WIRELESS, AUTOMATED MONITORING FOR POTENTIAL LANDSLIDE HAZARDS

A Thesis

by

EVAN ANDREW GARICH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2007

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	J. Tanner Blackburn
Committee Members,	Jean-Louis Briaud
	Chris Mathewson
Head of Department,	David Rosowsky

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ABSTRACT

Wireless, Automated Monitoring for Potential
Landslide Hazards. (May 2007)

Evan Andrew Garich, B.S., Portland State University
Chair of Advisory Committee: Dr. J. Tanner Blackburn

This thesis describes research efforts toward the development of a wireless sensor node, which can be employed in durable and expandable wireless sensor networks for remote monitoring of soil conditions in areas conducive to slope stability failures. Commercially available soil moisture probes and soil tilt sensors were combined with low-power, wireless data transmitters to form a self-configuring network of soil monitoring sensors.

The remote locations of many slope stability hazard sites eliminates the possibility of real-time, remote monitoring instrumentation that relies on AC power or land-based communication methods for operation and data transfer. Therefore, various power supply solutions and data transfer methods were explored during this research and are described herein. Additionally, sensor modification and calibrations are discussed.

Preliminary evaluations of field durability of the pilot instrumentation were undertaken during this research. Geotechnical engineering instrumentation must be able to withstand extreme weather related conditions. The wireless, solar-powered soil moisture and tilt sensor node was installed on the Texas A&M University campus, allowing evaluation of system reliability and instrument durability. Lastly, potential future research and conclusions arising from this research are presented.

This research has shown that commercially available wireless instrumentation can be modified for use in geotechnical applications. The development of an active power management system allows for sensors to be placed in remote locations and operated indefinitely, thus creating another option for monitoring applications in geotechnical and environmental problems.

ACKNOWLEDGEMENTS

I would like to thank my Advisor, Dr. J. Tanner Blackburn for his guidance throughout this project. Thanks to my advisory committee members, Dr. Jean-Louis Briaud and Dr. Christopher Mathewson. Additional thanks go to Dr. Jay Porter and his students, Matt Lyssy, Nathan McCrory and Troy Perales in the Engineering Technology and Industrial Distribution department at Texas A&M University for the help in this research. Finally I would like to acknowledge the Association of American Railroads and the United States Department of Transportation Eisenhower Fellowship Program for their support of this research.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Shallow landslides and debris-slides pose major hazards and cause significant damage to civil infrastructure, disrupting railroad and highway service throughout the country (e.g. Baum *et al.* 2000). Like deep-seated slope failures, shallow failures can be triggered by changes in soil moisture, often caused by excessive rainfall. Critical facilities located near potentially unstable slopes require systems that can provide warning if movement occurs (Kane and Beck 1999). Soil monitoring systems have been implemented by national, state and local agencies to detect conditions likely to trigger slope failures (Baum *et al.* 2005a). However, the range and reliability of current landslide monitoring systems are often limited because of instrumentation costs, data transmission methods and power requirements.

Commercial availability of low-power sensors, such as micro-electro-mechanical systems (MEMS) and the development of wireless data transmission systems (i.e. Berkeley motes) have led to extensive research and deployment of remote, wireless structural sensor networks (Lynch et al. 2001). However, continued investigation of durability, power optimization, and communication methods is required to promote implementation of sensor meshes in geotechnical monitoring applications.

The use of wireless sensor nodes eliminates the need for extensive cabling in monitoring projects, reducing material costs and increasing system reliability, because cables are often damaged. Because wireless sensor nodes can be placed without consideration of cabling needs, they show potential for application in situations where cabling would be difficult or costly, such as instrumentation along roadways.

In addition, these low-power systems are well-suited to remote monitoring applications, reducing the need for data-collecting site visits and enabling an increase in sampling rates. Perhaps the greatest benefit arises from early warnings that can be achieved using real time data, as remote units can be programmed to send alerts when threshold values are exceeded.

This thesis follows the style of the *Journal of Geotechnical and Geoenvironmental Engineering.*

The goal of this research was to develop a durable wireless sensor node, which can be employed in expandable wireless sensor networks for remote monitoring of soil conditions in areas conducive to slope stability failures. Commercially available soil moisture probes and accelerometers were combined with low-power wireless data transmitters to form a self-configuring network of soil monitoring sensors.

This research included the following components, which are described in this thesis:

- Laboratory calibration of soil moisture probes and biaxial accelerometers.
- Customization of a wireless data acquisition system for geotechnical applications, including modification of the power supply (to allow for solar charging).
- Development of an active power management system for the sensors and data acquisition system.
- Field evaluation of the prototype system.

2. BACKGROUND

2.1. CURRENT LANDSLIDE INSTRUMENTATION

Kane and Beck (1999) have provided an overview of current landslide instrumentation methods and applications, which are summarized herein. Landslide monitoring often includes observing groundwater levels and slope movements. The measurement of slope movement involves the observation of deformation direction, deformation magnitude, deformation rate, and the location of the failure surface. Deployed instrumentation systems can range from simple to complex, depending on the slope location and repercussions of a potential failure. Piezometers are often used to measure groundwater levels, and inclinometers, tiltmeters, extensometers and TDR (Time Domain Reflectometry) systems can be used to determine direction, rate of displacement and location of failure plane (Kane and Beck 1999).

Critical facilities located next to potential landslides have created a need for systems that can provide warning if movement occurs. Several systems have been installed in California that used land line phones or cell phones to relay data from remote locations to end users. These remote data acquisition systems consist of several components to ensure functionality and data delivery including: a data logger (to collect data and perform on-board calculations), data transmission system (modem or radio link) and a power supply (battery or AC power source). In addition to the hardware requirements, specialized software is typically required to process the raw data from the instrumentation (Kane and Beck 1999).

2.2. TECHNOLOGICAL ADVANCES

2.2.1. Tilt Sensors

Inertial electromechanical sensors have been in use since the 1920’s in a wide range of applications including navigation, guidance and control applications. These sensors have been decreasing in use, caused by the arrival (and adoption) of solid state accelerometers during the early 1990s (Barbour and Schmidt 2001). The first silicon-based solid state accelerometers were developed during the late 1970’s, driven by the development and implementation of acceleration-triggered automotive airbags (Knutti and Allen, 2004). These sensors are often referred to as micro-electro-mechanical systems (MEMS), although the term in not exclusive to accelerometers. Throughout the 1980s development continued, funded primarily by aerospace based research, and mass produced low-cost MEMS accelerometers became available (Knutti and Allen 2004). As costs have continued to decline, MEMS sensors have gained applications. Currently MEMS devices are used in several civil engineering applications, including structural monitoring of buildings and bridges, pavement monitoring and geotechnical soil monitoring.

2.2.2. Wireless Data Transmission Systems

Several commercially-available wireless data transmission systems have been developed for wireless sensing applications. Many of these systems follow the IEEE 802.15.4 and the Zigbee transmission specifications for wireless personal area networking. Common characteristics of wireless personal area networks include low power consumption, link quality indication, up to 16 radio channels depending on the frequency band, fully acknowledged protocol for data transfer reliability and synchronized timing (IEEE 2003).

Three networking topologies are commonly used to facilitate communication between sensor nodes and the data management/storage server: Star, Peer-to-peer, and Hybrid topologies. These topologies are shown in Figure 1. Star topologies limit transmission to a single relationship between the sensor node and a controller, whereas Peer-to-peer topologies (also referred to as ‘mesh networking’) allow sensor nodes to communicate with each other in addition to a controller. Peer-to-peer topologies allow for complex networks that can be self organizing and self healing. Data may be routed through multiple devices before reaching the controller, which can improve reliability and extend the range between sensor nodes and the data management/storage server. This connectivity is advantageous if wireless communication between one sensor and the controller becomes unreliable, the sensor node can reroute the data through other sensors, enabling the data to reach the controller. This rerouting can increase power consumption in sensor nodes that act as relays to the controller. A Hybrid network topology may also be used, consisting of a two-tier system where the sensor nodes communicate with one of several controllers that have the ability to communicate with each other (Lynch and Loh 2006).

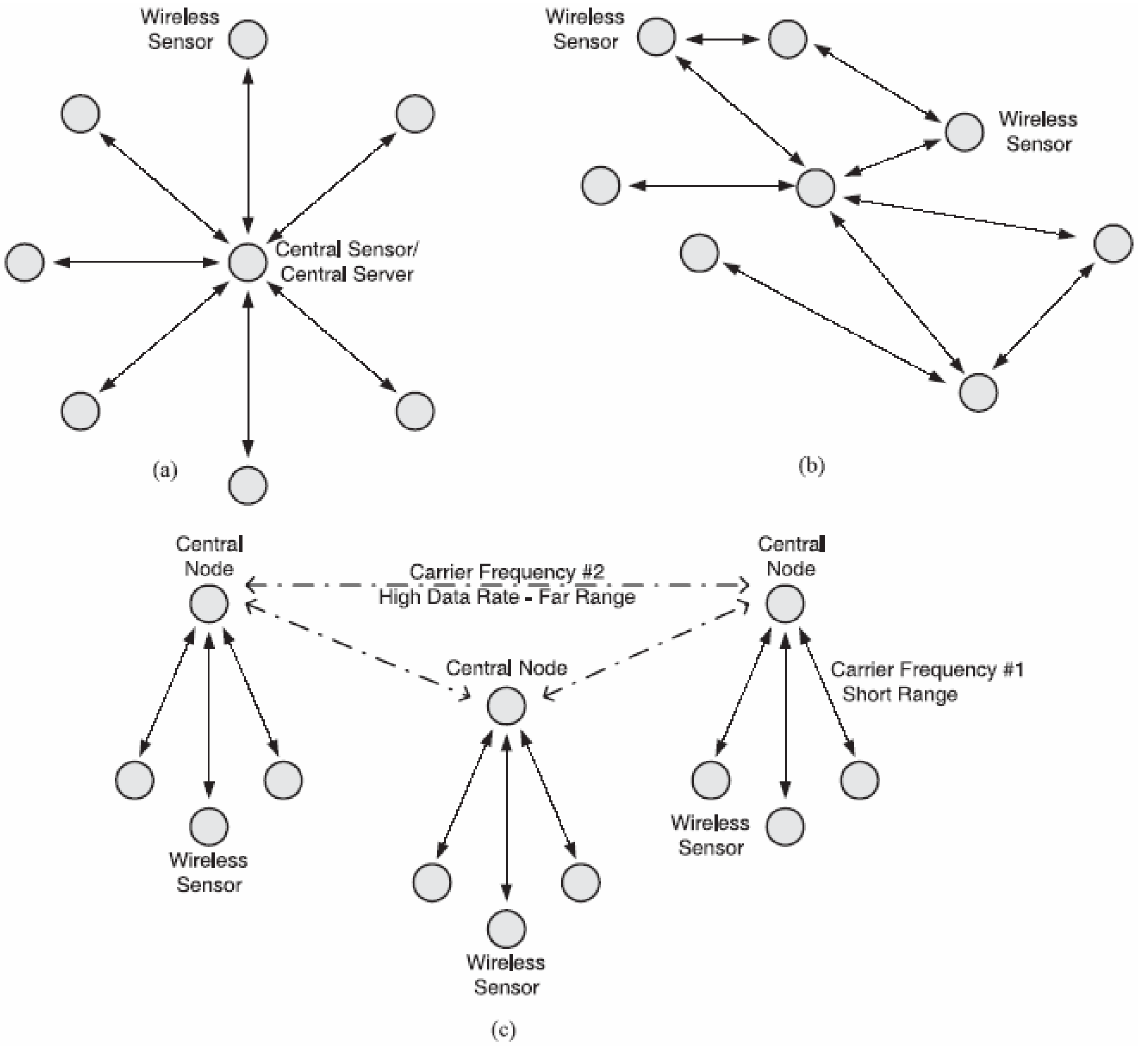

Figure 1: Common network topologies for wireless sensor monitoring networks: (a) Star, (b) Peer-to-peer or mesh, (c) Hybrid (Lynch et al. 2006).

2.2.3. Wireless Sensing Nodes Development

Since the mid-1990's researchers have realized the need to reduce the cost of monitoring civil infrastructure and increase the capabilities of available monitoring systems. Researchers have developed several generations of prototype wireless sensing nodes in a short period of time, leading to increased computing power, improved communications and reduced power consumption (Lynch et al. 2006). These sensing nodes tend to be highly customized for specific monitoring tasks; however, several of these prototypes have been developed into commercially available products.

2.2.4. Commercial Wireless Sensing Nodes

Application-ready hardware and software platforms have been commercially developed and are available to engineers looking to efficiently deploy a sensing network. Two open-source systems adopted within the engineering community are the Crossbow Mote, originally developed at the University of California at Berkeley, and the Intel iMote. In addition to open-source systems, systems with proprietary software are also available, including platforms from Ember, Microstrain, Sensametrics, Sensicast and Dust Networks (Lynch et al. 2006). The scope of this project included acquiring and modifying commercially available systems, rather than development of new wireless systems. Several of the systems mentioned in this section were evaluated and will be discussed in Section 3.2.

2.3. PROPOSED LANDSLIDE INSTRUMENTATION

Recent advances in monitoring capabilities have been recognized by several researchers that have proposed landslide monitoring systems. Towhata *et al*. (2005) have proposed a landslide warning system for urban areas. Instrumentation would include a moisture sensor, inclinometer and wireless communication device (Figure 2). The proposed system would be distributed to private citizens who wish to have some level of protection against landslides, thus the total cost should be less than $350. Soil moisture content and deformation data would be routed to a local disaster management center that would be responsible for analysis and issuing warnings or evacuation plans (Towhata *et al.* 2005). Figure 3 shows the flow a data for this proposed system.

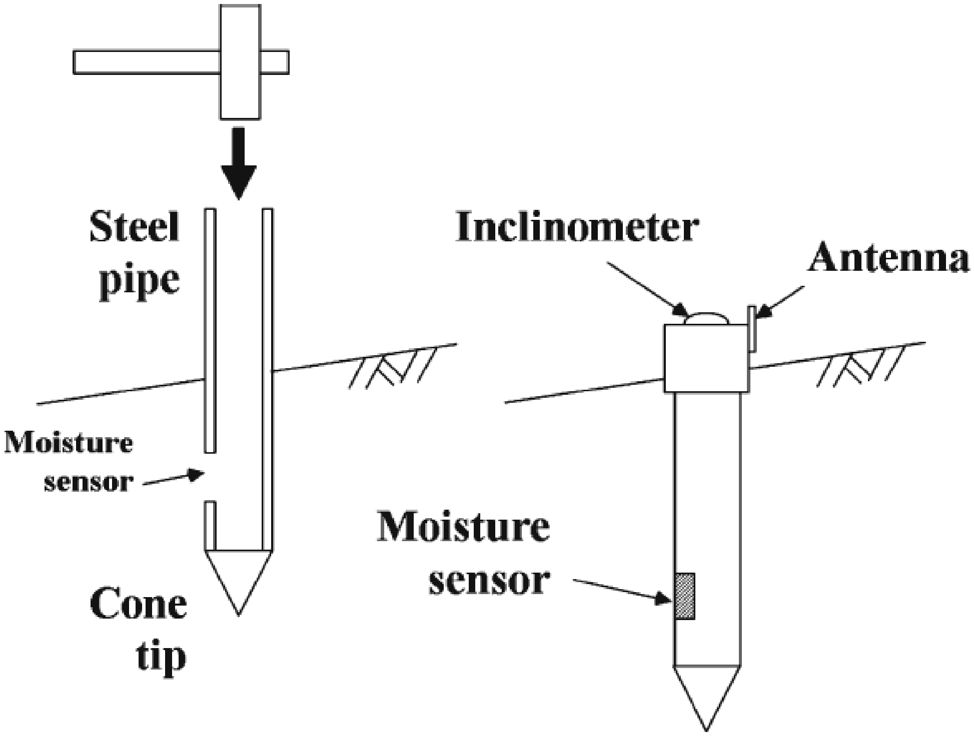

Figure 2. Installation of potential instrumentation unit (Towhata *et al.* 2005).

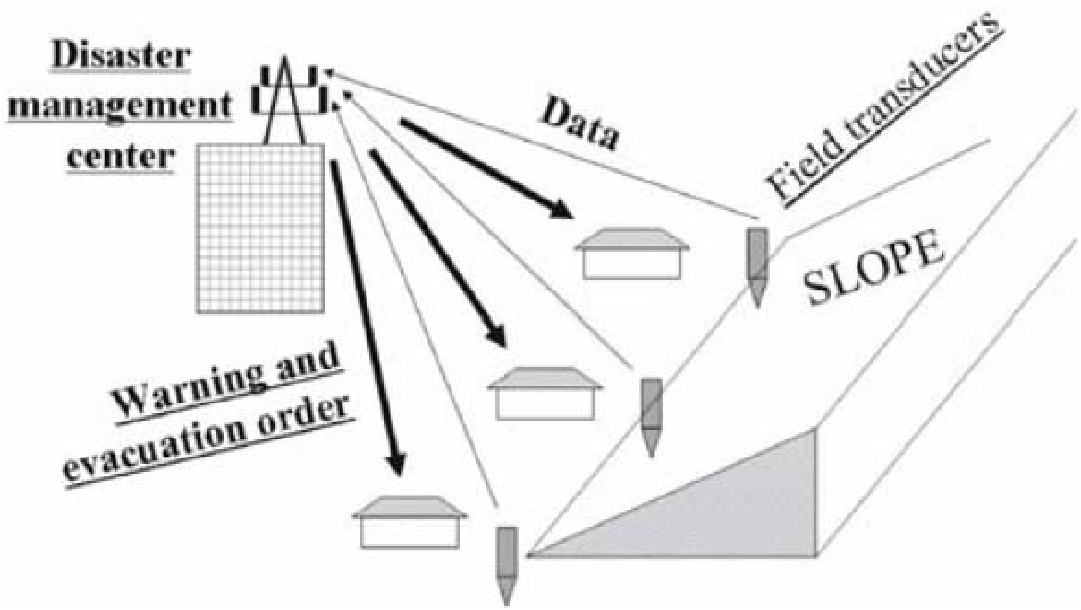

Figure 3. Data flow for warning system (Towhata *et al.* 2005).

Additional landslide monitoring and detection schemes have been proposed by Terzis *et al.* (2006). Sensor columns would be placed in grid patterns on potentially hazardous slopes. Each sensor column would contain instruments at several depths in order to detect slip surfaces within the slope, as shown in Figure 4. Instruments proposed for use in the columns include geophones, strain gages, pore pressure transducers and tensionometers. Sensor columns would detect deformation magnitude and locations and sensor data can be employed in a finite element model to predict landslide potential (Terzis *et al.* 2006). Although the proposed system of landslide detection and prediction could be implemented successfully, the cost associated with the implementation of this scheme could be quite prohibitive.

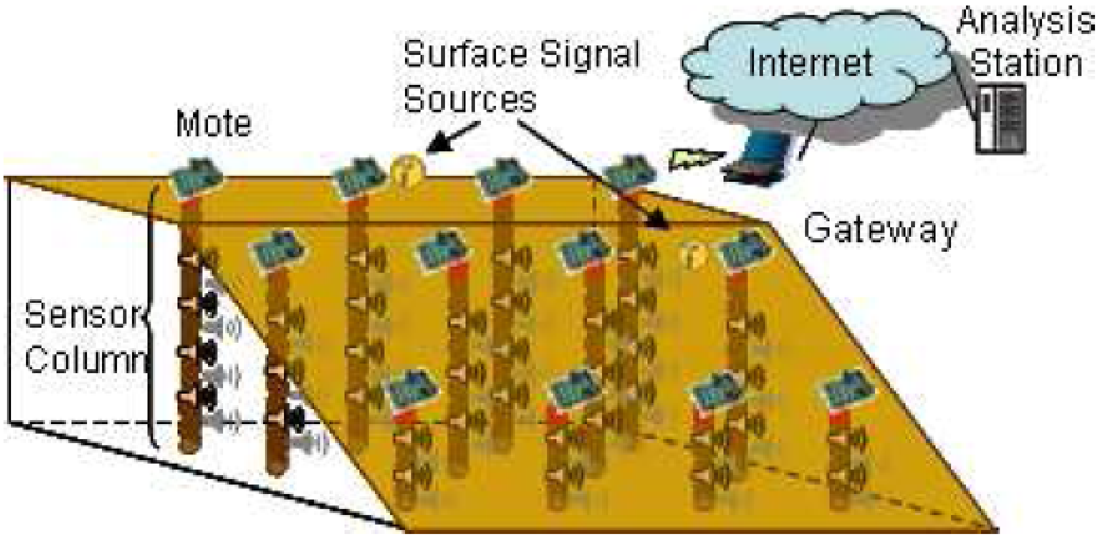

Figure 4. Proposed landslide detection system using an array of sensor columns (Terzis *et al.* 2006).

2.4. IMPLEMENTED INSTRUMENTATION

The U.S. Geological Survey (USGS) has developed and implemented several landslide monitoring sites in the Western United States. Two systems were deployed that provided near-real-time data availability to the general public via internet, located near Edmonds and Everett, WA. A costal bluff on the shore of Puget Sound was monitored with soil tensionometers, peizometers, water content sensors and rain gauges at two locations from 2001 to 2004 (Baum *et al.* 2005b). Figure 5 displays the instrumentation layout at the Edmonds site. Data from this site is stored on a commercial data logger and relayed to an on-site internet server via radio communication. The data is then accessed via internet by USGS offices and provided to the general public. Solar powered battery systems and AC power provide power to the site instrumentation. Instrumentation was programmed to record data hourly, except during times of intense precipitation when data was recorded every 15 minutes. Overall data reliability was high, although data loss did occur during instrumentation changes and loss of battery power, caused by lack of solar charging (Baum *et al.* 2005b).

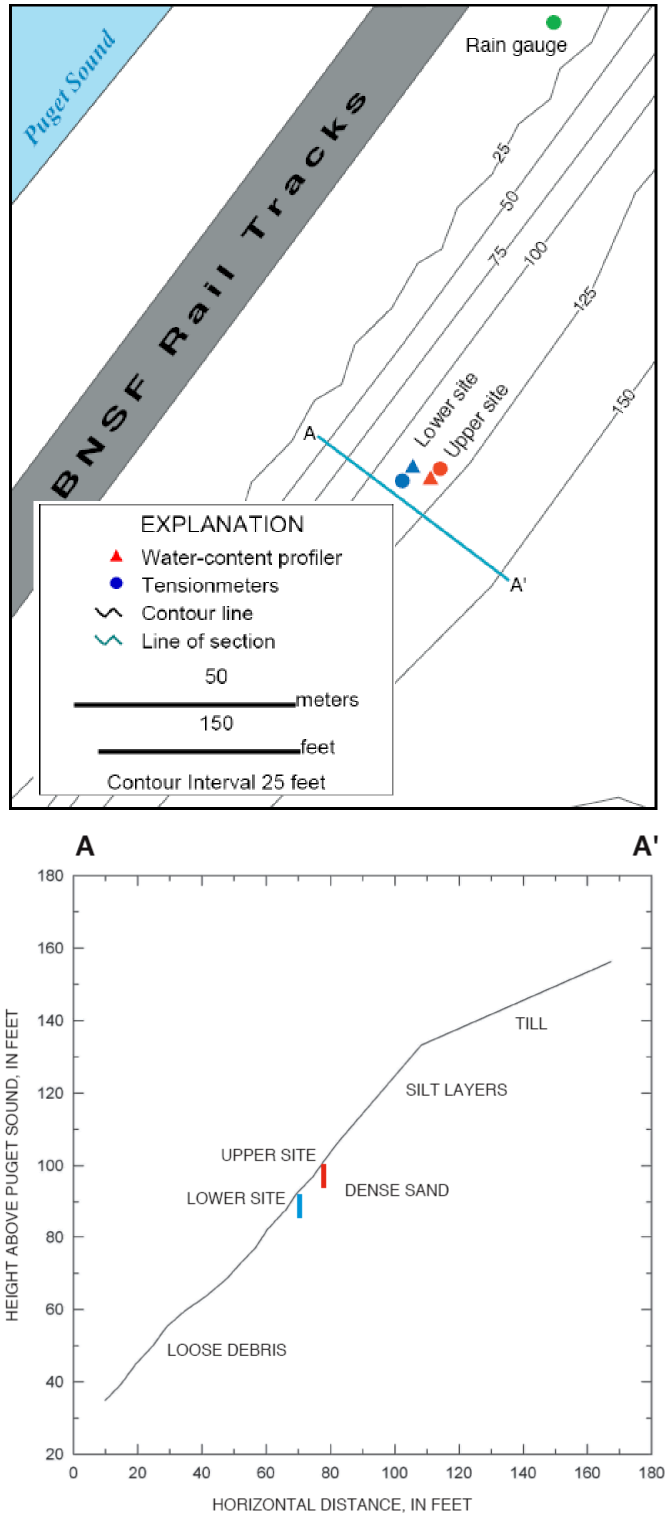

Figure 5. Instrumentation plan and section views for landslide monitoring near Edmonds, WA (Baum *et al.* 2005b).

Piezometers were placed in hand augured borings ranging from 107 cm to 165 cm in depth at both locations. Several difficulties were encountered with the piezometers including drift, noise and temperature sensitivity. These factors rendered the data from the piezometers unusable. Tipping bucket rain gauges provided reliable precipitation data. Water content reflectometers (which measure volumetric water content based on dielectric permittivity) and water content profilers (measurements based on soil capacitance) provided moisture contents at the two sites; however difficulties with cabling of the instruments caused several losses in data (Baum *et al.* 2005b).

Numerous shallow landslides occurred in the Seattle region during the monitoring of these sites. As expected, a correlation was observed between rainfall and landslide occurrences in the area. Soil moisture contents were typically 4 to 10 percent higher in the wet winter months than the dry summer season. Rainfall events that triggered landslide activity typically raised soil moisture levels an additional 2 to 4 percent above the wet season averages in a matter a several hours. Based on these findings the research recommended monitoring precipitation and soil moisture content between 0-2 m depth on the slopes of interest (Baum *et al.* 2005b).

To complement the instrumentation and research, rainfall data from the Seattle area has been correlated with slope failure occurrences to establish an intensity and duration threshold for predicting landslide likelihood. Baum *et al.* (2005a) have proposed a warning criteria system including three levels (Advisory, Watch and Warning) based on regional rainfall and landslide characteristics. A landslide "Advisory" would be issued when soil saturation levels are seen to rise to high levels of saturation. If a forecast of intense rainfall occurs during an "Advisory," an intermediate level "Watch" may be issued. Finally a "Warning" may be issued if near real-time observations indicate that rainfall intensity/durations and soil moisture levels are at a point that landslides are likely (Baum *et al.* 2005a).

Ludwig and Constable (2005) describe the use of wireless instrumentation during the construction of a 2.2 mile long 33 ft deep trench through downtown Reno, Nevada. Several buildings adjacent to the excavation were identified as "sensitive," including three historic structures. The excavation support system included soil-nail shoring, vertical piling with tiebacks and underpinning. Thirty-six Wi-Fi equipped digital tiltmeters were installed on 8 buildings to monitor the structures during construction. AC power was provided in all cases, except for three buildings where AC power was inaccessible, necessitating the use of 20 watt DC solar panels and rechargeable batteries. Weatherproof utility boxes housed the Wi-Fi transmitter, transformer and serial cable connection. A wide area network encompassing the entire project could not be deployed because of broadcast frequency restrictions. Thus, data was manually collected on-site every 6 days. The sensors worked properly throughout the project showing that reliable data can be received using wireless technology.

3. WIRELESS SOIL MONITORING SENSOR NODE DEVELOPMENT

Development of a wireless soil monitoring node included the selection and modification of sensors and wireless data transmission systems to meet power and durability requirements for field implementation. For this research tilt and soil moisture content were measured. The following sections describe the tilt and soil moisture content sensors used during this research.

3.1. SENSORS

3.1.1. Tilt Sensors

A commercially-available biaxial MEMS accelerometer (Analog Devices, ADXL203) was embedded in a weatherproof enclosure and customized for geotechnical applications by GeoTak Instrumentation of Houston, TX. This accelerometer is ratiometric, such that the tilt is output as an analog function of an input (excitation) voltage. The MEMS accelerometer was calibrated and validated through comparison with a Schaevitz™ AccuStar® electronic clinometer to investigate drift and linearity. The instruments were bound together and rotated through a range of angles. A regulated excitation voltage was provided to both sensors (5.68 V) and output voltage was tracked for each angle. Both instruments provided linear output voltage within a wide range, as displayed in Figure 6, with both units having correlation coefficients (R^2 values) greater than 0.99, respectively.

The comparison between the Schaevitz™ AccuStar® and MEMS accelerometer also included an analysis of electronic drift with time. Both accelerometers were secured to a surface and supplied with a regulated excitation voltage (6.38 V) for 4 days. Both accelerometers had constant output voltages (± 0.001V) throughout the test. This test procedure was conducted in a controlled laboratory environment and did not address thermal drift. According to Analog Devices specifications, the ADXL203 output voltages should exhibit less than 1% thermal drift within the range of operating temperatures (-40 to +125 ºC).

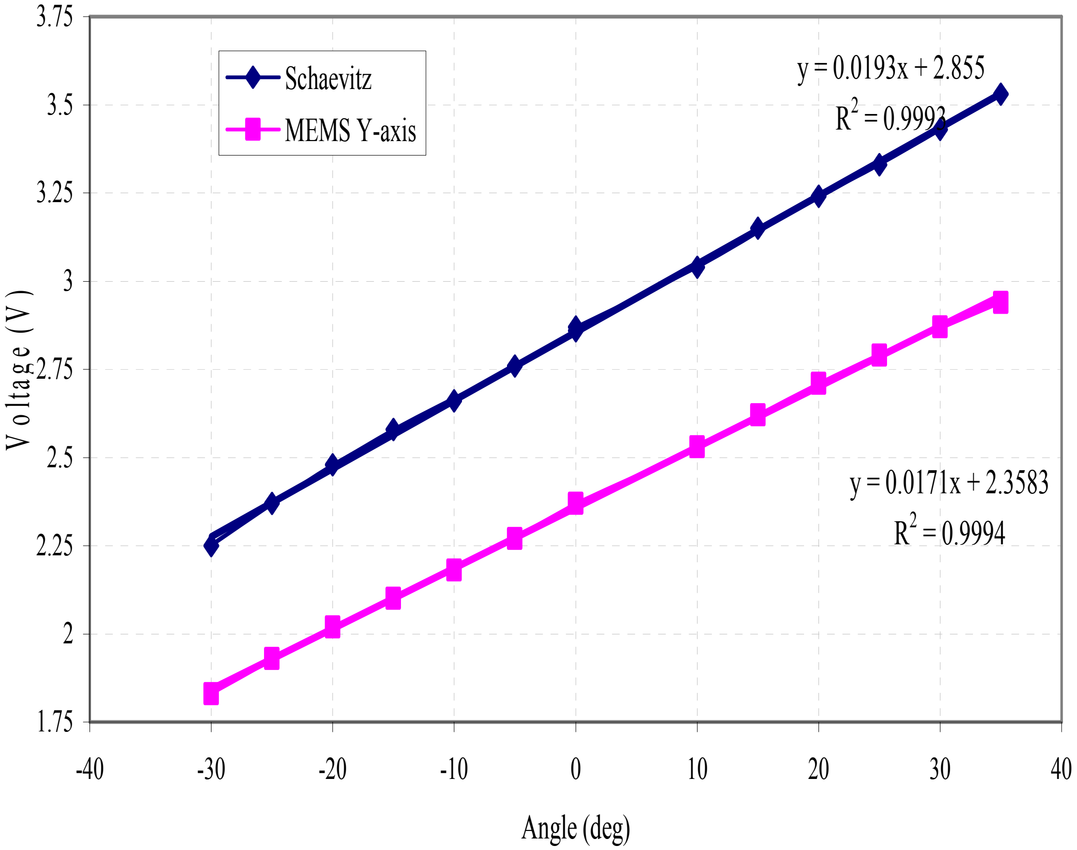

Figure 6. Comparison of Schaevitz Accustar and MEMS Accelerometer.

Preliminary sensor calibration was performed to provide a conversion from voltage output to tilt along the x and y-axis of the MEMS accelerometer. The calibration was performed by mounting the accelerometer on a plastic bracket that rotated along one plane as displayed in Figure 7. The rotating portion of the bracket was positioned at known angles and voltage outputs of the accelerometer were recorded. Once a full range of measurements was taken the bracket was rotated back through to check for hysteresis. Figure 8 displays the calibration about the y-axis for a regulated excitation voltage of 3.002 V. From this calibration a change in voltage of 0.00795 V equates to 1.0 degrees of rotation.

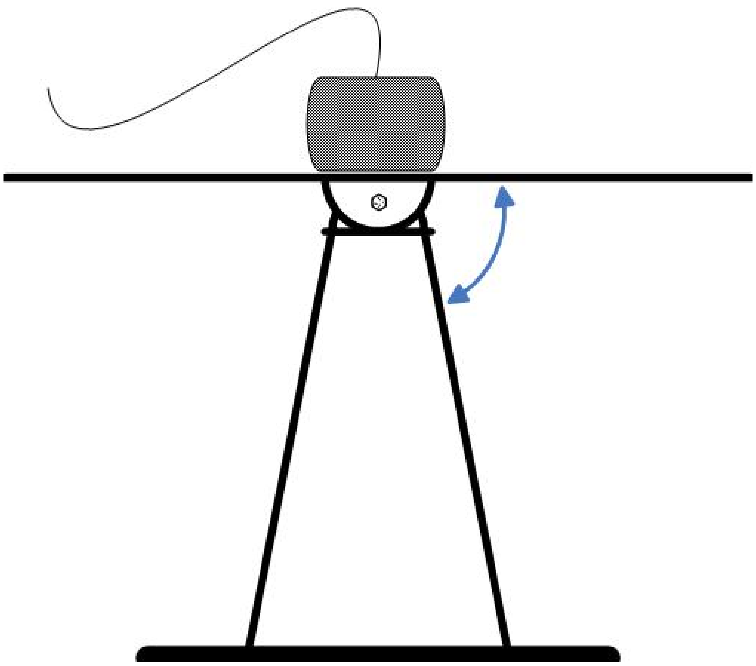

Figure 7. MEMS accelerometer calibration apparatus.

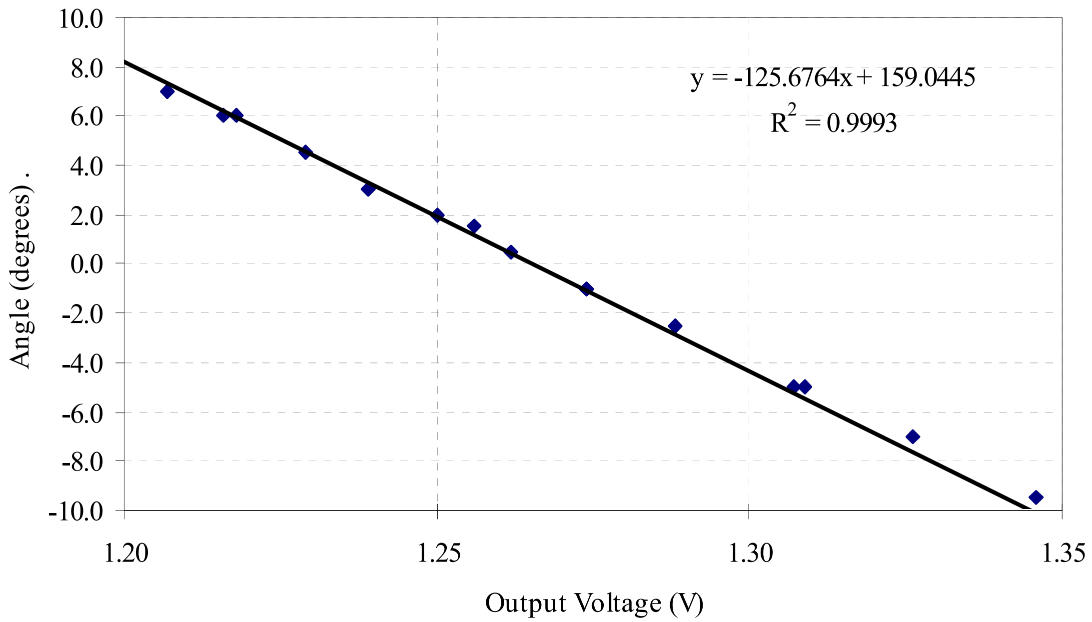

Figure 8. MEMS accelerometer Y-axis calibration.

3.1.2. Soil Moisture Sensors

Capacitance-based soil moisture probes were also included in the development of wireless soil monitoring nodes. The commercially-available soil probes (ECH$_2$0™ EC-5) used in this research observe soil moisture by comparing the dielectric constant of the surrounding soil with the dielectric constant of water. The soil moisture content can be determined because of the large difference between the dielectric constant of water (80) and air (1).

The ECH$_2$0™ EC-5 probe can operate in a temperature range from -40 to +60 ºC and takes readings in 10 milliseconds (Decagon 2006). The soil moisture probe requires individual calibration for different soil types; thus individual sensor calibration is required for each field installation. For this research, the soil moisture probes were calibrated for different soil types in a laboratory environment. Moisture content of the soil was determined following ASTM D 2216. Although the moisture probe measures volumetric water content (m^3/m^3), the laboratory the moisture content was determined by mass (mass of water/mass of solids); therefore, a conversion between volumetric and mass-based moisture content is required. Figure 9 displays the voltage-soil moisture calibration data for two soil types.

Thermal drift was also a concern for the moisture probe because of the temperature dependence of the electrical circuitry and dielectric permittivity of water. However, this was not investigated in a laboratory setting.

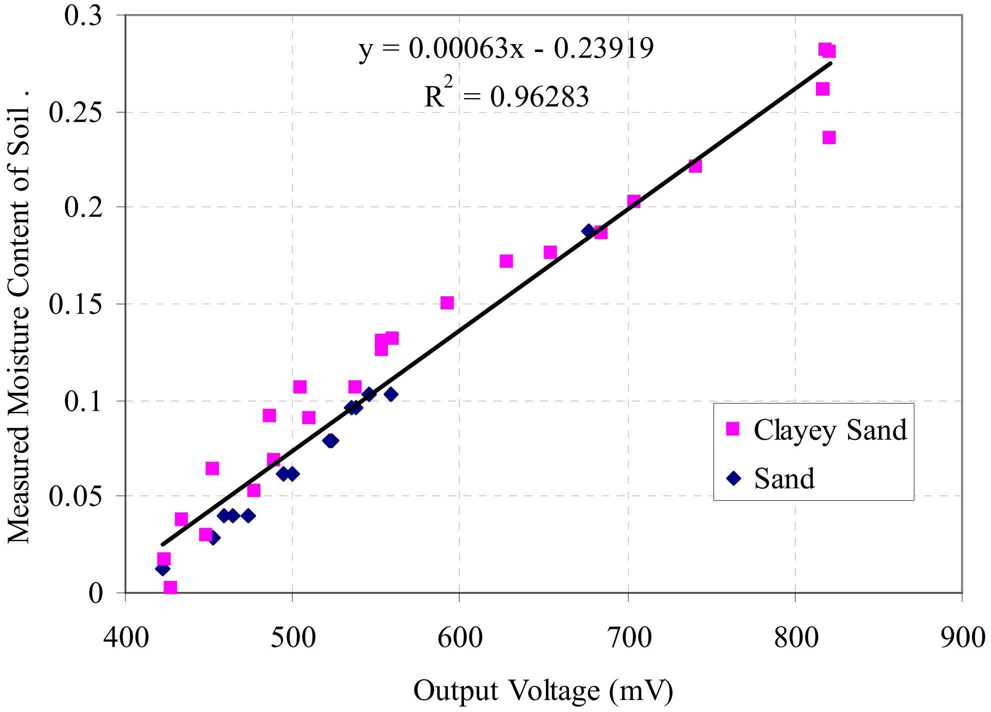

Figure 9. Calibration of volumetric soil moisture sensor, using a regulated excitation voltage of 3.002 V.

3.2. WIRELESS DATA TRANSMISSION SYSTEMS

As described in Section 2.2 technological advances have lead to development of several wireless data transmission systems and sensing nodes. For this research commercially available wireless data transmission systems were investigated for potential use in a geotechnical monitoring node.

3.2.1. Sensicast Wireless Monitoring Network

The Sensicast system utilizes a Hybrid network topology that requires three distinct hardware components. The Star Node provides the direct connections to the sensors and transmit data to a Mesh Node. The Mesh Node relays data to the Bridge Node, which is directly connected to a local area network (LAN) or PC. The user configures the mote system and logs data using the SensiMesh™ Gateway software on the connected PC, or remotely via the LAN connection. All of the components are designed to be supplied with an external AC power source, but do have a battery backup which can be used for up to 72 hours (Sensicast 2005).

3.2.2. Dust Networks Wireless Monitoring Network

Dust™ Networks SmartMesh hardware and software was acquired and adapted for this project. Dust Networks employs a mesh (Peer-to-peer) topology and provides a 'user-friendly' software interface for configuration and data management. The network consists of motes, which are used as sensor nodes, and a console/manager connected to a computer or LAN for data acquisition and configuration. The individual motes allow for analog and digital sensor outputs (two 0-5 V channels, five 0-1.5 V channels, and eight digital channels). The motes are powered by two AA batteries which allow continuous operation for several months to over a year; however, the motes do not supply power to external sensors. The motes are able to self configure into an existing wireless mesh network or form a new mesh network, if needed. If communication between two motes becomes unreliable the network can adapt the data path to improve reliability.

Although all devices in a mesh network have the ability to communicate with each other, a data manager is required to transfer the data from the sensor nodes to a data server. The data manager must be within range of at least one sensor node, and can be directly connected to a PC or internet connection, to transfer the data.

The Dust Networks SmartMesh software suite allows the user to optimize and customize the sensing network for specific applications. The Windows-based user interface requires no additional programming knowledge. Communication settings are customizable, which is advantageous for applications where power conservation is essential (such as geotechnical monitoring applications). For instance, the user can block certain motes from serving as relay motes, thereby conserving battery power of the blocked mote. Also, the accessible channels, sample rate and data transmission rate can be changed remotely through the software, while the network maintains operability.

Digital channels can be employed to actuate sensor power, conserving the power of the sensor excitation source. The software also provides network statistics for path reliability, data reliability and data latency. In addition to user defined sampling rates the motes can also be set up to report on ‘events’, when the voltage from the sensor exceeds a threshold value.

3.3. POWER SUPPLY AND MANAGEMENT

Because the final system will be deployed in remote locations, the system must be self contained and require minimal maintenance, including battery replacement. Efficient power management was achieved through optimized sampling rates, low-power sensors, remote sensor actuation and the use of solar power.

3.3.1. Voltage Regulation

The battery/solar cell power configuration provided DC power to all components of the sensor node, including data transmission unit and external sensors. The battery/solar cell combination is described in Section 3.3.2. Because batteries do not provide a constant voltage (time-dependent depletion), a voltage regulator was employed to provide a constant output voltage to the ratiometric sensors. An ON Semiconductor LP2950CZ-3.0 voltage regulator and 1 μF capacitor were used to provide an output voltage of 3.0 V to the sensors. Figure 10 displays the block diagram of the voltage regulator.

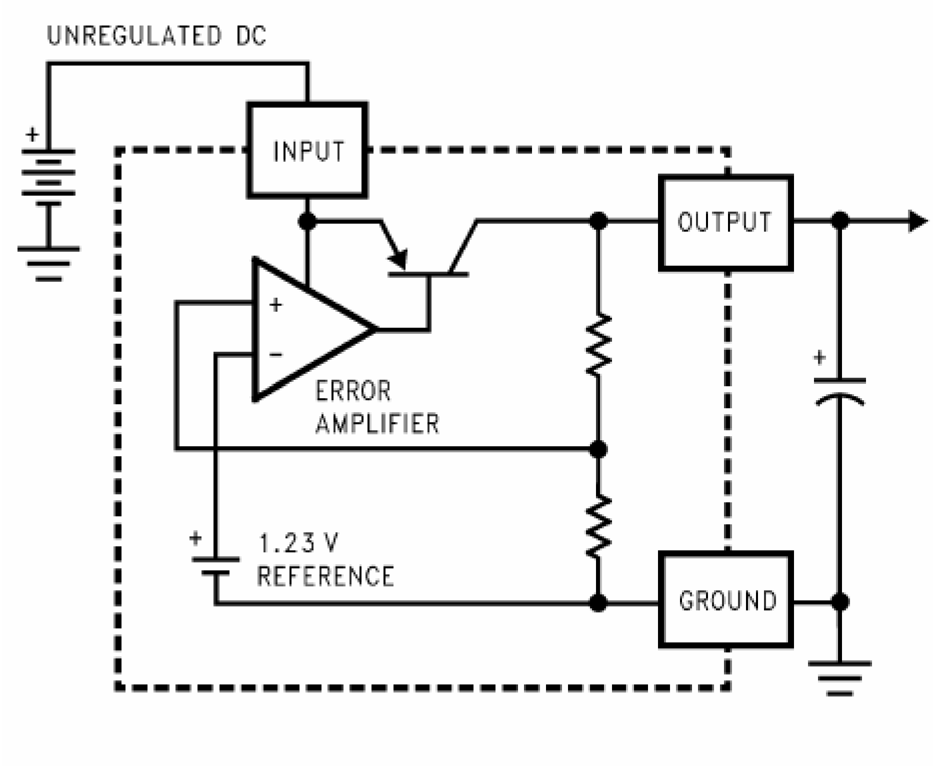

Figure 10. Block diagram of LP2950CZ voltage regulator (from www.us.oup.com).

3.3.2. Power Demand

As described in Section 3.1, the soil deformation and moisture content sensors were selected because of their low current draw during operation. Table 1 lists the current draws of each sensor type, the voltage regulator and the Dust Networks mote. The two values listed for the mote correspond to the operational current draw, when the mote is transmitting data, and the ‘sleep’ current draw, when the mote is inactive. A maximum system draw of 68 mA occurs when the mote is actively logging sensor data and transmitting this data to the data manager. A minimum of 43 mA is occurring during the sleeping periods, when the mote is inactive.

Table 1. Current draw for components of wireless monitoring network.

Component	**Current (at 3.002 V)**
Mote, while transmitting	25 mA
Mote, while sleeping	10 µA
EC-5 Moisture Probe	9 mA -13.6 mA
MEMS tilt sensor	0.5 mA
Voltage Regulator	29 mA

The sensors and data mote are powered by nickel metal-hydride (Ni-MH) batteries, which are charged by 6 V solar panels. The low current draw of the soil monitoring node allows the rechargeable batteries to provide enough power during periods of limited sun (cloudy days, nights). Ni-MH and sealed lead-gel batteries were investigated for use with the system, as both battery types can be continuously charged at low current levels (trickle charging) without damaging the batteries or causing potential failure. Because, occasionally, the solar panel would be charging the batteries while they were already fully charged, the current output of the solar panel had to be low enough to not damage the batteries. A continuous charging rate that is less than 1/20th of the system capacity is considered safe. If a fully charged battery system is charged at rates higher than this there is a possibility of overheating and permanent damage (Gonzalez *et al.* 1999).

Four AA sized Ni-MH batteries were used to provide over 5 V when fully charged and 8000 mA hours (2000 mA hours per battery) of power. A 6 V rated panel (max voltage about 9 V) with current output of 60-70 mA in direct sunlight, and 10-15 mA in shade or cloudy/rainy conditions was obtained. The panel contains photo diodes to prevent battery drain at night and is weatherproof.

3.4. PRELIMINARY CONFIGURATION

The original configuration of the sensors, mote and power supply was initially developed in a laboratory environment and is shown in Figure 11 (without solar panel). After preliminary evaluation of the sensor compatibilities and power requirements, the configuration was modified for geotechnical applications; this modification is described in Section 3.7.

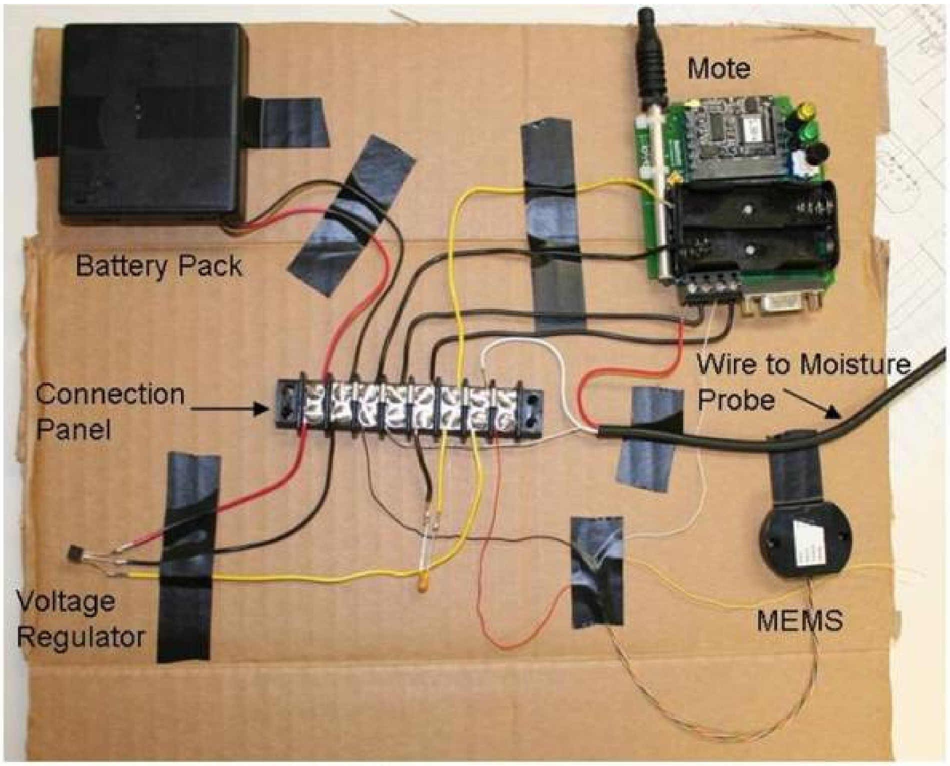

Figure 11: Soil moisture and tilt sensor node components.

3.5. POWER OPTIMIZATION

A field evaluation of the preliminary system demonstrated the need for an active power management system, which allowed for sensor actuation. An active sensor activation system provides power to the sensors only during sampling, rather than the previous system that employed constant power to the sensors, with periodic sampling. By actuating a digital channel to control the amount of time the sensors were powered, the amount of total system power consumption dropped dramatically. An actuator board was built as part of a research design project for undergraduate students in the

Engineering Technology and Industrial Distribution Department at Texas A&M University. The actuator board was designed to eliminate power to the sensors during 'sleep' cycles, while maintaining continuous power to the data mote. The actuator board was connected to the mote via the 15 pin VGA connection. Figure 12 displays the layout of the actuation board components and connection pins.

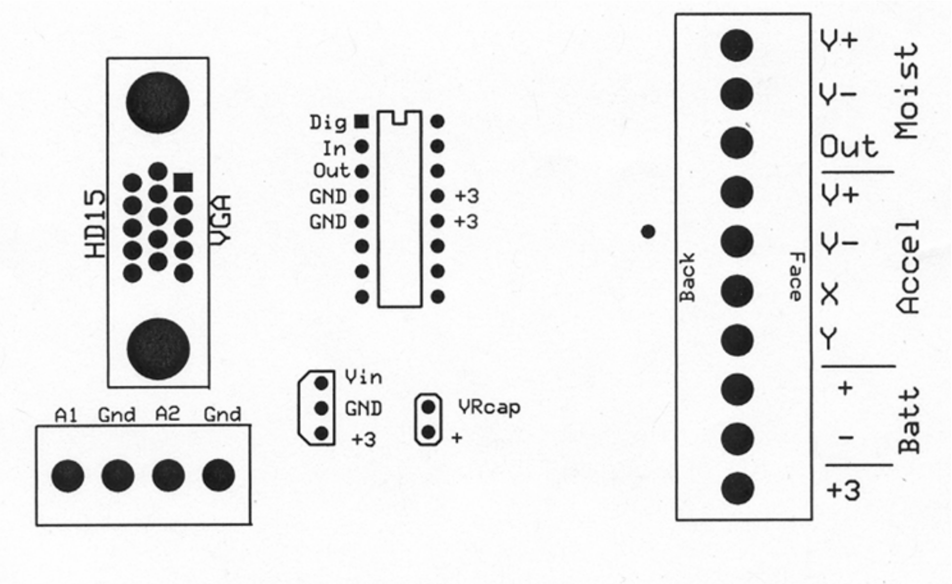

Figure 12. Diagram of actuation board connections.

The Dust Console software and sensor actuation board were configured such that a voltage and current would be available to power the sensors only while a measurement was being recorded. After the measurement was recorded by the mote the actuated channel turned off and power was to cut to the sensors. The system consumed 0.8-1.8 mA during 'sleep' cycles. The user was able to adjust the amount of time the sensors were powered prior to sampling, providing additional time for sensor stabilization. Initial field trials showed that the addition of the actuation board enabled the solar panel to maintain full charge of the batteries and keep the node working properly, even in complete cloud cover and rain.

3.6. REVISED CONFIGURATION

The actuation board required a revised layout for the soil sensor node, reducing the number of wires in the sensor node because of the circuitry of the actuation board. The voltage regulator was installed on the actuation board to reduce space and clutter around the sensor node. Figure 13 displays the actuation board attached to a mote.

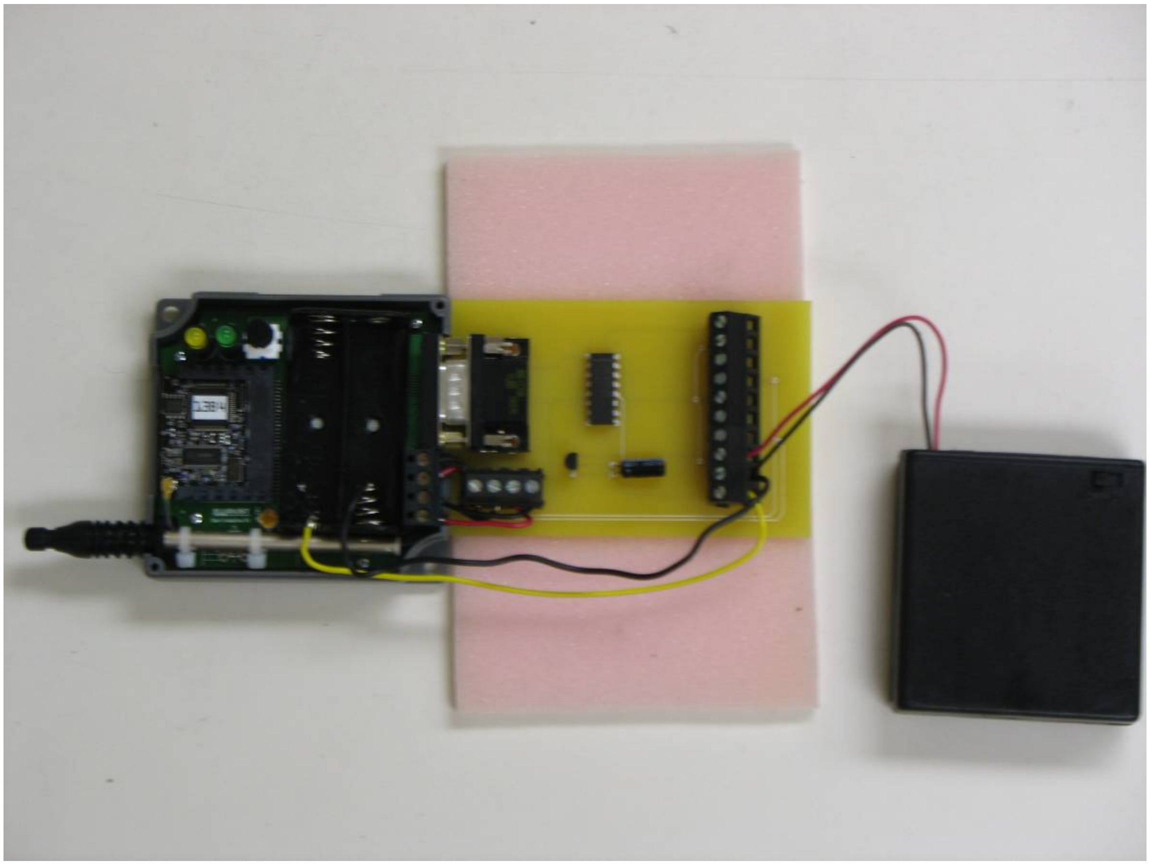

Figure 13. Mote and actuation board used in Trial 2, with battery pack shown.

3.7. WEATHERPROOFING

Geotechnical monitoring instrumentation must be designed for rugged use in outdoor environments. One key component of modifying the sensor node for geotechnical application was ensuring the long term operability of the equipment in all weather conditions. The wireless monitoring equipment and circuitry were housed in plastic electric panel boxes. These panel boxes were found to be easily modifiable, enabling the equipment to be installed in a weatherproof housing while still accessible throughout the trials.

3.7.1. Initial Housing (Trial 1)

The weatherproof housing was a plastic electrical junction box with interior dimensions of 6 in. X 6 in. X 4 in. To install the components in the housing 1 in. X 1 in. wood pieces were cut to fit within the box and adhered with epoxy. The wood blocks were used to elevate the components, making it easier to wire and make adjustments during the trial. The mote and connection panel were placed on the wood blocks and screwed in place. The battery pack was secured in the housing with Velcro, enabling quick removal and replacement if necessary. Two holes were drilled in the housing, allowing the mote antenna to be extended outside and for the sensor and solar panel wires to be connected to the internal components. Figure 14 displays the sensor node setup in the weatherproof housing. The mote is in the upper right corner and the connection panel is on the left side. The battery pack (not displayed) would be secured to the bottom side wall. The mote antenna can be seen extending through the right wall and the sensor wiring is extending from the bottom wall.

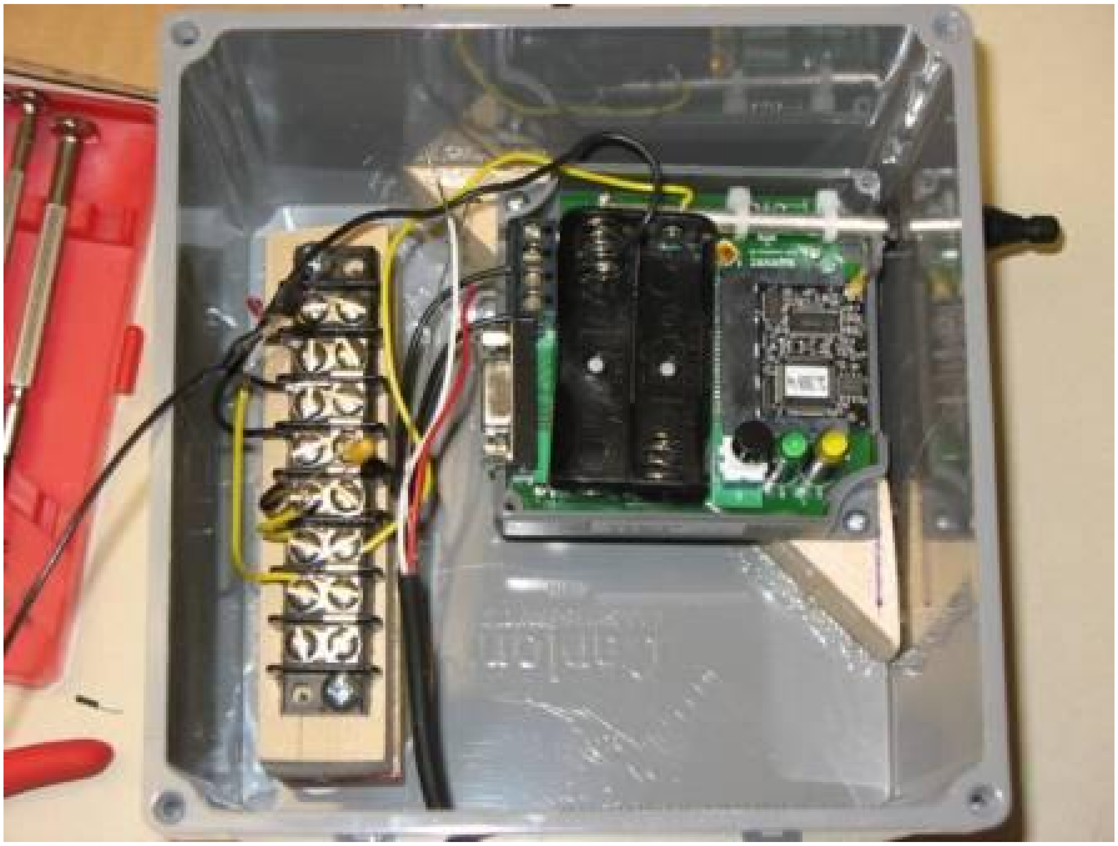

Figure 14. Instrument housing and internal wiring.

3.7.2. Trial 2 Housing

The dimensions of the mote with the actuation board attached to it necessitated a different weatherproof housing be used. Figure 15 displays the sensor node and housing used in Trial 2.

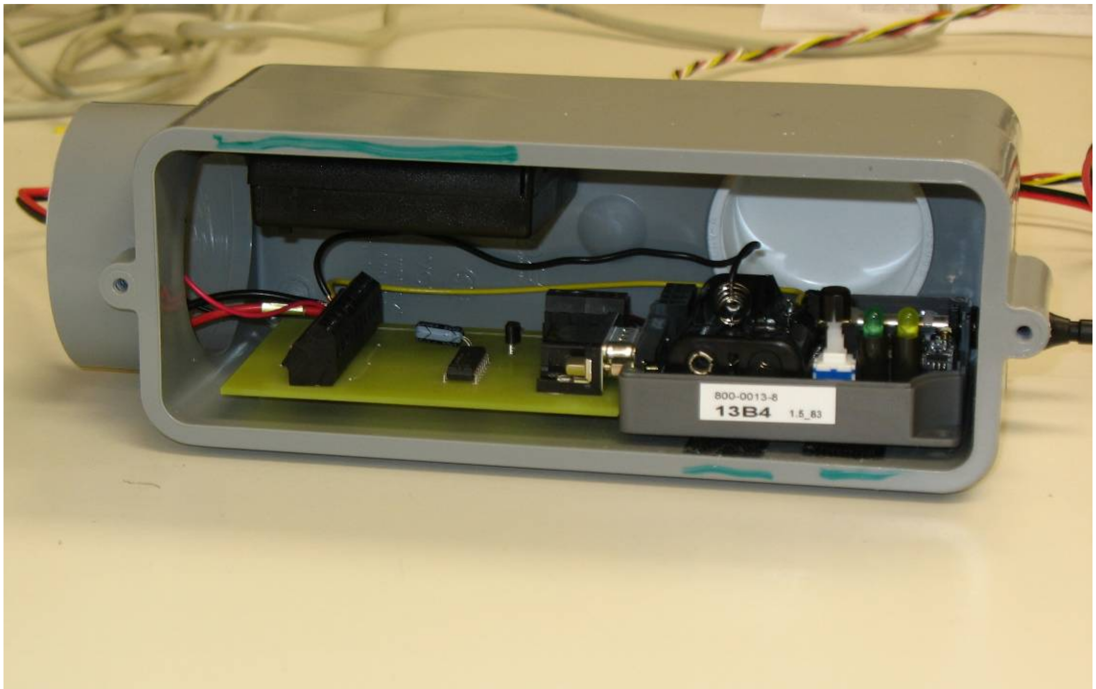

Figure 15. Trial 2 weatherproof housing with mote, actuation board and battery pack.

3.8. REMOTE SYSTEM MANAGEMENT

One aspect of this research focused on enabling this system to be deployed to remote locations. Cellular routers were investigated to provide real-time, remote access to sensor data, eliminating the need for an on-site PC. Several cellular routers are available including: Junxion Box, WAAV CM3, Entrée Box, Stomp Box and the Bluetree 4600.

The Junxion Box, manufactured by Junxion, Inc., was investigated as part of this research project. The Junxion Box enables remote connectivity to the internet via cellular data networks. Several generations of cellular data networks are supported including 1xRTT, 1xEV-DO, GPRS, EDGE, UMTS and HSDPA. The box can operate both a hardwired LAN or a Wi-Fi network. There are several routing options for devices connected behind the Junxion Box including: Static and DCHP IP addressing, IP passthrough, port forwarding, DMZ host and an on-board VPN. The Junxion box settings can be changed by directly connecting to a PC or remotely using the Field Commander software.

To enable remote operation of the sensor node the integration of a cellular router made by Junxion into the system was attempted. A PC data card modem (the Globe Trotter GT Max, manufactured by Option) was acquired to enable the Junxion Box to connect to the internet remotely via a cellular wide are network. The cellular networking capabilities have not been successfully integrated into this system, and this is the focus of ongoing research and development.

4. FIELD EVALUATION

This section describes field trials that were conducted to evaluate prototype sensor nodes described in Section 3. The results are presented for each trial and potential improvements are discussed.

4.1. TRIAL 1

4.1.1. Installation

The first field evaluation of the initial prototype sensor node was conducted on the Texas A&M University campus. The mote/battery housing was secured to two wooden stakes inserted in the ground. The soil moisture probe was placed approximately 5 inches below the ground surface. The MEMS accelerometer was placed in the same location, approximately 2 inches below the surface. The solar panel was connected to the battery pack and secured on top of the housing. Figure 16 displays the sensor node at the location of installation.

Figure 16. Field deployment of wireless soil monitoring node.

4.1.2. Operation

The first field trial of the wireless soil sensing node initiated on June 28, 2006 and monitored soil moisture and deformation for one week. The instrument was removed after one week to continue modifications to the system. The communication network consisted of a mesh network of four motes and one manager. The data manager was directly connected to a desktop PC indoors, and three motes were installed to relay data from the soil monitoring node to the data manager. The network could have functioned properly with two motes, one functioning solely to relay data to the manager, but four were used to evaluate the ability of the system to adapt transmission paths. Sampling rates ranged from one to ten minutes, and data was transmitted after every sampling event.

4.1.3. Data Transmission

The initial test exhibited good data reliability, with 1901 of the 1907 (99.7%) data measurements delivered to the manager and logged. This high reliability was achieved even though mote to mote communication performance was poor. Successful communication between individual motes was completed approximately 52% percent of the time during the trial. However, when motes did not receive data from the intended mote the system adapted transmission paths through alternate motes, resulting in high data reliability.

4.1.4. Soil Monitoring Results

The soil moisture probe was buried approximately five inches below the ground surface. The moisture probe data are presented in Figure 17. The moisture content jumps quickly early in the morning on June 30, which is attributed to sprinklers watering the area overnight. The moisture content remained elevated during the week, as 3.6 inches of rain fell during that period (National Weather Service). The soil moisture values drop late in the day on July 5 corresponding to a drop in battery voltage. The laboratory soil moisture content of adjacent soil was 26.2%, which indicates that the soil remained saturated throughout the field evaluation period. When the probe was removed it appeared to be located at an interface between two soil types, which is a likely cause of discrepancy between field and laboratory moisture contents. The cyclic trends in observed moisture content are attributed to temperature dependence of the dielectric permittivity of water and soil. The dielectric permittivity of water is known to decrease with increasing temperatures (Fernandez *et al.* 1997) and soil dielectric permittivity has exhibited both positive and negative temperature correlations (Campbell 2006). A positive temperature correlation was observed during this field evaluation.

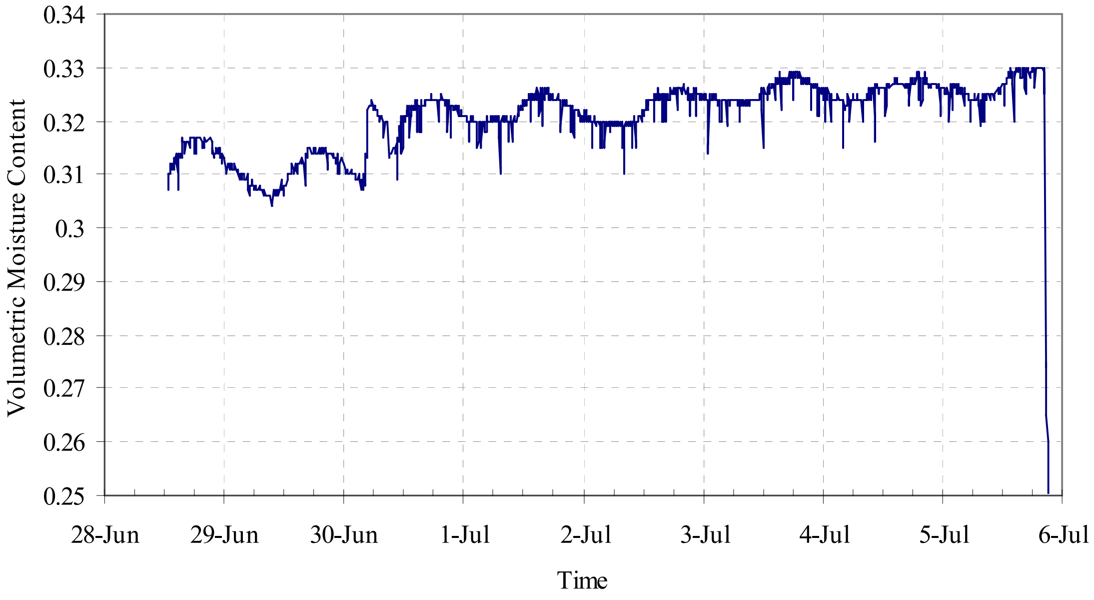

Figure 17. Soil moisture content measurements from Trial 1.

The biaxial tilt sensor was located approximately two inches below the surface, and the observed tilting about one axis is shown in Figure 18. Throughout the test, the MEMS sensor exhibited inconsistent behaviour. For example, on the morning of June 30 the sensor tilted approximately 19 degrees, returning to its previous state over the next three hours. The area surrounding the device was inspected while this was ongoing and no physical displacement was observed. The large tilt value that occurred on late July 5th corresponds to the termination of the field evaluation, where the input voltage was unreliable.

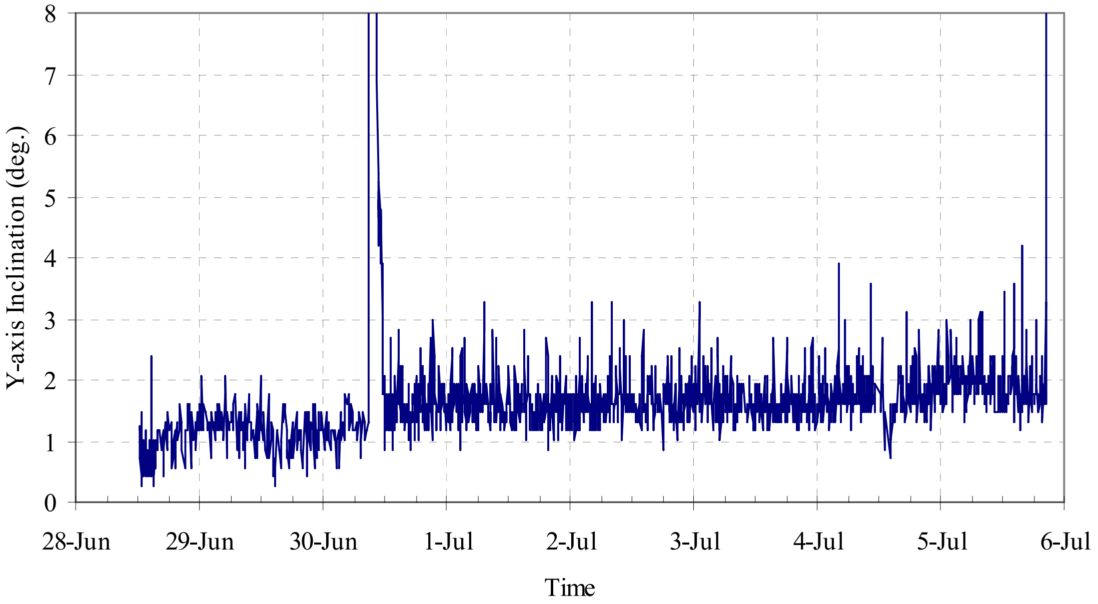

Figure 18. MEMS accelerometer inclination measurement from Trial 1.

4.2. TRIAL 2

4.2.1. Development

After the conclusion of the first trial the sensor node was modified to include an active power management system, described in Section 3.5. The housing was placed on a two inch diameter PVC pipe 5 feet in length that was embedded into the ground. Holes were drilled in the housing and the pipe, allowing the mote antenna and sensor wires to extend out of the housing.

4.2.2. Installation

The sensor node was installed at the same location as Trial 1. A different installation scheme was used in an attempt to address the wide variation in data readings from the MEMS accelerometer. Rather than placing the MEMS accelerometer directly in the soil, a receptacle was built in the PVC pipe to hold the accelerometer. To install the MEMS accelerometer was placed in a bushing which was then lowered and secured in the PVC pipe receptacle (Figure 19).

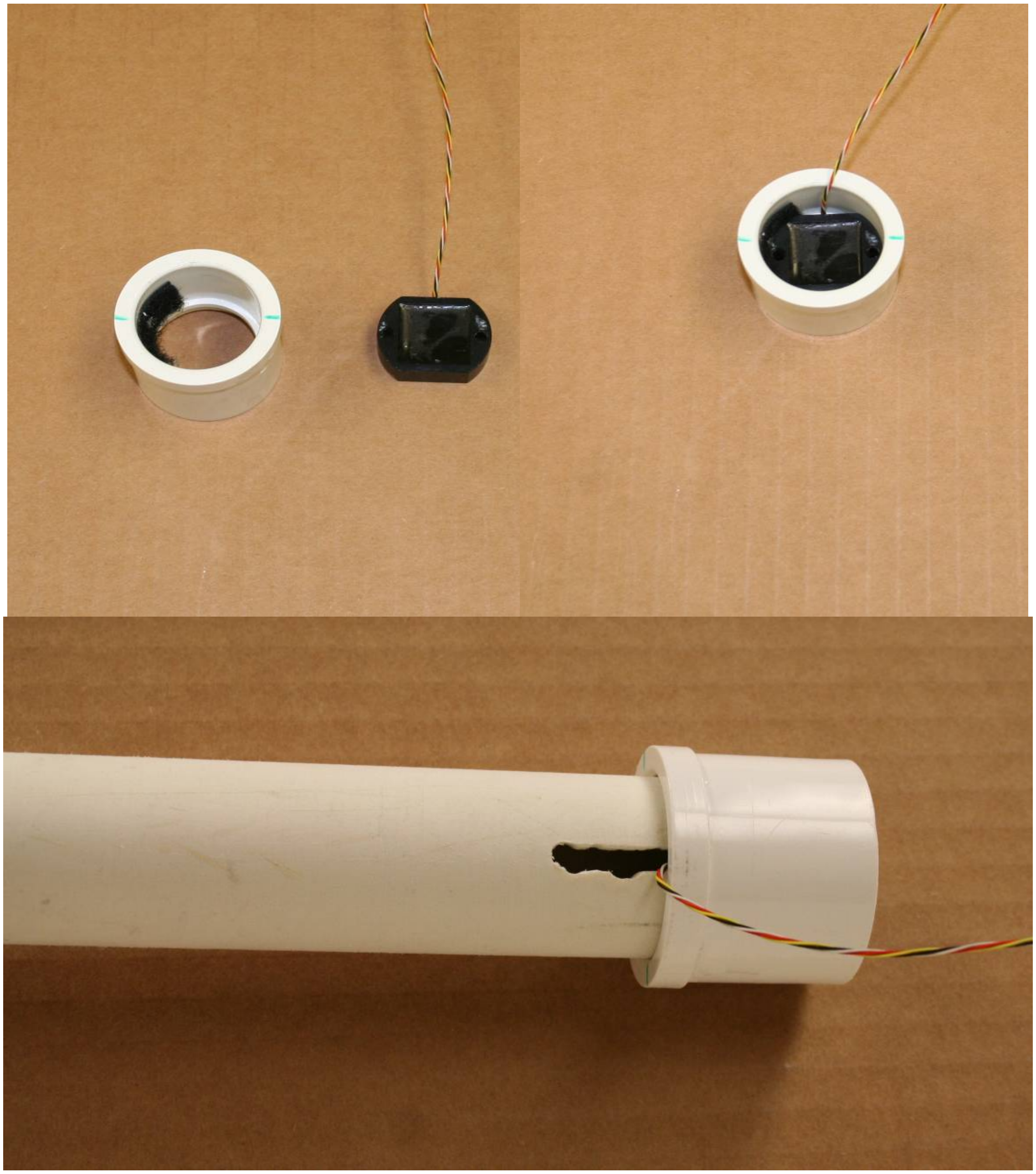

Figure 19. MEMS accelerometer installation. (Clockwise from upper left) MEMS accelerometer beside bushing, MEMS placed in bushing, 1 in. diameter pipe inserted in bushing used to place MEMS and bushing in receptacle.

The 2 inch diameter PVC pipe was embedded 25 inches below the ground surface. The MEMS accelerometer was located approximately 9 inches below the surface, inside the pipe. Figure 20 displays the trial 2 sensor node field installation.

Figure 20. Trial 2 field installation of sensor node.

4.2.3. Operation

Trial 2 began on September 22, 2006 and lasted for one week. A network of three motes was employed to record and relay the data to the manager. For this trial the manager was connected to the Texas A&M University civil engineering LAN to evaluate the remote data logging and mesh configuration capabilities.

Initially, the sensor node exhibited good power optimization, data transfer and durability. The initial voltage supplied from the battery pack increased over a several day period, indicating the solar panel was providing adequate power and that the actuation system was successfully reducing the power consumption of the sensors. During this trial, data was sampled every five minutes, while power was supplied to the sensors 15 seconds before each reading. This configuration resulted in the sensors being powered just 5% of the time, if readings were taken every 60 minutes and the sensors were powered for 15 seconds prior to readings the sensors would be powered less than 0.5% of the time.

The sensor node performed well until September 23, 2006 when the MEMS accelerometer output voltage dropped suddenly, returning to normal over a 12 hour period. The MEMS accelerometer was removed from the sensor node on September 26, 2006 to investigate drift and scatter in the data. The sensor node continued to record soil moisture data until Oct 2, 2006, when the trial ended. Additional problems were encountered during the field trial including the soil moisture probe's output voltage gradually decreasing over a 12 hour period on September 29, 2006. The voltage levels never recovered and did not appear to be related to a change in soil moisture content. Figures 21 and 22 display the data recorded from the MEMS accelerometer and soil moisture probe. Figure 23 displays the temperature inside the sensor node housing throughout the trial. The sensor node was taken out of operation when the MEMS accelerometer was removed (Sept. 26, 2006); therefore, there is a corresponding gap on the temperature and soil moisture figures (Figure 22 and 23, respectively). At the termination of Trial 2 the battery voltage was depleted, indicating the solar panel was no longer providing the necessary power to keep the system fully charged.

Investigation of the soil moisture probe revealed a small area of damage, perhaps a result of insect mastication or installation procedures. Measurement of current consumption of the soil moisture probe showed a drain of 200 mA, approximately 15 times higher than when measured prior to being damaged. This large increase in current consumption explains the drop in voltage of the sensor and drain of the batteries, even with the actuation board. It is possible this damage could also have affected the MEMS readings, resulting in the sudden drops in voltage that were seen in both trials.

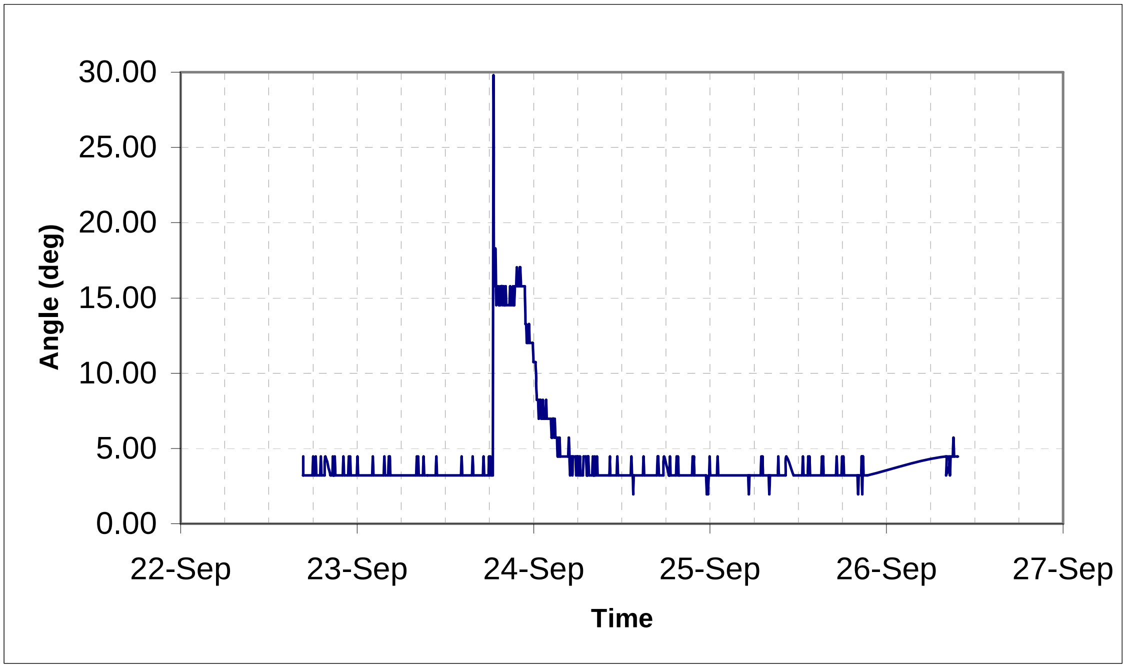

Figure 21. Tilt during Trial 2.

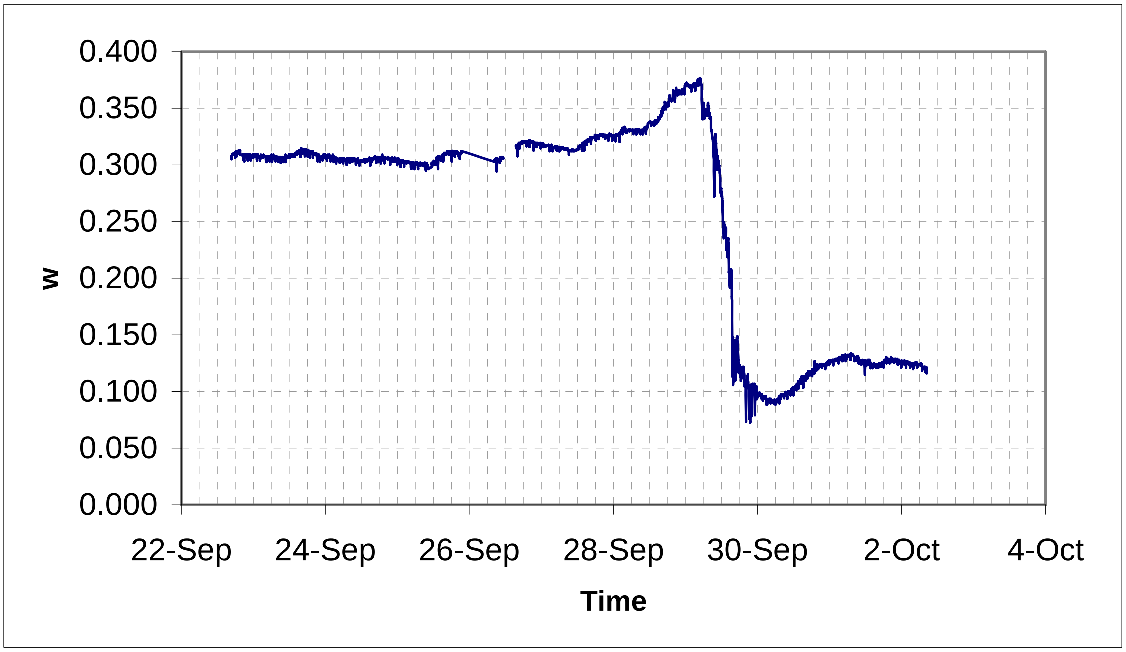

Figure 22. Soil moisture content during Trial 2.

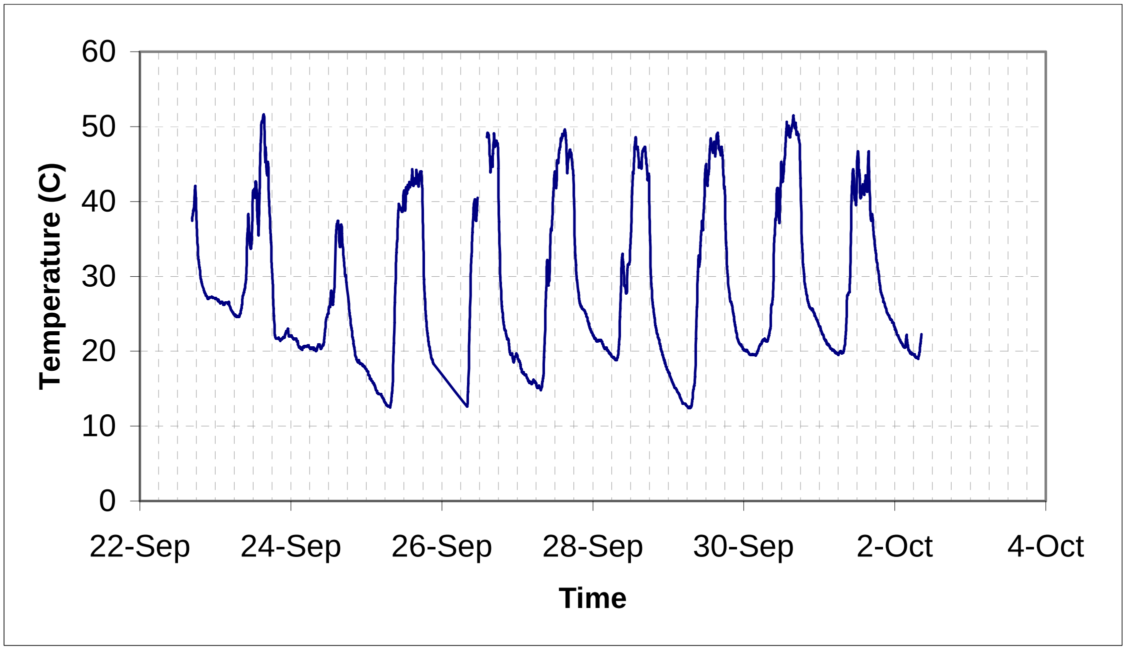

Figure 23. Temperature variation inside sensor housing during Trial 2.

4.3. MODIFICATIONS AFTER TRIAL 2

4.3.1. Data Resolution

Figure 21 shows the resolution of the tilt component of this system was greater than one degree of tilt, which was not sufficient for this application. The user interface and data acquisition component of the Dust Networks software only allows for three significant figures. Thus, for the initial system, a change in voltage of 0.01 V corresponded to over one degree of tilt. To eliminate this problem, a 99.4 kΩ resistor was added to the output terminal of the accelerometer, to scale the accelerometer range to 0-1 Volt, which increased resolution to 0.2 degrees. Figure 24 displays the calibration of the MEMS accelerometer with the resistor attached. Alternative solutions for increasing resolution were investigated, including multiplications circuits, but power requirements precluded their use.

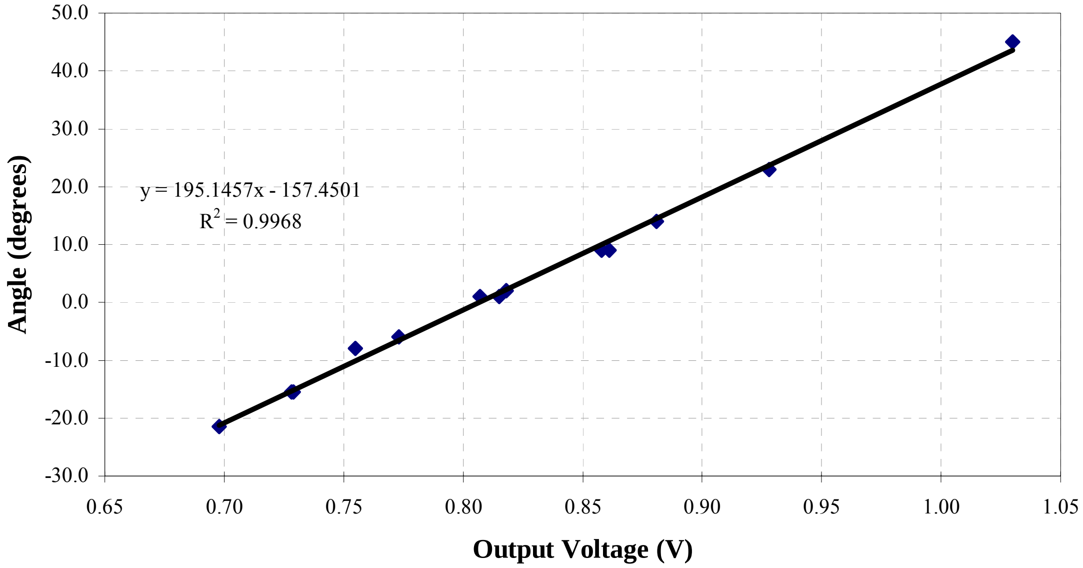

Figure 24. Calibration of MEMS x-axis to increase resolution.

To investigate the effects the increased system resolution the MEMS accelerometer was tested in the laboratory. The accelerometer was attached to a large desk in order to keep the tilt, and therefore the theoretical output, constant for the duration of the test. The test was conducted for 6 hours, with a 30 second sampling rate. The maximum recorded output voltage was 0.811 V and the minimum recorded voltage was 0.794 V, corresponding to 0.81° and -2.5°, respectively. The data from the test is displayed in figure 25. The temperature was also recorded during the test and is displayed in figure 26.

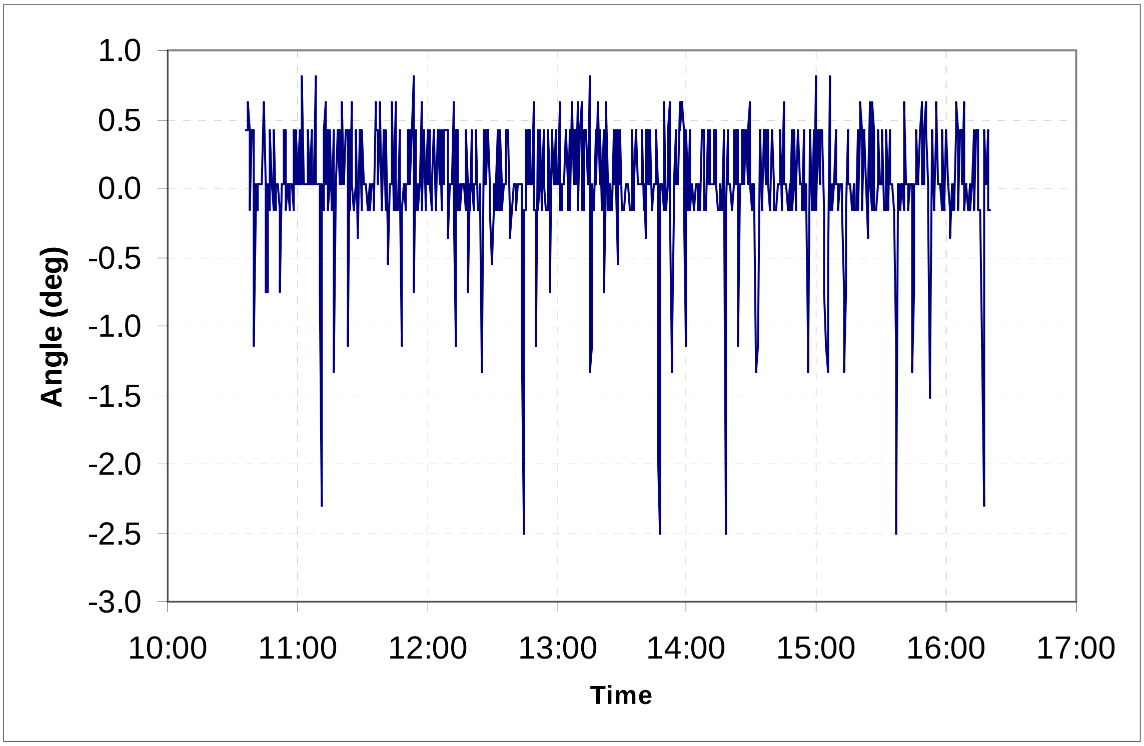

Figure 25. Output of the MEMS accelerometer during the constant tilt test.

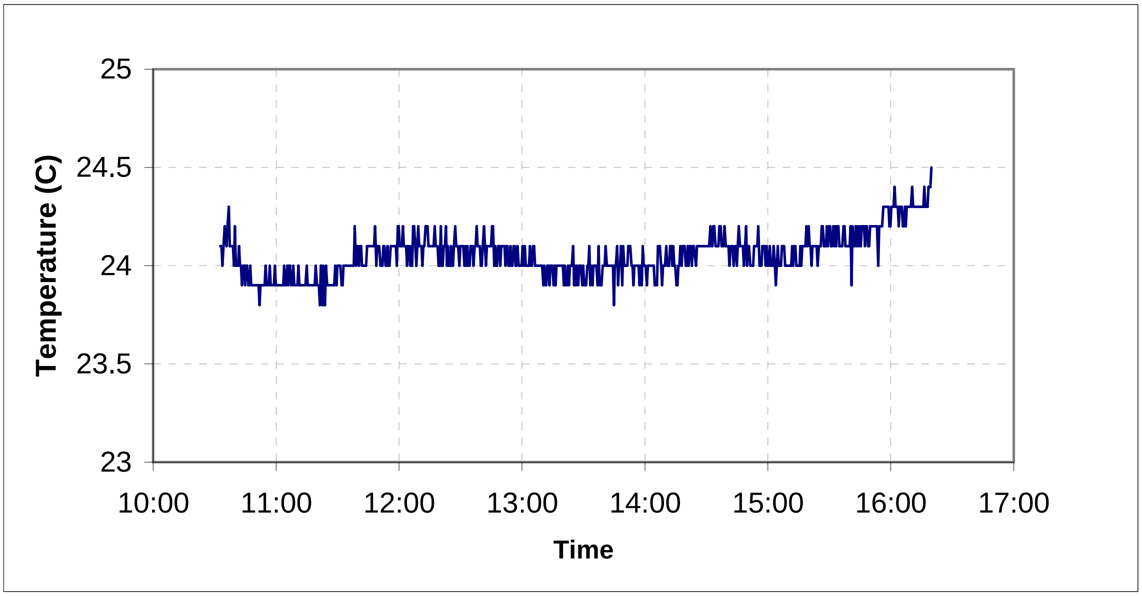

Figure 26. Temperature variation during the constant tilt test.

Of the 687 readings the mean was approximately 0.02º and the standard deviation was 0.46º. Although the MEMS tilt sensor exhibited unacceptable scatter, a moving average can be employed to minimize this problem. Caution must be exercised if this technique is used in the field because the moving average can prevent engineers from instantly detecting rapid soil deformations.

5. POTENTIAL FUTURE RESEARCH

The wireless sensing system created during this research requires additional development prior to field deployment for geotechnical applications. Potential starting points for this research include development of remote operability, site deployment testing, statistical analyses of data reliability and integration of additional sensors into the current node.

Initial investigation and development of remote operation and data access concentrated on the configuration of a cellular modem (Junxion Box) to remotely operate the Dust Networks manager. Remote operations will eliminate the need for a PC on site, which would be a likely source of vandalism and lacks necessary durability. A Virtual Private Network (VPN) between the Junxion Box and a server/PC will allow for secure data transmission and operation of the sensor node. Future research must focus on the configuration of this cellular modem system, such that the cellular service provider, cellular modem, and Dust Networks manager are compatible. Power supply for remote operation must also be taken into consideration. The power consumption of the Junxion Box and Dust Networks Manager must be determined, and a battery and solar panel system must be created to power this component.

Field evaluation of the complete wireless sensor mesh can be performed once the remote operation system is developed. Potential deployment sites include the railroad alignment running through the Bryan/College Station area and the National Geotechnical Experimentation Site located at the Texas A&M University Riverside Campus.

Creation of additional sensor nodes will allow for evaluation of the the expandability of the system. Hardware for two additional sensor nodes has already been acquired. Multiple sensor nodes will increase redundancy, increasing the likelihood of measuring slope movement and making it easier to recognize “false positives.” Statistical data analyses can be performed as more data is acquired, enabling the user to eliminate false positives and improve reliability of the system.

Additional types of sensors can be integrated into the sensor node to create sensor arrays that can measure additional soil properties (e.g. acceleration or suction), allowing engineers to customize the sensor node array for the specific geotechnical engineering application.

6. SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Shallow landslides and debris-slides pose major hazards and cause significant damage to civil infrastructure. Current landslide monitoring efforts are often limited to few, discrete locations, caused by instrumentation costs, data transmission methods and power requirements. The goal of this research was to develop a durable wireless sensor node, which can be employed in expandable wireless sensor networks for remote monitoring of soil conditions in areas conducive to slope stability failures.

Commercially available sensors were evaluated for potential integration into a wireless soil monitoring system. A biaxial MEMS accelerometer was used to measure tilt and a soil moisture probe was used to determine water content of the soil. These instruments were calibrated in the laboratory and evaluated during two field tests.

The wireless sensor node was developed using a commercially available wireless data transmission system (Dust Networks). Power was supplied by a combination of rechargeable batteries and a solar panel. An active power management component was implemented in the system, which dramatically lowered the power consumption of the system. Field evaluations of the wireless sensing system were performed on the Texas A&M University campus and demonstrated that the sensor node was adequately durable for field deployment; however, further development is required for remote data access.

Preliminary research was conducted to develop a cellular communications system for remote operation of the sensor node. Additional research is required for deployment of this component.

6.2 CONCLUSIONS

Laboratory development and field evaluations have demonstrated that the wireless sensor node shows potential for geotechnical applications requiring surface monitoring of soil conditions in remote locations, such as shallow landslides and debris slides. Continuing technological advancements have produced commercially available sensors that can operate effectively in situations were low power consumption is critical. The wireless and self configuring ability of the sensor node will allow for increased flexibility and expansion of soil monitoring locations, as need arises. Several soil nodes can be deployed on a hazardous site to provide a broad data set describing the soil conditions and deformations. Continuing research will result in a viable alternative to traditional slope monitoring instrumentation.

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