

Article

A Dual-Path IoT Sensing and Communication Framework for Smart Building and Construction-Site Structural Monitoring

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Abstract

Reliable structural monitoring for smart buildings and construction sites requires more than sensor acquisition; it requires sensing and communication paths that remain traceable, recoverable, and compatible with platform-side data processing under heterogeneous field constraints. This study presents a dual-path IoT sensing and communication framework that deliberately separates high-data-rate vibration monitoring from low-data-rate inclination-status monitoring while maintaining common requirements for preservation of available time information, data-source identification, and backend interpretability. The smart-building path integrates an ADXL355 triaxial accelerometer, ESP32-S3, Power over Ethernet (PoE), and Message Queuing Telemetry Transport (MQTT) for 200 Hz vibration acquisition, together with a second-order 10 Hz low-pass filter, 40-record batching, and a Flash LittleFS-based store-and-recovery mechanism that interleaves live and replayed records after reconnection. The construction-site path combines an SCL3300-D01 inclinometer with LoRaWAN, baseline-referenced relative-angle estimation, and a hysteresis state machine with distinct alarm and recovery thresholds. In a 24 h validation, four vibration nodes delivered all 69,120,000 expected records, and four forced-outage trials recovered all offline records while live transmission continued. Frequency-domain analysis confirmed attenuation of high-frequency components while retaining the dominant low-frequency response. The inclination path demonstrated quantifiable angle accuracy, correct alarm/recovery transitions, continuous LoRaWAN frame delivery over the observed interval, and correct backend decoding. The results show that path-specific communication design, combined with a common traceability concept, supports prototype functionality under the reported test conditions, not immediate construction-site deployment. Full 3D visual synchronization, BIM/GIS asset mapping, and digital-twin platform interfacing were not implemented and remain future development tasks.



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Keywords: internet of things; building vibration monitoring; construction-site inclination monitoring; ADXL355 accelerometer; SCL3300-D01 inclinometer; MQTT; LoRaWAN; disconnection recovery; digital twin

1. Introduction

Civil structures and temporary construction facilities are continuously exposed to dynamic and quasi-static disturbances arising from traffic, machinery, wind, earthquakes, thermal effects, foundation movement, and construction operations. Conventional visual inspection remains essential for identifying observable defects such as cracking, seepage, surface deterioration, and gross deformation, but it is inherently intermittent and strongly affected by accessibility, viewing conditions, environmental constraints, and inspector experience. Consequently, inspection alone cannot capture the time-resolved structural response associated with transient or progressive events. Structural health monitoring (SHM) addresses this limitation by converting physical responses into persistent digital records through sensing, data acquisition, and subsequent analysis, thereby enabling temporal comparison and engineering assessment [1,2].

The emergence of smart buildings, connected construction sites, and digital-twin-oriented engineering systems has shifted the monitoring requirement from isolated sensor measurements toward continuous and platform-consumable data streams. In such systems, the value of a measurement depends not only on its physical accuracy but also on whether its origin, measurement time, processing history, transmission state, and decoded meaning can be preserved across the end-to-end data path. Sensors, edge controllers, communication protocols, timestamping, payload definitions, disconnection handling, and backend parsing therefore constitute a critical front-end sensing and communication layer. Weaknesses at this layer propagate directly to higher-level functions such as dashboards, BIM/GIS mapping, state synchronization, alarm management, and maintenance decision support. A reliable and traceable data path is thus a prerequisite for, rather than a by-product of, future digital-twin integration.

A central systems challenge is that structural-monitoring scenarios are heterogeneous. Building vibration monitoring produces relatively high-rate time-series data and must preserve short-duration dynamic responses, whereas construction-site inclination monitoring is dominated by lower-rate state variation, threshold-based event reporting, and wireless deployment constraints related to cabling, power availability, and communication distance. MEMS sensors and IoT communication technologies make distributed deployment increasingly practical, but low-cost acquisition alone does not guarantee usable engineering data. The usefulness of the resulting records depends on the provenance and preservation of time information, packet delivery, offline preservation, payload consistency, frame continuity, and explicit experimental verification [3–5].

This study addresses this heterogeneity through a dual-path IoT sensing and communication framework with smart-building vibration monitoring and construction-site inclination monitoring as target application scenarios. The reported experiments establish prototype data-path behavior under the tested conditions, not immediate suitability for an operating construction site. Rather than imposing a single communication architecture on fundamentally different data characteristics, the framework assigns each scenario a path matched to its temporal resolution, connectivity, and deployment constraints, while retaining common principles for traceability and backend interpretation. The objective is to transform heterogeneous physical measurements into verifiable, platform-readable data sources that can subsequently support visualization, abnormal-condition tracking, and decision-support functions.

The first path, implemented as the Smart Building Structural Health Monitoring System, combines an ADXL355 triaxial MEMS accelerometer with an ESP32-S3 edge controller, PoE/Ethernet connectivity, and MQTT to acquire triaxial acceleration at 200 Hz. The node couples sensor-side high-pass filtering with an MCU-side 10 Hz second-order Butterworth low-pass filter and packages 40 samples into each MQTT message. To address a failure

mode that is particularly consequential for continuous waveform monitoring, the node also implements a Flash LittleFS-based offline-preservation mechanism. When communication is restored, live records and Flash-resident recovery records are transmitted in an interleaved manner, so historical data can be recovered without suspending current acquisition and transmission.

The second path, implemented as the Construction-Site Inclination Monitoring System, combines an SCL3300-D01 triaxial MEMS inclinometer, ESP32, SX1276-based LoRa communication, a LoRaWAN gateway, and backend reception/decoding. In addition to inclination, the payload reports temperature, battery status, and alarm state. A startup baseline is established and subsequent measurements are expressed as relative changes with respect to that reference. A rule-based hysteresis mechanism uses separate alarm and recovery thresholds together with consecutive-sample criteria to convert continuous inclination measurements into stable NORMAL/ALARM state records. This design emphasizes low-data-rate wireless status delivery and deterministic backend interpretation rather than high-rate waveform transport.

Figure 1 summarizes the two engineering contexts and highlights the separation of their sensing and communication paths.

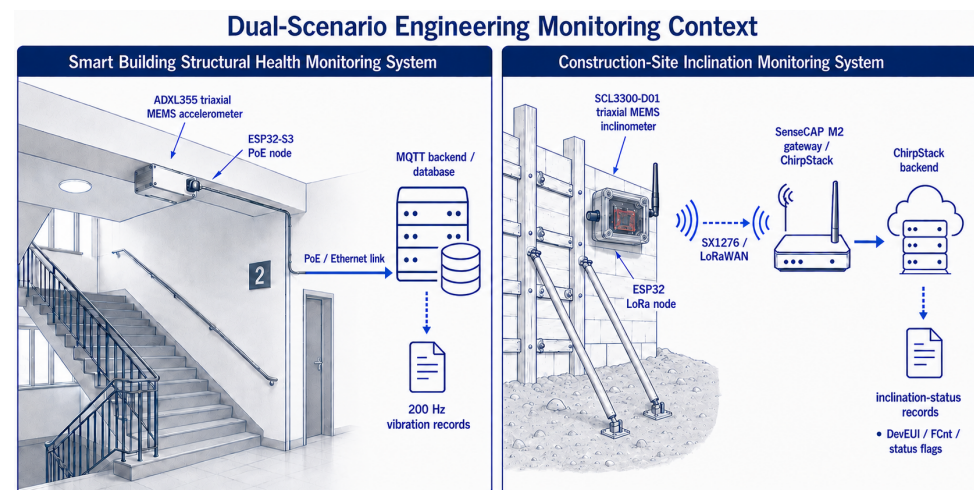


Figure 1. Dual-scenario engineering monitoring context.

The evaluation is organized around end-to-end data usability rather than sensor output alone. Four capabilities are examined. First, the ADXL355 path is tested for long-duration sampling completeness under the implemented filtering and 40-sample MQTT batching scheme. Second, the Flash LittleFS mechanism and live/flash interleaving strategy are tested under forced communication interruptions to determine whether offline records can be preserved and subsequently replayed without abandoning live transmission. Third, the SCL3300-D01 path is evaluated for baseline-referenced relative-angle measurement and deterministic NORMAL/ALARM switching under the configured hysteresis rules. Fourth, the LoRaWAN Frame Counter (FCnt) is used to assess packet continuity, while 30-byte payload decoding is checked to determine whether the transmitted records remain traceable and correctly reconstructable at the backend.

The resulting architecture is a front-end sensing and communication foundation, not a complete digital twin or a validated digital-twin connector. Its implemented outputs are machine-readable vibration records and inclination states at the backend parsing and storage layer. Full 3D visual synchronization and BIM/GIS asset mapping were not implemented in this study; together with platform-specific interfacing, they represent a future development phase. These functions require an additional asset-mapping and adapter

layer. The architectural schematics indicate intended downstream uses, not demonstrations of asset binding, platform interoperability, or synchronized 3D model updates. Separate implementation and validation are required, including the timing and deployment limitations discussed in Section 5.

The technical contribution is threefold. First, the study introduces a path-specific architecture that separates PoE/Ethernet/MQTT vibration transport from LoRaWAN inclination-status transport according to data rate and field constraints, while retaining a common traceability objective. The contribution is the explicit organization and separate evaluation of these sensing-to-backend paths under common record-interpretation requirements, rather than an implemented cross-stream fusion service or a demonstrated performance advantage. Second, the ADXL355 path integrates edge filtering, 40-record MQTT batching, remote control, Flash LittleFS-based disconnection preservation, and live/flash interleaved replay; this combination is validated through long-duration sampling, frequency-domain examination, and repeated forced-outage tests. Third, the SCL3300-D01 path integrates startup baseline estimation, relative-angle computation, hysteresis-based alarm/recovery logic, a fixed 30-byte LoRaWAN payload, frame-counter tracking, and backend decoding; its operation is validated through angle, state-transition, packet-continuity, and codec tests.

Collectively, these experiments evaluate the framework through directly observable and parsable records rather than through conceptual architecture alone. The results characterize data acquisition, edge processing, transmission continuity, outage recovery, state reporting, and decoding across both paths. This evidence supports the proposed positioning: a sensing and communication prototype whose data-layer functions were evaluated under the reported test conditions for intended smart-building and construction-site structural monitoring, and future digital-twin-oriented integration through additional platform adapters that have not been implemented or validated.

2. Related Work and Functional Positioning

Existing commercial monitoring systems commonly emphasize integrated platform delivery, field installation, and long-term operation, whereas academic studies frequently concentrate on a particular sensing modality, communication technology, diagnostic method, or upper-layer digital-twin function [6–9]. These perspectives are individually important, but a dual-scenario deployment introduces a different integration problem: high-rate building vibration data and low-rate construction-site inclination states have different requirements for bandwidth, power, storage, outage handling, and transport semantics. The present work therefore focuses on the architectural boundary at which heterogeneous field measurements are converted into reliable and platform-readable records.

Vibration-based SHM extracts information from structural responses in the time, frequency, or modal domains [3]. Common time-domain descriptors include peak amplitude, root mean square (RMS), peak factor, and event duration, whereas FFT-based analyses reveal dominant frequencies, spectral-energy distributions, and changes in frequency content. Wireless sensing has also been extensively investigated because it can reduce installation cost and improve deployment flexibility. Nevertheless, packet loss, power management, time synchronization, and communication reliability remain recurring implementation concerns, particularly when sensing data must be retained as an auditable engineering record [5,10,11].

At the sensing-node level, MEMS devices have been studied as practical alternatives for structural and engineering monitoring. Di Nuzzo et al. evaluated MEMS monitoring nodes against reference instrumentation and modal measurements [4], while Murray-Bergquist et al. investigated calibration, noise, spectral characteristics, and temperature effects in six-degree-of-freedom sensors [12]. For inclination monitoring, Green and Jasan

analyzed historical inclinometer sequences for anomaly detection and prediction [13]. Together, these studies indicate that the engineering utility of a sensing node depends on the complete acquisition chain—sampling, calibration, processing, communication, parsing, and validation—rather than on the sensing element in isolation.

Digital-twin-oriented monitoring extends this requirement further because field observations must be associated with physical assets, virtual representations, visualization interfaces, and decision-support processes. Prior work has addressed physical-to-digital information flow, semantic relationships among assets, and purpose-oriented digital-twin models [14–20]. The present study does not claim to implement these upper-layer functions. Instead, it targets the prerequisite sensing and communication layer that produces records for subsequent platform adapters; those adapters and their interoperability have not been implemented or evaluated.

Figure 2 provides a functional positioning diagram, not a quantitative comparison of key performance indicators. The present evaluation includes neither a controlled head-to-head benchmark against commercial SHM products nor a numerical comparison with comparable published IoT structural-monitoring systems. Its results characterize the implemented sensing, transport, preservation, and decoding functions. A direct benchmark would require a defined common test protocol and access to relevant configurations; proprietary implementation details may limit that access. However, this does not preclude a literature-based numerical comparison. Such a comparison would need explicit correspondence among metric definitions, sensing workloads, observation durations, network and outage conditions, and backend measurement boundaries, with remaining differences acknowledged. This study has not established that comparison basis. Public descriptions cannot be used to infer the absence of unreported functions. Accordingly, the related-work discussion identifies functional scope, not relative reliability, cost, power efficiency, or scalability. The lack of a quantitative benchmark remains a limitation on comparative conclusions.

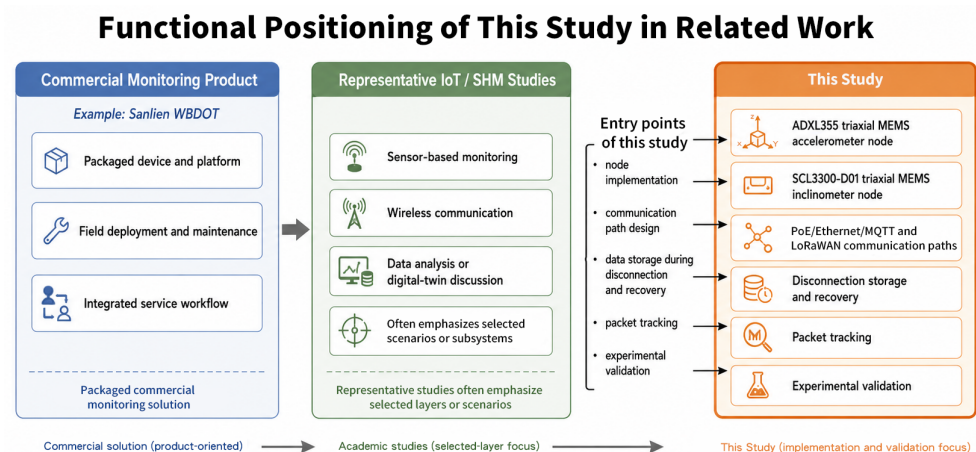


Figure 2. Functional positioning of this study in relation to commercial monitoring products and representative IoT/SHM studies.

3. Materials and Methods

3.1. Design Principles

The dual-path design follows a requirements-driven principle. The building-vibration path uses the ADXL355 triaxial MEMS accelerometer (Analog Devices, Inc., Wilmington, MA, USA), ESP32-S3, PoE/Ethernet, and MQTT to acquire and transport triaxial records at 200 Hz. It targets dynamic vibration and earthquake-response monitoring, for which preservation of device-associated time fields, sustained throughput, continuous acqui-

sition, and preservation of data during network interruption are primary requirements. In contrast, the construction-site inclination path uses the SCL3300-D01 triaxial MEMS inclinometer (Murata Electronics Oy, Vantaa, Finland), ESP32, SX1276, SenseCAP M2 gateway, LoRaWAN, ChirpStack, and backend codec processing. Its design prioritizes installation flexibility, low-volume wireless uplink, packet traceability, and robust state reporting rather than continuous waveform transmission.

Both paths follow a common record-provenance objective, but their time information is not equivalent. In the vibration path, the device-associated `unix_ms` field remains associated with its acceleration record during buffering and replay; reception time must not replace this recorded measurement-time field. In the inclination path, the 30-byte payload in carries sensing and status values but no device measurement timestamp. Device and frame identifiers belong to the associated LoRaWAN/backend metadata rather than to this payload. Such metadata support source and packet traceability, but reception time is not evidence of synchronized acquisition. Here, the preservation of time information means retaining the available fields and their provenance, not establishing absolute clock accuracy or inter-node synchronization. Firmware, payload definitions, and decoders must remain consistent for deterministic interpretation.

No dedicated cross-path clock-synchronization mechanism was implemented or validated, and no 24 h standalone clock-drift measurements were performed for either path. The 24 h vibration record counts therefore demonstrate sample-count completeness, not synchronization among nodes. Cross-scenario temporal fusion requires a stronger timing contract: an explicit common time reference or periodic synchronization mechanism, identified measurement-time semantics for both paths, and verification of the application-required alignment accuracy. These functions remain outside the present validation.

3.2. Overall Architecture

The implementation comprises two sensing-to-backend paths that were evaluated separately. In the smart-building path, the physical monitoring point is connected through an ESP32-S3 controller and PoE/Ethernet to an MQTT broker and backend database [21], supporting sustained transport and storage of high-rate vibration records. In the construction-site path, an ESP32 and SX1276 transceiver send inclination measurements through a SenseCAP M2 LoRaWAN gateway to ChirpStack, after which a payload codec and MQTT worker reconstruct and forward the application-level data. This path carries lower-rate status, alarm, and packet information.

The backend parses and stores each stream according to its transport and payload definition. A common traceability objective does not mean that the streams have been normalized into a shared cross-stream schema; neither such a unified model nor a joint data-fusion service is implemented or evaluated here. Full 3D visual synchronization and application-side asset mapping are not implemented. The downstream BIM/GIS, visualization, and digital-twin elements in the architectural schematics denote prospective extensions, not demonstrated platform functions, as shown in Figure 3.

The existing sensing-data interface is specified at record and payload level. Listing 1 defines vibration records containing `unix_ms`, `x_filtered`, `y_filtered`, and `z_filtered`; 40 records are grouped per MQTT publication, and Listing 2 distinguishes `src=live` from `src=flash`. The inclination interface is the fixed 30-byte payload which specifies offsets, integer types, scaling, acceleration, inclination, baseline-referenced changes, temperature, battery fields, and status flags. Listing 3 reconstructs these values in engineering units. Device EUI, frame counter, and FPort are associated network metadata, not additional fields within the 30-byte sensing payload. These definitions constitute the current sensing-data contract, not a BIM/GIS schema or a platform-specific digital-twin API.

Listing 1. ADXL355 real-time sampling and filtering procedure.

```

configure ADXL355 range = +/-2 g
enable sensor-side built-in first-order high-pass filter
enter measurement mode
initialize device time and MCU-side 10 Hz Butterworth low-pass~filter

every 5 ms:
    read raw X, Y, Z from ADXL355 through SPI
    convert raw two's-complement values to g
    apply MCU-side 10 Hz second-order Butterworth low-pass filter to X, Y, Z separately
    create AccelData(unix_ms, x_filtered, y_filtered, z_filtered)
    if dataQueue has space:
        push AccelData into dataQueue
    else:
        increase queueDropCount

```

Listing 2. ADXL355 MQTT batching, offline storage, and recovery procedure.

```

repeat in network task:
    pop up to 40 AccelData records from dataQueue
    if MQTT is connected:
        publish current batch with src=live
        if flash replay data are pending:
            publish at most one replay batch with src=flash
    else:
        append unsent records to RAM backup
        flush RAM backup to LittleFS when~required

when network is recovered:
    flush the remaining RAM backup to LittleFS
    open replay file and restore replay offset
    interleave one live batch and at most one flash batch
    update replay offset only after successful publish
    keep dataQueue consumption non-blocking as much as possible

```

Listing 3. SCL3300 30-byte payload decoding rule.

```

input 30-byte uplink payload
check payload length == 30
decode all signed 16-bit fields as big-endian integers
acceleration_g      = raw_acc/10,000
delta_acceleration_g = raw_dacc/10,000
angle_deg           = raw_angle/100
delta_angle_deg     = raw_dangle/100
temperature_C       = raw_temp/100
battery_voltage_V   = raw_batt/1000
battery_percentage   = battery_percentage byte
status_flags        = status byte
return decoded object in engineering units

```

The consistency shared by the paths is interpretive: source information is retained, available time fields are identified by origin, physical quantities are decoded using the defined units and scaling, and path-specific status is preserved. It is not identity of field layouts or state meanings. In particular, `src=live/src=flash` identifies the provenance of vibration delivery, whereas `NORMAL/ALARM` identifies an inclination decision state; these indicators are not interchangeable. Likewise, the vibration `unix_ms` field is not equivalent to LoRaWAN reception metadata. MQTT-related forwarding alone does not establish a common data model. These distinctions describe the existing data contracts and do not introduce a new backend schema.

Joint upper-layer use would require an additional integration layer that associates devices with building or site assets, maps measurements to BIM/GIS objects, reconciles units and coordinates, and implements the target platform interface and virtual-state update policy. Asset mapping and temporal alignment are distinct requirements: a uniform field layout does not establish a shared acquisition time, and FCnt or reception time cannot replace the missing device measurement timestamp in the inclination payload. No such cross-stream, asset-mapping, or semantic-adaptor layer is implemented or tested here. Full

3D synchronization therefore remains future development, not a function demonstrated by independent path validation.

Dual-Scenario Field Sensing and Communication Data Layer

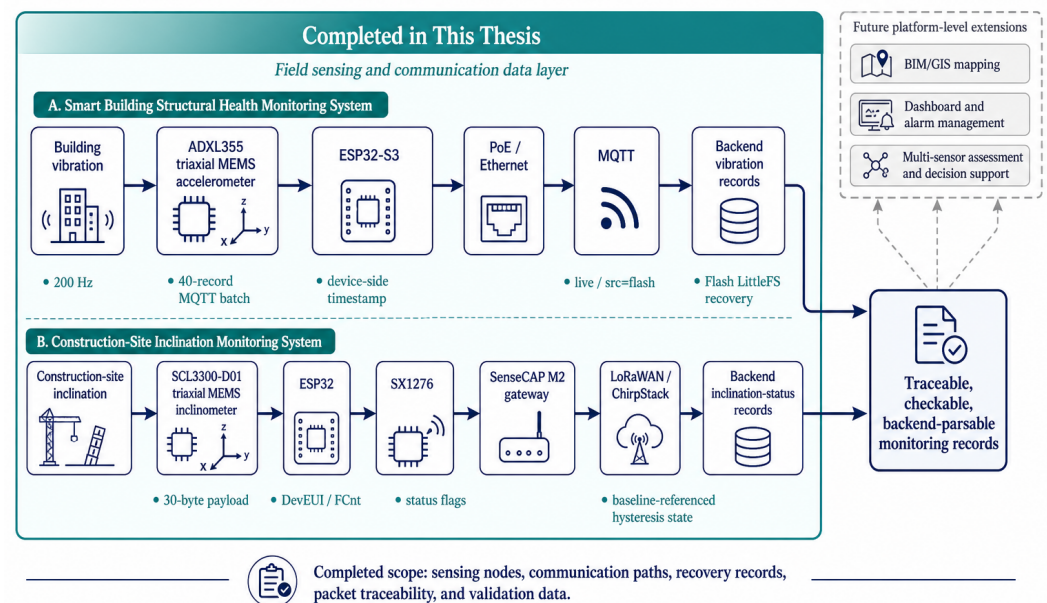


Figure 3. Dual-scenario field sensing and communication data-layer overview.

3.3. Functional Division of the Two Paths

Table 1 summarizes the functional division of the two sensing and communication paths.

Table 1. Functional division of the two sensing and communication paths.

Item	ADXL355 Accelerometer Vibration Path	SCL3300-D01 Inclinometer Path
Application scenario	Building vibration monitoring	Construction-site inclination monitoring
Main physical quantity	Triaxial dynamic acceleration	Triaxial inclination angle
Target time scale	Milliseconds to seconds	Seconds to hours
Sampling/update	200 Hz	Test version updates approximately every 600 ms
Edge processing	two-stage filtering and MQTT batches containing 40 samples	Baseline, delta values, hysteresis, and consecutive samples
Communication method	PoE/Ethernet/MQTT	LoRaWAN AS923
Offline strategy	Flash LittleFS-based disconnection recovery and live/flash interleaved recovery	RTC state and LoRaWAN session preservation
Main validation	24 h completeness and disconnection recovery	Angle, alarm, PDR, and codec

3.4. ADXL355 Accelerometer Node

The smart-building node comprises an ADXL355 three-axis MEMS accelerometer, an ESP32-S3 controller, a W5500 Ethernet controller, and a PoE power module. The ESP32-S3 provides dual-core processing capability, enabling sensing and network workloads to be separated so that communication activity does not unnecessarily interfere with periodic acquisition [22]. The W5500 integrates the TCP/IP stack, Ethernet MAC, and PHY required for wired connectivity to the backend network [23].

PoE was selected to combine centralized power delivery and wired data connectivity for continuous 200 Hz acquisition, rather than to demonstrate low-power operation. The validation concerns sensing and data-path behavior; dedicated electrical power measurements were not performed.

During initialization, the firmware establishes communication with the ADXL355 and configures the measurement parameters before acquisition begins. The accelerometer range is set to ± 2 g, and the 20-bit two's-complement output is converted using 256,000 LSB/g. At the sensor level, the built-in first-order high-pass filter is enabled, the output data rate is configured to 250 Hz, and the low-pass setting is 62.5 Hz. After these settings are applied, the device enters measurement mode and supplies the input stream for the MCU-side processing chain [24].

The ESP32-S3 reads the three acceleration axes every 5 ms, producing the target node-level sampling rate of 200 Hz. Each axis is then processed independently by an MCU-side second-order Butterworth low-pass filter with a 10 Hz cutoff. This stage is intended to retain the low-frequency structural response of interest while suppressing higher-frequency components before transmission. The per-axis filtering relation is given in Equation (1):

$$y[n] = b_0x[n] + b_1x[n-1] + b_2x[n-2] - a_1y[n-1] - a_2y[n-2]. \quad (1)$$

In Equation (1), $x[n]$ and $y[n]$ denote the input and filtered acceleration of one axis at discrete sample index n , respectively. The coefficients b_0, b_1, b_2 are the feedforward coefficients, and a_1, a_2 are the denominator coefficients after normalization to $a_0 = 1$. The explicit minus signs in Equation (1) define the feedback convention.

To make the stated filter design reproducible, its standard cutoff-prewarped bilinear-transform form is specified here. Let f_s be the MCU processing rate, f_c the cutoff frequency, and Q the quality factor. Define $K = \tan(\pi f_c / f_s)$ and $D = 1 + K/Q + K^2$. The normalized coefficients are

$$\begin{aligned} b_0 = b_2 &= \frac{K^2}{D}, & b_1 &= \frac{2K^2}{D}, \\ a_1 &= \frac{2(K^2 - 1)}{D}, & a_2 &= \frac{1 - K/Q + K^2}{D}, & a_0 &= 1. \end{aligned}$$

For $f_s = 200$ Hz, $f_c = 10$ Hz, and $Q = 1/\sqrt{2}$, the corresponding design values, rounded to ten decimal places, are

$$\begin{aligned} b_0 = b_2 &= 0.0200833656, & b_1 &= 0.0401667311, \\ a_1 &= -1.5610180758, & a_2 &= 0.6413515381, & a_0 &= 1. \end{aligned}$$

Here, 200 Hz refers to the MCU filtering sequence, not the sensor output data rate of 250 Hz. These values are a mathematical specification of the stated design, not coefficients recovered from the experimental firmware: the original initialization function or coefficient log is not available in the documentation used for this revision. Their exact correspondence to the experimental implementation therefore remains unverified. The approximately -37.56 dB attenuation at 60 Hz is retained as a theoretical design reference, not a new measurement or an independent firmware verification. No vibration data or PSD results are recomputed.

For network transmission, 40 consecutive samples are aggregated into one MQTT publication. At 200 Hz, a batch represents approximately 0.2 s of vibration data. This batching strategy reduces publication frequency and backend message-handling overhead relative to record-by-record transmission while preserving an explicit sequence of time-stamped measurements inside each batch.

Communication failure is handled as a data-preservation problem rather than as a simple reconnect operation. When Ethernet connectivity, broker connectivity, or MQTT publication is unavailable, unsent records are first buffered in RAM, which can hold 1000 records. As the RAM buffer fills, records are appended in binary form to a LittleFS file

in Flash. Before replay begins, any remaining RAM-resident records are consolidated into Flash so that the recovery stream has a persistent source. After reconnection, Flash records are read sequentially and transmitted as replay data. Crucially, replay is interleaved with current live batches, allowing recovery to progress without blocking ongoing measurement and minimizing the risk that restoration of historical data creates a second gap in the live stream. Figure 4 summarizes this data path.

The same append-and-replay procedure is intended to handle longer interruptions only while available storage capacity and successful Flash writes permit continued buffering. After reconnection, clearing the backlog requires delivery capacity beyond that needed by the ongoing live stream. Neither multi-hour outage behavior, maximum recoverable duration, backlog-clearance time, nor storage-full handling was validated. Consequently, lossless recovery is not claimed after the allocated storage is exhausted, and the short-outage results do not establish a multi-year storage lifetime.

Continued acquisition and buffering during a communication outage require the node to remain powered and storage writes to succeed. A PoE fault that also removes the node supply is a different failure mode: without an independent supply, the node cannot continue sampling during that interval. The reported trials do not establish abrupt-power-loss integrity, preservation of RAM-only records, or restart recovery.

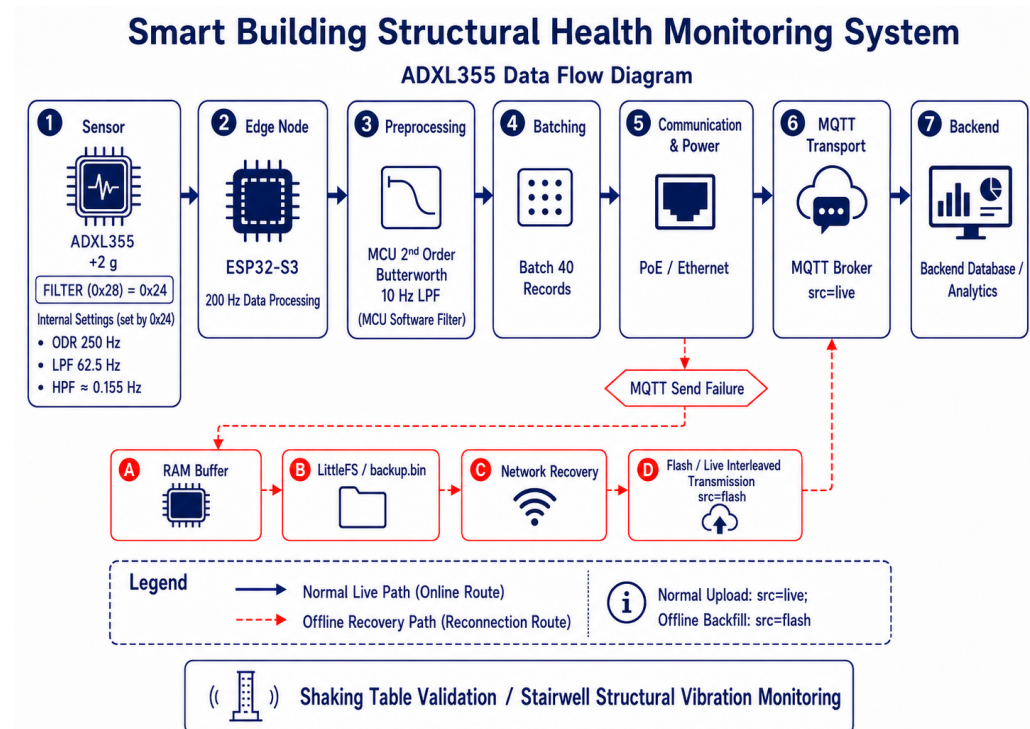


Figure 4. ADXL355 accelerometer IoT sensing data-flow diagram.

3.5. SCL3300-D01 Inclinator Node

The construction-site node comprises an SCL3300-D01 three-axis MEMS inclinometer, an ESP32 controller, an SX1276 LoRa transceiver, and a MAX17043 fuel gauge. The ESP32 acquires triaxial acceleration, triaxial inclination, and temperature through SPI; the SX1276 provides the LoRa physical link used by the LoRaWAN stack; and the MAX17043 supplies battery-state information for inclusion in the transmitted status. The startup description follows the SCL3300-D01 initialization sequence [25]. However, the mode-setting command or register record associated with the reported trials is not supplied in the documentation available for this revision; the activated hardware measurement mode cannot therefore be independently confirmed here.

The MAX17043 and the battery fields in Table 2 provide battery-status reporting, not an empirical battery-lifetime characterization or a validated remaining-runtime estimate. No state-resolved node-power measurements or battery-discharge test is reported for the NORMAL and ALARM operating profiles.

Equations (2)–(4) state the raw-register-to-engineering-unit conversions reported for acceleration, angle, and temperature, respectively. The variables r_a , r_θ , and r_T are the signed numerical data-register outputs, rather than complete SPI frames; a , θ , and T are the resulting acceleration in g, angle in degrees, and temperature in degrees Celsius.

$$a = \frac{r_a}{6000} \text{ [g]}, \quad (2)$$

$$\theta = \frac{r_\theta}{16,384} \times 90 \text{ [}^\circ\text{]}, \quad (3)$$

$$T = -273 + \frac{r_T}{18.9} \text{ [}^\circ\text{C]}. \quad (4)$$

The manufacturer specifies acceleration sensitivities of 6000 LSB/g for Mode 1, 3000 LSB/g for Mode 2, and 12,000 LSB/g for Modes 3 and 4 [25]. Thus, Equation (2) expresses the Mode 1 acceleration-scaling convention; its denominator alone does not establish which mode was activated in the experiments. In Equation (3), 16,384 is 2^{14} and belongs to the angle-output encoding, whose sensitivity is specified for all modes. The constants 18.9 and -273 in Equation (4) belong to the temperature conversion, not to the mode-dependent acceleration sensitivity. Hardware modes 1–4 must also be distinguished from the application states NORMAL and ALARM.

These register conversions precede the separate payload quantization in Table 2. For example, the factor 6000 in Equation (2) converts acceleration register counts to g, whereas the factor 10,000 in Listing 3 decodes the scaled integer acceleration field transmitted over LoRaWAN. The two factors belong to different processing stages and are not interchangeable.

Equation (5) defines the startup baseline $\bar{x}_0$ as the arithmetic mean of five valid measurements x_i , where $i = 1, \dots, 5$. The symbol x denotes the measured component for which a baseline is formed; the mean retains the same engineering unit as that component. This local reference is used to express subsequent changes relative to the startup orientation:

$$\bar{x}_0 = \frac{1}{5} \sum_{i=1}^5 x_i. \quad (5)$$

Equation (6) defines the baseline-referenced change Δx_k at update index k by subtracting the startup baseline $\bar{x}_0$ from the current measurement x_k . The difference retains the unit of x_k ; for an angle component it is measured in degrees. This specifies the subtraction direction in the equation:

$$\Delta x_k = x_k - \bar{x}_0. \quad (6)$$

Equation (7) specifies the hysteresis ordering for baseline-referenced angular changes. Here, T_{alarm} is the angular threshold for entering ALARM from NORMAL, and T_{clear} is the threshold for returning from ALARM to NORMAL; both are expressed in degrees. These threshold symbols are unrelated to the temperature T in Equation (4). Listing 4 requires an entering-alarm condition on any monitored angle and a clearing condition on all monitored angles, each with a consecutive-sample requirement:

$$T_{\text{clear}} < T_{\text{alarm}}. \quad (7)$$

The exact alarm and recovery thresholds and the consecutive-sample counts for the 25 trials are not specified in the available test documentation and remain unverified in this revision. They cannot be inferred from the stage-wise medians. The five samples used to initialize the baseline are not a specification of either state-transition count. This omission limits parameter-level reproducibility of the reported trials. The enlarged-threshold tests characterize the application state logic; they do not establish site-specific structural-safety thresholds.

Listing 4. SCL3300 baseline-referenced rule-based hysteresis state machine.

```

read startup samples from SCL3300
baseline = average(valid startup samples)
mode = NORMAL

every state-update interval:
    read acceleration, angle, and temperature
    compute dAcc and dAngle relative to baseline
    if mode == NORMAL:
        if any monitored angle exceeds alarm threshold
            for the required consecutive count:
                mode = ALARM
                set transition flag
    else if mode == ALARM:
        if all monitored angles are below clear threshold
            for the required consecutive count:
                mode = NORMAL
                set transition flag
    encode measurement, delta, temperature, battery, and status
    schedule LoRaWAN uplink according to normal, alarm, or heartbeat policy

```

The LoRaWAN uplink distinguishes measurement/status traffic from periodic liveness confirmation through the FPort field [26]. General sensing records are transmitted on FPort 1 using the fixed 30-byte structure shown in Table 2, whereas FPort 2 carries a one-byte 0xA5 heartbeat. The fixed payload explicitly encodes acceleration, inclination, baseline-referenced differences, temperature, battery state, and status flags, enabling deterministic reconstruction at the backend.

Table 2. SCL3300 inclinometer uplink payload.

Offset	Length	Type	Scale	Field
0	2	int16 BE	10^4	accX
2	2	int16 BE	10^4	accY
4	2	int16 BE	10^4	accZ
6	2	int16 BE	10^2	angleX
8	2	int16 BE	10^2	angleY
10	2	int16 BE	10^2	angleZ
12	2	int16 BE	10^2	temperature
14	2	int16 BE	10^4	delta accX
16	2	int16 BE	10^4	delta accY
18	2	int16 BE	10^4	delta accZ
20	2	int16 BE	10^2	delta angleX
22	2	int16 BE	10^2	delta angleY
24	2	int16 BE	10^2	delta angleZ
26	2	int16 BE	10^3	battery voltage
28	1	uint8	1	battery percentage
29	1	uint8	1	status flags

Figure 5 summarizes the acquisition, baseline processing, state determination, LoRaWAN transmission, and backend decoding sequence for the SCL3300-D01 path.

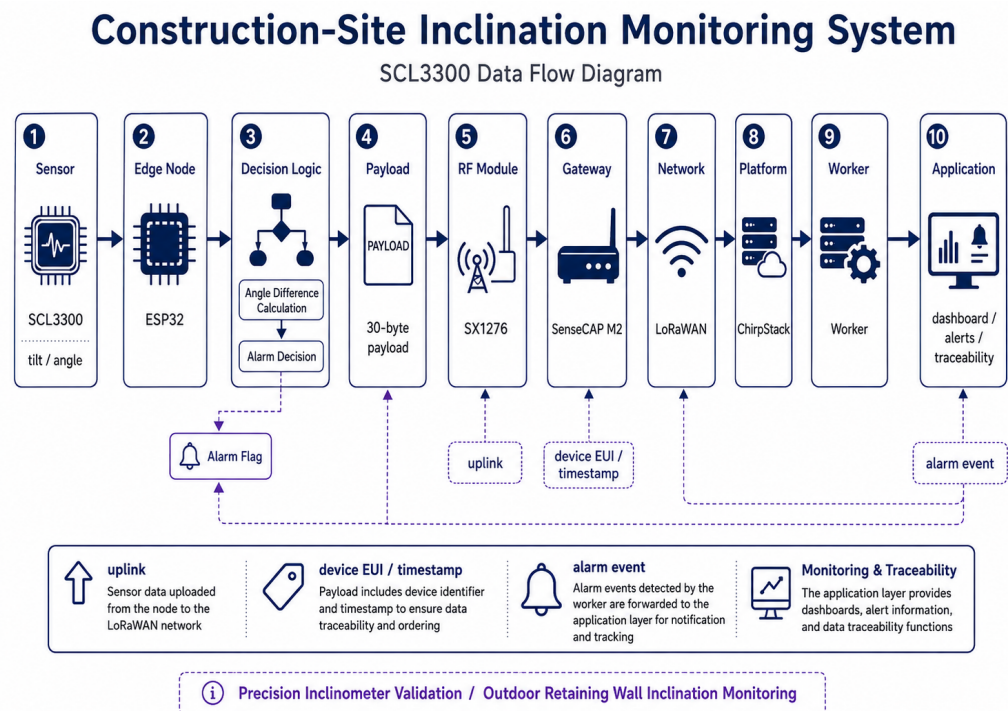


Figure 5. SCL3300-D01 inclinometer IoT sensing data-flow diagram.

3.6. Experimental Validation Method

The validation addresses prototype measurement and data-path functions under the reported test conditions. The 24 h sampling test, forced communication interruptions, stationary-angle measurements, and state-machine and codec checks do not constitute qualification for an operating construction site. Real-world environmental resilience, installed-cable reliability, and autonomous battery operation were not established. The target application context should therefore be distinguished from the scope of the reported validation. The available tests do not establish long-term timing stability, performance under ambient temperature variation, system-level electromagnetic immunity, or robustness to complex structural background vibration.

For the SCL3300-D01 path, specified-angle stationary measurements quantify baseline-referenced angle error, repeated alarm/recovery trials examine state transitions, LoRaWAN FCnt values indicate packet continuity, and known payloads check decoding. Equation (8) defines the signed angular error e_i at comparison point i as measured angle $\theta_{\text{SCL},i}$ minus reference angle $\theta_{\text{ref},i}$. All three angular quantities are in degrees, and a positive error indicates a measured value above the reference:

$$e_i = \theta_{\text{SCL},i} - \theta_{\text{ref},i}. \quad (8)$$

Equation (9) aggregates the signed errors into the root mean square error (RMSE), where N is the number of compared stationary-angle points for the evaluated axis and e_i is defined in Equation (8). The resulting RMSE_θ is non-negative and has the unit degrees.

$$\text{RMSE}_\theta = \sqrt{\frac{1}{N} \sum_{i=1}^N e_i^2}. \quad (9)$$

Equation (10) evaluates the packet delivery ratio (PDR) over the observed Frame Counter (FCnt) interval. Here, N_{observed} is the number of received frames, while $N_{\text{first FCnt}}$ and $N_{\text{last FCnt}}$ denote the first and last observed counter values, not additional packet counts.

Their difference plus one gives the inclusive counter-interval size. FCnt is associated LoRaWAN/backend metadata, not a field added to the 30-byte payload:

$$\text{PDR} = \frac{N_{\text{observed}}}{N_{\text{last FCnt}} - N_{\text{first FCnt}} + 1} \times 100\%. \quad (10)$$

4. Results

4.1. ADXL355 Accelerometer 24 h Sampling Results

Four ADXL355 nodes were operated continuously for 24 h. At the configured 200 Hz sampling rate, each node was expected to generate 17,280,000 records, corresponding to 69,120,000 records across all four nodes. The backend received exactly these counts for every node and for the aggregate data set, yielding a measured sample-completeness rate of 100% for the test interval. The per-node results are reported in Table 3.

Table 3. The 24 h sampling results of ADXL355 accelerometer nodes.

Sensor ID	Actual Received Data Records	Relative to Theoretical Data Count
009AF3A172E0	17,280,000	100%
08EADE020F3C	17,280,000	100%
3889D7020F3C	17,280,000	100%
70F7D7020F3C	17,280,000	100%
Total	69,120,000	100%

4.2. ADXL355 Accelerometer Disconnection-Recovery Results

Four forced network-interruption trials were used to evaluate the ADXL355 preservation and replay mechanism. Across the trials, 52,200 records were expected and all 52,200 were received after recovery, corresponding to an overall recovery rate of 100%. Of these records, 50,840 were explicitly labeled `src=flash`, confirming replay from persistent storage, while 1360 were labeled `src=live`, confirming that current data continued to be transmitted during the recovery process. Table 4 and Figure 6 summarize the four trials.

Table 4. ADXL355 accelerometer network-disconnection recovery results.

Round	Expected Records	Actual Records	<code>src=flash</code>	<code>src=live</code>	Recovery Rate
1	13,400	13,400	13,040	360	100%
2	12,960	12,960	12,520	440	100%
3	13,160	13,160	12,840	320	100%
4	12,680	12,680	12,440	240	100%
Total	52,200	52,200	50,840	1360	100%

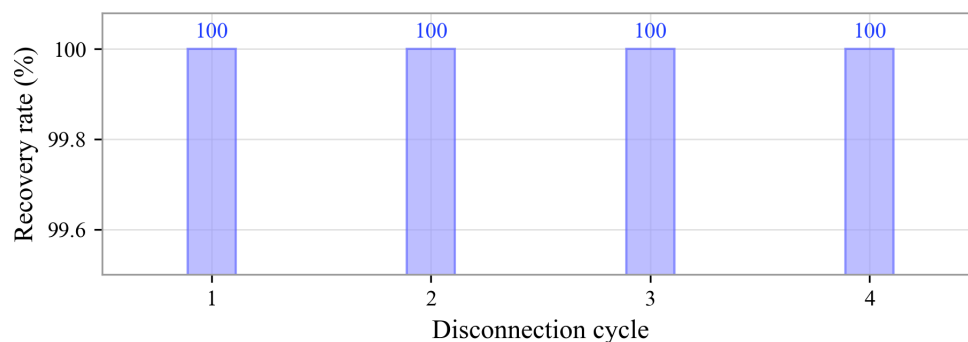


Figure 6. ADXL355 accelerometer recovery rate over four disconnection trials.

4.3. ADXL355 Accelerometer Frequency-Domain Check

Welch power spectral density (PSD) estimates were used to inspect the effect of the MCU-side 10 Hz second-order Butterworth low-pass filter. The Raw curves represent the unfiltered measurements, whereas the Offline LP10 curves represent the corresponding signals after application of the implemented 10 Hz filter. Across the displayed data, spectral energy above the cutoff is substantially reduced, with progressively stronger attenuation at higher frequencies, while the dominant low-frequency content below 10 Hz remains visible. Figure 7 presents the before/after PSD comparisons.

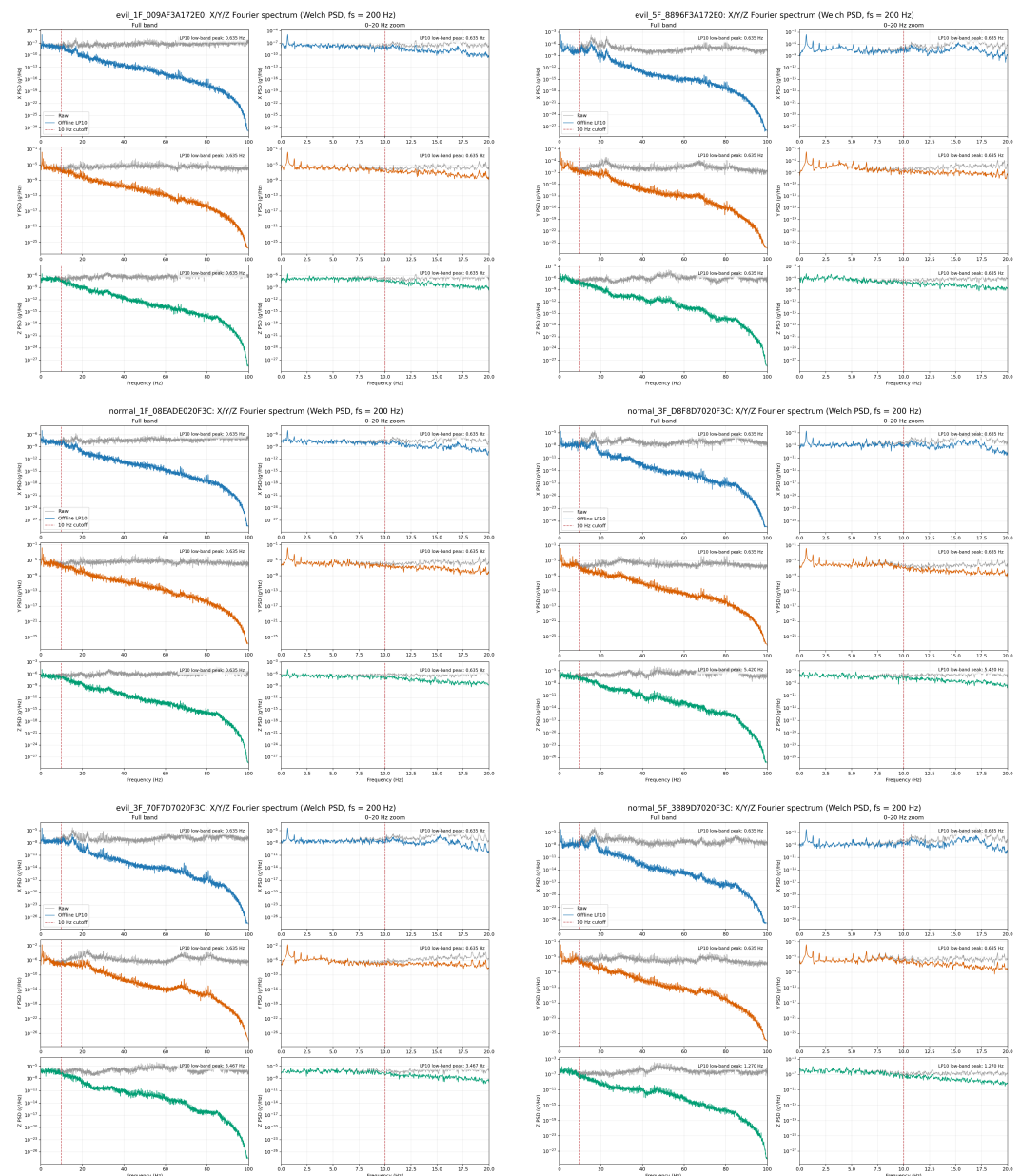


Figure 7. Welch PSD comparison plots before and after the MCU-side 10 Hz second-order Butterworth low-pass filter.

This comparison evaluates frequency-selective attenuation in the displayed records, not separation of vibration sources. Background components within the retained band are not distinguished from the response of interest by the low-pass filter alone; Figure 7 therefore does not establish noise rejection or monitoring specificity in an operating construction site.

4.4. SCL3300-D01 Inclinator Angle Results

The SCL3300-D01 angle evaluation was performed separately for the X and Y axes. For the X axis, five runs comprising 50 specified-angle stationary points produced an RMSE of 0.189° and a maximum absolute error of 0.443° after baseline establishment. For the Y axis, five runs comprising 64 points produced an MAE of 0.360° , an RMSE of 0.422° , and a maximum absolute error of 0.829° ; the fitted slope and R^2 were 1.001 and 0.9987, respectively. These results quantify both the magnitude and consistency of the baseline-referenced measurement error rather than treating the inclinometer output as an unverified status signal. Table 5 provides the complete metrics.

Table 5. SCL3300-D01 inclinometer X- and Y-axis angle validation results.

Metric	Result
X-axis included runs	5
Number of specified-angle stationary measurement points	50
Reference angle range	−14.6 to +18.9 degrees
X-axis RMSE	0.189 degrees
X-axis maximum absolute error	0.443 degrees
X-axis average of within-angle-point standard deviations	0.059 degrees
Y-axis included runs	5
Y-axis specified-angle stationary measurement points	64
Y-axis reference angle range	−16.1 to +14.7 degrees
Y-axis MAE/RMSE	0.360/0.422 degrees
Y-axis maximum absolute error	0.829 degrees
Y-axis slope/ R^2	1.001/0.9987
Y-axis signed mean error	+0.294 degrees
Y-axis average of within-angle-point standard deviations	0.060 degrees

4.5. SCL3300-D01 Inclinator Alarm, LoRaWAN Transmission, and Codec Results

The hysteresis-based alarm/recovery logic was evaluated in 25 complete trials, each containing six predefined state checkpoints. All 150 checkpoints matched the expected state, yielding 100% checkpoint accuracy for the tested sequence of NORMAL, ALARM, and recovery transitions. The median delay from the ALARM marker to state switching was 0.313 s, and the median delay from the NORMAL marker to switching was 0.235 s. Table 6 and Figure 8 summarize the state-machine results. These delays are the intervals from the recorded ALARM or NORMAL marker to local state switching in the state-machine tests. They are not measurements of LoRaWAN transmission time or end-to-end alarm delivery to the backend.

Figure 8 displays the median angle difference observed at each test stage; its bar heights are not alarm or recovery settings. The exact configuration gap is stated in Section 3.5. Table 6 reports agreement with the tested state checkpoints, not accuracy for identifying unsafe structures or evidence that the test thresholds are appropriate for field safety decisions.

Table 6. SCL3300-D01 inclinometer enlarged-threshold baseline-referenced rule-based hysteresis state-machine result.

Metric	Result
Included rounds	25 trials
Completed state-transition trials	25 trials
Checkpoint pass count	150/150
Alarm and recovery accuracy	100%
Median time from ALARM marker to state switching	0.313 s
Median time from NORMAL marker to state switching	0.235 s

During the LoRaWAN continuity observation, the FCnt values summarized in Table 7 increased monotonically from 728 to 892 and 165 packets were received. No frame-counter

gaps were observed, corresponding to a PDR of 100% over this specific observation interval. The traffic comprised 154 30-byte general-data packets on FPort 1 and 11 heartbeat packets on FPort 2. Backend codec correctness was evaluated separately using 100 known 30-byte payloads; all 100 were decoded correctly into the expected engineering fields. Table 7 reports the packet and codec results. The median RSSI of -19 dBm and median SNR of 12 dB characterize favorable link conditions; the observed PDR does not establish performance under heavy obstruction, multipath, or near the gateway coverage edge.

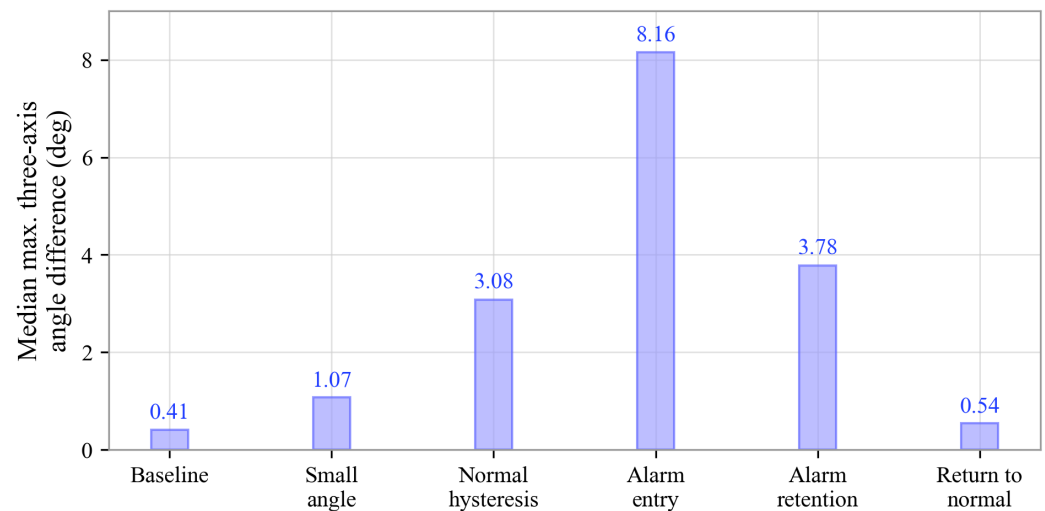


Figure 8. Median angle differences at each stage of the 25 trials.

Table 7. Current SCL3300-D01 inclinometer LoRaWAN data result.

Metric	Result
FCnt range	728–892
Total frames	165
30-byte general data frames	154
Periodic device status confirmation frames	11
Observed PDR	100%
Median RSSI	-19 dBm
Median SNR	12 dB
Codec all-field correctness rate	100% (actual correct 100 sets/expected comparison 100 sets)

5. Discussion

The ADXL355 results demonstrate the importance of treating communication interruption as part of the sensing design. A wired PoE/Ethernet path is well suited to continuous high-rate vibration data, but wired connectivity does not eliminate transient broker or network failures. The 24 h run yielded complete record delivery under sustained operation. In all four forced-outage trials, the Flash-backed replay path recovered every expected record. The simultaneous presence of `src=flash` and `src=live` records is particularly relevant: it confirms that recovery was not implemented as a stop-and-replay procedure but as an interleaved process in which historical restoration and current-state delivery coexist. This property strengthens temporal continuity for downstream monitoring systems.

The SCL3300-D01 path addresses a different systems problem. Construction-site inclination is naturally represented as a comparatively low-rate state variable, making

LoRaWAN and compact fixed-format payloads more appropriate than continuous high-throughput transport. The angle tests quantify the uncertainty of the baseline-referenced measurements, while the 150/150 state checkpoints show that the configured hysteresis logic behaved deterministically in the repeated laboratory trials. Frame-counter continuity and the 100-payload codec test further verify that the transmitted state can be traced and reconstructed at the backend. The significance of this path is therefore the integration of measurement, state abstraction, transport, and deterministic decoding within one verifiable low-data-rate workflow.

The two paths are complementary components of the proposed implementation, not experimentally ranked alternatives. Their different communication mechanisms address different temporal, bandwidth, and deployment requirements. The common record-provenance objective concerns source identity, explicitly interpreted time information, and path-specific record or payload semantics; it does not establish a unified cross-stream backend. The contribution is the implementation and separate evaluation of these sensing-to-backend functions. Neither a controlled comparator nor a quantitative literature benchmark was established, so the results do not show superiority over a uniform communication stack, commercial SHM systems, or published IoT frameworks.

The reported performance indicators also have distinct measurement boundaries. Table 3 concerns vibration record-count completeness, and Table 4 concerns preservation and reception within the tested interruption windows, not a maximum recoverable outage duration or a measured backlog-clearance advantage. The errors in Table 5 concern baseline-referenced stationary-angle measurements. Table 6 reports agreement with state checkpoints and local marker-to-switching intervals, not end-to-end alarm delivery. Table 7 separates FCnt-interval packet continuity from known-payload decoding correctness. These indicators cannot be pooled into a single monitoring-accuracy score or treated as interchangeable across systems without aligned definitions and conditions. Consequently, no cross-system ranking or incremental gain attributable to the dual-path choice or interleaved replay is established. Comparative evaluation with explicitly defined metrics and conditions remains future work.

The reported 100% completeness, recovery, checkpoint, PDR, and codec values apply only to the specific nodes, durations, forced-outage conditions, and wireless observation interval tested. They establish prototype functionality in those tests, not immediate construction-site applicability or guarantees under arbitrary field conditions. In particular, checkpoint agreement is not a field structural-hazard classification rate, and the favorable-link packet result is not an interference-tolerance assessment. The deployment requirements below remain unmeasured or unimplemented and delimit the conclusions supported by the evidence.

Electrical power consumption was not characterized, so a measured typical per-node power draw under continuous 200 Hz operation and a numerical full-building power budget cannot be reported. PoE provides centralized supply and wired connectivity but does not itself demonstrate energy efficiency. Scaling to dozens of nodes requires measurement of representative and peak node demand, including recovery operation, followed by consideration of active port count, per-port limits, the aggregate power budget of the power-sourcing equipment (PSE)/switch, cable and conversion losses, and operating margin. Node contributions add across powered ports, but a defensible wattage estimate requires measurements at a clearly defined electrical boundary so that losses are not omitted or counted twice.

For the battery-powered inclination path, MAX17043 status reporting does not establish battery lifespan. NORMAL and ALARM are application states, not measured power profiles. No state-resolved whole-node current measurements, full discharge record, or doc-

umented combination of usable battery capacity, activity durations, uplink configuration, and alarm duty profile is available for a defensible runtime projection. If alarm reporting increases radio activity, it may change average energy demand, but neither its magnitude nor the runtime difference between states can be quantified here. The approximately 600 ms update interval in Table 1 is not a documented transmission or sleep duty cycle. State-specific and mixed-profile power and endurance evaluation are needed before autonomous operating time or charging/maintenance intervals can be established. Payload decoding correctness does not validate battery-gauge accuracy or remaining runtime.

The four short forced-outage trials verify preservation and replay within their tested conditions, not multi-hour interruption tolerance. Longer interruptions increase the stored backlog and make Flash capacity, write behavior, and available replay throughput limiting factors. Repeated write/erase endurance, filesystem write amplification, storage-full behavior, and multi-year field lifetime were not characterized. LittleFS use alone is not evidence of a particular storage lifetime. Long-term deployment therefore requires joint evaluation of usable capacity, outage frequency and duration, recovery/deletion policies, and Flash endurance; larger-capacity or higher-endurance nonvolatile storage would be an engineering option rather than a tested feature of this implementation.

PoE installation also introduces physical failure modes that were not covered by the communication-outage trials. Cable crushing, pulling, abrasion, connector loosening, or exposure at connection points are deployment risks rather than failures observed in this study. Protected routing, strain relief, connection protection, and inspection should be assessed for the installation environment; no protective rating or cable-durability qualification is claimed. A cable or power-sourcing fault can affect both data and supply. Flash buffering requires continued node power and does not provide acquisition during a supply outage, guarantee retention of RAM-only data, or establish abrupt-power-loss recovery. The two paths serve different sensing workloads; no automatic failover from PoE vibration transport to LoRaWAN is implemented or validated.

The wireless observation was conducted under favorable link conditions and cannot quantify PDR degradation or additional alarm-delivery delay in cluttered or coverage-edge deployments. As an engineering expectation, reduced link margin can increase packet-loss probability; delivery may be delayed if further transmissions are scheduled, and an alarm can remain undelivered if no successful transmission occurs. The outcome depends on obstruction, multipath, interference, gateway and antenna placement, data-rate settings, and the configured reporting/retry policy. The local marker-to-state-switching intervals in Table 6 must be distinguished from end-to-end alarm latency. Longer field observations across RSSI/SNR regimes, including obstructed and gateway-edge locations, are required to assess delivery reliability and generation-to-backend alarm delay; these have not been performed here.

For an active construction site, radio-frequency (RF) interference from coexisting transmitters should be assessed separately from attenuation and multipath caused by obstructions. Changing site layouts and antenna or gateway positions are additional conditions requiring evaluation. These are deployment considerations, not observed interference sources or measured degradation in the present tests. Representative field observations must assess packet delivery and generation-to-backend alarm delay; gateway placement and radio settings are candidate configuration measures, not validated mitigations or guaranteed coverage solutions. These link-level considerations do not constitute a system-level electromagnetic immunity test of the sensing, supply, and wired communication chain. No interference source, susceptibility limit, or resulting measurement error is identified by the current validation.

Future coverage investigations could also consider complementary physical-layer approaches alongside gateway placement, antenna configuration, and LoRaWAN parameter selection. Self-powered absorptive reconfigurable intelligent surfaces have been studied for secure satellite-terrestrial links [27], while distributed split single-sideband time-modulated arrays have been studied for spatially selective secure communication [28]. These are distinct propagation-control and array-design approaches, not demonstrated LoRaWAN coverage solutions. Their potential relevance to difficult building or construction-site links is a research direction requiring separate evaluation of frequency, waveform, channel-control, hardware, and power constraints. Neither approach was implemented or evaluated in this work, and no coverage, latency, or security gain is claimed for the present framework.

Timing validation is also limited to the reported data-path behavior. No 24 h standalone drift characterization or dedicated cross-path synchronization was performed; record-count completeness does not establish absolute time accuracy or temporal alignment. The LoRaWAN packet observation is separate from the 24 h vibration test and should not be assigned that test duration. In particular, the 30-byte inclination payload contains no device measurement timestamp. Future fusion would require explicit measurement-time semantics, an application-appropriate common reference or periodic synchronization layer, and measured inter-node/cross-path alignment. Network-based synchronization or a shared external time reference are possible design options, not validated features of the current system.

Ambient-temperature robustness has not been established. The temperature conversion in Equation (4) and the field in Table 2 specify a sensor-temperature report, not a controlled characterization of ambient exposure, temperature-dependent angle error, or compensation performance. The startup reference in Equations (5) and (6) provides a fixed baseline; this operation alone does not remove time-varying measurement offsets after initialization. The stationary-angle errors therefore cannot be extrapolated to an environmental temperature range that was not characterized. No quantitative thermal-stability or temperature-compensation claim is made.

Complex structural background vibration is a separate limitation from packet delivery. A frequency-selective filter does not identify the physical source of a retained component: the PSD comparison in Figure 7 does not demonstrate separation of target responses from background vibration within the passband. Similarly, the enlarged-threshold state-machine trials do not establish a field false-alarm rate under nonstationary disturbances. Complete data delivery and correct decoding cannot establish freedom from these measurement effects. Generalization to engineering environments would require independent evidence on long-term timing, temperature-related stability, system-level interference tolerance, and signal/alarm interpretation under representative background vibration; such evidence is not provided by the current tests.

The current implementation ends at path-specific sensing-data structures, backend decoding, and record storage; independent validation does not establish a jointly operating platform. The missing upper-layer work includes a unified cross-stream model with explicit source, time, measurement, and state semantics, device-to-asset association, BIM/GIS object mappings, and platform-specific adapters. These are development requirements, not an implemented schema or API supplied by this study. Full 3D visual synchronization, joint model-state updates, and their consistency would need independent validation after that integration. This distinction preserves the data-path contribution without treating it as a completed digital-twin outcome.

6. Conclusions

This study developed a dual-path IoT sensing and communication prototype and evaluated its reported functions under the stated test conditions, with smart-building vibration monitoring and construction-site inclination-status monitoring as intended applications. The evidence supports prototype feasibility, not immediate deployment at an operating construction site. The framework is based on a simple but consequential design principle: heterogeneous sensing workloads should use communication paths matched to their temporal and field constraints, while sharing common requirements for traceability, preservation and explicit interpretation of available time information, payload interpretability, and backend verification. The contribution is the implementation and separate evaluation of two sensing-to-backend workflows under shared traceability requirements, not an implemented unified data model or a demonstrated cross-system performance advantage.

For the smart-building path, the ADXL355, ESP32-S3, PoE/Ethernet, and MQTT implementation combines 200 Hz triaxial acquisition with sensor/MCU filtering, 40-record batching, Flash LittleFS-based offline preservation, and live/flash interleaved recovery. This architecture is designed so that a temporary communication failure does not force a choice between recovering historical records and maintaining current transmission: both streams can progress after reconnection.

The 24 h test delivered all 69,120,000 expected vibration records from four nodes, and the four forced-outage trials recovered all 52,200 expected records. Welch PSD analysis further confirmed the intended reduction of frequency content above the 10 Hz cutoff while retaining the dominant lower-frequency components. Together, these results verify sustained acquisition, outage recovery, and explicit source traceability for the tested high-data-rate path.

For the construction-site path, the SCL3300-D01, ESP32, SX1276, LoRaWAN gateway, and backend decoder form a low-data-rate workflow in which raw inclination measurements are converted into baseline-referenced changes and stable NORMAL/ALARM states before transmission. The fixed payload additionally carries temperature, battery information, and status flags, allowing the backend to reconstruct both the physical measurement and its operational context.

The SCL3300-D01 validation quantified the angle error on both axes, achieved the expected state at all 150 checkpoints across 25 alarm/recovery trials, observed no frame-counter gaps among 165 LoRaWAN packets, and correctly decoded all 100 known test payloads. These results support the implemented measurement, state-transition, transport, and codec functions within the evaluated conditions.

Overall, the reported tests illustrate complementary data-path functions within a shared data-layer concept; they do not establish comprehensive satisfaction of real-world deployment requirements. The ADXL355 path emphasizes continuous high-rate acquisition and interruption recovery; the SCL3300-D01 path emphasizes low-volume wireless status reporting and deterministic state interpretation. In both cases, device identity, time-related information, source/state markers, and explicit payload definitions preserve the provenance and meaning of the data as they move from the physical site to the backend.

The proposed framework provides separately evaluated sensing-to-backend functions within the reported test conditions. It does not demonstrate comparative superiority, building-scale power efficiency, inclination-node battery lifespan, multi-hour outage tolerance, multi-year Flash endurance, site interference tolerance, installed PoE-cable durability, or synchronized cross-path fusion. Ambient-temperature robustness, system-level electromagnetic immunity, and monitoring specificity under complex background vibration are also uncharacterized. Full 3D visual synchronization, BIM/GIS asset mapping, and digital-twin platform interfacing were not implemented and remain future development tasks.

Further work must establish environmental, power, timing, and comparative performance and implement and independently validate the required cross-stream, asset-mapping, and platform-adaptor layers before broader field-applicability or joint-platform claims can be made.

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