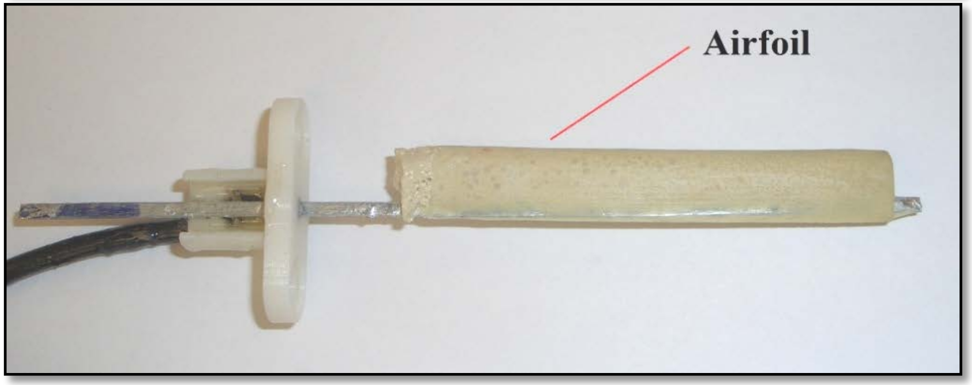
- Experiment with methods to increase sensor dynamics.

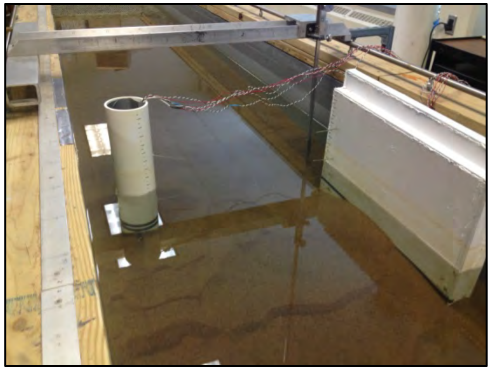


Laboratory Study

- Model phases:
  - Pier and abutment study:
    - Able to demonstrate concept.
    - Collect library of whisker sensor outputs for classification.
  - Riverbank stability study.

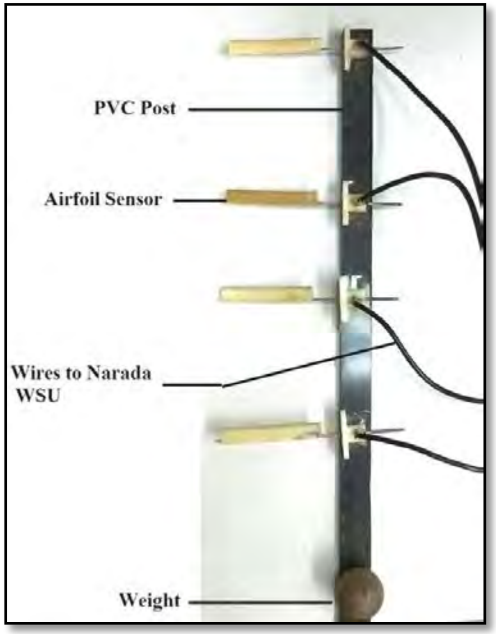


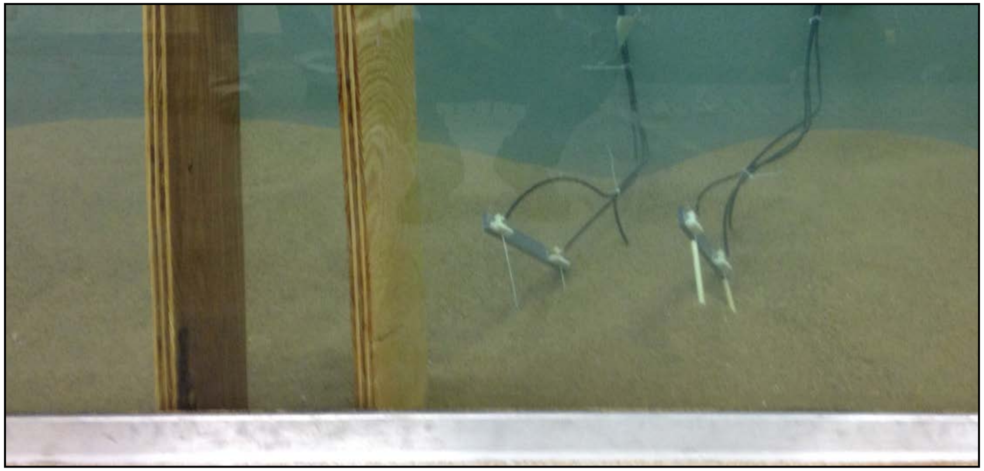




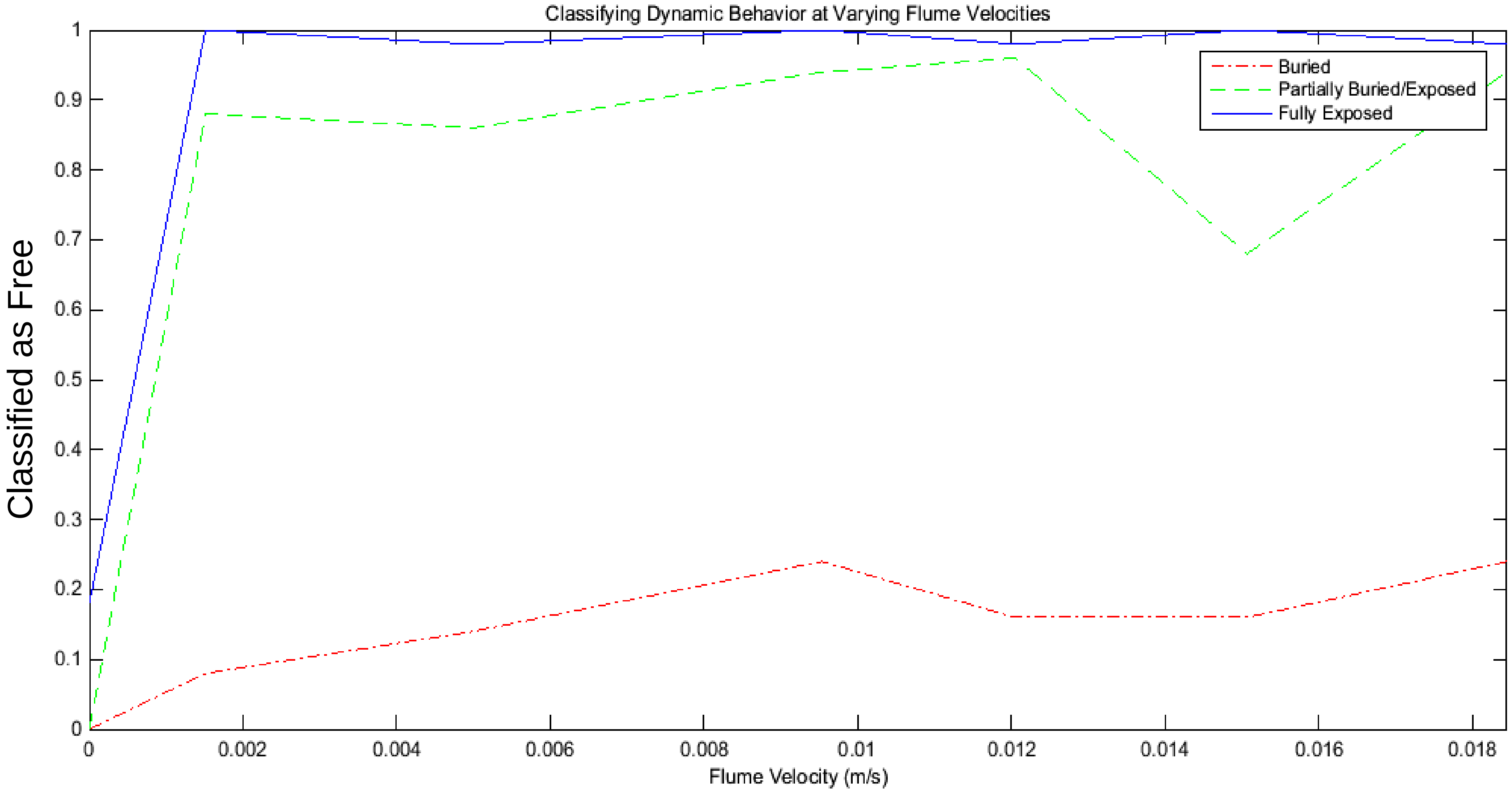
Laboratory Study

- Riverbank stability study:
  - Tested submerged conditions (more data).
  - Some scale issues due to size of flume and whiskers.

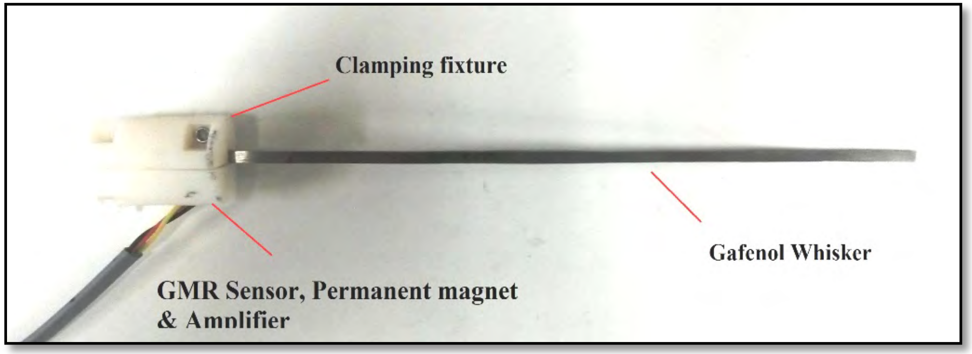




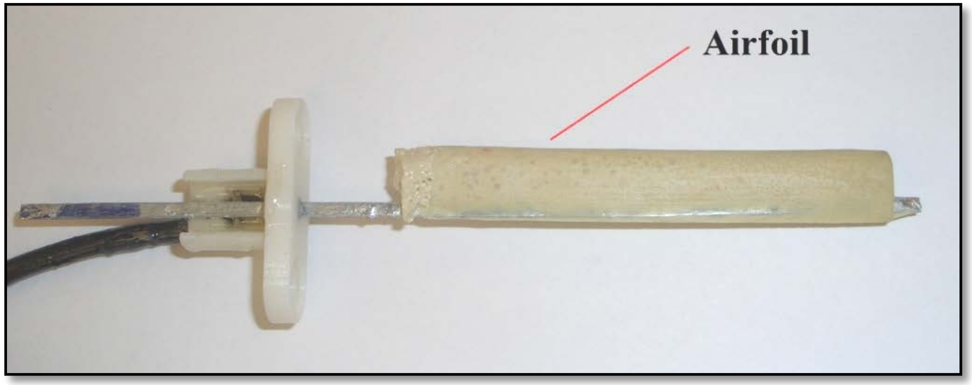
Laboratory Study – Whisker Sensitivity



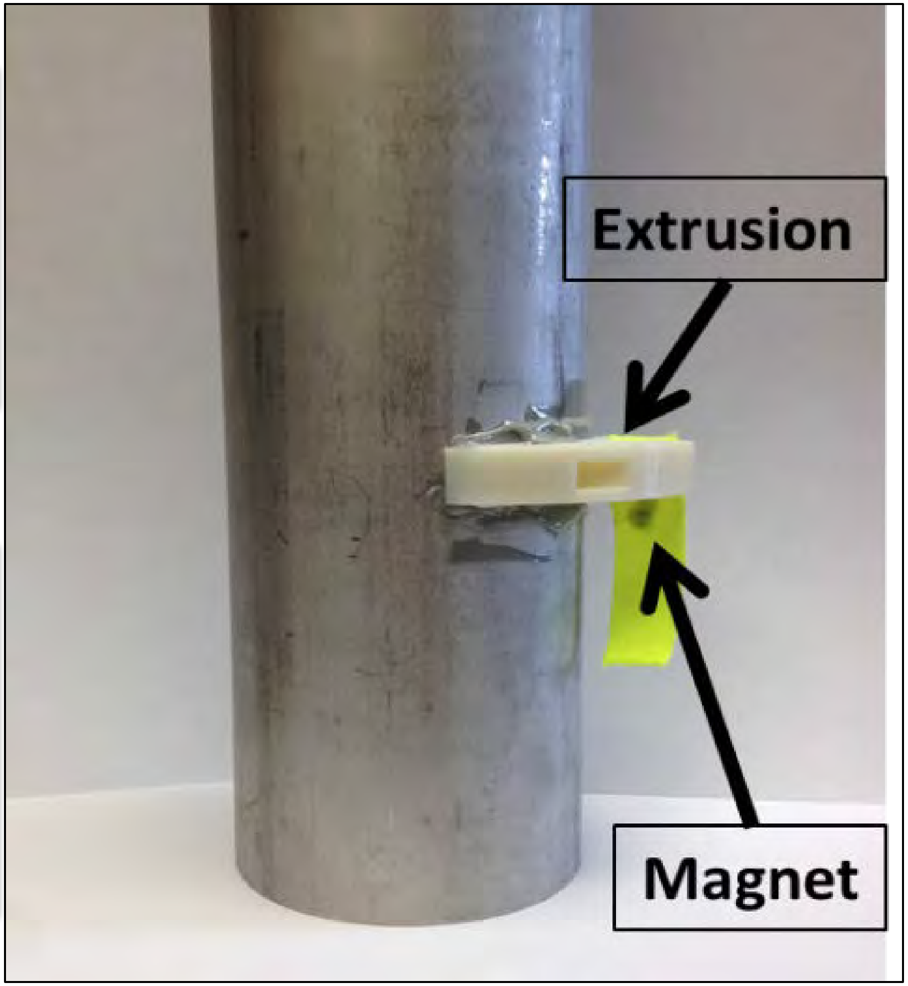
Transducer Enhancement



Whisker Sensor.



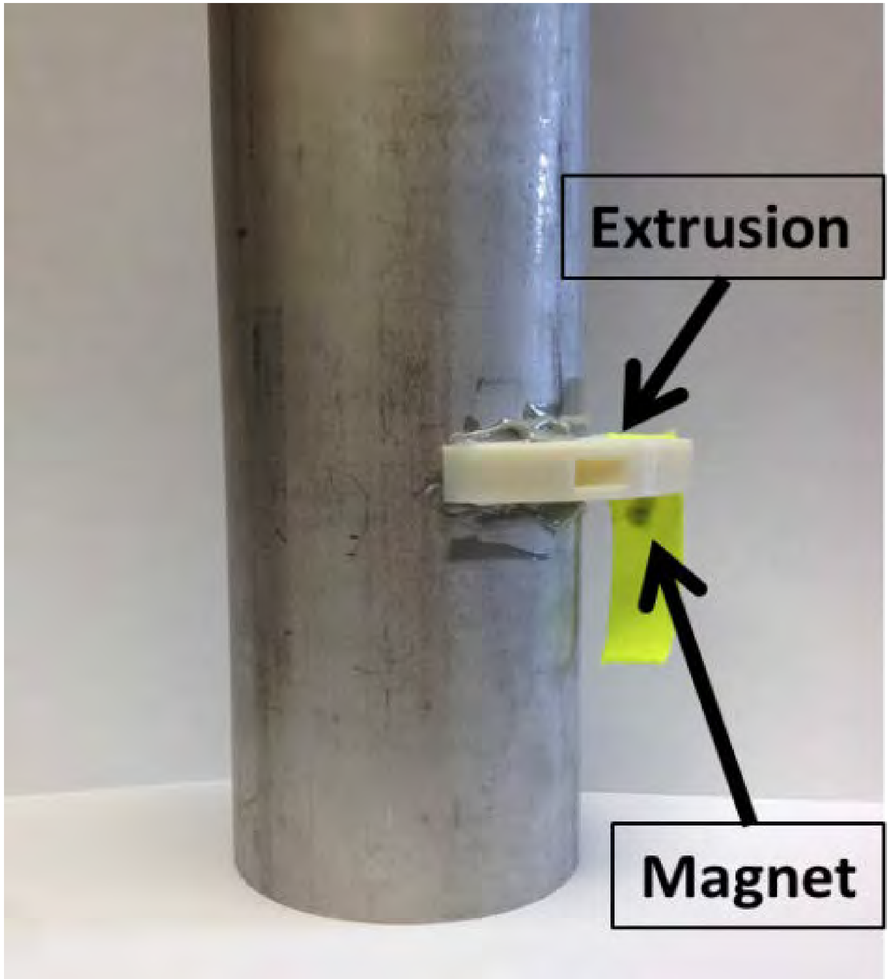
Airfoil Sensor.



Seaweed Sensor.

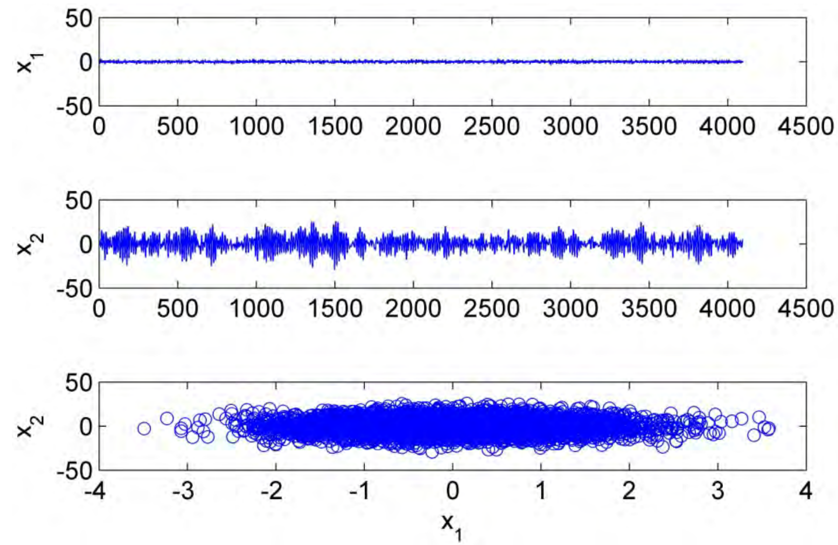
Magnetostrictive Fiber "Seaweed"

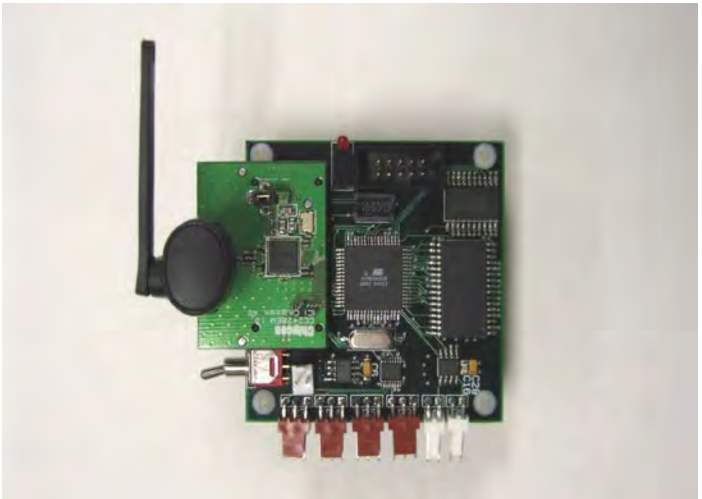
- Low-velocity flows and debris are serious concerns:
  - Limited signals generated in metal whiskers.
  - Susceptible to breakage at base under high loading rates and high numbers of fatigue cycles.
- Fiber-based seaweed sensor configuration is more flexible and is likely to be more durable.



Signal Processing Tasks

- Build library of signal signatures:
  - Turbulent flow.
  - Laminar flow.
  - Air excited sensor.
  - Sensor faults.
- Establish classification criterion and thresholds:
  - Signal magnitude.
  - DTFT.
  - Fault signal detection.
- Interrogate spatial information:
  - Bed detection algorithm.
  - Overtopping detection algorithm.

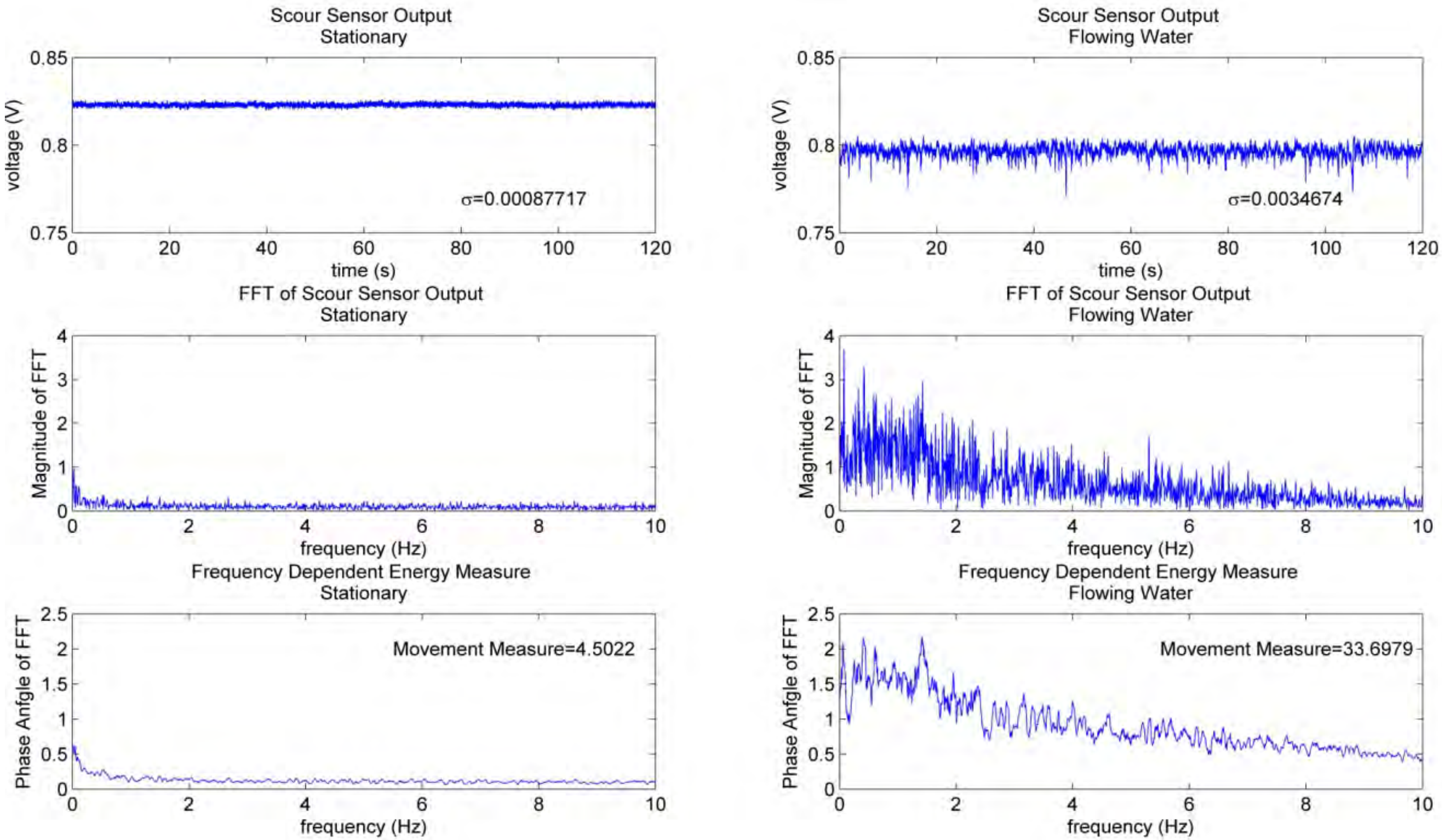




Embedded wireless sensing and data interrogation platform.

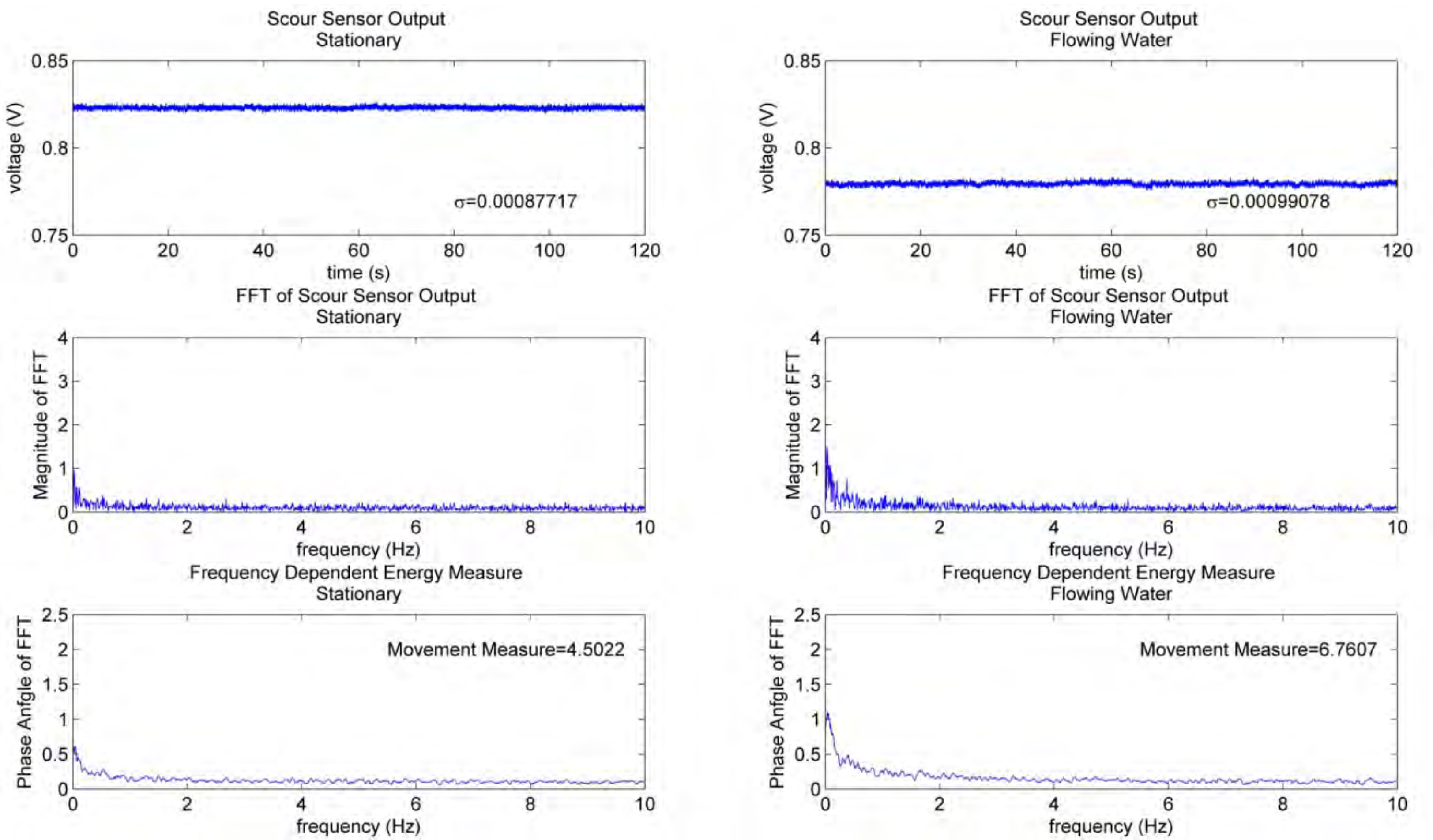
Signal Processing

- High-velocity flow:



Signal Processing

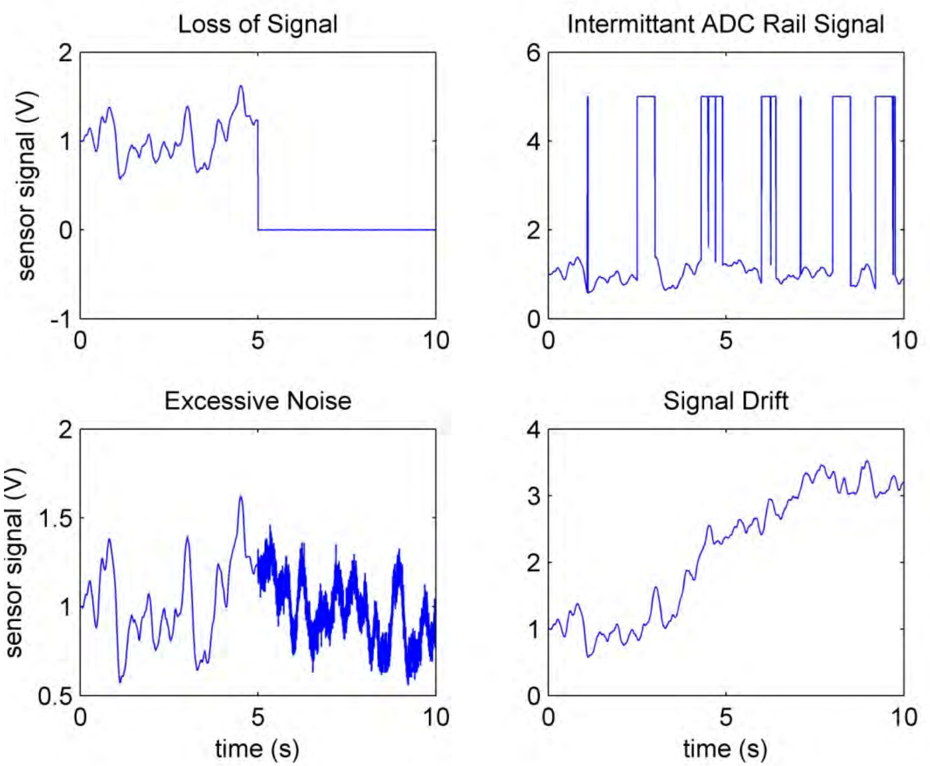
- Low-velocity flow:



Sensor Fault Detection

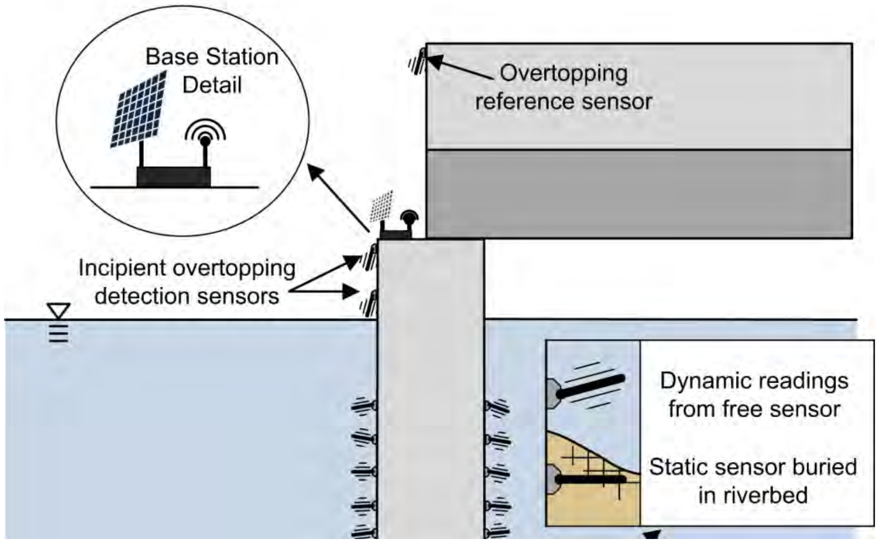
- Electronics are prone to failure over time:
  - Array of sensors provides some redundancy.
  - Need to autonomously identify faulty sensors and exclude their output.
- Algorithm will identify common sensor faults:
  - Loss of signal.
  - Intermittent railing.
  - Excessive noise.
  - Drift.
- Geometrically anomalous behavior will be flagged:
  - Sensor failure.
  - Impingement by debris.

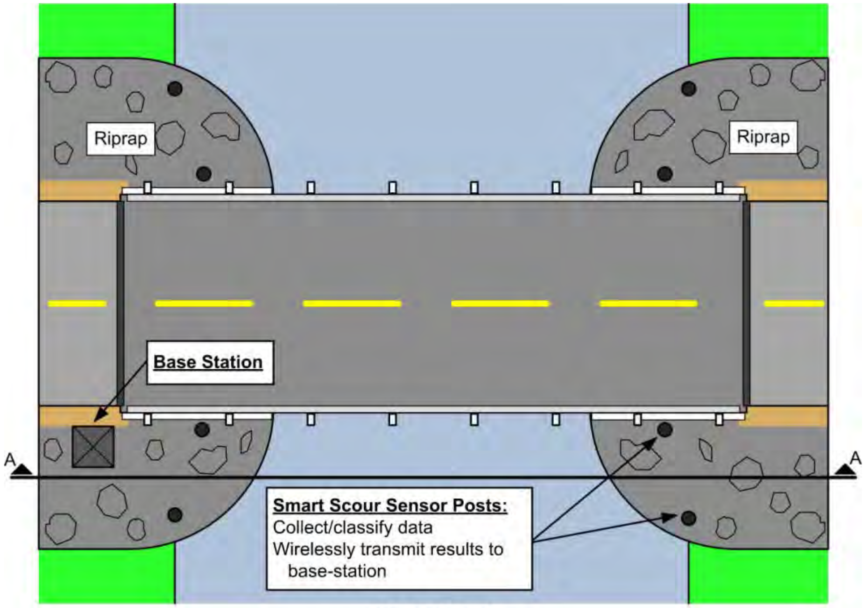
Common sensor failure modes



Embedded Monitoring System

- Automated data interrogation is key component of proposed system.
- Base-station aggregated data from bridge site:
  - Link to command and control:
    - Local area network (LAN).
    - Cellular data network.

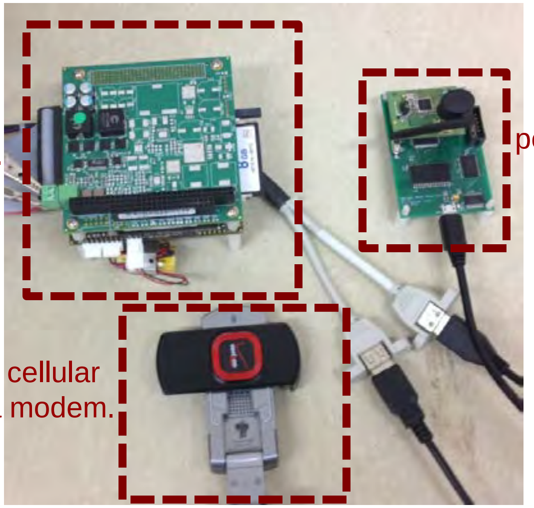




Plan View

Single board computer with Linux installation.

Zigbee low-power wireless modem.

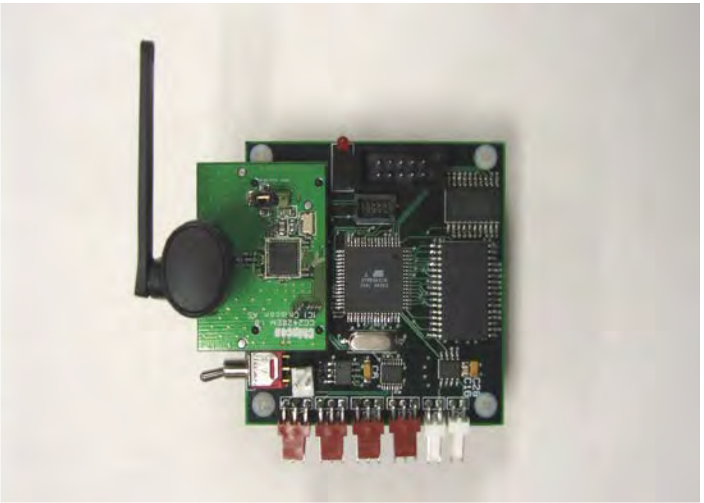


G4 cellular data modem.

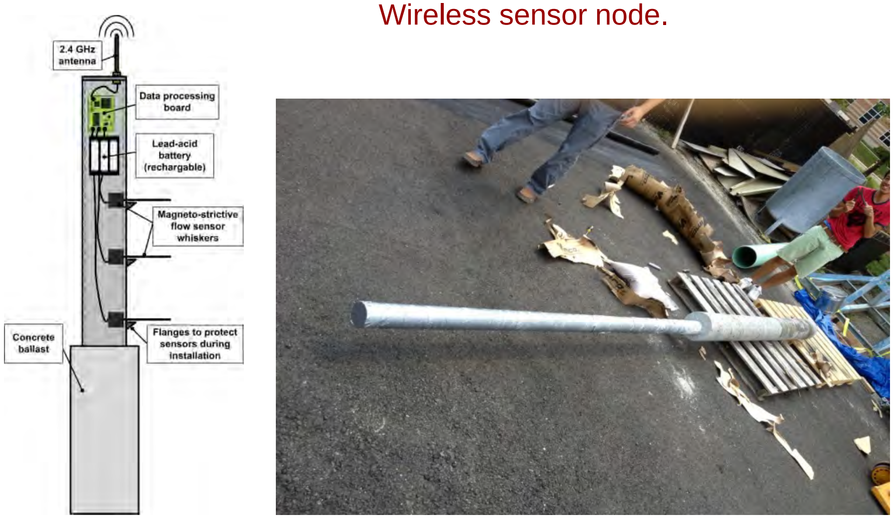
Components of embedded wireless base station.

Modular Smart Scour Sensing Posts

- Modular installation of sensor transducers at and around bridges:
  - At abutment.
  - At pier.
  - At edge of riprap.
  - At riverbank.
  - Up channel.
- Installed using hollow stem auger.
- Embedded sensing platform:
  - Low-power.
  - Low-cost.
  - Automated data interrogation.
  - Scavenge power from environment:
    - Solar power.
    - Thermal gradient.



Wireless sensor node.



Embedded wireless sensing and data interrogation platform.

Wireless System

- Communication:
  - On-site: IEEE802.15.4
  - Remote to DOT: 4G Cellular
- Power management:
  - Low-power microcontroller controls power to the system
  - Turns on system daily for 10-minute interval
  - Resynchronization of power managers twice daily over low-power channel (within 1s)

Base station.

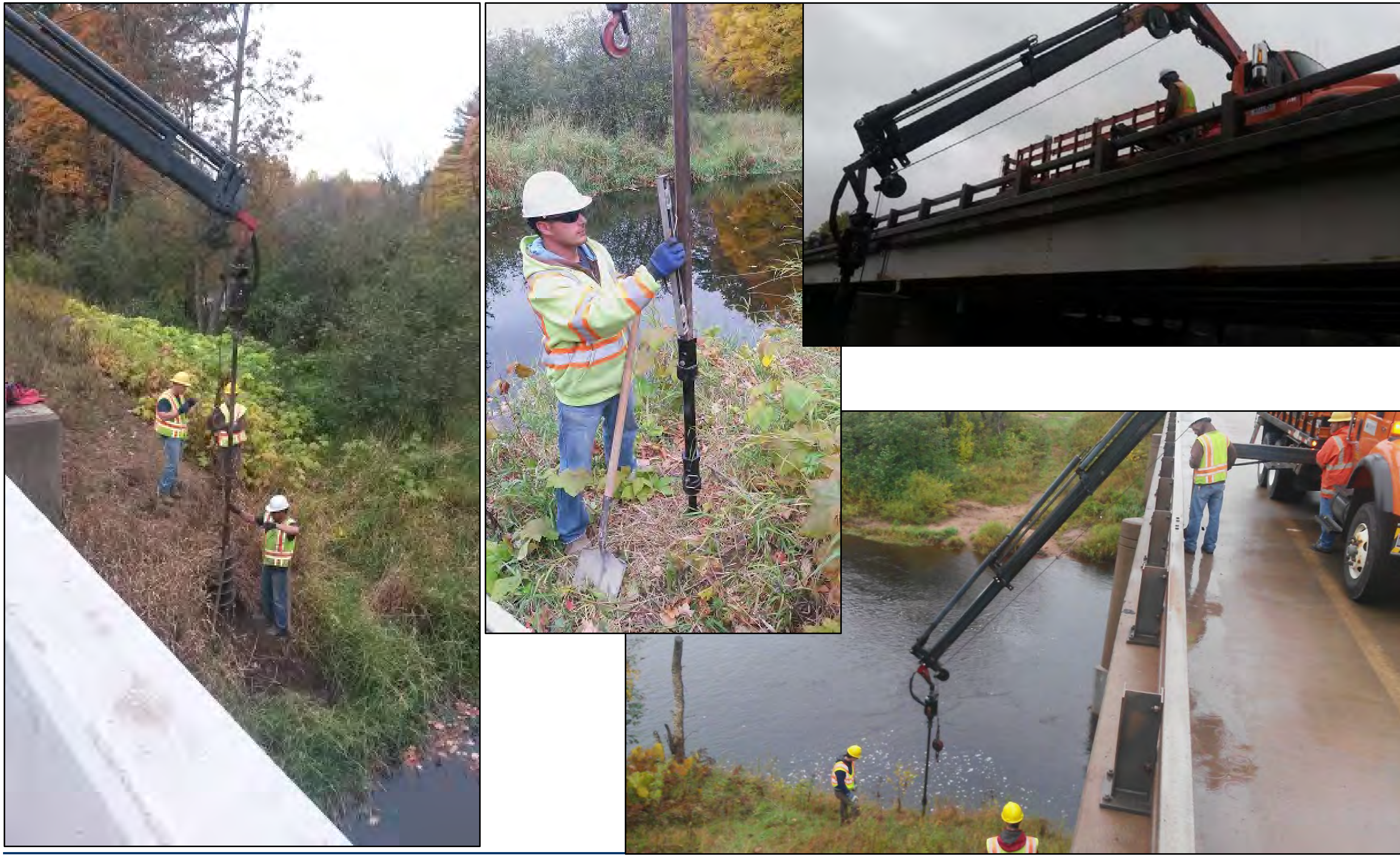
Post electronics.

Power manager.

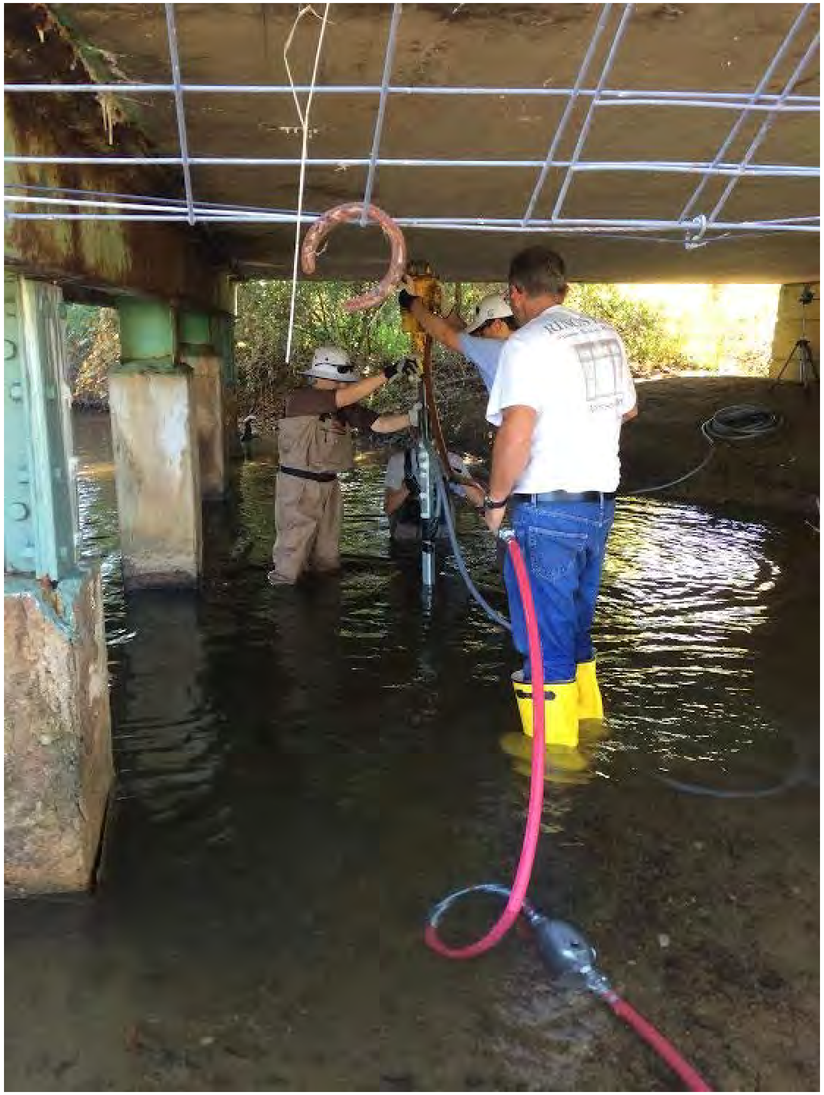
Auger Installation (Wet)

Photos from Alison Flatau, UMD.

Auger Installation (Dry)



Vibrationally Driven Installation



- Most versatile installation method:
  - Wet or dry installations possible.
  - Highly portable equipment.
  - Segmented pipe allowed for longer posts.
- Rapid installation.

Photo courtesy of Alison Flatau (UMD)

Vibrationally Driven Installation

Video courtesy of Alison Flatau (UMD)

Riverbank Monitoring

Photo from Steven Day, UMD.

Photo from Steven Day, UMD.

MI Field Validation Sites

- 2 Michigan field validations sites installed in October, 2014:
  - Pilgrim River.
  - Sturgeon River.

Pilgrim River Bridge; US41.

Sturgeon River Bridge; M38.

MI Field Validation Sites

- Pilgrim River Site:
  - 2 Posts on upstream side of bridge at abutments.
  - Scour-critical bridge, shallow foundations, loamy soil, high organic content.

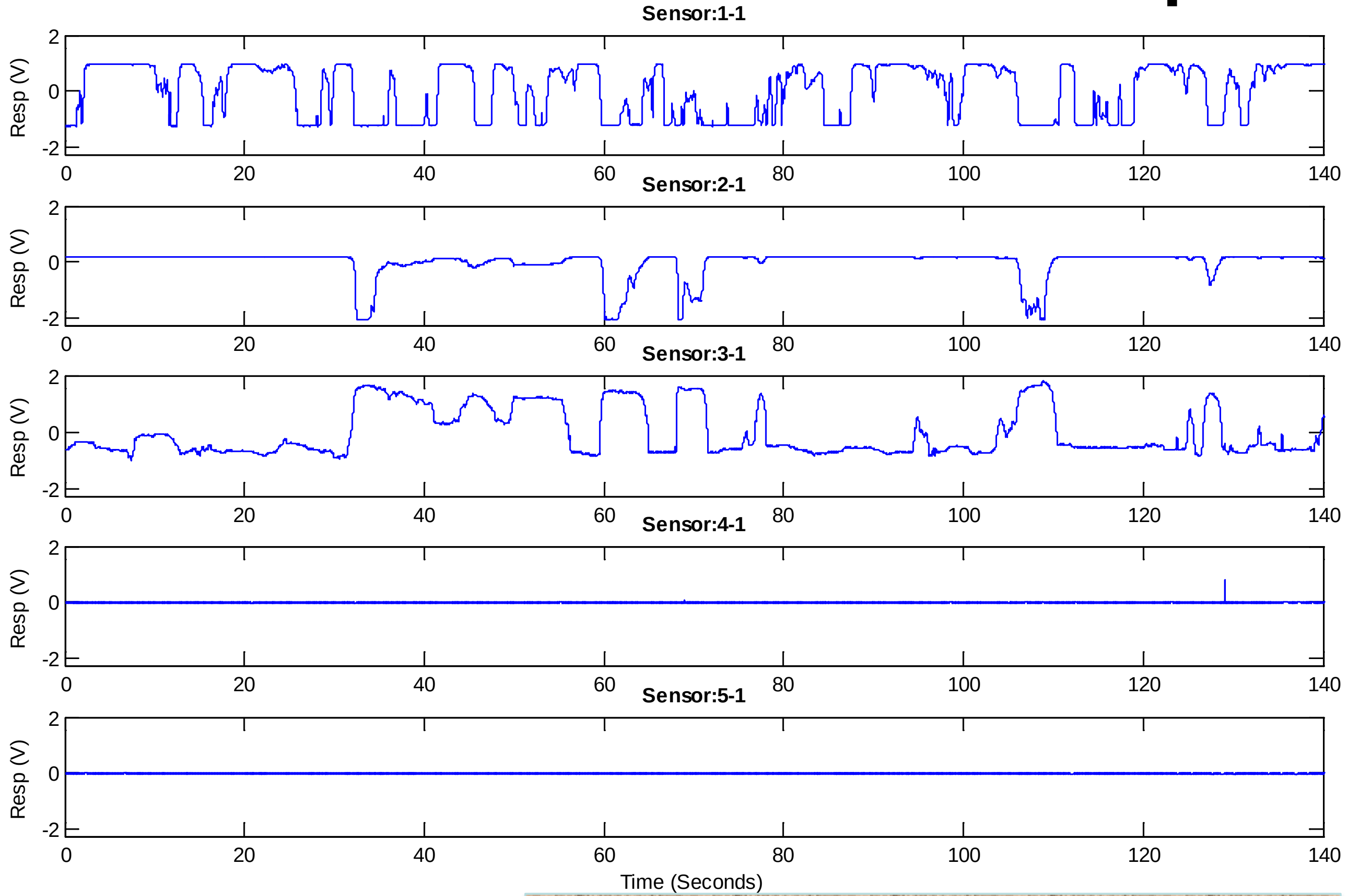


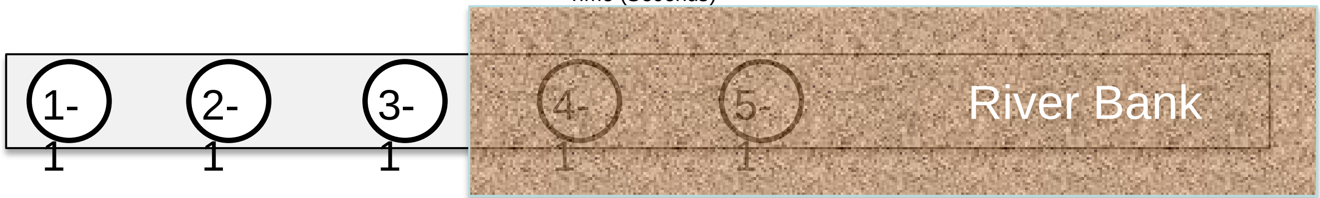

MI Field Validation Sites

- Sturgeon River Site:
  - 2 Posts on upstream side of bridge, at abutment and at pier.
  - Scour-critical bridge, shallow foundations, sandy soil.

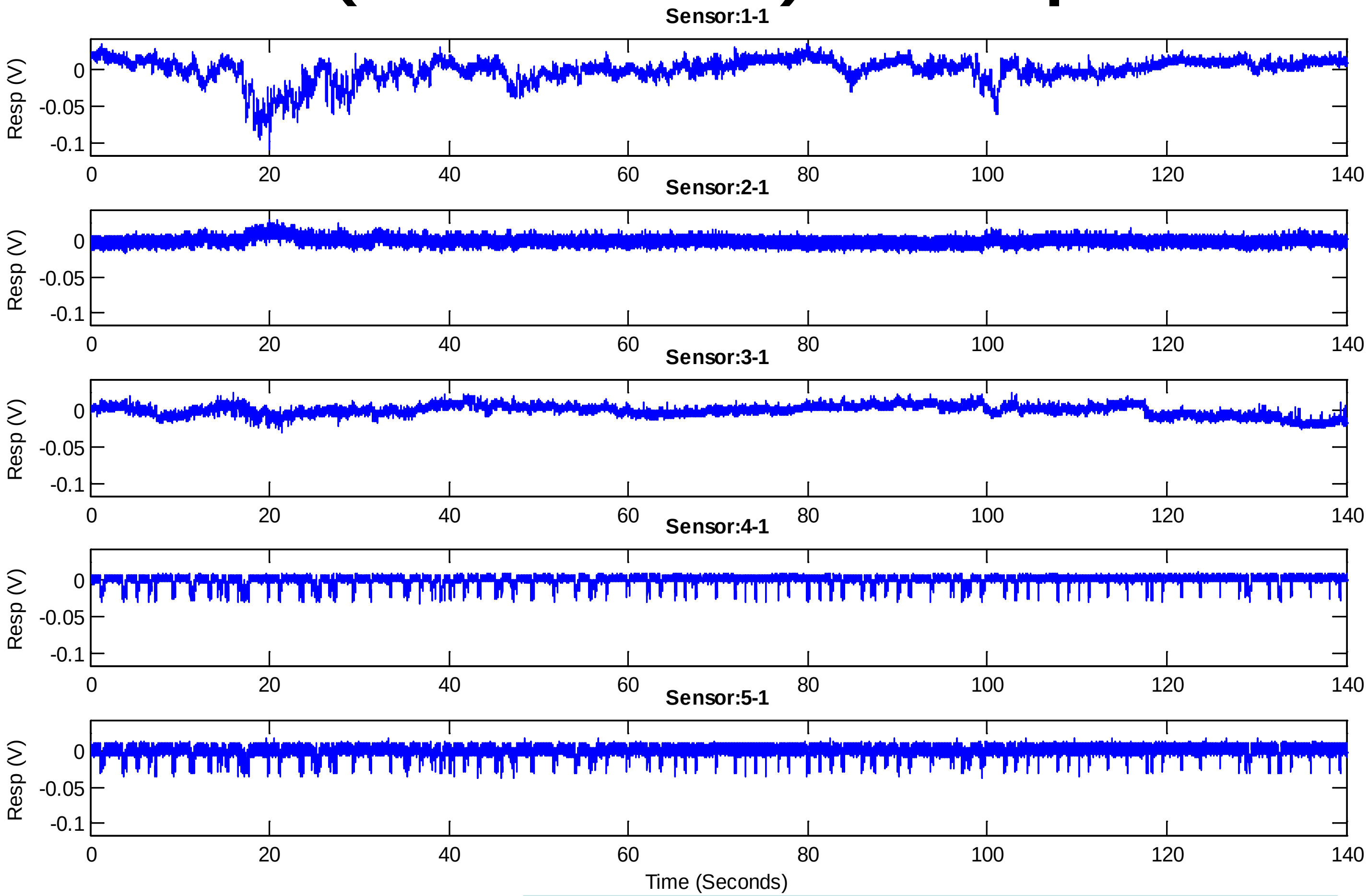
Autonomous Base Stations

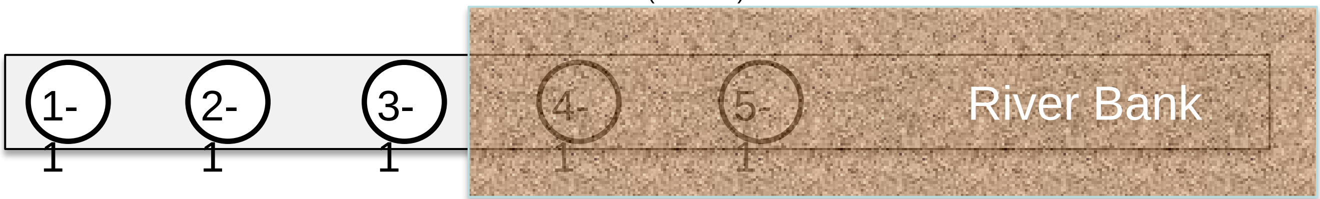
Underwater Seaweed Response





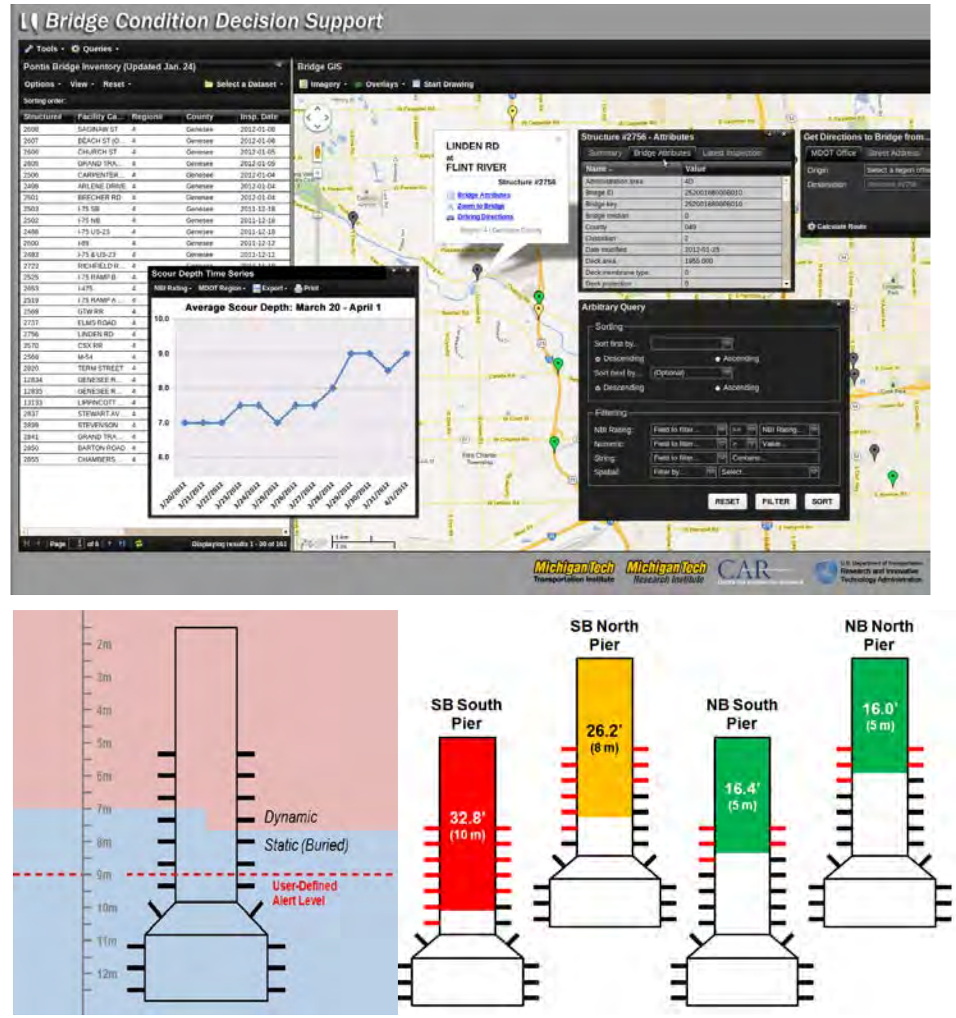
In Air (low wind) Response





Decision Support

- Decision support client should maximize autonomy, provide remote access:
  - Data repository.
  - Presentation of information via web client.
  - Query remote sensors for additional information.
  - Automated alerts under user-defined conditions.
- Global versus bridge-level information:
  - Network of bridges.
  - Single bridge details.



Proto Decision Support Client.

Client-Side View

- Single event for channel 0 spanning entire year.
- Multiple events for channel 1, none have been dismissed so all contribute to severity rating.
- One event for channel 2.

summary

MD 450 - BACON RIDGE BRANCH

Bridge Id: 100000020072010
Location: 0.89 MI E OF RUTLAND RD
Number of Alerts: 9
Severity Rating: 225

Sensor	Channel	State	Scour Depth	Status	Start	End
TST01	0	Minor Scour	4	Minor Scour	2020/01/01 00:00:00	2020/12/13 05:10:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/11/02 09:40:00	2020/11/03 06:20:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/10/22 01:50:00	2020/11/01 06:50:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/08/31 01:50:00	2020/09/01 10:10:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/08/23 20:40:00	2020/08/28 20:00:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/08/13 14:20:00	2020/08/20 06:40:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/07/24 03:20:00	2020/07/25 23:20:00
TST01	1	Moderate Scour	5	Moderate Scour	2020/07/01 12:30:00	2020/07/11 16:00:00
TST01	2	Severe Scour	6	Severe Scour	2020/10/22 20:40:00	2020/10/22 21:10:00

Top 10 Scour Critical Location View

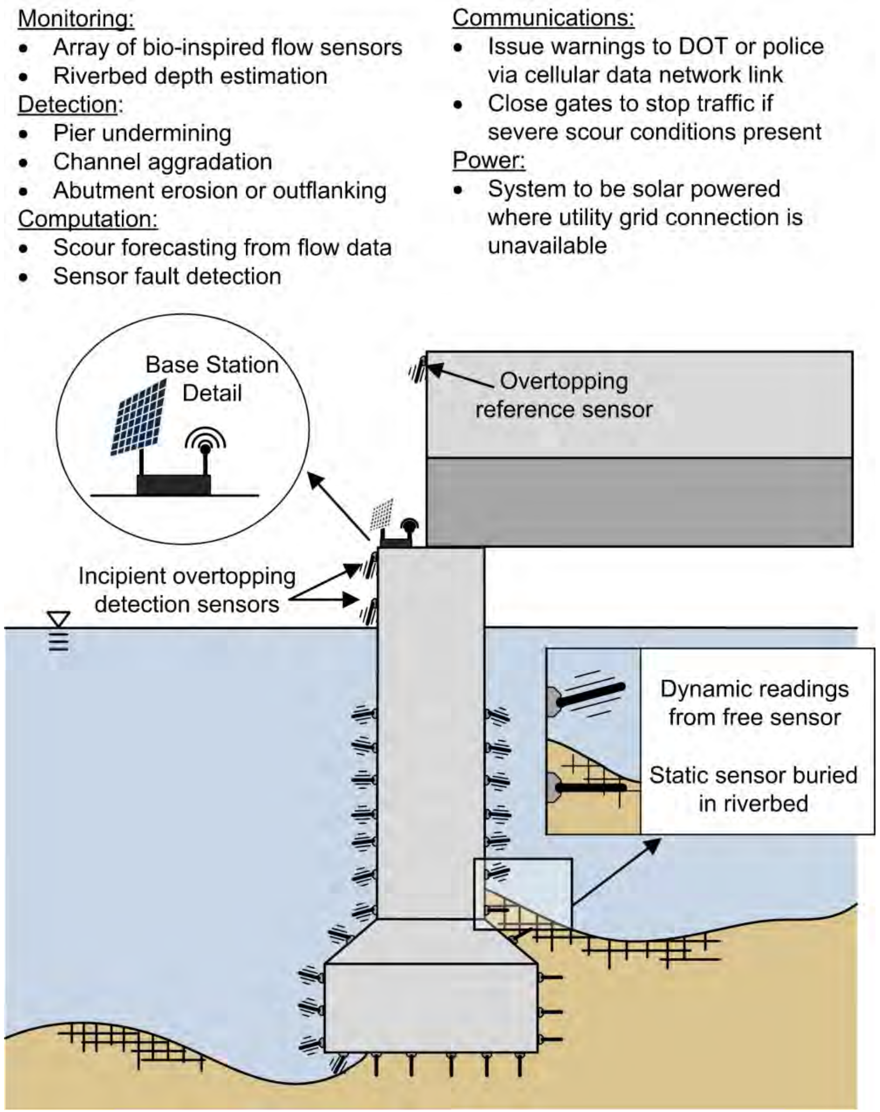
- Lists up to 10 bridges with the highest severity ratings:
  - Clicking on a link zooms to the bridge and opens the summary view.

Decision Support System Objectives

- Details panel will offer more comprehensive view of a bridge and associated data:
  - Graphical view of past alerts and sensor states.
  - Display sensor location and configuration.
  - Dismiss alerts that are no longer relevant to the user.
- Alert panel:
  - Allow user to register sensor/channel with alert keys to generate future alerts.
  - Set up new alert keys if existing ones do not cover a particular case.

Conclusion

- Proposed system is simple and cost effective:
  - Robust sensors will survive in difficult conditions.
  - Inexpensive components make it suitable for mass installation.
- Automatically captures and logs peak scour events:
  - Simplicity of algorithm leads to better autonomy.
  - Relatively insensitive to environmental and water quality problems.
- Future goals:
  - Acoustic data transmission.
  - Energy scavenging from geothermal gradient.
  - Multi-use base station.



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