In-Depth Technical Analysis of a Modular PCB Design:
Arduino Nano + MPU-9250 + Power Regulation + LED Control

Task 8

May 17, 2025

1 Project Overview

This document presents a compartmentalized, real-world design and analysis of a modular embedded system powered by a 3S Li-ion battery pack. It includes:

- Voltage regulation using LM2596T-5 and AMS1117-3.3
- Microcontroller: Arduino Nano v3
- Sensor: Raw MPU-9250 IMU using I2C
- Level shifting using BSS138 N-MOSFETs
- GPIO-driven LEDs

Each section provides detailed justifications for component selection, placement, values, and electrical interactions — optimized for stability, compatibility, and manufacturability.

2 Power Supply: 3S Battery Pack to LM2596T-5 Buck Regulator

2.1 Battery Selection and Voltage Profile

The circuit is powered by a 3-cell (3S) Li-ion battery pack composed of 18650 cells. Each cell has a nominal voltage of 3.7 V and a full charge voltage of 4.2 V. Thus:

$$V_{\text{nominal}} = 3 \times 3.7\,\text{V} = 11.1\,\text{V} \qquad V_{\text{max}} = 3 \times 4.2\,\text{V} = 12.6\,\text{V}$$

This voltage is too high for direct use with 5 V logic. Hence, a switching voltage regulator is necessary.

2.2 LM2596T-5 Overview

The LM2596T-5 is a fixed 5 V, 3 A step-down (buck) converter operating at 150 kHz. It provides:

- High efficiency (70–85%)
- Simple design (requires few external components)
- Adequate current capability for microcontroller + sensor + LEDs

2.3 Input Stage

- **Fuse F1**: Protects against short circuits or overcurrent. Selected based on max expected current draw (usually 1–2 A).
- **C4, C8**: 220 μF electrolytic + 0.1 μF ceramic: filters high-frequency switching noise and battery ripple.

2.4 Output Stage

- **C2, C9**: Again 220 μF + 0.1 μF combination filters output ripple to maintain a steady 5 V for sensitive loads like microcontrollers.
- **ON/OFF Pin**: Tied to GND to keep the regulator always enabled.
- **FB Pin**: Left floating because it is unused in fixed-output versions.

2.5 Why a Buck Regulator?

Linear regulators (like 7805) would waste significant power as heat:

$$P_{\text{loss}} = (V_{\text{in}} - V_{\text{out}}) \times I = (11.1\,\text{V} - 5\,\text{V}) \times 0.5\,\text{A} = 3.05\,\text{W}$$

Buck regulators like LM2596 maintain efficiency by switching, not dissipating.

3 Microcontroller Power: Arduino Nano

3.1 Power Supply Considerations

The Arduino Nano operates at 5 V logic and has two main power input options:

- **VIN Pin:** Accepts unregulated input (7–12 V), passed through onboard AMS1117-5.0 linear regulator
- **5V Pin:** Accepts regulated 5 V directly (bypasses onboard regulator)

In this design, we power the Nano via its `5V` pin, using the output of the LM2596T-5 buck converter. This ensures:

- Higher efficiency (bypasses a second regulator)
- Less heat dissipation
- Reduced voltage ripple due to external capacitor filtering

3.2 Grounding

The `GND` pin of the Nano is tied to the common ground shared by the LM2596, AMS1117-3.3, and all peripherals. A star-grounding pattern or solid plane is ideal in layout.

3.3 Decoupling Capacitor

- **C5 (0.1 μF)**: Placed physically close to the Nano's 5V pin
- Purpose: Bypasses high-frequency noise, ensures stable logic operation

3.4 Why Decoupling is Needed

Any high-speed digital IC like a microcontroller causes brief, high-current pulses on the supply rail due to internal gate switching. These cause voltage dips (transients) unless mitigated. A 0.1 μF ceramic capacitor acts as a fast-response local reservoir.

$$I = C\frac{dV}{dt} \Rightarrow \text{Small C, small distance = fast compensation}$$

4 3.3V Regulation for MPU9250

4.1 Why a Separate 3.3V Regulator is Needed

The MPU-9250 is a 3.3 V device. Its core voltage `VDD` and I/O voltage `VDDIO` must be held within 3.0–3.6 V for proper function and to prevent damage.

4.2 Regulator Used: AMS1117-3.3

This is a popular, low-cost linear LDO (Low Dropout) regulator. Key specs:

- Fixed 3.3 V output
- Dropout voltage: typically 1.1 V
- Max current: 800 mA

4.3 Voltage Drop Consideration

Since the input is 5 V (from LM2596), and AMS1117 requires 1.1 V headroom:

$$V_{\text{in}} - V_{\text{out}} = 5.0\,\text{V} - 3.3\,\text{V} = 1.7\,\text{V}$$

This is sufficient for stable operation, with room for ripple or minor dropouts.

4.4 Output Capacitors

- **C6 (10 μF Electrolytic)**: Prevents output instability by lowering impedance at low frequencies
- **C7 (0.1 μF Ceramic)**: Filters high-frequency noise

4.5 Thermal Consideration

Power dissipated:

$$P = (V_{\text{in}} - V_{\text{out}}) \times I = 1.7\,\text{V} \times 0.05\,\text{A} = 85\,\text{mW}$$

Well within safe thermal limits without heatsink for small loads like MPU9250.

4.6 Why Not Use Nano's 3.3V Pin?

The Nano's onboard 3.3V regulator can supply only 50 mA — marginal or unsafe for MPU9250 which can peak above that under certain motion modes.

5 MPU-9250 IMU Integration

5.1 Introduction

The InvenSense MPU-9250 is a 9-DOF (Degrees of Freedom) MEMS sensor integrating:

- A 3-axis accelerometer
- A 3-axis gyroscope
- A 3-axis magnetometer

In this project, the raw IC version (not breakout board) is used, requiring full manual power, decoupling, and logic-level design.

5.2 I^2C Communication

The MPU-9250 communicates via I^2C protocol. Key pins:

- **SCL**: Serial clock
- **SDA**: Serial data

5.3 Address Selection

The device's 7-bit I^2C address is set by the logic level of the `AD0` pin:

- `AD0` = GND ⇒ Address = 0x68 (default)
- `AD0` = HIGH (3.3 V) ⇒ Address = 0x69

5.4 Power Pins

- **VDD** and **VDDIO**: Both connected to regulated 3.3 V from AMS1117
- **GND**: Connected to system ground
- **REGOUT**: Left floating or decoupled with 0.1 μF (not needed if VDD is already 3.3 V)

5.5 Unused Pins

- **AUX_DA, AUX_CL, FSYNC, INT**: Can be tied to GND or pulled to specific GPIO if interrupts are used.
- **RESV_***: Reserved pins — tie to GND or leave floating as per datasheet.

5.6 Bypass Capacitor

- **C10 (0.1 μF)** between VDD and GND near the MPU9250
- Purpose: Stabilizes local power rail, reduces sensor glitches due to current draw on motion bursts

5.7 I^2C Pull-up Resistors

- **R1, R2 (4.7 kΩ)** between SDA/SCL and 3.3 V
- Reason: I^2C is an open-drain protocol; pull-ups are needed to bring lines HIGH

5.8 Why Raw Sensor Over Breakout Module?

- Full control over layout and decoupling
- Lower BOM cost in large runs
- Teaches signal-level interfacing and protection techniques

6 Level Shifting: BSS138 MOSFET-Based Bidirectional Logic Interface

6.1 The Problem

The Arduino Nano uses 5 V logic, while the MPU9250 operates at 3.3 V logic. Direct connection may:

- Exceed MPU's absolute maximum input voltage
- Cause undefined behavior or permanent damage

6.2 Why Not a Voltage Divider?

Voltage dividers are unsuitable for high-speed signals like I^2C due to:

- Lack of drive strength
- Slower rise/fall times
- Unidirectionality

6.3 The Solution: BSS138 Level Shifting Circuit

Each line (SDA, SCL) passes through a BSS138 MOSFET wired as a bidirectional level shifter.

6.4 How It Works (Circuit Description)

- **Gate (G)** connected to GND
- **Source (S)** connected to 5 V side (e.g., Arduino A4/A5)
- **Drain (D)** connected to 3.3 V side (MPU)
- **Pull-up resistors** on both sides

Principle: When the Arduino side pulls SDA low, the MOSFET turns on due to $V_{gs} > V_{th}$ and pulls the 3.3 V side low. When no pull-down is active, the pull-up resistors on each side restore HIGH logic level independently.

6.5 Why BSS138?

- Low threshold voltage ($V_{th} \approx 1.3\,\text{V}$)
- Logic-level operation at 3.3 V
- Widely used in commercial I^2C level-shifter modules

6.6 Limitations

- Slight delay due to MOSFET switching
- Works well for up to 400 kHz I^2C; less ideal for faster standards