20th IMEKO TC10 Conference
"Measurement for Diagnostics, Optimization and Control to Support Competitiveness and Innovation"
Lisbon, Portugal, September 28–29, 2026

Proposal for Design and Preliminary Testing of an Affordable In-Place Inclinometer System for Geotechnical Monitoring

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***Abstract* – Precision geotechnical monitoring is vital for infrastructure safety, yet traditional manual methods for inclinometer measurements suffer from intermittent data collection, creating "temporal gaps" that hide potential failures. While commercial In-Place Inclinometer (IPI) systems offer continuous monitoring, their high cost and mechanical complexity make large-scale deployment unviable. The proposed solution establishes an economically viable alternative utilizing affordable, high-precision Micro-Electromechanical Systems (MEMS) sensors. This paper describes the development of a miniaturized sensor node built around the Murata SCL3300-D01 3D MEMS and the STM32G0F1 microcontroller. The solution replaces expensive rigid joints with a continuous multilayer flexible tubing system and introduces a 3D-printed "spider spring" centring mechanism. Preliminary results demonstrate the feasibility of a high-density, IoT-enabled sensor chain capable of providing real-time, high-resolution deformation data for critical geotechnical structures such as highway embankments and dams.**

Keywords – In-Place Inclinometer, AIOT, MEMS, Geotechnical Monitoring.

I. INTRODUCTION

Geotechnical monitoring is a central requirement for the safety and resilience of critical infrastructure such as slopes, embankments, dams, levees, tunnels, and retaining structures. In these systems, deformation can evolve gradually under rainfall, seepage, traffic loading, excavation, or other environmental and operational drivers until it reaches a critical condition, making early detection essential for risk mitigation. Among the available monitoring techniques, inclinometer measurements remain one of the most established methods for identifying lateral movements and estimating the depth of potential slip surfaces.

Traditional inclinometer practice, however, is still dominated by manual probing. Although reliable, it is inherently intermittent, labour intensive, and dependent on-site access, trained personnel, and traffic or operational interruptions. This creates temporal gaps between readings that may extend from days to weeks or even longer, which is problematic in contexts where deformation can accelerate rapidly. In practical terms, these gaps reduce the ability to capture the onset of instability and limit the usefulness of monitoring as an early warning tool.

The need for a more continuous and automated solution is particularly strong in modern infrastructure networks, where asset owners are expected to manage larger portfolios with limited inspection resources and increasing climate-related uncertainty. More frequent intense rainfall events and the associated rise in slope and embankment instability reinforce the value of always-on monitoring. At the same time, the operational cost of existing commercial in-place inclinometer systems often prevents large-scale deployment, especially when many instrumented sections are needed to reduce spatial aliasing and improve the detection of localized shear zones. The proposed work addresses this gap by developing an economically viable IPI node based on MEMS sensing and embedded intelligence, aiming to combine continuous monitoring with a lower-cost and more scalable architecture.

II. STATE-OF-THE-ART

Geotechnical monitoring is a fundamental requirement for assessing the stability of natural slopes and critical infrastructure like tunnels, dams, and embankments [1-2]. The primary method for tracking lateral subsurface deformation involves the installation of grooved inclinometer casings—typically made of ABS plastic or aluminum—into boreholes [3-4]. By measuring the angular deviation of these casings from the vertical gravity vector, engineers can calculate the cumulative horizontal displacement profile. This data provides a critical window for early-stage detection of movements, enabling remedial actions to prevent catastrophic structural failure [5].

Despite its criticality, the industry remains tethered to the traversing inclinometer probe, a technology that has seen minimal architectural evolution since the late 1960s [6]. These probes utilize high-precision servo-accelerometers to measure tilt. However, the operational methodology is inherently flawed for modern risk management: it requires a technician to manually raise the probe typically at 0.5m intervals [6].

This manual process creates a significant "temporal gap" in data. In high-risk scenarios, such as active landslides or urban excavations, ground failure can occur in the days or weeks between manual readings [7]. Furthermore, the human error associated with probe positioning and cable stretching introduces noise that can mask subtle, early-stage movements.

To automate data collection, In-Place Inclinometers (IPIs) were introduced, consisting of a string of sensors fixed at specific depths. However, current commercial IPI systems (e.g., Geokon, Measurand, Sisgeo, Soil Instruments) face two major systemic barriers:

1. *Mechanical complexity*: Traditional IPIs rely on rigid sensor bodies (often stainless steel) interconnected by complex universal joints or flexible couplings [8]. These joints are designed to allow the string to deform with the casing, but they are expensive to manufacture and hard to assemble. Recent attempts to use carbon fiber rods [9] have improved weight but not the underlying cost of the specialized interconnectivity.
2. *Spatial aliasing due to prohibitive costs*: Because each commercial sensor unit is expensive, asset owners often opt for "sparse placement," installing sensors only at 2 m or 3 m intervals. This leads to spatial aliasing, where the system may fail to detect a narrow shear plane that develops between two sensors, leading to a false sense of security [10].

The emergence of Micro Electro-mechanical Systems (MEMS) has initiated a paradigm shift in geotechnical instrumentation [11-12]. Unlike bulky servo-accelerometers, MEMS sensors utilize etched silicon structures to detect changes in capacitance caused by gravitational acceleration. They are inherently more robust, energy-efficient, and - crucially - orders of magnitude cheaper.

The proposed system focusses on transitioning MEMS from simple sensors to Artificial Intelligence of Things (AIoT) nodes, building also upon foundational contributions already established by master's students:

- *Data intelligence and visualization*: Palma et al. [13] advanced the data layer by developing a Business Intelligence (BI) web platform that moves beyond static spreadsheets, integrating wireless IPI prototypes with real-time data preprocessing to enable dynamic monitoring and visualization.
- *Adaptive sampling logic*: Eugénio et al. [14] strengthened the system's autonomy at the edge by introducing a Finite State Machine (FSM) approach for dam monitoring, wherein trigger-event detection — such as sudden rises in reservoir level — enables the system to autonomously transition between a low-power routine state and a high-frequency emergency state, effectively resolving the classical tension between energy efficiency and data resolution in remote infrastructure.

Together, these contributions lay the groundwork for a fully adaptive, intelligence-driven AIoT architecture.

III. DESCRIPTION OF THE PROPOSED SOLUTION

The complete proposed system, shown in Fig. 1, is a complete IPI architecture composed of sensor nodes, a master datalogger, a communication gateway, and a web-based visualization dashboard built upon a QGIS layer. Its defining idea is to replace the traditional rigid-link architecture with a flexible and mechanically simpler chain that can conform to casing deformation while reducing cost and assembly complexity.

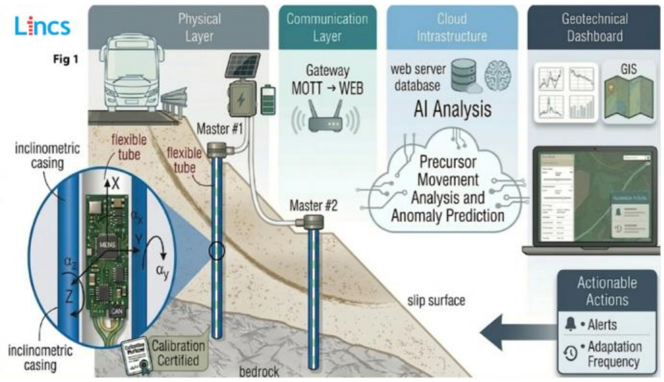

Fig. 1. Proposed IPI system

IV. RESULTS AND DISCUSSIONS

The main result so far is the demonstration that a low-cost MEMS-based IPI node can be conceptually and mechanically integrated into a geotechnical monitoring system without relying on the expensive architecture of commercial solutions. The proposal establishes that the key innovation is not only the choice of sensor, but the full node design: compact PCB, master-slave communication, flexible housing, centring device, and calibration workflow. This is a significant point because it shifts the problem from sensor replacement alone to system redesign.

A second important result is that the project has already identified the practical constraints that will govern success in the field. These include mechanical alignment, watertightness, drift control, repeatability, data continuity, and energy autonomy. The system must therefore be validated not just in terms of nominal angular accuracy, but also in terms of durability, long-term stability, and resilience to harsh installation and environmental conditions. The planned comparison with manual readings and the use of a real highway slope as a test site show that the work is oriented toward operational relevance, not only laboratory demonstration.

From a broader perspective, the proposal suggests that the system may help reduce monitoring cost enough to make continuous inclinometric surveillance feasible on a much larger set of infrastructures. If successful, that would close the gap between high-quality but intermittent manual monitoring and expensive commercial IPI chains. In that sense, the node prototype has significance beyond a single device: it may support a new monitoring model based on affordability, density, and continuous observation.

V. CONCLUSIONS AND OUTLOOK

The extended paper will present a low-cost IPI node concept intended to bridge the gap between the need for continuous geotechnical monitoring and the high cost of existing commercial systems. By combining MEMS sensing, embedded processing, flexible mechanical integration, and a traceable calibration framework, the proposed design aims to support dense, remote, and economically viable deformation monitoring. The early work already completed supports the technical feasibility of the concept while defining the main challenges that still need to be solved.

Future work beyond this paper will focus on four main tasks. First, the mechanical and electronic design will be refined to improve robustness, watertightness, and installation reliability. Second, a rigorous calibration and traceability workflow will be completed so that each node can be quantitatively assessed before field deployment. Third, the software stack will be expanded with adaptive sampling, data storage, visualization, and GIS integration. Fourth, the system will be validated in the laboratory and then on a real slope, comparing its results with conventional traversing inclinometer readings.

If successful, the work will provide a practical path toward more proactive infrastructure monitoring and can serve as a basis for future developments in autonomous sensing, digital calibration, and AI-assisted geotechnical interpretation.

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