MSc Robotics Dissertation · B81EZ · Presentation Assessment B31VZ

HERIOT WATT UNIVERSITY

Battery-Free Smart Mats for Real-Time Inventory Tracking

Velostat pressure sensing, corrected with TinyML, on a battery-free BLE sensor mat.

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AGENDA

What I'll cover today

01 **Objectives**

The research question this project set out to answer

02 **Background & system**

Where this fits, and how the mat, electronics and receiver work together

03 **Methodology**

Design decisions, problems solved, and why each choice was made

04 **Results & analysis**

What the data shows, and what it means

05 **What's next & demo**

Limitations, TinyML roadmap, and a live demo with backup

06 **Quality planning**

Standards, scope and how deliverables were kept on track

RESEARCH QUESTION & OBJECTIVES

One question, three measurable objectives

Can a battery-free, pressure-sensing mat detect when an item is added to or removed from a shelf, accurately enough for real-time inventory tracking, without tagging the item itself?

1

Sense

Build an 8x8 Velostat pressure grid that detects placement and removal events across a shelf mat.

2

Broadcast

Achieve battery-free operation: BLE beacon broadcast, powered indoors from ambient (solar) energy.

3

Correct

Layer TinyML correction for Velostat's known nonlinearity on top of a classical calibration baseline.

Retailers don't actually know what's on the shelf

Invertory Drift:

Theft

Error

misplacements

Solution

RFID

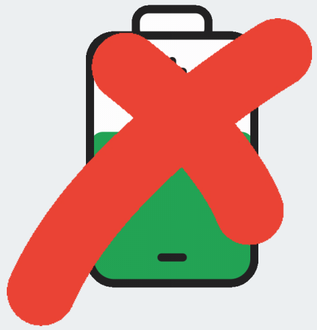
Expensive

What we need?

Smart Mat

- Count
- Detect
- Update

Wires



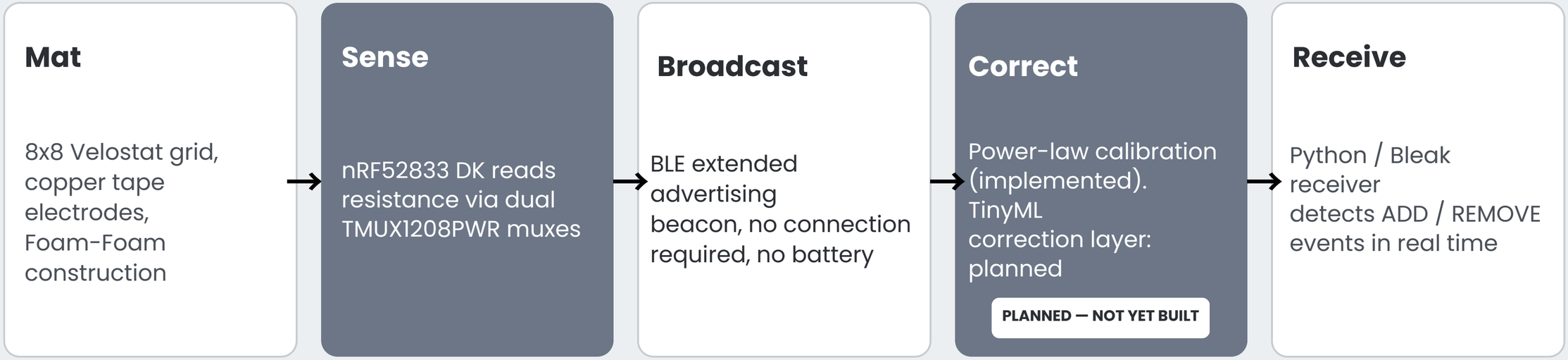
Battery

Velostat

A piezoresistive material that can changes electrical resistance under pressure.

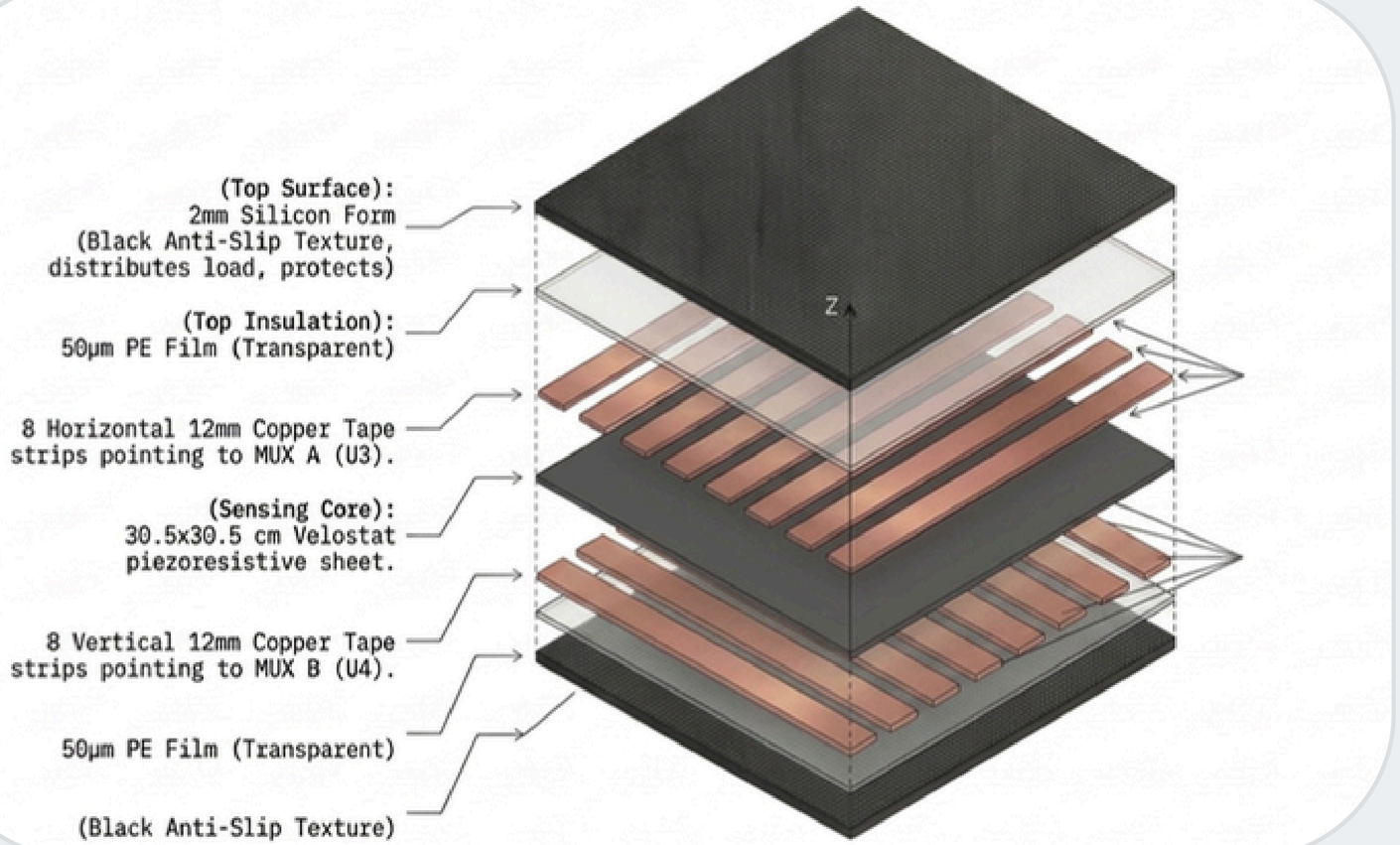
METHODOLOGY — SYSTEM OVERVIEW

From a footstep on foam to a number on a screen



Every stage is designed around one constraint: no battery, so no stage can assume continuous power.

Mat Construction



Literature Review:

- **(Sharma and Bi nong, 2023)** showed that a silicone foam layer above the sensing surface ensures uniform pressure distribution for items with small contact areas essential for cylindrical bottles and tins in a retail context.
- **(Kciuk et al., 2023)**Protective PE sheets insulate the circuitry from short circuit and moisture.
- **(Fatema et al., 2024)** At 5cm pitch, crosstalk reduce by **99.5%** versus the 1cm baseline. 5cm pitch is not possible for 8 strips construction. so we use 3.52cm pitch with 12mm tape. Crosstalk reduce by **24%**.

References :

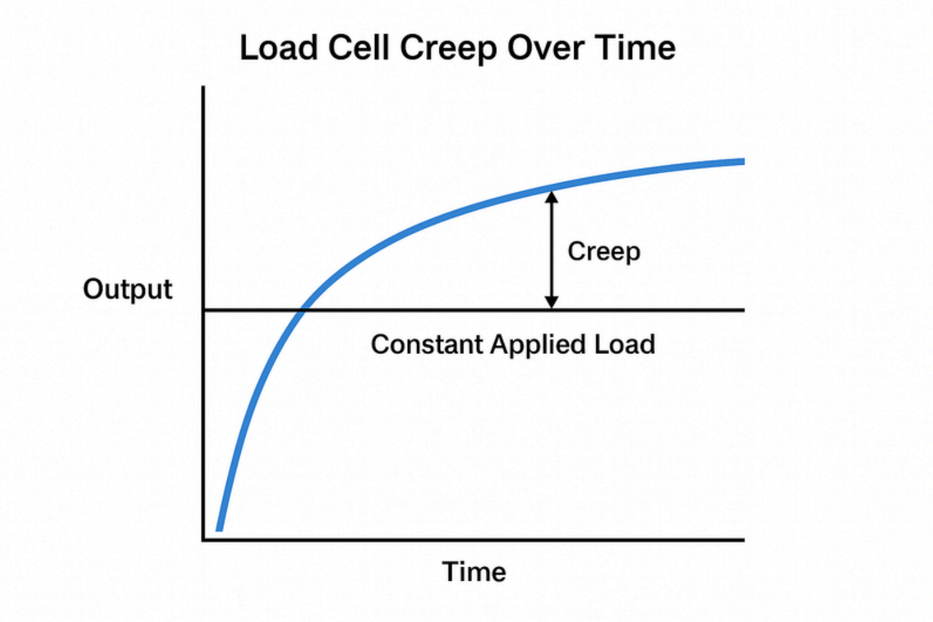
Smart Mat Material Selection 6 Sharma, M. D. and J. Binong (2023). “Performance Evaluation of a Specialized Pressure Sensor for Pick and Place Operations”. In: Engineering Proceedings 58.1, p. 74. doi: 10.3390/ecsa-10-16586.

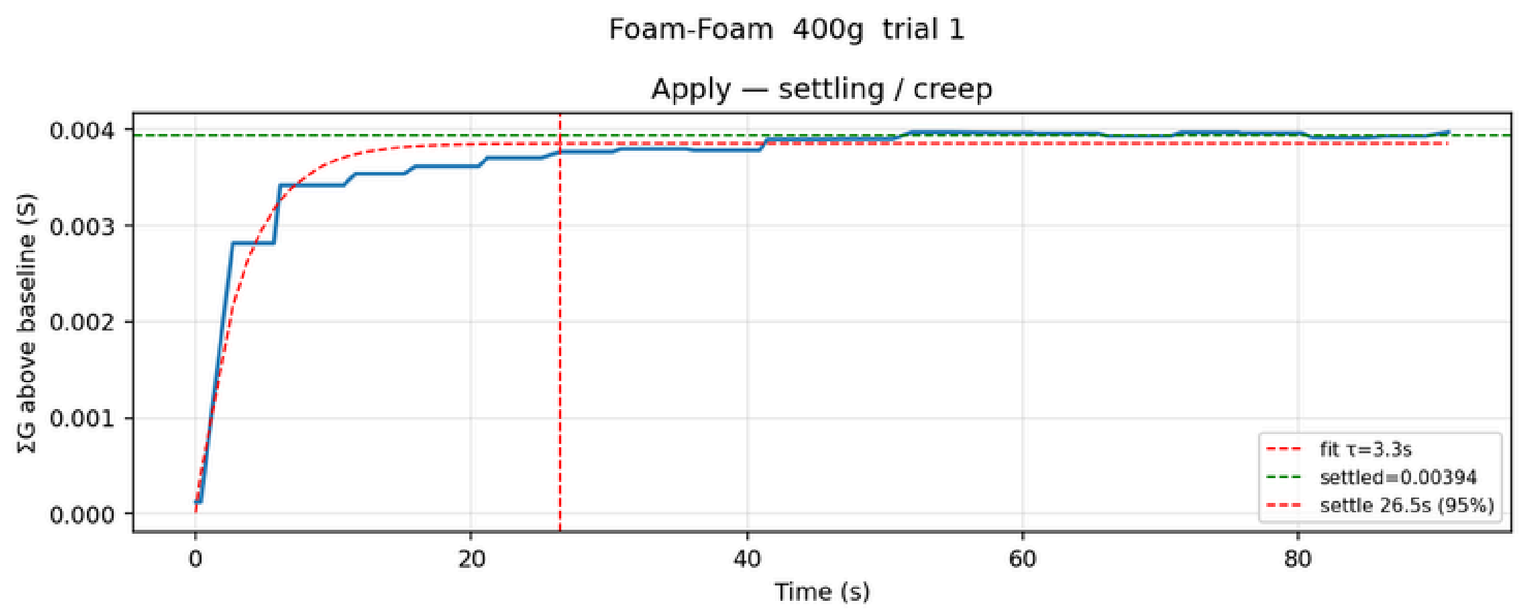
Kciuk, M. et al. (2023). “Intelligent Medical Velostat Pressure Sensor Mat Based on Artificial Neural Network and Arduino Embedded System”. In: Applied System Innovation 6.5, p. 84. doi: 10.3390/asi6050084.

Fatema, A. et al. (2024). “Investigation of the Long-Term Reliability of a Velostat Based Flexible Pressure Sensor Array for 210 Days”. In: IEEE Transactions on Device and Materials Reliability 24.1, pp. 41–48. doi: 10.1109/TDMR.2023. 3340711.

Velostat's natural drift and creep

Creep and drift are both time-dependent changes or errors that happen in physical materials, sensors, and instruments under load or over time.



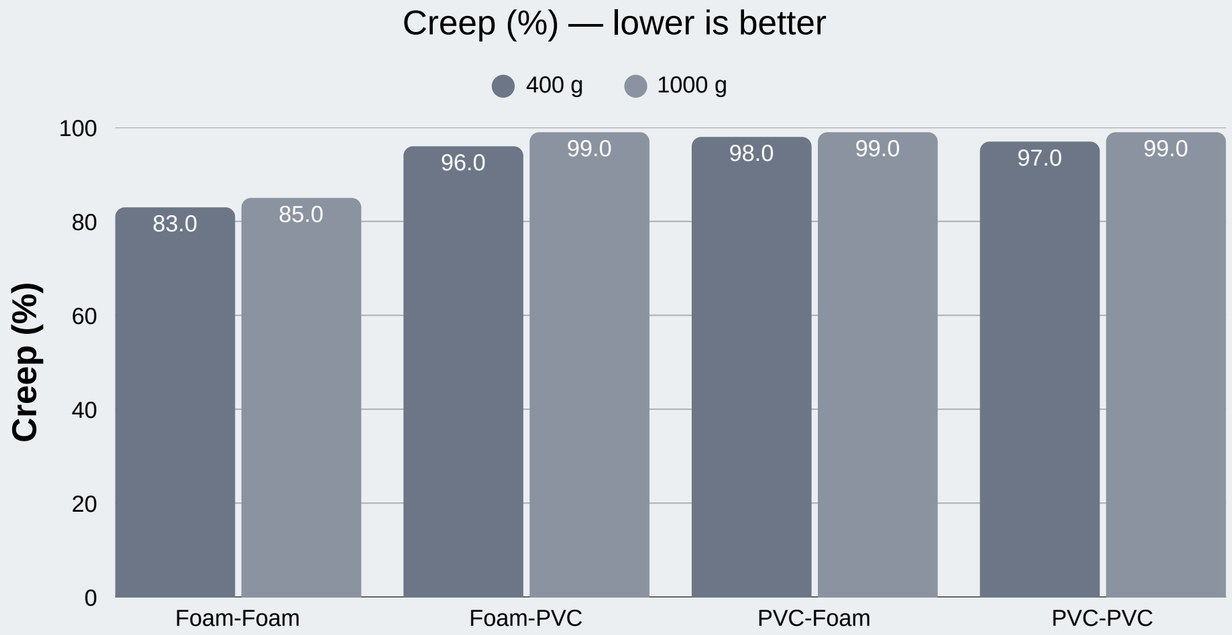


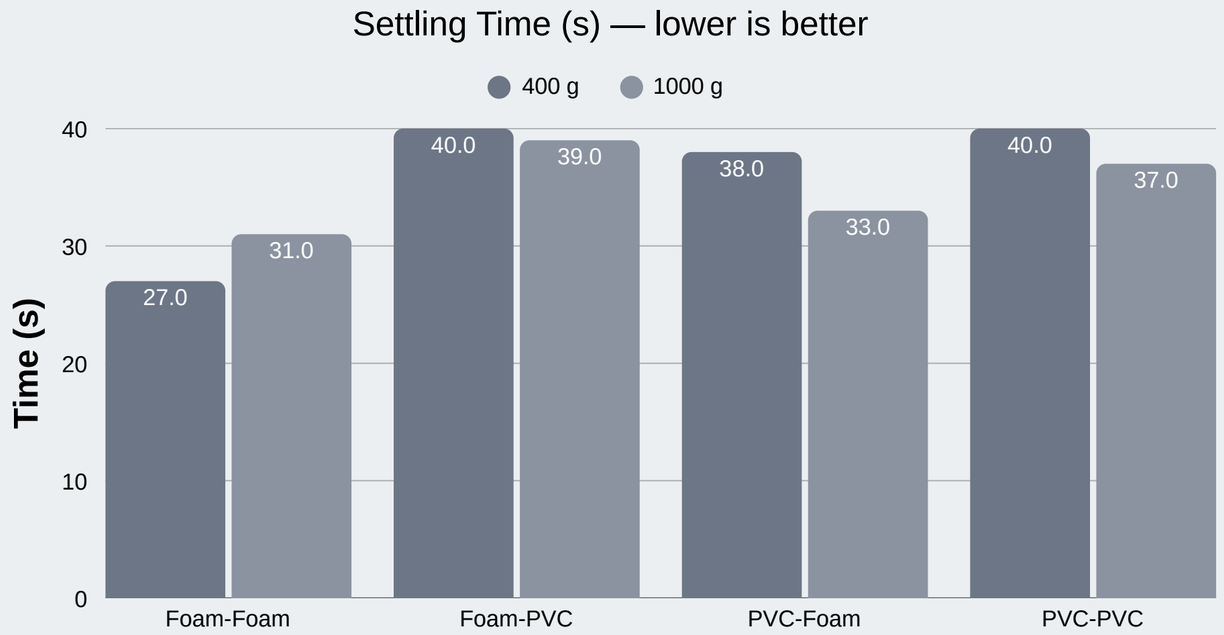
Core assessment: a mat that hasn't been touched still drifts. Calculating absolute weight from raw resistance, continuously, is mathematically unstable over long time horizons.

Choosing the right foam layering

Four layer constructions were built and tested at two loads **(400 g, 1000 g)** 5 trails of each.

Foam-Foam construction shows **85% creep** and **avg (30 sec)** settling time.



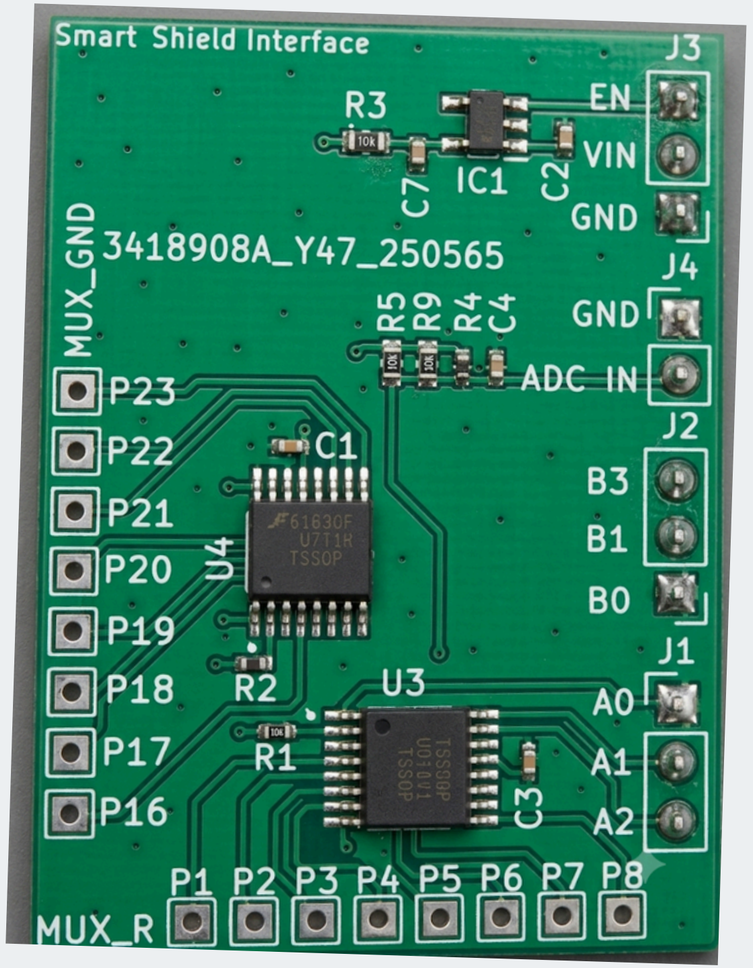


Reading 64 pressure points with custom PCB

The problem: an 8x8 grid means 64 signals, but the nRF52833 doesn't have 64 analogue inputs.

The solution: dual TMUX1208PWR multiplexers, on custom PCB, take turns routing each cell through to a single SAADC channel — 14-bit resolution, 16x oversampling.

In plain terms: one chip can't listen to 64 pressure points at once, so a fast electronic switch lets it check each pad in turn, hundreds of times a second.

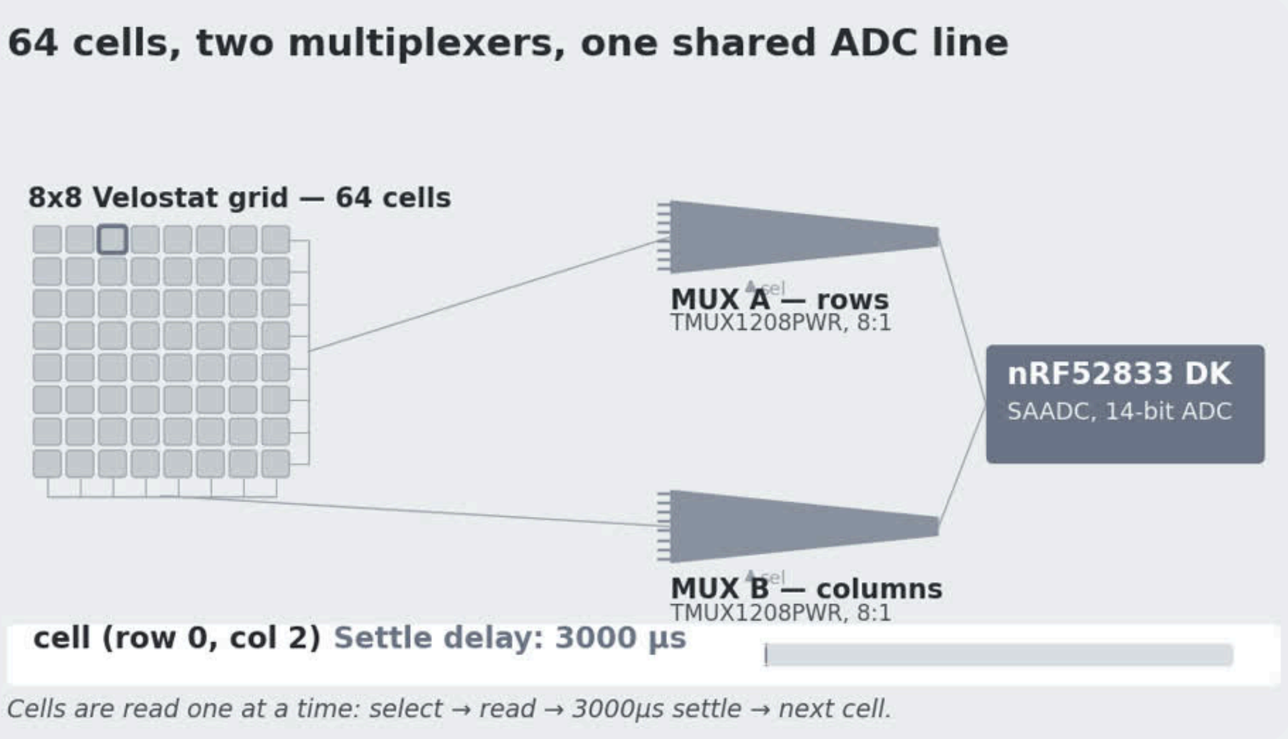


Design by: Spyridon Daskalakis / Muhammad Umair

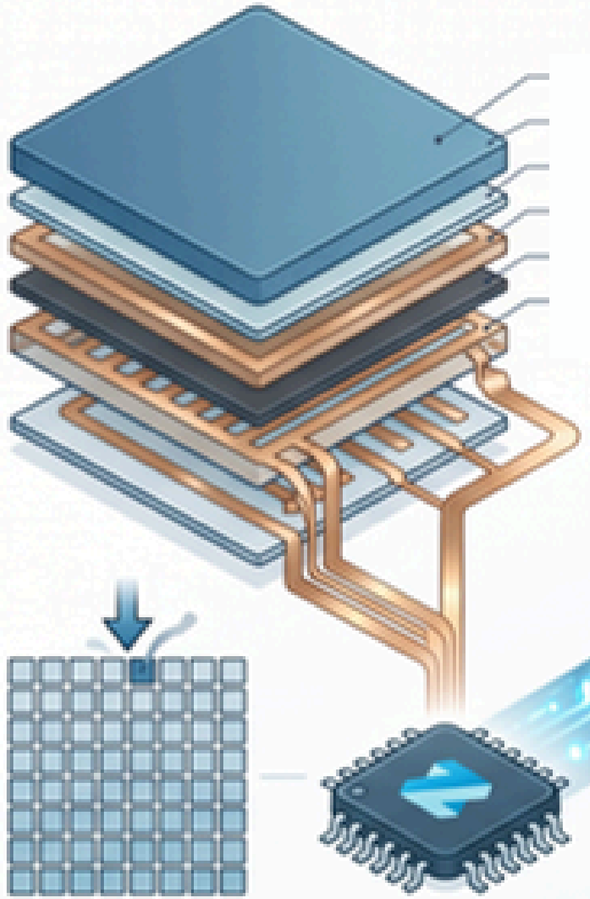
Data leakage

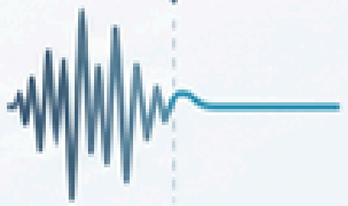
When the multiplexer switches from one cell to the next, the previous reading briefly leaks into the new one, early data was noisy and unreliable as a result.

ACQTIME (40us)	Longer ADC acquisition window per read
Settle delay (3000us)	Time given for the mux to fully switch before sampling
2 dummy reads (80us)	Discarded reads per channel switch, to flush residual charge

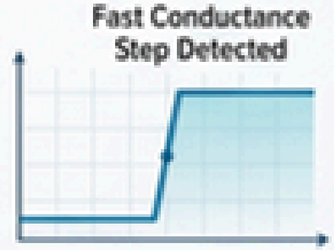


Data Journey: From Physical mat to Inventory tracking





$$N = \left(\frac{a}{R}\right)^{1/b}$$



INVENTORY UPDATED:
ITEM ADDED/REMOVED

1. DATA ACQUISITION

12 mm copper electrodes & Velostat core. Reads 64-cell grid via multiplexers.

nRF52833 Controller (Cycles TMUX1208 MUXs)

2. WIRELESS TRANSMISSION

Broadcasts 64 raw resistance values without continuous power-heavy connections.

3. SIGNAL RECEPTION

Python-based receiver continuously scans and decodes advertising payload in real time (using Bleak library).

4. SIGNAL PROCESSING & FILTERING

Applies per-cell idle baseline filter. Accounts for large resistance variance (approx. 6,872–19,270Ω).

5. DATA ANALYSIS

Raw resistance converts to conductance ($\sum G = \sum 1/R$). Power-law equation transforms electrical signals into weight-based estimates.

6. INVENTORY DECISION

Detects discrete **ADD** or **REMOVE** events. Distinguishes fast steps from slow Velostat creep drift.

How long is the MCU actually awake?

239.6 ms active

238.08 ms scan + 1.53 ms broadcast, once per 5 s cycle

4.79% duty cycle

MCU asleep ≈95.2% of every 5 s cycle

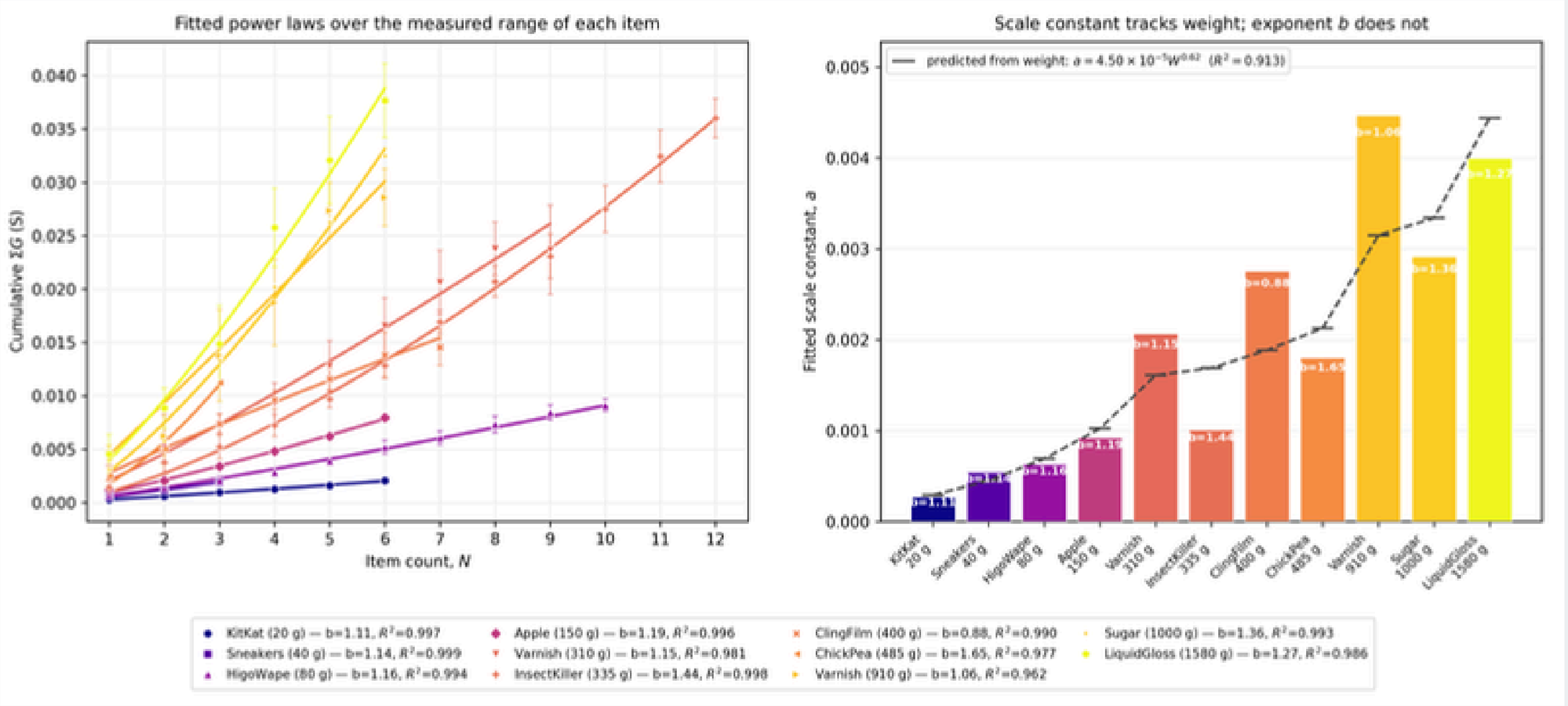
mostly idle, well suited to indoor solar harvesting between scans.

Boradcast time estimated from BLE extended-advertising PHY timing - 1M PHY single packet

RESULTS & ANALYSIS

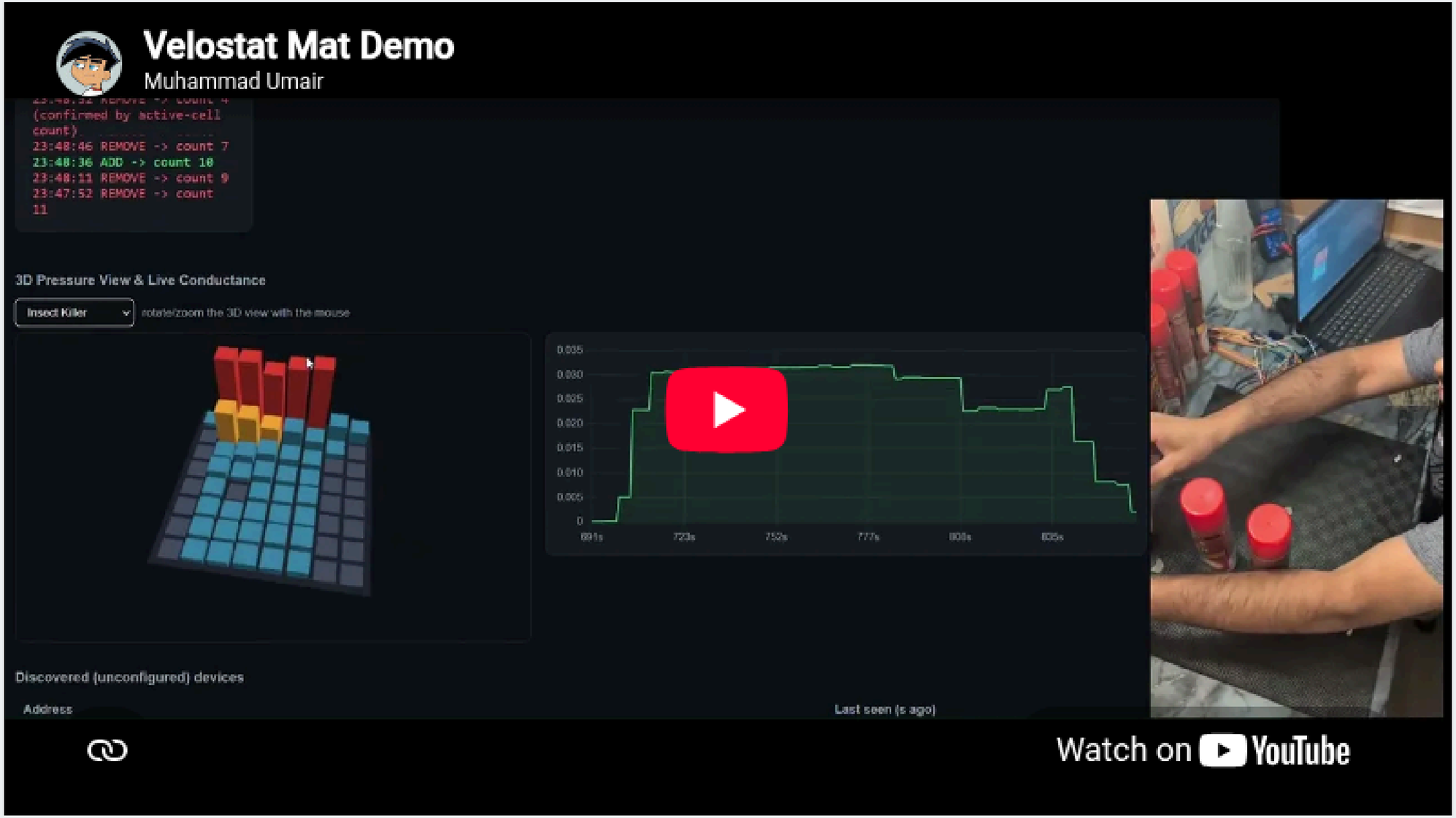
Calibration across 11 item types, 20g to 1.5kg

Each item type gets its own fitted power-law curve, $\Sigma G = a \cdot N^b$. Scale constant a tracks weight predictably across types — but exponent b depends on contact geometry, so curves cannot be shared between items even at similar weight.



Demo Video

Youtube link



HONEST ASSESSMENT

What's not solved yet

Occasional resync failures

Rare, but not yet eliminated under **fast sequential events**.

Off-by-one miscounts

Edge cases at the boundary between two **closely-timed events**.

Extrapolation error

Accuracy drops beyond the calibrated **count range**.

Root cause: small-trial calibration with only 10 data points per item. More trials across a wider count range are needed before TinyML training begins — this is the immediate next step.

PROGRESS TO DATE — WEEKS 1-9

Where the project stands now

- ✓ 8x8 mat built and characterised; Foam-Foam construction selected from a 4-way comparison
- ✓ MUX crosstalk resolved through timing and settling fixes
- ✓ Full classical pipeline implemented: conductance summation, power-law calibration, adaptive event detection
- ✓ Six item types calibrated (20g-1kg) with per-item calibration curves
- ✓ Problem reframed from weight regression to discrete event detection — validated against creep behaviour
- ✓ Dissertation draft; weekly reports submitted to supervisor throughout

WHAT'S NEXT

From classical baseline to TinyML correction

The classical pipeline is the functional baseline. The next phase trains an Edge Impulse model to correct Velostat's nonlinearity on top of it.

Data to collect

Full 64-cell grid snapshots over time, timestamped against manually logged ADD / REMOVE / NO-EVENT ground truth.

Coverage needed

Repeated trials across the full count range, varied placement speed and position, and substantial pure-creep examples.

Deployment target

Edge Impulse model correcting nonlinearity on-device, alongside the existing classical calibration.

TIMELINE

Path to submission

May
Setup & literature

Jun
Hardware + classical pipeline

Jul
Calibration, event detection, reframing

Early Aug (Now)
Data collection & Calibrated

Mid Aug
Write-up & final submission

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Thank you

Questions welcome.

Muhammad Umair
github.com/Erorre-AI/Battery-Free-Velostat-Smart-Mat