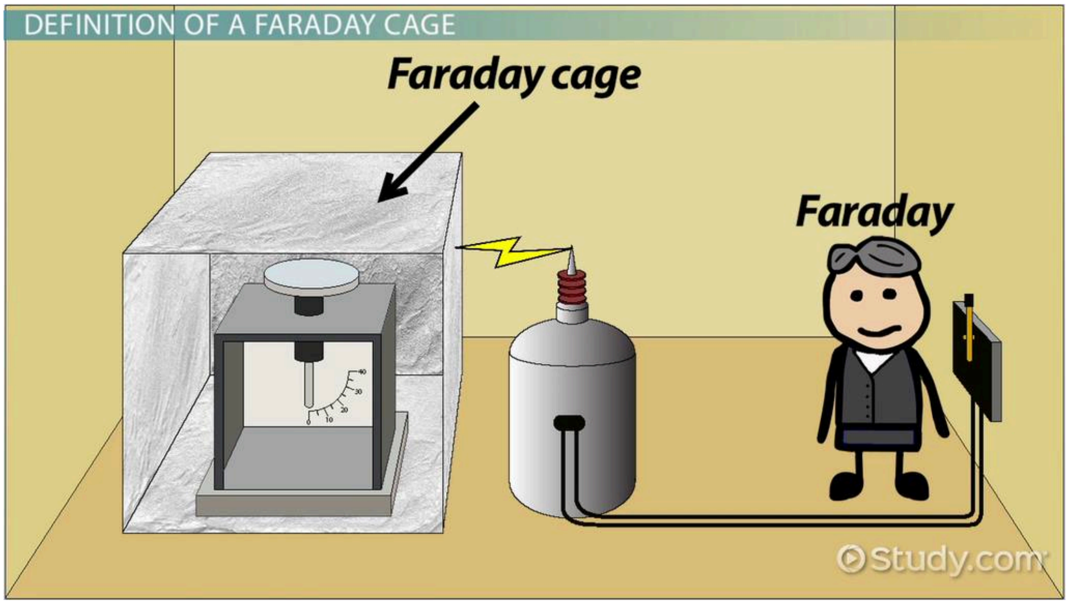
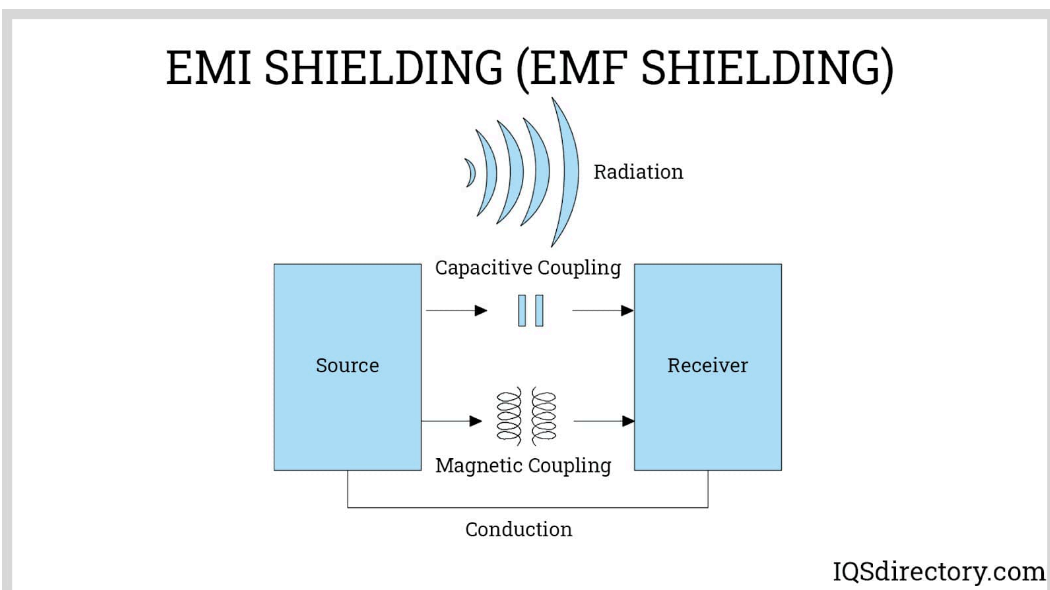
FARADAY CAGE WITH ACTIVE TEMPERATURE CONTROL AND LIGHT/UV MONITORING

Introduction:





Modern electronic and optical experiments require an environment that is free from electromagnetic interference (EMI), radio-frequency (RF) noise, and ambient optical disturbances (UV–IR light). The goal of this project is to design a Faraday cage–based controlled experimentation chamber that:

- Blocks external RF and EM waves
- Blocks UV–IR light to eliminate optical interference

- Maintains stable temperature using TEC-based PID control
- Monitors and logs temperature, humidity, and light intensit
- Ensures safe, reliable, and interference-free operation

This chamber is designed for experiments requiring precision measurements, sensor calibration, and noise-free electronics operation, as described in the Introduction slides of the Faraday Cage report.

The main challenges identified across Eval-1 and Eval-2 were:

1. Preventing all external EM radiation from entering the box
2. Ensuring no internal radiation escapes
3. Maintaining a user-defined temperature reliably
4. Preventing UV–IR light leakage
5. Stabilizing the system without damaging the TEC
6. Providing web-based monitoring and control
7. Ensuring safe cable routing without creating EM leakage paths

This combined requirement evolved significantly from our initial designs.

Evolution Across Evaluations:

Evaluation-1:

The earliest design focused on studying the basic Faraday cage principle, the behavior of electric fields inside conductors, and general EM shielding requirements.

Key learning:

- Electric fields cancel internally due to surface charge redistribution
- Magnetic field shielding requires continuous conductive surfaces
- Wire connections must not break shielding continuity

Evaluation-2:

We built the full-mathematical model in this.
TEC Step response experiments:
Step input change in voltage and its corresponding change in temperature is mapped every 15 minutes.
Extracted Thermal models:

From experiments:

- $\Delta T = -1.94°C$
- $\Delta I = 0.184$ A
- **Gain:**

$$K = -10.54 \frac{^{\circ}C}{A}$$

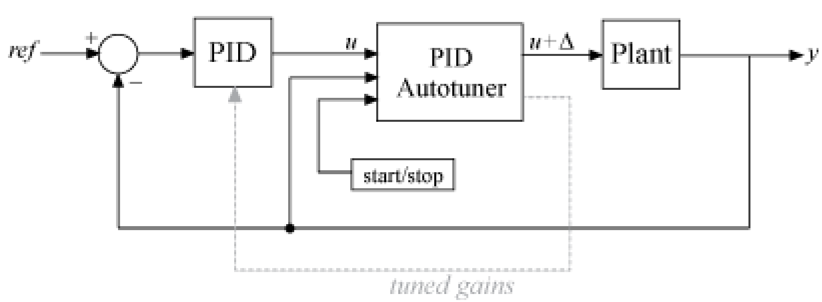
- **Time constant:**

$$\tau \approx 63.8 \text{ s}$$

- **Transfer function:**

$$G(s) = \frac{-10.54}{63.8s + 1}$$

PID Auto-Tuning Using MATLAB/Simulink



Auto-tuning produced baseline values for:

- Kp
- Ki
- Kd

This stage was successful theoretically, but several practical problems emerged.

Why Mathematical Modelling Failed in Practice

1. TEC system is nonlinear
2. Behavior changes with temperature, load, and conduction paths.
3. Multiple TECs → Model invalid
4. Your model assumes 1 TEC; final system has 4 TECs in parallel.
5. Enclosure heat capacity changes dynamically
6. Sensor inaccuracies (TMP36 nonlinearity)
7. You later had to switch to polynomial calibration.
8. PWM → current spikes → model breaks
9. H-bridge characterization showed PWM switching caused:
10. Current surges
11. TEC overheating
12. Waveform distortion

These experimental findings (from our mid-eval presentations) make it clear: A mathematical model cannot reliably control the real system.

Evaluation-3: (Final practical stratergy + Ziegler-Nicholas Control)

This stage represents the refined and realistic engineering solution.
ZN is experiment-driven, not model-driven.

It uses actual system oscillations, making it ideal for:

- nonlinear thermal systems
- TECs with dynamic heating/cooling response
- multiple TECs running in parallel
- uncertainties in conduction, insulation, airflow
- sensor noise

ZN tuning simply requires measuring:

- Ultimate gain (Ku)
- Ultimate period (Pu)

Thus, ZN bypasses all weaknesses of the Eval-2 mathematical model. This final strategy is the most robust and experimentally validated.

Why Ziegler–Nichols (ZN) Was Necessary

ZN is robust because:

- It only requires observing oscillations, not modelling physics
- It adapts to nonlinear systems
- It gives real-world stable Kp, Ki, Kd

- It handles delays, temperature inertia, and noise
- It automatically compensates for changing thermal loads

ZN tuning was validated through oscillation plots and automatic parameter detection

Therefore:
Shifting from mathematical modelling → ZN tuning was not only logical but essential for ensuring practical stability.

Experimental Characterisation:

H-Bridge Characterisation

We measured:

- Current vs PWM
- Frequency components
- Effects of rapid polarity switching
- Thermal stress on TEC

Finding:

- Linear PWM–current relation
- Rapid polarity switching = high power loss + TEC damage risk
- Must avoid using H-bridge like a motor driver
- Use it only to set direction, not high-frequency switching

TEC Characterisation:

Experiments included:

- Free-air TEC test
- TEC with water-cooled heatsink
- Cold-side/hot-side step response
- Voltage → temperature mapping

Results:

- Without heatsink, TEC overheats rapidly
- With water-cooled sink, temperatures drop much lower
- PID must respect the TEC thermal limits
- Time response is slow → first order model works only in small regions
- Real system needs ZN + delay protection

Temperature Sensor Calibration:

The TMP36 was not linearly accurate:

- Offset varied with temperature
- Required polynomial regression

Final calibration equation

$T=-0.0104x^2+1.7907x+2.6407$

This gave very accurate values for $T < 40°C$.

Final System Architecture

Mechanical Construction:

- 20×20×20 cm aluminium enclosure (natural Faraday cage)
- PIR foam for thermal insulation
- Copper sheet lining for additional RF shielding
- Single wire port surrounded by gasket to prevent RF leakage
- Four TEC modules mounted on four vertical sides
- Heatsinks on the external hot sides
- UV + visible light sensor inside for optical integrity monitoring

Electronics System:

Components

- ESP32 microcontroller
- BTS7960 H-bridge
- TEC1-12706 modules × 4
- RC low-pass filter
- TMP36 temperature sensor
- BH1750 / generic LDR for light measurement

- UV sensor module
- 12 V 10 A power supply

Control Flow

1. Sensors monitored every 1 second
2. PID control computes output
3. Direction decided by error sign
4. PWM sent through RC filter
5. H-bridge switches polarity only when needed
6. Web UI updates via ESP32 (through thingspeak for temperature monitoring)

Light + UV + RF Shielding Justification. To enhance the scientific usability:

UV/Visible Light Sensors

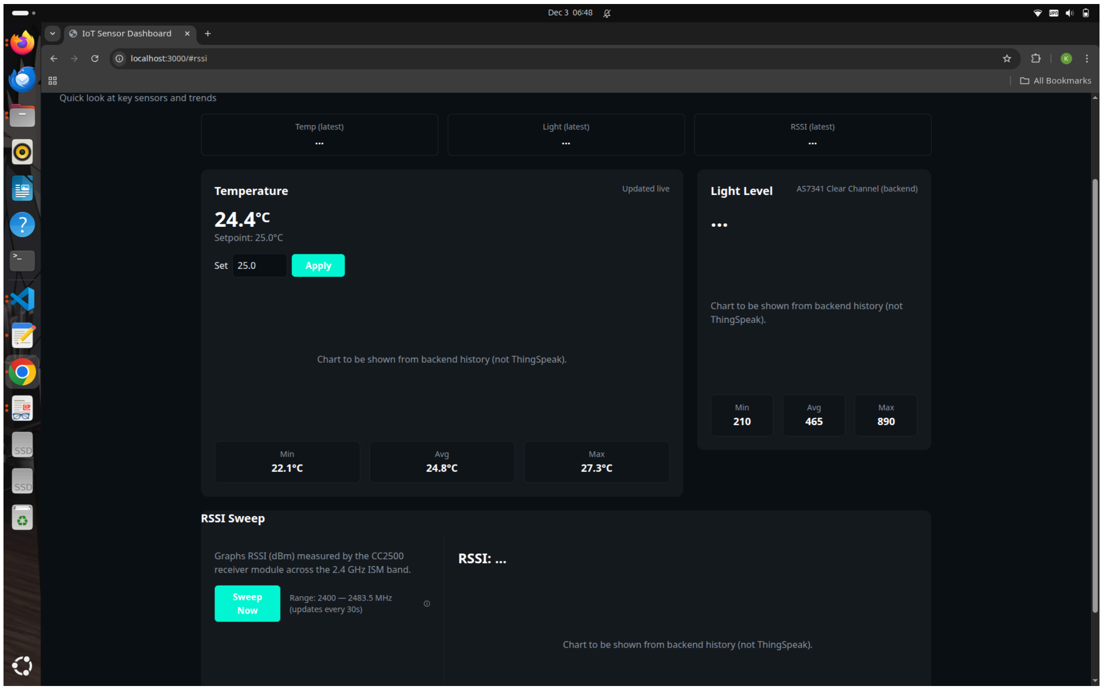
- Detect optical leakage
- Validate PIR insulation completeness
- Avoid measurement noise for optical experiments

RF Shielding Enhancements

- Copper tape lining
- Ferrite beads for all wires
- Single gland output instead of multiple drill holes

These measures ensure the cage behaves as a complete electromagnetic isolation chamber.

Website Integration:



- Real-time dashboard
- Setpoint entry
- Live temperature, light values

Final Summary & Conclusion

This project progressed from a conceptual Faraday cage to a full-fledged controlled environment chamber incorporating:

- Robust EMI and RF shielding
- Full thermal regulation using PID + ZN tuning
- TEC management with safe polarity switching & RC filtering
- Accurate TMP36 calibration
- Integrated UV + visible light monitoring
- Comprehensive hardware + software architecture

Through three evaluation phases, we resolved:

- TEC overheating
- PWM current spikes

- Sensor non-linearity
- Poor insulation placement
- Multi-wire leakage problems

The final system is scientifically reliable, experimentally validated, and ready for advanced testing and characterization.