Evaluation of Wireless Sensor Node for Measuring Slope Inclination in Geotechnical Applications

Karen M. Furlani, Patrick K. Miller, and Michael A. Mooney

***Abstract*— Digital inclinometers are used in geotechnical engineering to monitor lateral deformations of excavation walls, retaining walls, embankments and landslide areas. Current conventional slope inclination measurement requires a person to manually lower a probe into a grooved casing and record inclination at prescribed intervals as the probe is drawn upwards. Developing an automated inclinometer system would enable continuous monitoring for use in intelligent construction as well as provide significant savings in terms of equipment, material and labor costs. This paper investigates the use of low-cost wireless sensor nodes as an alternative to traditional inclinometer systems used in geotechnical engineering applications.**

***Index Terms*— Accelerometers, Automation, Inclinometers, Wireless Sensor Nodes.**

I. INTRODUCTION

The advent of new sensing and communication technologies is enabling industry to significantly re-engineer traditional systems and processes to improve performance, increase efficiencies and reduce costs. Currently, the construction industry lags behind manufacturing, transportation and agriculture industries in terms of field-level automation [1]. In general, the field-level application of technology is limited as traditional manual processes still dominate. And, while demand for information in the field has multiplied, the means of collecting and disseminating information to the appropriate users has, for the most part, remained unchanged. The move towards an "intelligent" construction site, wherein monitoring data is used in real-time construction decisions, will require continuous streams of data; a significant shift from the current approach of discrete manual data collected once per day, week or month.

Inclination monitoring techniques used for measuring subsurface lateral movements is a field-level application that is ripe for innovation. Obtaining slope inclination measurements using current methods is a costly and labor-intensive process. Intelligent construction requires that more continuous data be delivered to users (e.g. analysis programs, machinery, operators, and project managers) in a timely manner. Recent advances in microelectromechanical systems (MEMS) and wireless communication technologies provide the opportunity to re-evaluate existing equipment and monitoring methods to determine if new technologies can be smarter, less expensive and effectively used in geotechnical applications.

K. M. Furlani was with Colorado School of Mines, Golden, CO 80401 USA. She is now with CH2M HILL, Englewood, CO 80112 USA (phone: 303-440-8433; email: karen@furlani.com).

M. A. Mooney is with the Engineering Department, Colorado School of Mines, Golden, CO 80401 USA (email: mooney@mines.edu).

P.K. Miller is with Colorado School of Mines, Golden, CO 80401 (e-mail: pamiller@mines.edu).

II. TRADITIONAL INCLINOMETER SYSTEMS

Traditional inclinometer systems measure biaxial tilt using a sensing probe with multiple accelerometers attached via a cable to a data acquisition component [2]. Typically, a special type of grooved PVC casing is installed in areas of potential ground movement. The casing's grooves control the orientation of the inclinometer probe and ensure repeatability during future surveys of the same borehole. During a traverse, the probe is manually lowered into the casing and then drawn upwards from the bottom halting every 0.5 m or 0.61 m (U.S. Probe) for tilt measurements; in a subsequent traverse, the probe is rotated 180 degrees and the process is repeated. These two traverses comprise what is commonly referred to as a "two-pass survey". Colored markers on the cable provide depth guidance to the operator. Survey data is downloaded from a datalogger to a PC for post-processing to analyze ground movement. An alternative to traversing inclinometers are in-place inclinometers. In-place inclinometers employ a fixed string of sensors and do not require on-site manipulation. Geodaq, Inc. recently began offering a commercial system that employs a non-traversing system with tilt-sensors daisy-chained the length of the borehole [3]. These inclinometer systems remain dedicated to one borehole throughout a monitoring period. The greatest disadvantage to current in-place inclinometers when compared with the traversing type is cost: multiple in-place systems must be employed for a project, whereas one traversing system can be used to survey a large number of boreholes.

A network of wireless inclinometers each designed to autonomously operate in a dedicated borehole throughout the monitoring process may result in more timely delivery of project information for use in intelligent geoconstruction. An automated system could be designed to traverse a borehole and upon surfacing at ground level, wirelessly relay the collected data to a remote computer for post-processing and routing to the appropriate users. However, to dedicate a tilt-sensing mechanism to one borehole throughout a project's lifecycle, equipment costs must be significantly reduced since multiple units will be deployed during a typical application. By comparison, traditional inclinometer systems are manually operated to survey a potentially limitless quantity of boreholes. Thus a single replacement inclinometer must cost significantly less than the US$10,000 for traditional inclinometer equipment.

III. WIRELESS SENSOR NODES

Wireless sensor networks provide a promising platform for field applications. They consist of small, low-power, wireless nodes that merge sensing elements with limited computing power and storage. These sensor nodes combine a sensing element, or transducer, with analog to digital (A/D) bit conversion, signal processing, memory, radio-frequency communications and power. These sensor nodes are designed to operate as part of an integrated wireless sensor network. The main advantages are their small physical size (typically less than 6 cm square), low cost, modest power consumption, and diversity in design and usage [4].

Our application requires a low-cost, low-g accelerometer wireless sensor node with minimal noise, reasonable shock resistivity, triaxial measurements and high sensitivity coupled with a minimum angle range of ±30 degrees. Low cost is important for developing an economically viable system dedicated to individual boreholes throughout the life-cycle of a project. Low-g (±1g range) accelerometers are most appropriate for measuring tilt. Greater sensitivity, coupled with high A/D bit conversion, increase the resolution by decreasing the minimum degree of change that can be measured. Another important characteristic is a low noise floor to provide a high signal-to-noise ratio and thus greater repeatability.

Three requirements significantly governed our sensor node choice: the need for small physical size, triaxial measurements, and rapid initialization. Our application requires a physical footprint small enough to fit within traditional inclinometer casings; most field applications in the United States use casing with an inside diameter of 5.89 cm. Initial requirements included triaxial measurements which can be achieved with a triaxial accelerometer or with two biaxial accelerometers mounted on one board to gain a third axis. While only biaxial measurements are required to measure tilt, a third axis aligned vertically with the borehole could be used to signal that the sensor has stabilized and is no longer accelerating up or down the borehole. The project's human factors requirements demanded a system with rapid initialization, quick delivery time, simple set-up and use.

Several off-the-shelf products integrate wireless sensor platforms with low-g accelerometers for tilt-sensing applications. Crossbow Technologies Inc. (www.xbow.com) offers the Berkeley sensor "mote" that integrates a radio transceiver, A/D processor chip, flash memory and various sensors (including accelerometers). These are low-powered devices at 8-30 Volts. The host platform is designed to integrate with a variety of sensing mechanisms, including temperature and pressure, for an almost "plug and play" scenario.

Microstrain, Inc. offers a series of wireless sensors that includes the G-link Wireless Accelerometer System (www.microstrain.com), which was used in this study (Fig. 1). G-link is a wireless accelerometer sensor node with a radio transceiver, computer processing and flash memory. The G-link sensor platform incorporates two Analog Devices ADXL 203 biaxial accelerometers (www.analog.com) with three active channels, programmable-gain amplifiers (PGA), a 12 bit A/D converter, a microprocessor, 2 Mb flash memory for storage of logged data, a 916 MHz radio transceiver, antenna and a 9-volt battery.

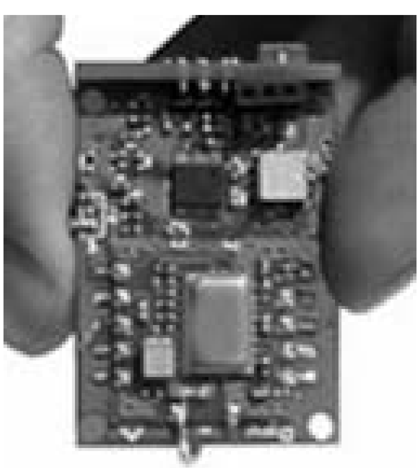


Fig. 1. G-link Wireless Accelerometer Node from Microstrain, Inc. (Photo Courtesy of Microstrain, Inc.)

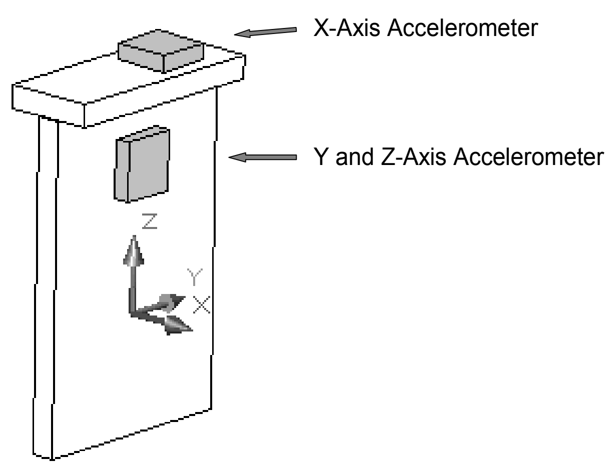


Fig. 2. G-link Wireless Inclinometer Schematic with Axis Designations.

The sensor node has an analog low-pass filter with a break frequency of 5 Hz. The wireless base station integrates a 916 MHz wireless radio transceiver and antenna with power from a 9V battery or power supply. The transceiver base station communicates via a RS-232 or USB interface and is controlled by software residing on a host computer; it sends instructions to and receives data from the G-link wirelessly. The base station is designed to operate with multiple sensor nodes [5] though only one sensor node was used in this study.

IV. LABORATORY EVALUATION OF PERFORMANCE

Based on the manufacturer's specifications, the sensitivity for the ADXL 203 accelerometer with a supply voltage of 3 Volts is 600 mV/g. The sensitivity varies depending on the gain and the electronics of the node, such that the theoretical sensitivity at a gain of 5 is equal to the sensitivity with a gain of 1 multiplied by 5. With a gain of 5, the accelerometer sensitivity theoretically increases to 3000 mV/g. However, the sensitivity of the sensor node will be slightly different than the sensitivity of the accelerometer itself. Thus the G-link sensor node was tested using an angular calibration device in the laboratory to determine the sensitivity, from which the theoretical resolutions are calculated.

Using increments of 1.0 degrees, the calibration device was rotated through ±40 degrees. For applications measuring angles in the range of ±20 degrees, a linear relationship can be used between the output signal and the tilt angle [6]. Equation (1) was used to calculate the experimental angle at each increment. Fig. 2 details the relationship between inclination angle and acceleration (or tilt) of the sensor node. The voltage out (Vout) varies from 0 to 3 Volts, with the output at 0 g equaling 1.5 Volts. The voltage range and the A/D bit conversion are constants at 3 Volts and 2^{12} bits (4096), respectively.

$$\theta = \sin^{-1}\left[\frac{V_{out} - V_{0g}}{Sensitivity(V/g)}\right]\left(\frac{1}{1g}\right) \qquad (1)$$

$$y = mx + b$$
$$V_{out} = m(\sin\theta) + b \qquad (2)$$

To confirm a linear relationship between the output in Volts and the sine of the angle of inclination (1), a linear least squares best fit was used. The resulting linear equation (2) was used in conjunction with (1) to calculate the sensitivity of the sensor node, where m is the sensitivity in V/g.

The G-link's amplifier was set with a gain of 5. 1000 datapoints were averaged for each angle of inclination. The sensitivity in the x and y directions were 2253 and 2094 mV/g respectively. This resulted in theoretical resolutions of 0.019 and 0.020 degrees respectively, i.e., the smallest detectable change in angle is 0.019 degrees. Increasing the gain from 1 to 5 improves sensitivity though it also limits the angular range to ±42 degrees – acceptable tolerances for this application. Due to the increased amplification of noise in addition to the signal, the sensitivity does not increase by a factor of 5 with a gain increase by 5. Thus, under controlled operating conditions in the laboratory, the theoretical resolution, i.e. the smallest change in inclination angle that can be detected, is 0.020 degrees with the gain set to 5.

Testing the repeatability or noise of the sensor node is important to quantify its precision of repeated measurements. To determine repeatability, 30 datasets each comprised of 1000 data points were collected at three different values for both the x and y axis of the G-link. The sensor was oriented at -15, 0, and +15 degrees as referenced on the calibration device for each axis. The 30 datasets were taken consecutively over a period of several hours at a sampling rate of 32 Hz.

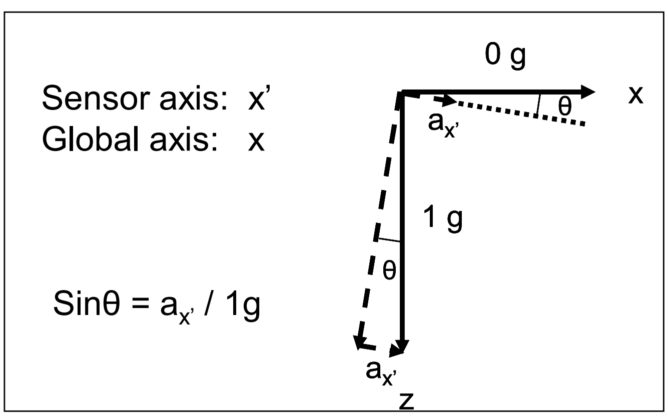


Fig. 3. Relationship Between Inclination Angle and Acceleration.

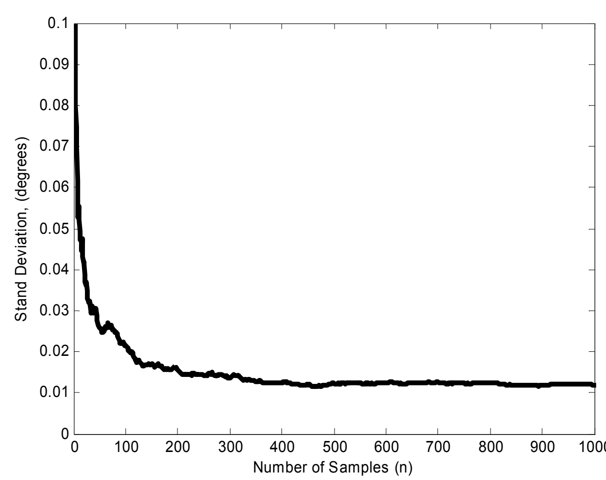


Fig. 4. G-link Repeatability as a Function of Number of Averaged Data Samples.

Using MATLAB, the running average at each data sample, n = 1:1000, was calculated for each of the 30 datasets. A combined running average of all 30 datasets was then calculated for each n. The variance at each n for the combined mean was calculated. The standard deviation based on this variance is defined as the repeatability. At n = 1000 the standard deviation for the G-link with a gain of 5 was 0.012 and 0.013 degrees for the x and y axes respectively. The repeatability was consistent at all angles tested; therefore, it is not a function of the angle of the G-link. A hypothesis test based on the chi-squared statistic was performed. Given a sample size of 30 and the previously mentioned standard deviation the upper bound of the repeatability, within a 95% confidence interval, was 0.016 and 0.017 degrees for the x and y axes respectively[7]. This ensures that the sensor's resolution is indeed limited by the theoretical resolution and not by the amplified noise level.

1000 samples were used for the resolution and repeatability tests to ensure the minimum standard deviation and an accurate mean value at each reading. However, the repeatability improved little after 100 samples and virtually no improvement was observed past 400 samples (Fig 4).

V. FIELD PERFORMANCE

The G-link wireless accelerometer node set to a gain of 5 was evaluated for field accuracy by comparing its performance with a traditional inclinometer system. This involved coupling the G-link sensor with a traditional inclinometer probe to compare results between the two systems (Fig. 5). A waterproof enclosure and method of attachment for the G-link sensor node was developed.

Field surveys were conducted to compare the inclination measurement data collected using the G-link sensor with data simultaneously collected with a traditional inclinometer system, Slope Indicator's Digitilt Inclinometer System [8].

Fig. 5. G-link Y-axis Aligned with SINC Probe Wheels (left) and G-link Attached to Probe Upon Entering Casing (right).

For the field test, two consecutive two-traverse surveys were performed in the same borehole. A standard two-pass survey incorporates two traverses with the probe rotated 180 degrees for the second traverse. This approach provided two complete sets of inclination measurement data simultaneously collected by both systems: the G-link accelerometer sensor node and Slope Indicator's Digitilt Inclinometer probe (SINC). A two-pass survey provides two readings per axis at each depth interval of 0.61 m (two feet, which is the standard depth increment for English probes); during post processing the two readings at each depth are averaged in order to calculate lateral deviation. Per Fig. 4, 400 was the target number of samples to be acquired for each reading during the field test. Over 90% of readings were an average of 400 samples; 100% of readings were an average of at least 250 samples.

The G-link and SINC axes were aligned to enable a side-by-side comparison of their measurement data. Two methods were used to compare the performance of G-link sensor node to the performance of the SINC: incremental inclination angle error and cumulative displacement error. Incremental inclination angle error is the difference between the discrete angle of inclination measured at each depth during two consecutive traverses or surveys. Incremental inclination angles were calculated using Equation (1).

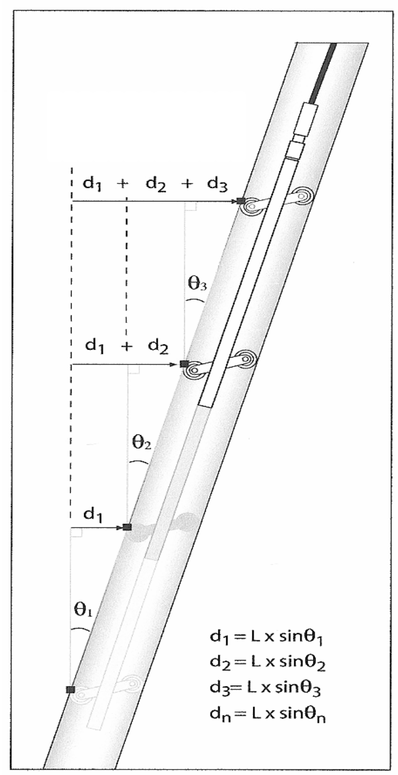


Fig. 6. Cumulative Displacement (Picture Courtesy of Slope Indicator, Inc.)

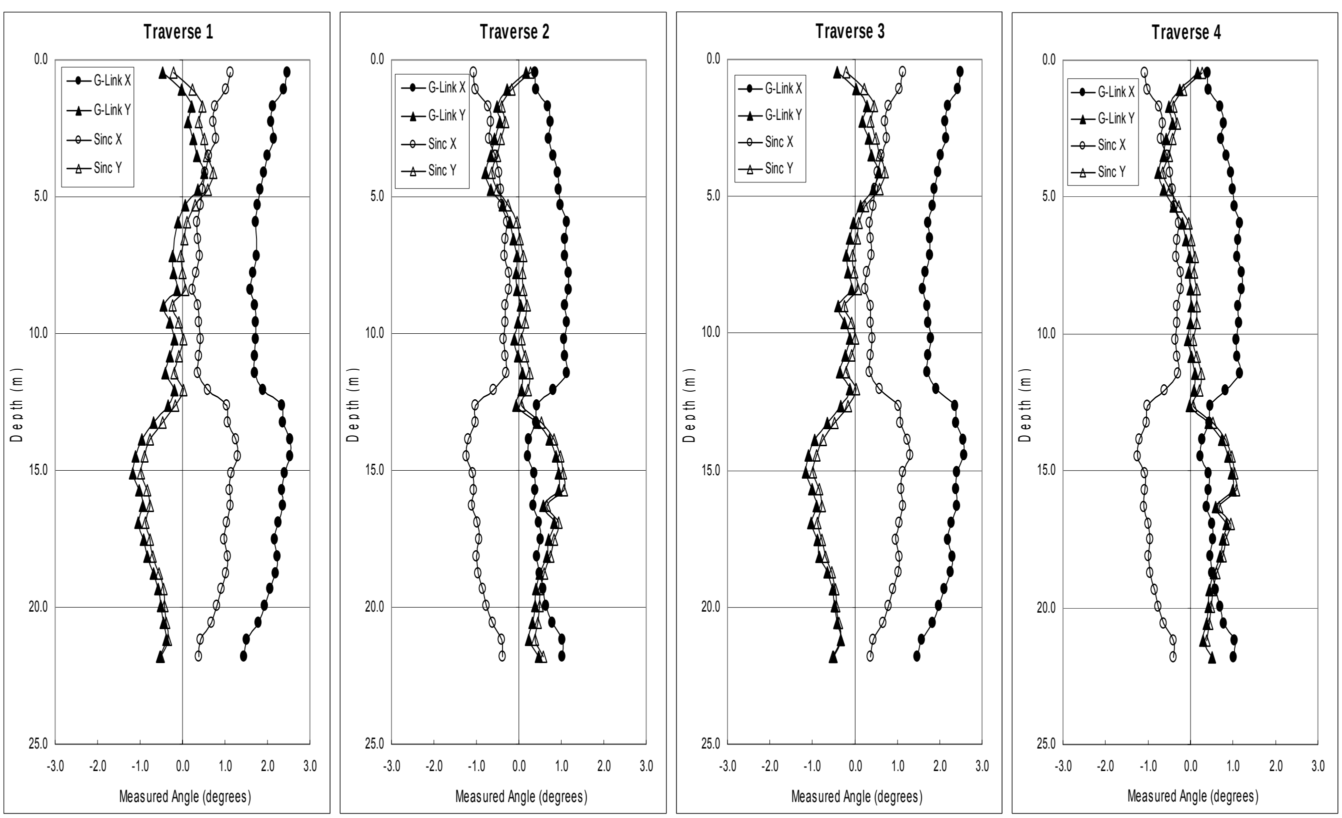
The cumulative displacement error is the difference between the cumulative lateral displacement calculated for each traverse or survey. The cumulative displacement is obtained by summing the displacement values measured at each depth (Fig. 6). The displacement values are calculated using Equation (1) combined with Equation (3) to solve for d, lateral displacement. L is the SINC's English-unit probe measurement interval of 0.61 m (2 feet) (i.e. the distance between the upper and lower set of wheels; also the depth reading increment).

$$d = L \sin\theta \qquad (3)$$

The incremental inclination angle error and the cumulative displacement error were evaluated two ways: by comparing traverses and by comparing surveys. Each survey is comprised of two traverses; this matches the SINC method of taking readings in the "0"direction and then rotating the probe 180 degrees to take readings in the "180" direction. Thus, a total of four traverses were conducted during the field test, with traverse 1 and 3 in the same "0" direction and traverse 2 and 4 in the same "180" direction. Angles are measured by the sensor in both the x and y axes during each traverse. The sensors' x and y axes correspond to the B and A axes of the SINC, respectively. For simplicity, the SINC B and A axes will hereafter be referred to as x and y. Measurements begin at the bottom of the borehole and proceed to the surface in increments of L = 0.61 m.

Fig. 7 displays the measured angles by traverse for the G-link and SINC. Note that one reading in traverse 1 at a depth of 6.5 meters is missing due to human error while taking the field data. The offset between the G-link and SINC x axis likely suggests that the calibration of the G-link x axis is offset by approximately one degree. Overall the values correspond well with one another. However, the difference between the measured angle of the G-link and SINC tends to increase with decreasing depth. This may be a symptom of sensor drift.

To calculate the errors by traverse, traverse 1 was subtracted from traverse 3 and traverse 2 was subtracted from traverse 4. The resulting errors are effectively the sensors' field repeatability when measuring the casing twice at the same orientation. This is desirable since an automated traversing mechanism may be designed as a one-pass system without rotating 180 degrees. The field repeatability will include the sensor noise as well as any human error introduced by trying to duplicate the exact depth at which the previous reading was acquired. The lab repeatability study was immune to human error because the sensor was not moved between data sets.



(a) (b) (c) (d)

Fig. 7. Measured Angles Versus Depth for Both Axes of the G-link and SINC for Each of the 4 Traverses.

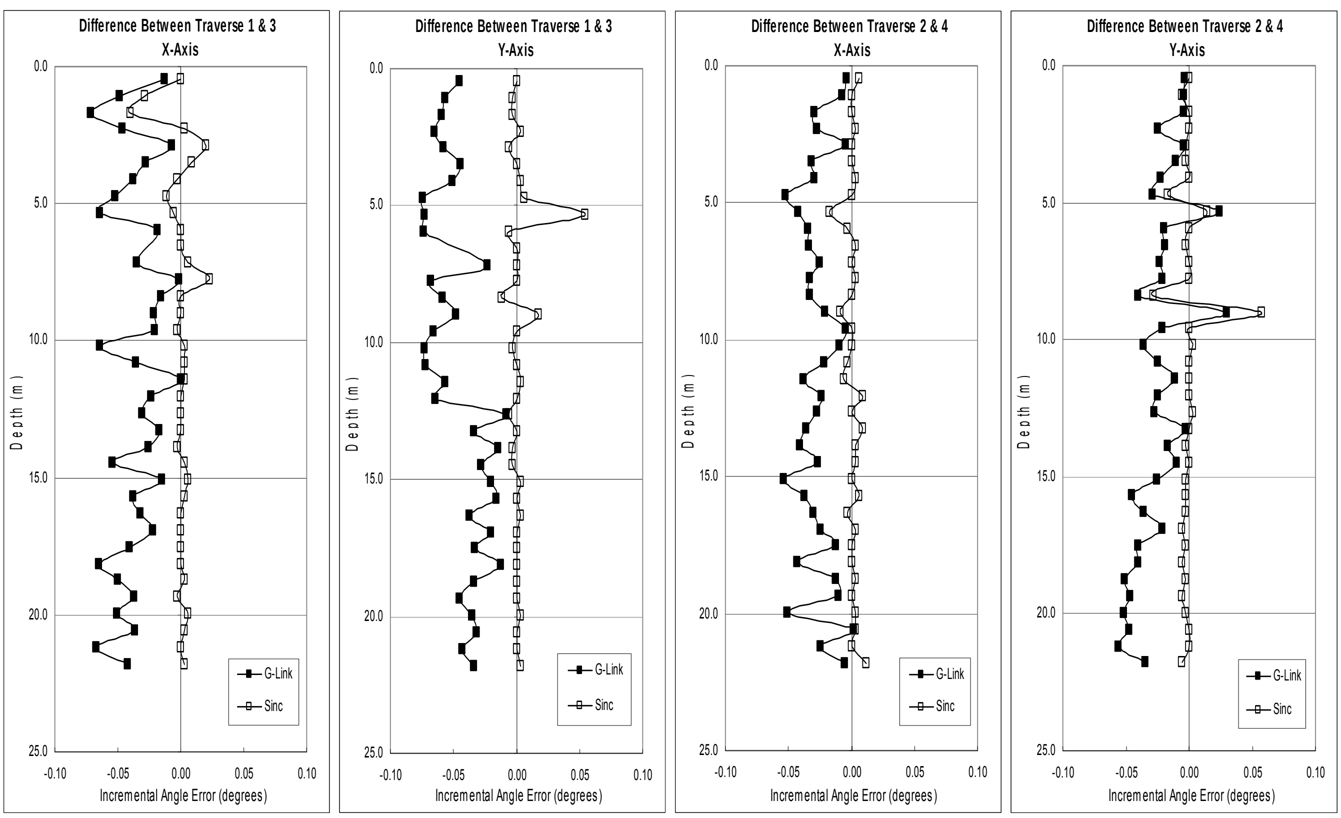
Fig. 8 compares the incremental error for sister traverses for both the G-link and the SINC. The G-link has a greater error between sister traverses than the SINC. Due to the generally small error in the SINC, it seems reasonable that locations where the SINC error spikes and is mirrored by the G-link error, are locations more heavily influenced by human error. It is curious that in all four comparisons the error of the G-link is predominantly negative.

To compare data between surveys, the 0 and 180 measurements collected at each depth were averaged; this follows the SINC guidelines for data reduction. Thus, traverses 1 and 2 were averaged for survey 1, and traverses 3 and 4 were averaged for survey 2. Fig. 9 displays the averaged angles of the two surveys.

The difference between the two surveys is again the field repeatability; this time indicating how precisely each system measured the borehole when the traverses are combined to help eliminate sensor offset. Fig. 10 displays the incremental angle errors between survey 1 and 2. Comparing Fig. 8 with Fig. 10 it is apparent that averaging the 0 and 180 measurement decreases the error. Table I displays the mean of the absolute value of the incremental error between the sister traverses and surveys.

Averaging the traverses also centers the incremental angle error about zero, which is extremely beneficial when considering the cumulative effect of the errors. Fig. 11 displays the cumulative displacement errors calculated from the differences of survey 1 and 2. Generally the cumulative displacement errors of both the G-link and SINC are quite small. However, the G-link y-axis shows a sharp increase in cumulative displacement error at approximately 12 m. This corresponds to Fig. 10 where the y-axis values are negatively biased from 0 to 12 m in depth.

The relative field performance of the G-link was fair when compared to the SINC. The errors between surveys and traverses for an ideal system are zero; since all data were collected within a 2 hour time period there was essentially no chance for ground movement between measurement readings. The absolute cumulative displacement error between surveys for the SINC was 0.17 mm and 0.43 mm for the x and y axes, respectively. The G-link's absolute cumulative displacement error was 1.7 mm and 4.0 mm for the same axes; approximately 10 times greater than the errors reported with the SINC. The incremental inclinometer angle error and the errors between traverses support this general trend.



(a) (b) (c) (d)

Fig. 8. Measured Angles Versus Depth Comparison of Sister Traverses for Both Axes of the G-link and SINC.

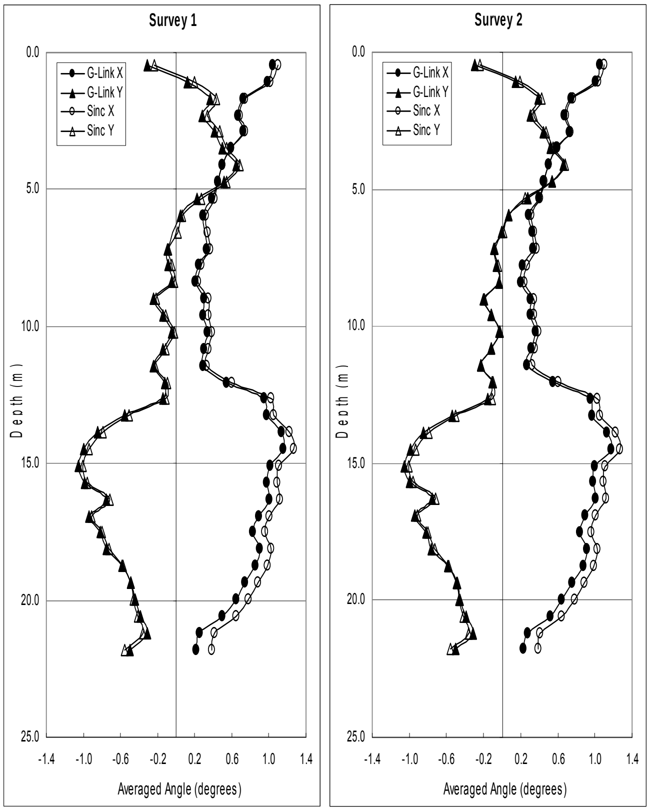


Fig. 9. Averaged Angles Versus Depth for Survey 1 & 2.

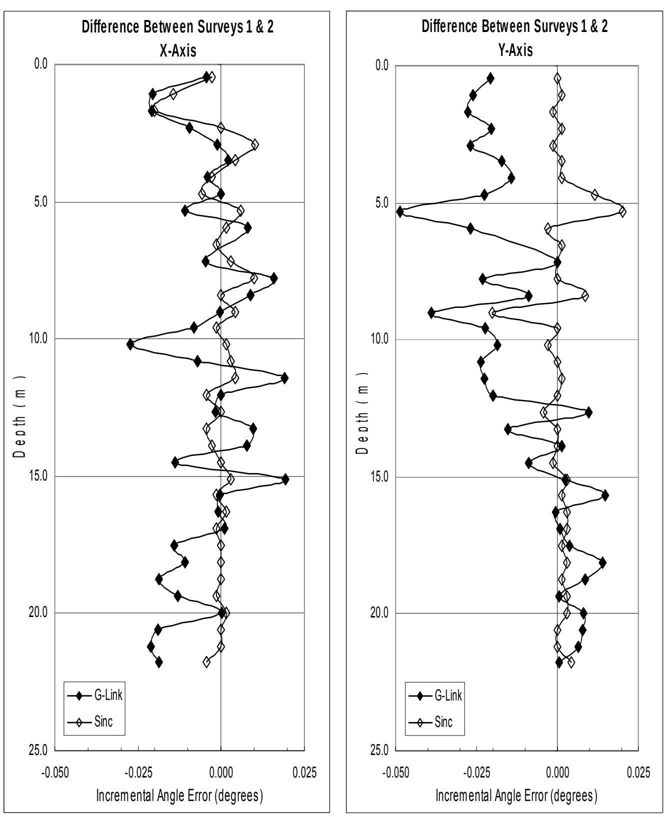


Fig. 10. Incremental Angle Error Between Surveys.

Table I: Mean of the Absolute Values of the Incremental Angle Errors (degrees)

	Mean Inclination Angle Error (deg)			
	G-link X	G-Link Y	SINC X	SINC Y
Resolution	0.019	0.020	0.0030	0.0030
Repeatability	0.012	0.013	0.0030	0.0030
Traverse 1 - 3	0.034	0.044	0.0053	0.0039
Traverse 2 - 4	0.026	0.027	0.0030	0.0050
Survey 1 - 2	0.010	0.015	0.0034	0.0030

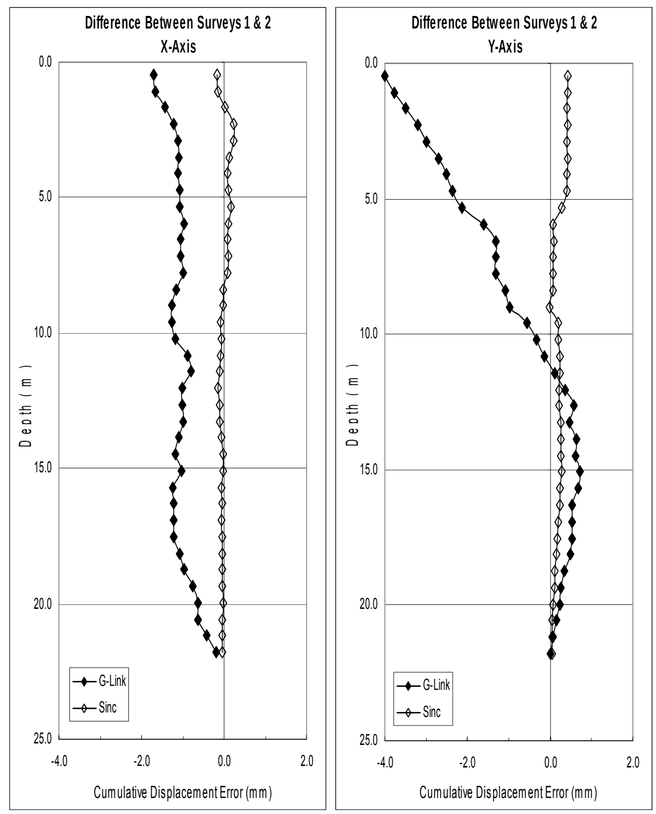


Fig. 11. Cumulative Displacement Error Between Surveys.

VI. CONCLUSIONS AND RECOMMENDATIONS

Lab and field testing was performed to evaluate a low cost wireless sensor node for inclination monitoring. The G-link wireless sensor's performance in the field matched well with expected results based on the laboratory calibration. The G-links performance did not match the SINC performance primarily due to discrepancies in resolution. Limited by 12 bit A/D conversion, the resolution of the G-link is 0.020 degrees for a measurement range of ±42 degrees. This is one-sixth the 0.003 degree resolution of the SINC, which uses a 16 bit A/D conversion. The repeatability or noise of the G-link was found to be 0.013 degrees for 400 averaged samples as compared with a reported 0.003 degrees (not measured here) for the SINC.

There are several possible configuration changes to the G-link sensor node that could improve its performance results.

Assuming the theoretical sensitivity and supply voltage remain constant at 560 mV/g and 3 Volts, respectively, increasing the A/D conversion from 12 bits to 16 bits will increase the theoretical resolution to 0.0047 degrees with a gain of 1. With a gain of 5, the theoretical resolution will increase to 0.00094 degrees; better than the 0.003 degrees theoretical resolution of the SINC. However, exchanging the 12-bit A/D converter for a higher bit conversion of 16 will increase the sensor node cost.

Further increasing the sensor node's gain will increase the sensitivity, resulting in increased resolution; the trade-off is a limiting of the angular measurement range and an amplification of noise in addition to the desired signal. Increasing the gain to 30, with 12 bit A/D, will theoretically match the SINC resolution of 0.003 degrees, though the angular range is severely limited at ±5.3 degrees and the effect of noise amplification is quantitatively unknown. External factors potentially affecting the performance of the sensor node include its location on the probe, mounting method and sampling time.

Perhaps a more economical way to enhance the performance of the G-link sensor would be to take readings more often, or at a smaller reading interval. Traditionally, the root-sum-square method is a widely accepted technique to calculate error propagation. This implies that the cumulative error will decrease with the square of the number of measurements; if four times as many measurements are taken within the same distance the cumulative error will be one-half. The G-link housing used in the field test was approximately 16 cm, while the reading interval was 61 cm. Therefore, if the G-link was used alone, uncoupled from the SINC, it would not be unreasonable to quadruple the number of readings. While an increase in readings would require more data space, if the G-link was able to upload its data after each traverse the current 2 MB Flash memory card would be adequate.

While the evaluation of errors between surveys supports a direct comparison with the SINC, the errors between traverses are relevant for an automated traversing system designed to operate without the redundancy of a two-pass survey. The traverse-only errors for both the G-link and SINC vary depending on the axis being evaluated, and in all instances the SINC and G-link errors improve when the traverses are combined and evaluated by survey.

While the low-cost wireless accelerometer sensor node evaluated in this study does not match the SINC, the performance is sufficient for many geo-monitoring applications where extremely high precision is not necessary. Modifications to the A/D converter and/or amplifier will likely improve the performance of the node such that it could become an option for high resolution applications. Moreover, the performance of the wireless sensor node presented here demonstrates the potential for networks of low-cost wireless sensors in intelligent construction.

ACKNOWLEDGMENT

The authors would like to thank Clyde Anderson and CTL Thompson, Inc., a geotechnical engineering firm with offices in Denver and Colorado Springs, Colorado, for their assistance in field data collection.

REFERENCES

[1] Palmer, et al., "Intelligent and Automated Construction Job Site Tactical Plan," Available Online: http://www.fiatech.org [October 2004].

[2] Dunnicliff, J., "Geotechnical Instrumentation for Monitoring Field Performance," New York, Wiley & Sons Inc., 1993.

[3] Geodaq, "Geodaq INC300 Series Inclinometer Data Sheet," Available Online: http://www.geodaq.com [October 2004].

[4] Ruiz-Sandoval, M., Spencer, Jr., B.F. , and Kurata, N., "Development of a High Sensitivity Accelerometer for the Mica Platform," Proceedings of the 4th International Workshop on Structural Health Monitoring, September 2003, Palo Alto, California, USA, pgs. 1027-1034.

[5] Trutor, B. and Townsend, C., "Application Note: Using Multiple Remote Wireless Link Sensor Nodes to Simultaneously Log Sensor Data," Available Online: http://www.microstrain.com/wirelessaccelerometers.htm [October 2004].

[6] Clifford, M.A., "Accelerometers Jump Into the Consumer Goods Market," Sensors Magazine, August 2004, pgs. 36-39.

[7] Walpole, Ronald E., and Myers, Raymond H., "Probability and Statistics for Engineers and Scientists," Fourth Edition, New York, MacMillian Publishing Company, 1989.

[8] Slope Indicator, "Digitilt Inclinometer Probe 50302599", Available Online: http://www.slopeindicator.com/pdf/manuals/digitilt-probe.pdf [2000].