Hardware for Continuous Wireless Geophysical Monitoring of Dams and Levees*

Kerri Stone
kstone@mines.edu

Brian Hoenes
bhoenes@mines.edu

Tracy Camp
tcamp@mines.edu

Department of Mathematics and Computer Science
Colorado School of Mines
Golden, CO 80401

Abstract

Current dam monitoring practices are incapable of detecting early onsets of *internal erosion*, a primary failure mode in embankment dams. Current dam monitoring occurs infrequently, with limited automation and little adaptability. Geophysical self potential and seismic methods are capable of detecting incipient failure modes in dams and levees. Traditional geophysical surveys, however, result in a long lag time between internal erosion initiation and its detection. Moreover, traditional geophysical survey methods are laborious and expensive. This research enables cost effective geophysical monitoring of dams and levees via the development of a geophysical based wireless hardware platform. The custom platform, referred to as *gsMote*, has the following features: high resolution and low noise analog to digital conversion, high data rate persistent on mote storage, dynamically configurable gain and signal filters, gigabyte scale persistent data storage, powerful inter-mote radio communications, and flexible mote to world wide web high speed serial communications. The *gsMote* platform will enable continuous and non-invasive geophysical monitoring of dams and levees. This continuous monitoring will allow early detection of subsurface anomalies, decrease cost of repair, and lower the probability of catastrophic dam and levee failures.

Keywords

wireless sensor network, mote platform, structural monitoring, wireless monitoring, geophysical monitoring, earth dam, dam, levee

1 Introduction

Current dam and levee monitoring practices are incapable of detecting early onsets of *internal erosion*, a primary failure mode. Current monitoring occurs infrequently, with limited automation and little adaptability. Dam and levee operators and owners periodically collect measurements from widely-spaced instruments. These instruments, including piezometers, inclinometers, settlement points, and seepage weirs, record sparse measurements within a structure composed of heterogeneous and spatially-diverse materials. Beyond this basic level of monitoring, structure owners may also send survey teams to sites to manually collect additional physical measurements and to perform more in-depth survey analyses (e.g., geophysical, topographic). The frequency of such inspection, instrumentation monitoring, and manual survey varies significantly based on hazard classification, reservoir level, and other dam features [1, 2]. While the U.S. Bureau of Reclamation (USBR) aims for annual surveys of high-risk structures [3], the extent of such monitoring varies significantly. In their annual infrastructure report card, the American Society of Civil Engineers identified over 15,000 high risk dams in the United States with over 30% of these high risk dams not being inspected in the last five years [4].

Current dam monitoring practices result in a long lag time between the start of *internal erosion* and its detection. This long lag time precipitates expensive, disruptive, and technically challenging repairs. Additionally, the lagged detection time may consequent in *catastrophic failure*. A study evaluating the timeline of *internal erosion* progression as a failure mode indicates that "...the potential for loss of life in the event of a [dam] failure is very dependent on the warning time" [5]. The study also concludes that for many earth dams with poor seepage controls, continuous monitoring would be needed to detect failure processes (*internal erosion*, specifically) in time to warn and prevent imminent failure [5].

To compound issues with current dam monitoring practice, many of our nation's earthen dams are at or near their intended design lives. The American Society of Civil

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Engineers estimates that by 2020, 85 percent of all dams will be 50 years old, or older [6]. Aging infrastructure combined with outdated monitoring practice is a recipe for disaster. Now, more than ever, we require improved monitoring techniques and systems capable of continuous monitoring and autonomous dam safety assessment.

This paper presents the design and development of a custom geophysical hardware platform, hereinafter referred to as *gsMote*. The *gsMote* platform integrates non-invasive sensing techniques into a wireless platform, which will allow for continuous monitoring and performance evaluation of dam and levee structures at significantly lower cost than periodic geophysical surveys. This continuous monitoring will enable early detection of anomalies in the subsurface, decreasing cost of repair, and lowering the probability of *catastrophic failures*.

2 Background

A wireless sensor network (WSN) comprises several relatively inexpensive battery operated wireless embedded devices, called motes. Each mote is equipped with a microprocessor for data analysis and processing, a radio for wireless communication, and various embedded and externally connected sensors. Motes can be designed to interface with environmental, geophysical, and geotechnical sensors. A field of motes equipped with these sensors provides an autonomous and continuous method to interrogate and to assess structural integrity. WSNs equipped with physical and geophysical sensors have proven successful in the continuous monitoring of various structures such as landslides and bridges [7, 8, 9]. Our research shows that WSNs have not yet been used to monitor dams or levees for incipient failure modes, such as *internal erosion*. Figure 1 shows a conceptual deployment of a WSN dam monitoring system. A WSN equipped with nondestructive evaluation (NDE) techniques will allow continuous condition assessment of dams and levees.

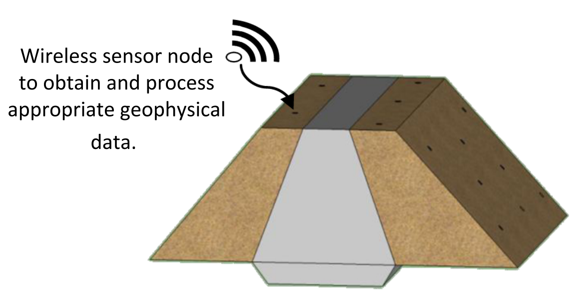


Figure 1: Dam and WSN monitoring system.

Geophysicists are studying the applicability of geophysical sensing techniques to monitor and assess subsurface conditions of earthen dams and levees [10, 11, 12, 13, 14, 15, 16]. NDE, or noninvasive geophysical techniques, offer a means to inspect the subsurface and core of a dam without disrupting the structure by drilling or boring. Two geophysical sensing techniques that produce measurable signals with *internal erosion* are self potential (SP) and seismic (both active and passive) [17, 18].

Self potential (SP) is a non-invasive geophysical monitoring technique that measures the electrical potential between two ground surface points produced by naturally occurring electrical current within the earth. In current practice, two related SP survey techniques are typically used to aid in dam characterization and seepage detection. The first technique involves two electrodes wired to a voltmeter, where one of the electrodes is fixed at the base station and the other electrode is mobile. Survey teams take measurements at multiple locations between the stationary reference electrode and the mobile field electrode to create a grid of SP measurements. This grid network is then manually inverted and processed to create a map of relative electrical potential, where the potential scale is arbitrarily referenced to the base station location. This relative electrical potential map details subsurface voltage differences and can be used to identify underground areas with increased current (e.g., areas with increased fluid movement). The second SP technique is termed the *gradient method*, and still involves two electrodes connected to a voltmeter. The *gradient method* differs in that the electrode pair is "rolled" along a line in a leap-frog pattern, providing incremental electric potential measurements that are each relative to the previous measurement. These incremental measurements are then summed along a line, producing the electrical potential relative to the first measurement location.

Researchers have shown that both SP survey techniques are a reliable analysis method for identifying leaks in embankment dams [18], however, manually performing SP surveys and processing the data is a time-consuming process. Typical SP field efforts take several days to complete adequate data coverage on a single structure. As a result, spurious noise events from sources such as man-made currents or distant lighting strikes can contaminate SP data sets. Also, SP data can be negatively affected by temporal drifts in measurements due to temperature fluctuations, instrument drift, and long wavelength telluric currents within the ground caused by solar wind interactions. Furthermore, the cost associated with standard SP surveys is too high to allow for frequent inspections of dam subsurfaces.

Research into the applicability of using passive and active seismic techniques to analyze subsurface conditions of earthen dams has been underway for years by various institutions and groups [17, 19, 20, 21]. Passive seismic studies survey *natural* low frequency subsurface waves while active seismic studies survey reflections of an *intentional* seismic source (e.g., hitting a metal plate with a mallet). Traditional geophysical seismic studies are wired and manual, where field crews place geophones on the ground surface in linear arrays and record active seismic refraction and/or passive and active surface wave measurements. The seismic data is stored to disk on site and then manually processed and analyzed by a geophysicist offsite. A seismic field campaign for a single site can often take several days to complete, and cost tens of thousands of dollars. Furthermore, results of such efforts usually consist of sparse 1D and/or 2D data coverage that only represent the characteristics of a small portion of a given structure during a short period of time (the length of the survey). Manual seismic studies offer little to no capacity to infer temporal changes in physical properties or processes occurring within the structure.

Integrating geophysical sensing techniques into a WSN provides a means to continuously assess the structural integrity of dams and levees without incurring time delays between internal erosion initiation and its detection. This integration, however, is not as simple as attaching geophysical sensors to an off-the-shelf mote. Active geophysical sensing techniques require high sampling rates, produce a very low voltage signal, and cover a wide dynamic range. These high sample rates and low signal strength demand high speed and high resolution analog to digital converters (ADCs), dynamically configurable signal amplification hardware, large quantities of high data write rate persistant random access memory, and signal filters (denoising hardware). Off-the-shelf mote platforms do not include sufficient hardware to support active geophysical sensing techniques.

3 Enabling Continuous Monitoring

To enable continuous geophysical monitoring of dams and levees, this research developed a custom geophysical mote platform. We call this custom mote platform *gsMote* (geophysical signal mote). Geophysical sensing techniques, such as seismic, require kilohertz scale signal sampling at sub-microsecond precision and produce kilobytes of data per mote over a few seconds. These geophysical sensing requirements could not be met by currently available off the shelf motes. Our *gsMote* platform has integrated SP and seismic sensors as well as supporting hardware needed for active geophysical sensing techniques. Figure 2 conceptually depicts *gsMote* system configuration and simplified interaction with *internal erosion*. The following sections detail factors which necessitated the design and fabrication of custom motes to support dam and levee geophysical monitoring applications.

3.1 Analog to Digital Converter

High Resolution and Low Noise Analog to Digital Conversion: the electrical signal produced by the physical phenomena sensed by the geophysical sensors is very low voltage, covers a large dynamic range, and takes place in a noisy uncontrolled natural environment. High resolution (16-bit) analog to digital converters (ADCs) with configurable variable gain are necessary to reliably discern the target signals. Additionally, because the signal is amplified prior to conversion, the amplification and conversion circuits must be low noise. Commercially available mote platforms have on-chip ADCs that are limited to 12-bit resolution, have no configurable variable gain, and experience significant switching noise from the digital microprocessor clock signal.

3.2 High Data Rate Persistent Storage

Ferroelectric RAM (FeRAM): the kilohertz scale sampling over several seconds produces data significantly in excess of the volatile memory capacity of commercial motes. Additionally, the flash memory and EEPROM on the motes do not support the write speeds necessary for the sampling. Furthermore, the memory has to operate in a low-power environment and power-off persistence is desirable.

3.3 Signal Filters

Dynamically Configurable Filters: to increase the signal to noise ratio of the incoming signal, configurable denoising filters are required. Commercially available motes do not include filters.

3.4 Persistent Storage

Large Persistent Master Mote Data Storage: with seismic sampling occurring several times per hour, hundreds of megabytes of data are produced daily and require persistent storage. Currently available motes are limited to a few megabytes of persistent storage.

3.5 Communication

Powerful Radios: remote deployment locations and the physical scale of dams and levees make it desirable to have more powerful radios. This allows for deployments over a large area and radio connectivity to high bandwidth gateways for remote data access and system monitoring. The commercially available mote radios are limited to sub-150 meter ranges.

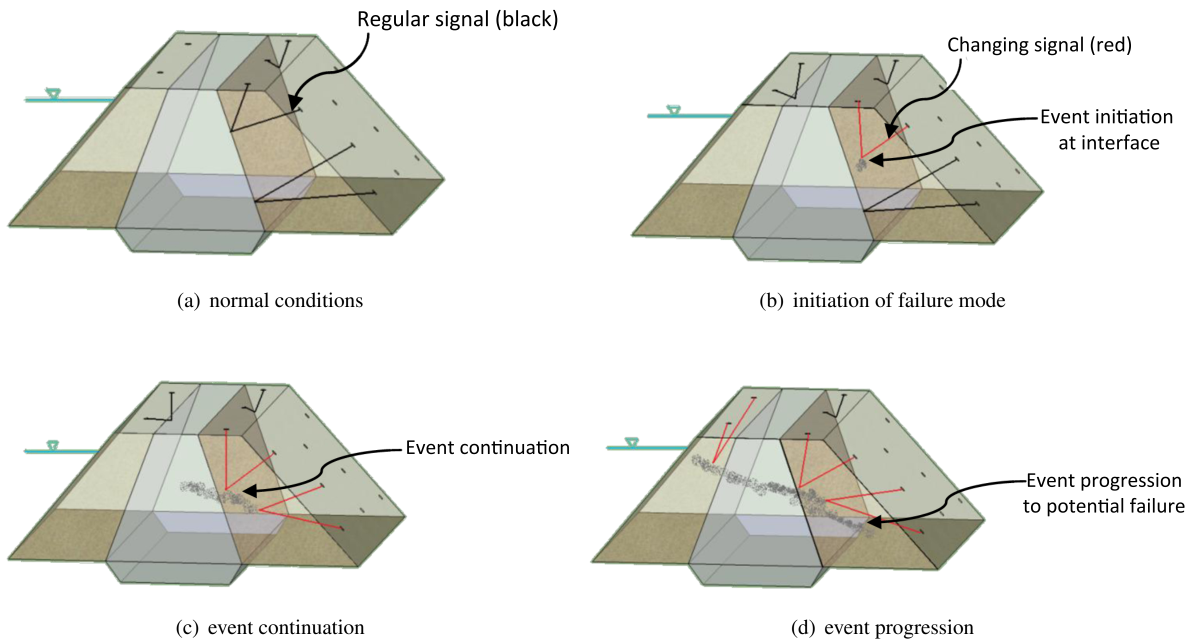


Figure 2: Conceptual representation of a WSN deployed at the surface of an embankment dam and equipped with NDE methods to assess subsurface conditions. (a) Geophysical signals are "regular" under normal dam operating conditions (black lines indicate regular signals). (b) At initiation of a failure mode, geophysical signals indicate subsurface changes, such as *internal erosion*, as shown conceptually here (red lines indicate changing signals). (c) As the event continues, the subsurface features grow and the WSN senses continued subsurface changes. (d) Without intervention, internal erosion will typically grow and may progress to failure. The time between initiation (b) and potential failure (d) is nondeterministic and varies from a few days to a few years. The depiction of earthen embankment dam internal erosion progression was first introduced by [2].

4 gsMote

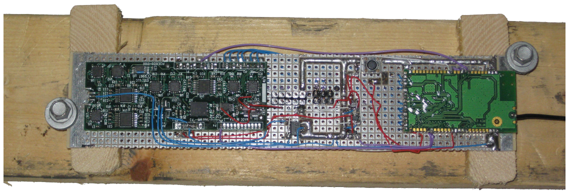
We have developed ten first generation *gsMotes*. The motes were prototyped with design assistance and components donated by Earth Science Systems, LLC [22]. The mote design requirements were based on providing automated and unattended SP *gradient* sensing and both active and passive seismic sensing in a ruggedized field deployable wireless package. The mote prototypes were fabricated on perfboard and encased in a handmade PVC watertight enclosure. Figure 3 displays the mote prototype and the handmade PVC enclosure. The mote electronics include the following features:

- **Sensing**: three axis accelerometer for seismic measurements, waterproof connections for externally connected self potential electrodes, temperature sensors for calibration purposes (both self potential sensors and for time synchronization).
- **Processing**: dynamically configurable direct and alternating current filters, low noise variable gain amplifiers (1 – 128 times), off-chip 16-bit ADC, AVR XMEGA256A microprocessor providing 32 million instructions per second of processing power for mote data analysis.
- **Storing**: 64 kb of ferroelectric random access memory to support single cycle data writes and persistent storage, 32 gb of persistent high capacity flash memory on the master mote.
- **Communicating**: 900 mHz variable power radios with 2 km range in high power mode.

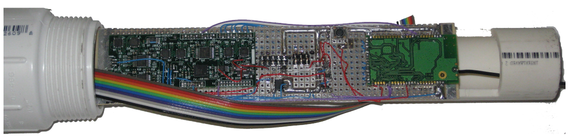
We have developed the first generation *mote* firmware in C. The firmware provides for unattended periodic and event based geophysical sensor sampling. It features submicrosecond precision at up to 4 kHz sampling rates with high data-rate transfer to the ferroelectric memory and includes low-power sleep and standby modes. The master *gsMote* has the ability to serve as a seismic sentinal for active seismic monitoring by sampling seismic signals at a low rate (100 Hz) and waking the array of *gsMotes* for a sampling event on the appearance of an active seismic source. Active seismic data collection can also be manually initiated with a button push or seismic source trigger signal.

The preliminary *gsMote* is an excellent platform to perform initial protocol tests, application development, and early system deployments. Our *gsMote* platform is a novel approach to geophysical monitoring applications

(a) PVC enclosure



(b) *gsMote* prototype



(c) *gsMote* sitting in PVC enclosure

Figure 3: (a) Hand-made PVC waterproof geophysical mote enclosure. The enclosure includes a waterproof connection to attach external SP electrodes. (b) Image of our first generation *gsMote* prototype. (c) First generation *gsMote* platform in the waterproof PVC enclosure.

and will enable advanced monitoring of dams and levees.

5 Future Work

Dam monitoring application development is currently underway. Upon application completion, we will deploy a continuous monitoring system made up of first generation *gsMote* platforms at a field site. This initial deployment will assist in assessing system performance and *gsMote* design. In the future we will develop a second generation *gsMote* platform with support for additional sensors. The enhanced sensor support capability will allow for more effective monitoring, allow the monitoring to be tailored to the particular dam environment, and allow for cross-over into other monitoring and automation domains.

6 Conclusion

Current dam monitoring practices are incapable of detecting early onsets of *internal erosion*, a primary failure mode in embankment dams. Current dam monitoring occurs infrequently, with limited automation and little adaptability. Our *gsMote* platform will enable the development of continuous and non-invasive dam and levee monitoring systems. The *gsMote* platform design addresses requirements of geophysical sensing techniques including high accuracy and high speed ADCs, ample and high-speed ferroelectric RAM, configurable filters, and signal amplifiers. Our *gsMote* platform enables continuous monitoring and performance assessment of dams and levees, allowing for early detection of anomalies in the subsurface, decreasing cost of repair, and lowering the probability of *catastrophic failures*.

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