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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.

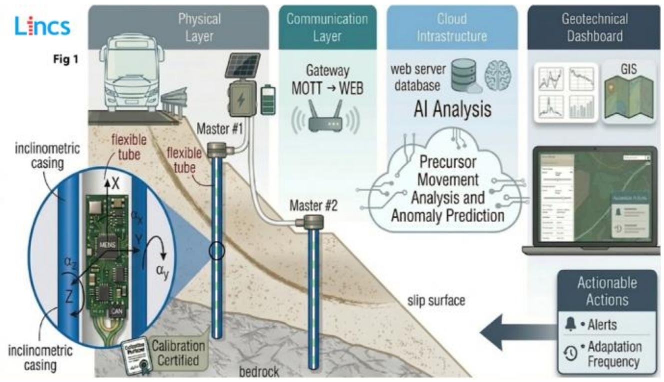

Fig. 1. Proposed IPI system

III.1 Node architecture

The node architecture is organized around four requirements: compactness, robustness, low power consumption, and calibration traceability. Compactness ensures the node fits within standard inclinometer casing, while robustness is needed for exposure to moisture, temperature variation, vibration, and long-term field use. Low power consumption supports autonomous operation, and traceability is needed so that small angular errors do not undermine the inferred displacement profile.

Each sensor node integrates a MEMS inclinometric sensor, a small microcontroller, dedicated power-management circuitry, and local communication hardware interfacing, forming a self-contained, field-deployable unit capable of autonomous data acquisition and transmission.

The selected sensing approach is based on the Murata SCL3300-D01 MEMS accelerometer/tiltmeter and an STM32G0F1 microcontroller. This combination was chosen after preliminary assessment of cost and precision, with the goal of producing a compact node suitable for standard inclinometer casing. The electronics are housed in a custom enclosure, while the mechanical design uses flexible multilayer tubing as the carrier structure. This approach minimizes the number of expensive mechanical joints and helps improve watertightness.

The following figures present the circuit diagrams of the three main functional blocks of the sensor node PCB: the power supply, filtering, and protection circuitry (Fig. 2); the STM32 microcontroller and CAN (Control Area Network) bus interface (Fig. 3); and the MEMS accelerometer sensor circuit (Fig. 4).

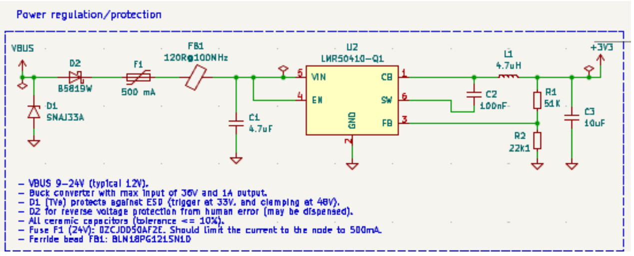

Fig. 2. PCB diagram with power supply of a system node

The power regulation and protection block (Fig. 2) conditions the input voltage VBUS (ranging from 9 to 24 V, with a typical value of 12 V) down to a stable 3.3 V rail using the LMR50410-QL buck converter (U2), rated for a maximum input of 36 V and 1 A output. Reverse voltage protection is ensured by the Schottky diode D1 (SMAJ33A), while transient overvoltage events are suppressed by the TVS diode D1 (P4SB19W), which triggers at 30 V and clamps at 40 V. Input filtering is handled by a 120 Ω ferrite bead (FB1) rated at 500 mA, which limits current to the node and attenuates high-frequency noise. The design employs all-ceramic capacitors with a tolerance of ±10%, and a 4.7 µH inductor (L1) supports the switching regulator output stage, complemented by bulk and decoupling capacitors on both input and output sides.

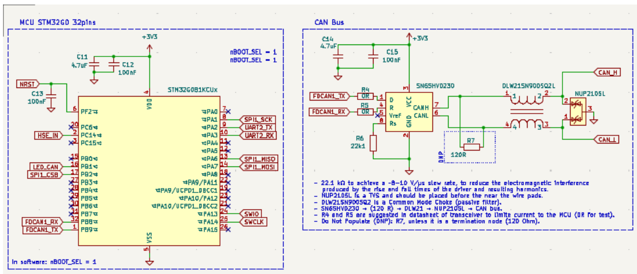

Fig. 3. PCB diagram with MCU and CAN bus of a system node

The microcontroller block (Fig. 3) is built around the STM32G0B1xUx, a 32-pin device (5 mm x 5 mm) configured with boot mode selection via the nBOOT_SEL pin. The MCU exposes SPI, USART, and GPIO peripherals, with dedicated lines for CAN communication (TCAN_RX, TCAN_TX) and sensor interfacing (SPI1_SCK, SPI1_MOSI, SPI1_MISO, SPI1_CS0). The CAN bus interface employs the SN65HVD230 transceiver, selected for its compatibility with 3.3 V logic, paired with the DLM2SWS0S021 common-mode choke to suppress electromagnetic interference on the CAN_H and CAN_L differential lines. A 22.5 Ω series resistance is placed on each line to reduce reflections and dampen ringing caused by cable and PCB parasitics. The termination resistor (MFR2591) of 120 Ω is marked as DNP (Do Not Populate), indicating it is only fitted on nodes serving as bus endpoints.

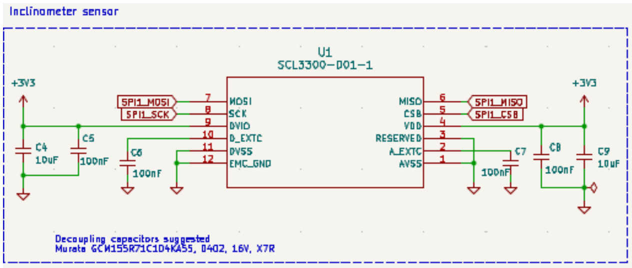

Fig. 4. PCB circuit of Murata accelerometer sensor

The inclinometer block (Fig. 4) is centred on the SCL3300-D01-1 (V1), a high-performance MEMS tilt sensor by Murata, communicating with the MCU via a 4-wire SPI interface (SPI1_MOSI, SPI1_MISO, SPI1_SCK, SPI1_CS0). The device operates from the 3.3 V supply rail and exposes dedicated analog and digital ground pins (AVSS, CMC_GND), as well as external reference pins (A_EXTC, D_EXTC) for optional analog conditioning. Decoupling is achieved through a combination of 10µF and 100nF ceramic capacitors placed symmetrically on both the analog and digital supply pins, following Murata's recommended layout using GCM155R71C104KA55 components in a compact 0402 package rated at 16 V, X7R dielectric — ensuring stable operation across the expected temperature range of the monitoring environment.

Fig. 5 shows the sensor node PCB in its bare and fully assembled states. The board measures approximately 1 cm × 6 cm, a form factor deliberately chosen to allow insertion into a multilayer protective tube with a 12 mm inner diameter (16 mm OD). This mechanical constraint was a key design driver, imposing strict limitations on component placement and routing strategy, and ultimately defining the elongated layout adopted for the board.

The functional blocks are distributed along the length of the PCB to comply with these dimensional requirements. The top side houses the power regulation stage, including the buck converter and its associated passive components, together with the STM32 microcontroller and the CAN bus transceiver and connector. The MEMS inclinometer sensor and its decoupling capacitors are placed on the bottom side of the board, physically separating the sensitive analog device from the digital switching noise generated by the microcontroller and communication circuitry on the opposing face. The power input terminals and CAN bus connector are located at opposite ends of the board, ensuring clean signal routing and minimising interference between the power and communication domains.

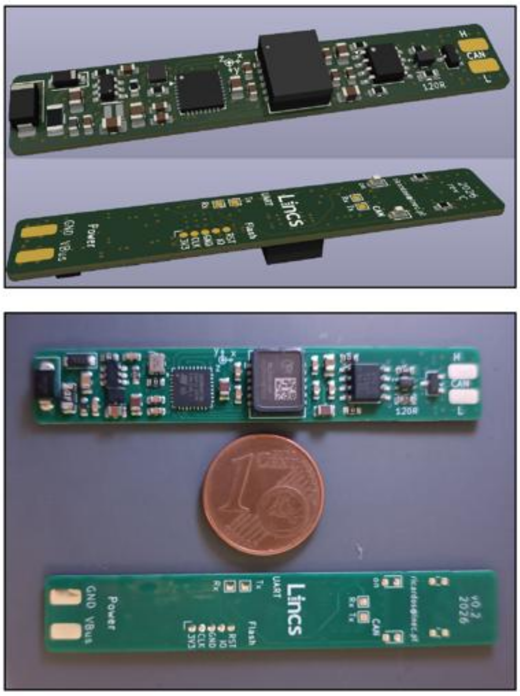

Fig. 5. PCB of sensor node: design and assembled

Overall, the fabricated prototype demonstrates that all required functional blocks — power management, processing, communication, and sensing — can be successfully integrated within the tight mechanical envelope imposed by the target deployment infrastructure, validating the proposed hardware architecture for the sensor node.

A simplified centring mechanism, based on a spider-spring concept and 3D-printed components, keeps the node aligned within the casing. This is important because misalignment can reduce measurement quality and introduce friction or repeatability problems. The flexible housing allows the sensor string to adapt to casing bending without relying on rigid articulations, which are a major cost driver in commercial systems. In practical terms, the design aims to make dense sensor placement economically viable rather than merely cheaper in component terms.

Fig. 6 illustrates the physical integration of the sensor node PCB within the multilayer flexible tube, alongside the centring mechanism used to position the assembly within the inclinometer casing.

The top image confirms the compatibility between the PCB form factor and the tube inner diameter, showing the board being inserted into the white protective tube with minimal clearance, consistent with the 12 mm inner diameter constraint that governed the PCB layout design.

The bottom image provides a cross-sectional view of the full mechanical assembly. The sensor node, enclosed within its white protective flexible tube, is housed inside a larger inclinometer casing tube. To ensure accurate and repeatable angular measurements, a centring mechanism (3D printed prototype) consisting of narrower spacer legs is employed to maintain the sensor node coaxially aligned within the outer casing. This mechanism, visible as a set of radially distributed legs contacting the inner wall of the blue outer tube, prevents lateral displacement of the sensor during installation and operation, which is critical for the measurement accuracy of the MEMS inclinometer.

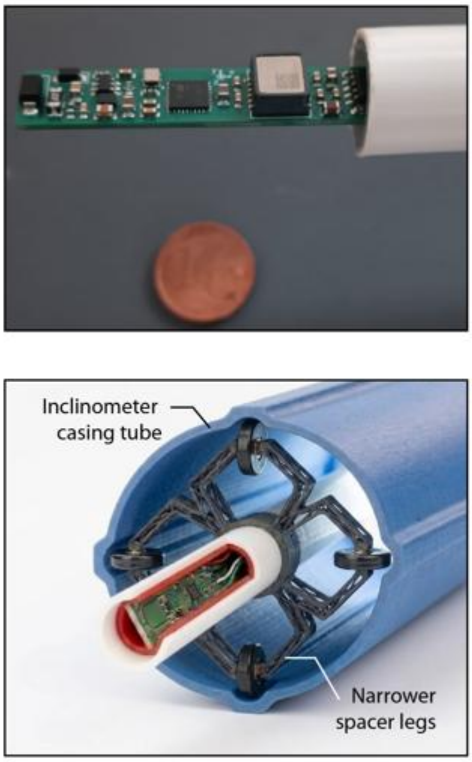

Fig. 6. PCB inside Multilayer flexible pipe and Centering mechanism inside the Inclinometer casing

The assembly demonstrates a well-engineered mechanical solution that addresses the practical challenges of deploying a miniaturised electronic node within a tubular inclinometer infrastructure, ensuring both physical protection of the PCB and geometric consistency of the sensor orientation across different installation sites.

It is also worth noting that the node architecture supports local signal handling and sleep-wake control, reducing unnecessary energy use. The MEMS sensor choice allows a much denser sensing chain than would be economically feasible with conventional commercial IPIs. That density matters because the critical shear zone in a slope may be narrow and easily missed when sensors are spaced too far apart. In that sense, the node design is not only a hardware solution but also a monitoring strategy.

III.2 Master and Gateway architectures

In the architecture of this system, the Master node and the Gateway perform distinct roles within the data pipeline, moving from the physical sensor chain to the cloud infrastructure.

The Master node (Datalogger) is the primary controller located at the head of the inclinometer casing. Its functions are focused on local management and hardware control:

- *Sensor coordination*: It initiates and establishes communication with each individual sensor node (slave) in the chain using the CAN bus protocol.
- *Power management*: It acts as a control switch, providing power to the sensor chain only when readings are being taken to maximize energy efficiency.
- *Edge intelligence*: It operates an autonomous Finite State Machine (FSM) that can switch the system from "Routine" to "Alarm" mode, automatically increasing sampling frequency if movement is detected.
- *Local caching*: It includes internal flash memory to cache up to a month of raw data if network connectivity is lost, ensuring no data is lost during cellular outages.

The Gateway resides in the "Communication Layer" and serves as the intermediary between the field hardware and the web server. Its functions are primarily focused on data transmission and protocol translation:

- *Internet connectivity*: It receives the local data packets from the Master node and facilitates their transfer over the internet.
- *MQTT protocol*: It directs data to the designated web server via the MQTT protocol.
- *Routing*: It handles the network-level tasks of directing data into a time-series database for storage and analysis.

III.3 Geotechnical dashboard and GIS integration

The final layer of the system architecture is the Geotechnical Dashboard, which serves as the primary interface for infrastructure managers to interpret complex deformation data and make informed safety decisions. This component moves beyond traditional delayed manual reporting by providing a real-time "Single Source of Truth" for structural health.

Central to the dashboard is the development of a custom QGIS Add-on, which enables the seamless integration of sensor data within a Geographic Information System (GIS) environment.

- *Spatial context*: The system allows displacement profiles to be overlaid directly onto 3D topographic models, enabling engineers to visualize soil movement in direct relation to site-specific topography and infrastructure assets.
- *Interactive mapp*ing: The interface includes a location map widget and an intelligent spatial alert system that color-codes sensor nodes on the map based on their current risk status. High-risk areas are automatically highlighted to facilitate timely interventions.

The dashboard is designed to present both high-level summaries and detailed technical data through various widgets:

- *Cumulative displacement profiles*: Users can view interactive plots for Direction X and Direction Y cumulative displacements, allowing for the identification of specific shear planes and the depth of movement.
- *KPI – Key Performance Indicator – cards*: Critical metrics are displayed prominently, including the latest displacement values, maximum depth of movement, and the recent change status.
- *Historical analysis*: The backend architecture, utilizing a time-series database and MQTT ingestion, ensures that all measurements are second-timestamped. This allows engineers to correlate soil movements with environmental variables such as intense rainfall or heavy traffic loads.

To ensure data reliability, the dashboard incorporates AI algorithms trained for:

- *Signal interpretation*: These models distinguish between harmless environmental fluctuations and actual precursor failure signatures.
- *Automated response*: When the AI identifies a pattern indicative of a potential failure, it can automatically trigger the adaptive sampling logic in the field hardware, increasing reading frequency to capture high-resolution data during critical acceleration phases.

III.4 Preliminary testing

Preliminary testing is intended to verify both the behaviour of the sensing node and the behaviour of the overall system under controlled conditions. Earlier proof-of-concept work already demonstrated the feasibility of low-cost automated inclinometric monitoring, but also revealed limitations in reliability, measurement stability, communication resilience, and power management [15]. The present design is an attempt to address those weaknesses before field deployment.

Testing must cover offset stability, scale-factor behaviour, temperature sensitivity, cross-axis effects, and repeatability after repeated power cycles. It must also assess communication integrity, synchronization along the sensor chain, resistance to water ingress, and the mechanical performance of the centring mechanism. These issues are essential because a field IPI system is only useful if the measurements are consistent across the entire chain and robust under variable environmental conditions. The planned validation route includes traceable calibration using LNEC metrology infrastructure and high-precision angular reference equipment. This is especially relevant for MEMS-based systems, since low-cost sensors only become engineering-grade instruments when their errors are carefully characterized and corrected. Preliminary testing is therefore not a peripheral activity; it is central to proving that the node can deliver credible geotechnical measurements.

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 paper presents 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 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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