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Development and laboratory testing of a low-cost wireless in-place inclinometer prototype

Développement et tests en laboratoire d'un prototype d'inclinomètre sans fil à faible coût

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ABSTRACT: This paper introduces a low-cost in-place inclinometer tailored for geotechnical engineering applications, specifically designed for monitoring lateral (transverse) deformations in embankments, retaining walls or natural slopes. The developed system utilizes Micro-Electro-Mechanical System (MEMS) accelerometers, which are pivotal in tilt measurement, offering precise and compact solutions for monitoring inclinations in geotechnical applications. The hardware configuration involves connecting multiple accelerometer sensors in series, interfacing them with small low-cost microcontrollers. These sensors communicate data wirelessly to a central master node. The master node further transmits the collected data to the web infrastructure. The software architecture of the system is developed to achieve real-time data processing and analysis. This integration enables efficient storage, retrieval, and visualization of the displacement data, empowering geotechnical engineers with accurate, timely, and actionable insights. Laboratory testing and validation of this inclinometer system demonstrates that it may be useful in providing general information for slope stability assessments, excavation safety, and foundation integrity evaluations. The MEMS accelerometer used is quite low-cost, with a mere 10-bit output resolution, and, thus, may not meet the requirements for high-risk projects. Plans are underway to explore alternative MEMS that offer enhanced precision and accuracy for tilt measurement while still maintaining affordability.

RÉSUMÉ : Cet article présente un système d'inclinomètre à faible coût conçu sur mesure pour les applications de génie géotechnique, spécifiquement élaboré pour surveiller les déformations latérales (transversales) dans les remblais, les murs de soutènement ou les pentes naturelles. Le système développé utilise des accéléromètres à système micro-électromécanique (MEMS), cruciaux pour la mesure de l'inclinaison, offrant des solutions précises et compactes pour la surveillance des inclinaisons dans les applications géotechniques. La configuration matérielle implique la connexion en série de plusieurs capteurs d'accéléromètre, en les interférant avec de petits microcontrôleurs économiques. Ces capteurs transmettent sans fil les données à un nœud central maître. Ce nœud maître transmet ensuite les données collectées à l'infrastructure Web. L'architecture logicielle du système est conçue pour permettre un traitement et une analyse des données en temps réel. Cette intégration permet un stockage, une récupération et une visualisation efficaces des données de déplacement, fournissant aux ingénieurs géotechniciens des informations précises, opportunes et exploitables. Les tests de laboratoire et la validation de ce système d'inclinomètre démontrent qu'il peut être utile pour fournir des données cruciales pour les évaluations de la stabilité des pentes, la sécurité des excavations et l'intégrité des fondations. Le capteur MEMS utilisé est assez économique, avec une résolution de sortie de seulement 10 bits, et pourrait ne pas répondre aux exigences des projets hautement significatifs et à haut risque. Des plans sont en cours pour explorer des capteurs alternatifs offrant une précision et une précision accrues pour la mesure de l'inclinaison tout en maintenant un coût abordable.

Keywords: fixed-in-place inclinometer; low-cost; MEMS acceleration sensors; ground movement; embankments

1 INTRODUCTION

Inclinometer monitoring is a geotechnical technique used to measure and track the changes in inclination of a natural slope, retaining wall, or embankment, over time. This method typically involves the use of a metal or plastic pipe (casing) with inner grooves in two orthogonal directions that is installed into a borehole drilled within the ground being monitored (Dunnicliff, 1982; Stevens & Zehrbach, 2000). By regularly measuring the inclinations of that casing at specific depths, engineers and geotechnical experts can determine the lateral deformations in two directions and assess the stability of slopes, tunnels, excavations, dams, and other geotechnical structures (Ding et al., 2000; Stark & Choi, 2008; Uhlemann et al., 2016).

Inclinometer monitoring provides valuable data on ground movements, enabling also early detection of potential issues and allowing for timely remedial actions to prevent accidents or damage to structures (Stark & Choi, 2008).

The most used instrument type, the transversing inclinometer probe, which uses a servo-accelerometer sensor, was introduced to the industry in the late 60s (Green & Mikkelsen, 2008). Servo accelerometers measure acceleration based on force balance and inertial principles, and are known for their high precision, robustness, durability, and ability to withstand harsh environments. The casing's shape is established through consecutive manual measurements, usually placing the transversing probe at 50 cm intervals, which is the typical distance between the wheels that guide the probe along the casing grooves. These measurements yield a profile of the casing in two orthogonal directions. Machan & Bennett (2008) presents a detailed description of the procedures involved in the measurement and data collection using the transversing inclinometer probe.

One notable drawback of servo accelerometers used in such probes is their relatively high cost. Other limitations, which can cause measurement errors if not properly accounted for, include sensitivity to temperature changes and limited frequency response (high frequency readings may result in feedback loop that can introduce phase lag). These limitations make servo accelerometers less suitable and prohibitive for applications that require the use of a fixed In-Place Inclinometer (IPI) solution, or automatic acquisition and remote access of high-frequency reads.

IPI involve the installation of multiple sensors at discrete depths along the tube casing and are useful when frequent monitoring of ground movement is essential or when site accessibility is limited (Uhlemann et al., 2016). This approach saves valuable time and labour that would otherwise be spent on manual measurements using the transversing inclinometer probe. Additionally, it enables the seamless collection of regular data through the utilization of automated data acquisition equipment, providing valuable information on the ground deformation vector and rate of movement.

Micro Electro-mechanical Systems (MEMS) accelerometers have gained prominence in the last decade (Li et al., 2014), supplanting the traditional servo accelerometer, and finding a growing application in IPI.

The principle of MEMS accelerometers relies on detecting changes, for example, in capacitance, piezoelectricity, or thermal conductivity caused by accelerative forces (Niu et al., 2018). When the accelerometer undergoes acceleration, these microstructures move, leading to a change in capacitance or other quantifiable properties. This change is then converted into an electrical signal, which can be analysed and used to ascertain the acceleration applied to the sensor.

Ground movements are typically deemed quasi-static. Thus, by measuring the components of the gravitational acceleration vector along a three axis MEMS accelerometer, mathematical algorithms can be applied to ascertain the sensor's orientation relative to Earth's gravitational field.

The rapid advancements in MEMS technology as led to significant reductions in sensor cost, size, and energy consumption of inclinometer solutions. At present, some companies, including, sisgeo.com, geosense.co.uk, signalquest.com, measurand.com and soilinstruments.com, have their own commercially available IPI solutions.

Those solutions use a series of MEMS accelerometers housed within rigid bodies that are somewhat interconnected by flexible joints enabling relative tilt movement between each sensor. Each available solution features its joint mechanism and rigid body design. Some are specifically designed for insertion into traditional grooved casings, whereas others offer greater versatility, allowing placement inside unguided casings. The IPI from measurement.com don’t require any centring of the rigid bodies within the casing, relying on the casing’s wall for the support of the flexible joints. Full information about the MEMS accelerometers used in commercial solutions is not disclosed by the companies. Recently, Freddi et al. (2023) presented laboratory testing of prototypes and preproduction samples of a lightweight IPI solution, using carbon fibre rods for the rigid body.

These solutions can result in relatively expensive IPI systems, specially, for use cases where many inclinometers, with a high sensor count, are necessary. Often, to reduce costs, only a minimal number of sensors are placed, or they are installed far apart from each other (Allasia et al., 2020). Also, all of them transmit data from sensors through wires, using a serial wired communication protocol (e.g., RS485 or SDI-12).

A prototype of a low-cost IPI system, designed for budget-constrained scenarios, is presented. A notable aspect of the developed system is the wireless transmission of data from each sensor to a master node. This minimizes the need for extensive wiring and connections and results in cost savings.

While there is an inherent acceptance of reduced tilt precision and accuracy in comparison with available expensive commercial solutions, the system's design should be tailored to maintain its utility and reliability across typical geotechnical monitoring applications.

2 MATERIALS AND METHODS

The IPI prototype comprises four sensor nodes and a master node. Each sensor node wirelessly transmits angle data obtained from its accelerometer to the master node. The master node forwards this data to a web-based timeseries database at predetermined time intervals.

2.1 Hardware components

Sensor nodes comprise an accelerometer board (HW-86C) and a microcontroller (ESP8266 D1 mini R2), both readily available at affordable prices (< 3 euros per unit). A custom-designed PCB board manages power distribution and ensures seamless communication between the microcontroller and the accelerometer with no wiring. Figure 1(a) shows the main components of each sensor node.

The sensor board employs the consumer-grade ADXL345, a triple-axis MEMS accelerometer with 10-bit digital output, providing a wide measurement range and low power consumption. Table 1 shows an estimate of the main source of error and the corresponding tilt errors. After compensation of some errors, through calibration, the ideal performance corresponds to a tilt error of 0.1º. Despite being 10 to 100 times less accurate than servo-accelerometers, this error level, if achieved, could be adequate for some less demanding cases.

Table 1. ADXL345 error source estimate (Analog Devices)

Sensor parameter	Perfor mance	Condition/Note	Tilt Error
Noise density	290 ug/√Hz	Bandwidth at 6.25 Hz	0.05º
Bias drift	-	10 days	0.057º
Initial offset	35 mg	No compensation	2º
		With compensation	0º
Total error	No compen sation	Bandwidth at 6.25 Hz	2.1º
	With compen sation	Bandwidth at 6.25 Hz	0.1º

The electronic components of each sensor node are enclosed within a stainless-steel pipe (probe) with about 30 mm outer diameter and 10 mm length. Node sensors are powered by an 5V parallel circuit source. Each one operates at around 50 mA when active and can peak at a maximum of 300 mA (during 1 to 5 milliseconds) wireless transmission. Wireless transmission occurs in a staggered manner, one sensor at a time, with intervals of about 100 miliseconds, to prevent current overload.

The connection between each sensor probe is established using multi-layer ½ inch (PVC?) pipes and compression pipe fittings typicaly used in fluid applications. Figure 1(b) shows the prototype setup prior assembly with the four node sensors. A flexible joint is omitted, because laboratory testing is conducted using an apparatus with a rigid casing (Figure 1(c)). The goal is to eliminate potential errors arising from joint movements, focusing exclusively on assessing the accuracy and precision of sensor‘s angle measurements. To ensure a precise fit and centering in the rigid casing, 3D printed PLA elements are affixed at the extremities of each probe.

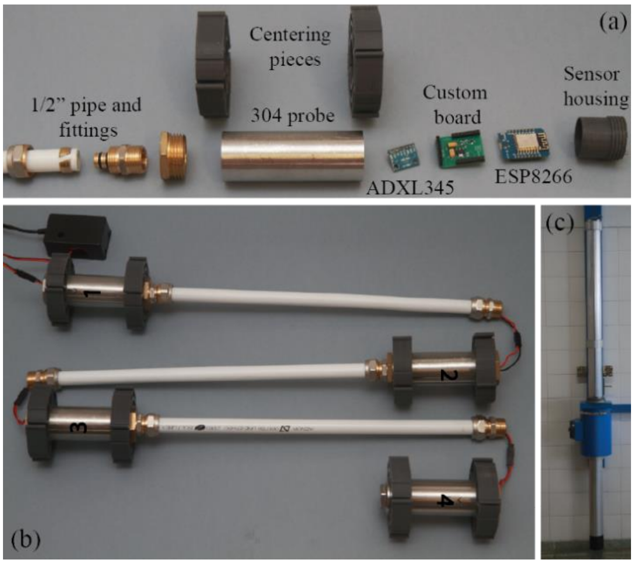

Figure 1. (a) sensor node components; (b) inclinometer prototype setup; (c) Calibration rigid casing used in tests

2.2 Software of nodes and acquisition system

Each sensor node's microcontroller is programmed in C++ using Arduino IDE to: (i) retrieve gravitational forces (g_x and g_y) from the accelerometer via the I2C protocol, (ii) compute the corresponding angles (a_x and a_y), (iii) employ a low-pass filter for enhanced accuracy, and (iv) wirelessly transmit this data to the master node. Each ESP device has a unique MAC address which is used to identification purposes. The transmission occurs at regular intervals controlled by a user variable. In the laboratory tests, data was transmitted every 10 s. Wireless transmission is achieved using the ESP-NOW protocol. ESP-NOW enables direct, fast, and low-power communication among multiple ESP microcontrollers over long distances (up to 400 m) without the need for a router.

The master node acts as an acquisition system and an internet gateway, being composed by two ESP8266 microcontrollers. The first microcontroller receives data wirelessly from the node sensors, stores the readings in an array, and sends the aggregated sensor data in JSON format over Serial at regular intervals (30 seconds interval has been set in lab tests). Its code also features a timeout mechanism to ensure data transmission, even if not all sensors have provided readings within a specified time frame. The second microcontroller establishes a secure Wi-Fi connection, receives incoming JSON data from the Serial port (containing measurements from all sensors), and forwards it to a remote broker using the MQTT (Message Queuing Telemetry Transport) protocol. This microcontroller operates as an MQTT client, publishing data to a specific topic (with a name defined by an inclinometer code).

A free MQTT broker has been established using HiveMQ's cloud service (hivemq.com), which controls and aggregates all messages published.

A local server with Telegraf, InfluxDb and Grafana docker containers was established. Telegraf systematically gathers data from MQTT topics. This data is seamlessly relayed to an InfluxDB timeseries database, wherein a timestamp is attributed to each message, forming a robust backend infrastructure. Finally, the visual representation of the acquired data is facilitated through integration with a Grafana dashboard viewer, enhancing the overall monitoring and visualization capabilities of the system.

2.3 Setup of laboratory testing

The inclinometer prototype underwent testing utilizing an apparatus equipped with a top-mounted pivot, enabling a rigid casing to rotate within a range of +/-20º along a vertical plane. Each sensor probe was manually aligned to ensure that the accelerometer's X and Y axes corresponded with the orthogonal grooves on the casing. A portable tiltmeter (servo accelerometer from Slope Indicator with a tilt error of approximately 0.011º) was positioned on a tilt plate installed perpendicular to the casing. All readings from the sensor probes and tiltmeter were zeroed with respect to the vertical position of the casing to eliminate any potential zero-g bias offset errors.

The angles computed from the sensor probes were then compared with those recorded by the tiltmeter. The prototype was placed into the casing with two different orientations to assess the angles of rotation along the sensor's X and Y axes (a_x and a_y). Readings from the sensor and tiltmeter were taken at regular intervals of about 0.5º within a range of about ±15º, under an ambient temperature of 18ºC.

3 RESULTS AND DISCUSSION

Figure 2 shows the results obtained when the X-axis of the accelerometers is aligned with the casing tilt motion. Results for the other prototype orientations are omitted due to space limitations, as they align closely with the findings presented here.

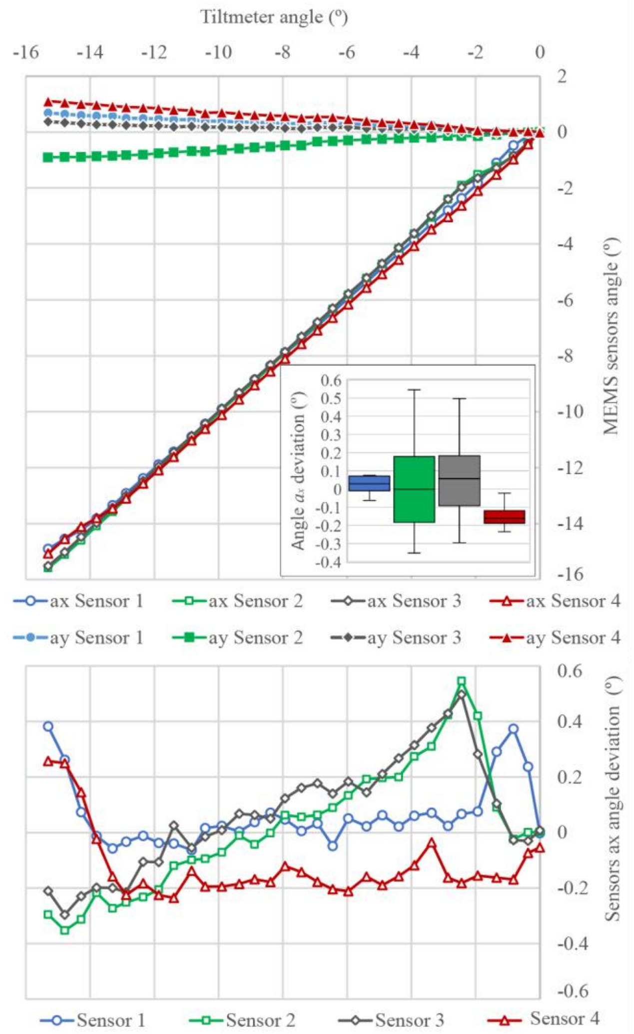

Figure 2. Results from the inclinometer prototype, with the X-axis sensors aligned to the casing rotation (-15º to 0º)

The top plot displays the relative angles resulting from each sensor probe (a_x and a_y) against the relative angles computed from the uniaxial tiltmeter. The bottom plot depicts the deviation of a_x relative angles from sensors in relation to those provided by the tiltmeter. The points of these plots derived from an average of not less than ten measurements for each sensor at every casing tilt position. The boxplot shows the interquartile range between the first and third quartiles, and the median of the deviation angles a_x of the sensors in relation to the tiltmeter for the entire range of rotation tested.

The results shown in Figure 2 allows for the following main findings:

- Average a_x angle deviations of sensors are within ±0.2º for a most of the tested range; Higher deviations, up to 0.5º, are observed in Sensor 1 within the tilt range [0.5º; 1.5º], and in Sensors 2 and 3 in [2º; 4º]; All sensors exhibit increasing a_x deviations for tilt angles greater than 14º but remain below 0.4º.
- All sensors show non-null relative a_y angles, demonstrating an almost linear relationship with the casing tilt angles. At a tilt angle of 15º, the sensor's a_y deviations range between ±1º; This suggests a misalignment of the accelerometers' actual axes, wherein the casing's tilt motion induces an undesired roll movement of the sensors (a_y).
- Median values of a_x deviations for the entire tested range are 0.028º, -0.0006º, 0.057º and -0.163º for sensors 1, 2, 3 and 4, respectively; Sensors 1 and 4 show narrow interquartile range for the a_x deviations (less than 0,06º), when compared with sensors 2 and 3 (up to 0,35º).

As anticipated, owing to the extremely low-cost of the tested accelerometers, which are based on the consumer-grade ADXL345, the angle deviations are considerably higher when compared to force balanced sensors used in the transversing inclinometer probes.

Observed errors exceed the advertised total error of 0.1º for this sensor. This discrepancy may arise from certain limitations in the way angles are compared within the testing apparatus and misalignment due to the zero-g offset of sensors in relation to the casing orientation. The uniaxial tiltmeter used as reference also exhibits some error, with an expanded uncertainty of 0.011º/º (e.g., an error of 0,055º for a 5º tilt). Future enhancements to the testing apparatus and the calibration of sensor probes, ensuring their precise alignment within the casing tube, are required to yield reduced errors.

Results also suggest that precision and accuracy of the ADXL345 vary among different batches of the sensor. This variation is likely attributed to microstructural imperfections, resulting from the sensor's manufacturing process or other factors. It is also noted that errors due to temperature drift have not been addressed (the datasheet indicates a variation of 0.02º/ºC).

MEMS accelerometers of greater sensitivity, accuracy, and precision than the ADXL345 are available. For instance, the ADXL355 is promoted with a total angle error that is about 20 times lower, but it also comes with a 20-fold increase in cost, and a larger chip form factor. In our ongoing developments, we are assessing alternative MEMS featuring newer technologies and manufacturing processes, all of which incur only a slight additional cost compared to the ADXL345.

4 CONCLUSIONS

This paper presents a prototype for a low-cost in-place inclinometer system, integrating MEMS accelerometers, and wirelessly transmitting its data to a master node acting as an acquisition system and a gateway to the internet.

Laboratory test results suggest that an in-place inclinometer based on this prototype may offer a general understanding of ground movements in low-risk scenarios, where total errors of about 0,4º are acceptable. Its use is not advised in high-risk works where extreme precise inclinometer monitoring is critical.

Investigations are ongoing to incorporate the optimal commercial MEMS accelerometer from other manufacturers in the developed prototype, with a focus on achieving the best price-to-quality ratio.

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