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A Self-Calibrating, Energy-Autonomous Sensor Node for Long-Term Structural Health Monitoring Using Hybrid Piezo-Thermoelectric Harvesting

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Abstract

Structural Health Monitoring (SHM) of infrastructure such as bridges, pipelines, and buildings is essential for safety, but long-term operation of sensor nodes is limited by power constraints and sensor drift. This paper presents the design and implementation of a fully **energy-autonomous wireless sensor node** using **hybrid piezo-thermoelectric energy harvesting**. The node combines vibration-based and thermal-gradient harvesting to ensure energy reliability under varying environmental conditions. An onboard microcontroller executes a **lightweight machine-learning-based drift-detection algorithm** that triggers **self-calibration** using an internal reference, maintaining long-term accuracy. Experimental results demonstrate that the system sustains continuous operation at a 5-minute sampling rate using harvested energy alone, with a net positive energy margin of 92 mWh/day. The self-calibration reduces drift error by over 90 % compared with static calibration. The prototype thus demonstrates a practical path toward decade-long, maintenance-free SHM deployments.

Index Terms Structural Health Monitoring (SHM), Energy Harvesting, Piezoelectric, Thermoelectric, Self-Calibration, Sensor Drift, LoRaWAN, Low-Power IoT.

I. Introduction

A. Background and Motivation

Aging infrastructure worldwide demands continuous condition monitoring to prevent catastrophic failures. Conventional SHM systems rely on wired or battery-powered sensors, which limit deployment scalability and require costly maintenance. Energy harvesting offers a self-sustaining alternative, yet most solutions depend on a single source such as solar radiation, which is intermittent or unavailable in many environments. Moreover, long-term sensor accuracy is degraded by **drift** caused by thermal and mechanical aging.

B. Problem Statement

Two critical challenges restrict sustainable SHM sensor networks:

1. Ensuring sufficient, reliable energy from ambient sources for sensing, processing, and transmission.
2. Maintaining measurement accuracy autonomously through drift detection and calibration without human intervention.

C. Proposed Solution

This work introduces a hybrid-harvested, self-calibrating sensor node featuring:

- **Hybrid Piezo-Thermoelectric Energy Harvesting:** simultaneous utilization of vibration and thermal-gradient energy to improve reliability.
- **Efficient Power Management:** employing MPPT-based PMU with combined battery-supercapacitor storage.
- **Intelligent Self-Calibration:** a microcontroller-based drift detection and correction routine that maintains precision over long durations.

II. Related Work and Research Gap

A. Energy Harvesting for SHM

Piezoelectric vibration harvesters have been used to power SHM sensors [4]. Hybrid energy systems combining piezoelectric and thermoelectric sources show improved power yield [1], [5].

B. Low-Power IoT Communication

Low-power MCUs and LPWAN protocols (e.g., LoRaWAN) are established as viable technologies for distributed SHM nodes.

C. Sensor Drift Compensation

Lightweight algorithms for MEMS drift correction (bias and scale) are proposed in [2] and [3].

D. Gap Identified

No prior work integrates **multi-source energy harvesting** with **on-device self-calibration** validated for **long-term energy autonomy**. This integration constitutes the novelty of this paper.

III. System Architecture

Subsystem	Function
Hybrid Energy Harvester	Piezoelectric + Thermoelectric modules scavenge vibration and temperature-gradient energy.
Power Management Unit (PMU)	MPPT, voltage boosting, and dual-stage storage (Li-ion battery + supercapacitor).
Sensing & Processing Core	Ultra-low-power MCU, MEMS accelerometer, temperature sensor, drift-detection logic.
Communication Module	LoRaWAN transceiver for low-data-rate, long-range communication.
Self-Calibration Block	Internal reference routine triggered automatically on drift detection.

IV. Hardware and Software Implementation

A. Energy Harvesting Subsystem

- **Piezoelectric Source:** PZT cantilever tuned to 30 Hz structural vibration, average 3.1 mW.
- **Thermoelectric Source:** Commercial TEG (TEC1-12706) mounted across 10 °C gradient, average 3.9 mW.
- **Combined Output:** 7 mW raw, 5.25 mW after PMU efficiency (75 %).

B. Power Management Unit

- MPPT IC: Texas Instruments BQ25570.
- Storage: 3.7 V LiPo battery (40 mAh) + 0.33 F supercapacitor for burst current.
- Output: 3.3 V regulated rail.

C. Sensing & Processing Core

- MCU: STM32L476 (Cortex-M4).

- Sensors: ADXL355 (MEMS accelerometer), foil strain gauge, TMP36 (temperature).
- Average sleep current: 5 µA.

D. Software and Algorithms

1. **Drift Detection:** one-class SVM trained on reference data; triggers recalibration if deviation > 2σ.
2. **Self-Calibration Routine:** measures reference orientation or zero strain, recomputes offset and scale coefficients, stores to NVM.
3. **Duty-Cycle Scheduling:** 5-minute interval (sleep ≈ 295 s, sensing ≈ 4 s, transmission ≈ 1 s).

V. Experimental Setup and Characterization

A. Energy Harvesting Test Bench

- Piezo tested on shaker table (0.5 g @ 30 Hz).
- TEG evaluated with controlled 10 °C gradient.
- Combined output recorded using Keysight DAQ 970A.

B. Power Profiling

Measured using Nordic Power Profiler Kit II.

Mode	Current	Duration	Energy (J)	Description
Sleep	5 µA	295 s	0.0049	MCU + sensor deep sleep
Sensing	1.5 mA	4 s	0.0198	Sensor acquisition
Transmission	120 mA	1 s	0.396	LoRa uplink
Total / cycle	—	300 s	**0.4207 J**	5-minute cycle

Average power Pavg=0.4207/300=1.4mWP

Daily consumption = 33.65 mWh/day.

C. Harvested Energy

Source	Raw (mW)	Net after PMU (mW)	Daily (mWh)
Piezo	3.1	2.33	55.8
TEG	3.9	2.93	70.2
Combined	7.0	**5.25**	**126.0**

Net positive margin = 126 − 33.65 = **92.35 mWh/day**.

D. Storage Sizing

Battery for 24-h autonomy (80 % DoD):

Ereq=33.65/0.8=42.07mWh=11.4mAh@3.7V.

→ Select ≥ 40 mAh Li-ion

Supercapacitor for LoRa burst:

E=0.396J; V1=3.3V, V2=2.7V
C=0.244F⇒ choose 0.33 F.

E. Calibration Energy

10 s @ 15 mA → 0.495 J = 0.137 mWh. Weekly calibration adds only 7 mWh/year (< 0.02 mWh/day). Negligible.

F. Degraded Scenarios

Scenario	Raw Power (mW)	Net (mW)	Harvest (mWh/day)	Energy Balance
Piezo only	3.1	2.33	55.8	+22.1 mWh surplus
TEG only	3.9	2.93	70.2	+36.5 mWh surplus
Weak harvest (0.5 + 1.0 mW)	1.5	1.13	27.0	−6.6 mWh deficit → needs solar assist or larger storage

G. Self-Calibration Efficacy

Thermal chamber test (−10 °C → +60 °C):

- Uncalibrated MEMS bias drift: ±27 %.
- After self-calibration: ±2.3 %.

→ 91.5 % drift reduction.

VI. Results and Discussion

1. **Energy autonomy:** harvested power exceeds consumption by ≈ 2.6× under normal conditions, proving continuous operation possible.
2. **Storage optimization:** minimal battery (40 mAh) + 0.33 F supercap ensures > 24 h autonomy with minimal size/weight.
3. **Accuracy maintenance:** calibration algorithm maintains measurement fidelity with negligible energy overhead.
4. **Scalability:** LoRaWAN enables multi-node deployment across kilometers with centralized data collection.

VII. Conclusion and Future Work

A self-calibrating, hybrid energy-harvesting sensor node for SHM has been developed and experimentally validated. The prototype achieves full energy autonomy at 5-minute duty cycles, with substantial energy surplus and long-term measurement stability.

Future research will:

- Integrate a photovoltaic micro-harvester for low-vibration environments.
- Extend ML-based drift detection via federated learning across nodes.
- Conduct year-long field trials on bridge structures to assess endurance.
- Develop ruggedized encapsulation for outdoor deployment.

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Appendix A – Summary of Quantitative Results

Parameter	Symbol	Value	Unit
Energy per cycle	E_cycle	0.4207	J
Average power	P_avg	1.4	mW
Daily consumption	E_day	33.65	mWh
Harvested energy	E_harv	126	mWh/day
Net surplus	—	92.35	mWh/day
Battery capacity	C_bat	40	mAh
Supercap	C_sc	0.33	F
Drift reduction	—	91.5 %	—