CALIBRAZIONE MAGNETOMETRO

In magnetometers, **hard iron** and **soft iron distortions** are two types of magnetic interference that can affect the accuracy of magnetic field readings. Here's how they differ:

Non è necessario raccogliere nuovi campioni per compensare il soft iron rispetto all'hard iron. Gli stessi campioni usati per correggere l'errore di hard iron possono essere usati anche per il soft iron. La raccolta di dati in diverse orientazioni del magnetometro è sufficiente per entrambi i tipi di compensazione.

1. Hard Iron Distortion

- **Cause:** Hard iron distortion is caused by permanent magnetic materials or components that create a constant, unchanging magnetic field around the magnetometer. This includes objects like magnets or certain metals with a permanent magnetic field near the sensor.

- **Effect on Magnetometer**: This type of distortion creates a **constant bias** in the magnetic readings, meaning it offsets the field readings in a fixed direction. The interference is the same regardless of the magnetometer's orientation.

- **Correction**: Hard iron distortion is typically corrected by **calibration** procedures that measure and subtract the offset. This is often done by rotating the magnetometer in multiple orientations and finding the fixed offset in each axis.

2. Soft Iron Distortion

- **Cause:** Soft iron distortion is caused by ferromagnetic materials that are not themselves magnetized but can temporarily distort the magnetic field when they are close to the magnetometer. Examples include metals like iron or steel, which become magnetized when exposed to an external magnetic field.

- **Effect on Magnetometer**: Soft iron distortion creates a **direction-dependent distortion** in the magnetic field readings. Unlike hard iron distortion, soft iron distortion varies based on the relative position and orientation of the sensor to the interfering material.

- **Correction**: Soft iron distortion is typically corrected using **matrix transformations** that model the distortion based on the field's direction. Calibrating for soft iron distortion is more complex, as it requires measuring how the magnetic field is skewed and scaling it accordingly.

1. Preparazione delle misurazioni

Assicurati che il magnetometro possa raccogliere dati grezzi (X, Y, Z) in tempo reale. Durante la calibrazione, è importante muovere il dispositivo su più assi (X, Y, Z) per raccogliere un'ampia gamma di dati.

2. Raccolta dei dati in più orientamenti

Devi raccogliere dati dal magnetometro muovendo l'oggetto su cui è montato in tutte le direzioni. Questo passaggio serve a campionare il campo magnetico in tutte le posizioni possibili.

- Ruota il magnetometro in modo casuale, cercando di coprire il più possibile tutte le angolazioni (idealmente ruotalo su sfere o ellissi tridimensionali).

- Raccogli un numero significativo di misurazioni di X, Y e Z in ciascuna di queste posizioni.

L'output dovrebbe essere una nuvola di punti che rappresentano le letture del campo magnetico in uno spazio tridimensionale.

3. Correzione dell'errore di hard iron

L'errore di **hard iron** si manifesta come uno spostamento del centro della nuvola di punti rispetto all'origine (0, 0, 0). Questo significa che il campo magnetico percepito è traslato rispetto a quello reale.

Procedura:

- Trova il centroide della nuvola di punti. Questo rappresenta l'offset causato dall'errore di hard iron.

$$\text{offset}_x = \frac{X_{\max} + X_{\min}}{2}$$
$$\text{offset}_y = \frac{Y_{\max} + Y_{\min}}{2}$$
$$\text{offset}_z = \frac{Z_{\max} + Z_{\min}}{2}$$

- Sottrai questo offset dai valori di X, Y e Z per correggere l'errore di hard iron.

$$X_{\text{corretto}} = X_{\text{grezzo}} - \text{offset}_x$$
$$Y_{\text{corretto}} = Y_{\text{grezzo}} - \text{offset}_y$$
$$Z_{\text{corretto}} = Z_{\text{grezzo}} - \text{offset}_z$$

4. Correzione dell'errore di soft iron

L'errore di **soft iron** distorce la nuvola di punti, facendola apparire come un'ellissoide anziché una sfera perfetta. Questo accade perché i materiali vicini causano variazioni di scala differenti lungo i tre assi.

Procedura:

- Dopo aver corretto per l'hard iron, avrai una nuvola di punti centrata sull'origine, ma con una forma ellissoidale.
- Per correggere l'errore di soft iron, devi "trasformare" l'ellissoide in una sfera. Questo si fa attraverso la normalizzazione delle scale lungo gli assi X, Y e Z.

Formula for Soft Iron Calibration:

The soft iron calibration requires the application of a **scaling matrix** to the hard iron-calibrated readings. The formula for soft iron correction is:

$$\begin{pmatrix} \mathrm{X}_{\text{final}} \\ \mathrm{Y}_{\text{final}} \\ \mathrm{Z}_{\text{final}} \end{pmatrix} = \mathbf{S} \cdot \begin{pmatrix} \mathrm{X}_{\text{calibrated}} \\ \mathrm{Y}_{\text{calibrated}} \\ \mathrm{Z}_{\text{calibrated}} \end{pmatrix}$$

where $\mathbf{S}$ is the **soft iron correction matrix**. This matrix compensates for the scaling and skewing caused by soft iron distortions.

In practice, $\mathbf{S}$ can be calculated as:

$$\mathbf{S} = \mathbf{C}^{-1} \cdot \mathbf{M}^{-1}$$

where:

- $\mathbf{C}$ is a **scaling matrix** that normalizes the ellipsoid along each axis.
- $\mathbf{M}$ is a **rotation matrix** that accounts for the misalignment between the magnetometer's axes and the reference coordinate system.

A simplified version is to scale each axis independently, if you assume no cross-axis interference (i.e., $\mathbf{M}$ is the identity matrix):

$$\mathrm{X}_{\text{final}} = \frac{\mathrm{X}_{\text{calibrated}}}{\text{Scale}_X}$$
$$\mathrm{Y}_{\text{final}} = \frac{\mathrm{Y}_{\text{calibrated}}}{\text{Scale}_Y}$$
$$\mathrm{Z}_{\text{final}} = \frac{\mathrm{Z}_{\text{calibrated}}}{\text{Scale}_Z}$$

$$\text{scale}_x = \frac{2}{X_{\max} - X_{\min}}$$

$$\text{scale}_y = \frac{2}{Y_{\max} - Y_{\min}}$$

$$\text{scale}_z = \frac{2}{Z_{\max} - Z_{\min}}$$

Moltiplica ogni coordinata X, Y e Z per i relativi fattori di scala calcolati sopra.

$$X_{\text{calibrato}} = X_{\text{corretto}} \times \text{scale}_x$$

$$Y_{\text{calibrato}} = Y_{\text{corretto}} \times \text{scale}_y$$

$$Z_{\text{calibrato}} = Z_{\text{corretto}} \times \text{scale}_z$$

Steps for Soft Iron Calibration

1. **Calculate Scaling Factor for Soft Iron Calibration:** The **soft iron scaling factor** normalizes the range of the magnetometer readings for each axis. The scaling factor is calculated based on the maximum and minimum values of each axis. This ensures that the magnitude of the magnetic field in each direction is consistent.

   For the X-axis, the **soft iron scaling factor** is calculated as:

   $$\text{Scale}_X = \frac{\text{average range of all axes}}{\text{range of the X-axis}}$$

   Where the range for the X-axis is:

   $$\text{Range}_X = \frac{X_{\max} - X_{\min}}{2}$$

   The average range of all axes (assuming you have max and min values for the Y and Z axes) can be calculated as:

   $$\text{Average Range} = \frac{(\text{Range}_X + \text{Range}_Y + \text{Range}_Z)}{3}$$

   If we only consider the X-axis for simplicity, we can calculate the **soft iron scaling factor** for X based on the observed range.

2. **Apply the Soft Iron Calibration Formula:** Once you have the scaling factor for each axis, apply the scaling to the previously **hard iron and sensitivity-adjusted** values.

Example with X-Axis Data

Given:

- $X_{\text{max}} = 300$
- $X_{\text{min}} = -120$

1. **Calculate the X-Axis Range:** The range for the X-axis is:

$$\text{Range}_X = \frac{X_{\text{max}} - X_{\text{min}}}{2}$$

Substituting the values:

$$\text{Range}_X = \frac{300 - (-120)}{2} = \frac{300 + 120}{2} = \frac{420}{2} = 210$$

Let's assume the Y **and Z ranges** are close to this value (say, 220 and 200). The **average range** of all three axes would be:

$$\text{Average Range} = \frac{210 + 220 + 200}{3} = \frac{630}{3} = 210$$

For simplicity, we are using an average value equal to the X-axis range. In real applications, the Y and Z values could differ more significantly.

2. **Apply the Soft Iron Scaling:** For the X-axis:

$$X_{\text{final}} = \frac{X_{\text{adjusted}}}{\text{Range}_X} \times \text{Average Range}$$

Given that the **average range** is equal to the X-axis range in this example, the scaling factor is effectively 1, so the soft iron adjustment does not significantly change the result in this specific case.

However, if the Y or Z ranges were significantly different from the X-axis, this formula would correct for those discrepancies.

5. Verifica e iterazione

Una volta effettuate le correzioni di hard iron e soft iron, verifica la correttezza dei dati muovendo nuovamente il magnetometro in tutte le direzioni. Le misurazioni corrette dovrebbero ora formare una sfera attorno all'origine, indicando che il magnetometro è calibrato correttamente.

In sintesi

1. **Misura il campo magnetico** in tutte le direzioni muovendo il dispositivo.
2. **Correggi l'hard iron** sottraendo l'offset.
3. **Correggi il soft iron** scalando le letture per rendere sferica la nuvola di punti.

Non è necessario conoscere la posizione finale del magnetometro, poiché la calibrazione si basa su misurazioni relative.

l magnetometro **AK8963**, integrato nel sensore **MPU9250**, ha un parametro chiamato **"Sensitivity Adjustment"** (regolazione della sensibilità), che serve a calibrare la sensibilità del sensore in base ai valori forniti dal produttore per garantire misurazioni corrette. Questo processo è necessario perché ogni magnetometro potrebbe avere una sensibilità leggermente diversa a causa delle tolleranze di fabbricazione.

Passaggi per l'Adjustement della Sensitivity del AK8963

1. **Leggere i valori di calibrazione dalla EEPROM:** Il magnetometro AK8963 contiene valori di calibrazione univoci per ogni singolo dispositivo, memorizzati nella sua EEPROM. Questi valori vengono letti e utilizzati per calibrare le letture del magnetometro.

I valori di calibrazione sono disponibili in tre registri: **ASAX**, **ASAY** e **ASAZ** (indirizzi 0x10, 0x11 e 0x12), e rappresentano la sensibilità di ciascun asse X, Y, Z. Questi valori sono espressi in una scala da 0 a 255 e vengono utilizzati per correggere la sensibilità di ciascun asse.

2. **Convertire i valori di calibrazione:** I valori letti dalla EEPROM devono essere convertiti in un fattore di correzione utilizzando la seguente formula:

$$\text{Sensitivity Adjustment Factor} = \frac{(ASA + 128)}{256}$$

? Dove **ASA** rappresenta il valore letto da uno dei registri di calibrazione (**ASAX, ASAY, ASAZ**). Questa formula converte il valore in un fattore di scala che può essere utilizzato per correggere le letture del magnetometro.

$$\text{X\_corretto} = X\_grezzo \times \text{Sensitivity Adjustment Factor\_X}$$

$$\text{Y\_corretto} = Y\_grezzo \times \text{Sensitivity Adjustment Factor\_Y}$$

$$\text{Z\_corretto} = Z\_grezzo \times \text{Sensitivity Adjustment Factor\_Z}$$

? **Applicare la correzione alle letture del magnetometro:** Una volta ottenuti i fattori di correzione per ciascun asse (X, Y, Z), dovrai moltiplicare ogni lettura grezza del magnetometro per il fattore corrispondente.

1. Raw Data Limits (int16)

The raw data from the magnetometer is a signed 16-bit integer (**int16**), so it ranges from **-32768** to **32767**. These raw values need to be interpreted in the context of the sensor's physical range of ±4800 µT. Therefore:

- Raw data of **-32768** corresponds to **-4800 µT**.
- Raw data of **32767** corresponds to **+4800 µT**.

2. Scaling Factor for the Magnetometer

The raw data is scaled to this physical range using a scaling factor. To convert the raw data to microteslas (µT), the scaling factor is:

$$\text{Scaling factor} = \frac{4800\,\mu T}{32768} \approx 0.1465\,\mu T/\text{LSB}$$

This means that each Least Significant Bit (LSB) in the raw data corresponds to about **0.1465 µT**.

3. Applying the Sensitivity Adjustment

Now, the sensitivity adjustment values from the ASAX, ASAY, and ASAZ registers further tweak the output by a small percentage, as in the formula:

$$\text{Magnetic field (in µT)} = \text{Raw data} \times \left(\frac{(\text{Sensitivity Adjustment Value} - 128)}{256} + 1\right)$$

However, the sensitivity adjustment factors typically adjust the raw readings by just a small amount (on the order of 1% to 5%). Even with the adjustment applied, the final result must still respect the sensor's physical limits of ±4800 µT.

Example (Corrected):

Let's use your example of a raw data value of **32767** on the X-axis, and a sensitivity adjustment value of 140:

1. First, convert the raw data to microteslas using the scaling factor:

$$\text{Magnetic field (unadjusted)} = 32767 \times 0.1465\,\mu T/\text{LSB} \approx 4799.85\,\mu T$$

2. Apply the sensitivity adjustment (with ASAX = 140):

$$\text{Magnetic field (adjusted)} = 4799.85 \times \left(\frac{140-128}{256}+1\right) = 4799.85 \times 1.046875 \approx 5024.7\,\mu T$$

In this case, the value **5024.7 µT** exceeds the sensor's physical limit of **4800 µT**, indicating saturation.

4. Saturation

When the raw data approaches or exceeds the limits of ±32768, the sensor is **saturated**, and it cannot accurately measure magnetic fields beyond ±4800 µT. In this case, the readings are capped at the maximum range (±4800 µT), and any adjustment beyond that limit would be invalid.

Key Takeaways:

- **Raw data values near ±32767** indicate that the sensor is near or at its measurement limits of **±4800 µT**.
- The maximum measurable magnetic field strength is **4800 µT**, so even after applying the sensitivity adjustment, the final output must not exceed this value.
- In practice, if you see raw values near the maximum or minimum, the sensor is likely saturated, and you can't trust values beyond the physical limit.

After performing the **hard iron** and **soft iron** calibration and sensitivity adjustment, you need to multiply the final sensor reading by this sensitivity value to convert the reading into **µT** (microteslas), which represents the actual magnetic field strength in the real world.

Formula to Convert LSB to µT:

$$\text{Magnetic Field}(\mu T) = \text{Final Calibrated Value (LSB)} \times \text{Sensitivity } (\mu\text{T/LSB})$$

For the MPU9250, the sensitivity is **0.15 µT/LSB.**

Example of Applying the Sensitivity Value:

Let's continue with the example we've been working through.

Assume after hard iron, soft iron, and sensitivity adjustment, you have a **final calibrated value** for the X-axis of:

$$X_{\text{final}} = 71.25\,\text{LSB}$$

Now, convert this value to microteslas (µT) using the sensitivity value:

$$X_{\text{final}}(\mu T) = X_{\text{final}}(\text{LSB}) \times 0.15\,\mu T/\text{LSB}$$

Substitute the value:

$$X_{\text{final}}(\mu T) = 71.25 \times 0.15 = 10.6875\,\mu T$$

So, the actual magnetic field strength on the X-axis after full calibration and conversion is approximately **10.69 µT**.

When to Apply the Sensitivity:

1. **Perform all calibration steps** (hard iron, soft iron, and sensitivity adjustment using `ASA` values).
2. **Convert the final calibrated value (in LSB)** to µT using the sensitivity value of **0.15 µT/LSB.**

$$gimuNew[k_{imu}].magvalue[i] = (int16)\left(\left(\left(\frac{(float)gimuNew[k_{imu}].magvalue[i] - offset[k_{imu}][i]}{scale[k_{imu}][i]}\right)\right) * sensitivity * factor[k_{imu}][i] * avg[k_{imu}]\right);$$

$$avg[k_{imu}] = \frac{scale[k_{imu}][0] + scale[k_{imu}][1] + scale[k_{imu}][2]}{3};$$

$$sensitivity = 0{,}1495\ uT/LSB$$

$$scale[k_{imu}][i] = \frac{(Magmaxval[k_{imu}][i] - Magminval[k_{imu}][i])}{2}$$

$$offset[k_{imu}][i] = \left(\frac{Magmaxval[k_{imu}][i] + Magminval[k_{imu}][i]}{2}\right);$$ for MPU9250

$$offset[k_{imu}][i] = 0;$$ for LIS2MDL

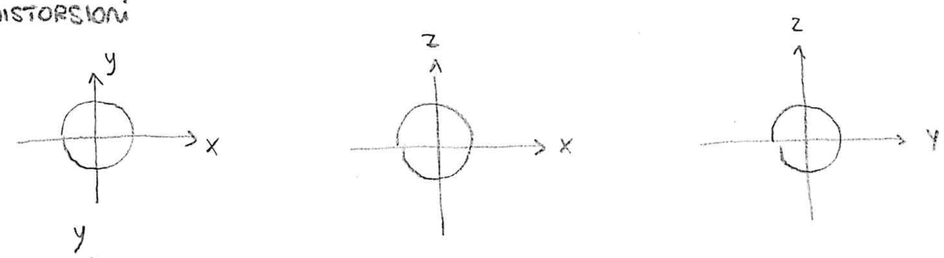
$$factor[k_{imu}][i] = \frac{((float)MagCal[k_{imu}][i]+128)*1.0}{256};$$ for MPU9250

$$factor[k_{imu}][i] = 1;$$ for LIS2MDL

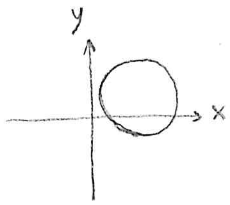
i = asse

k_imu = numero imu

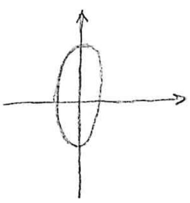
PLOTTARE IN 2D LE MISURAZIONI fatte con il magnetometro permette di individuare DISTORSIONI



NO DISTORTION

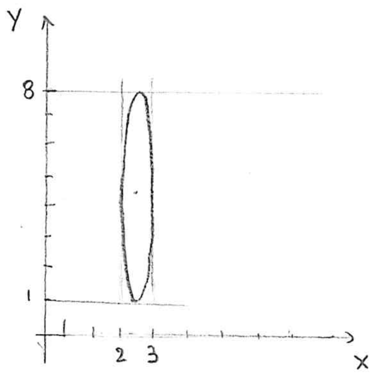


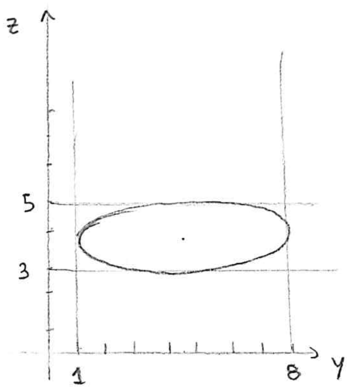
HARD IRON DISTORTION
- spherical shape
- offset from 0

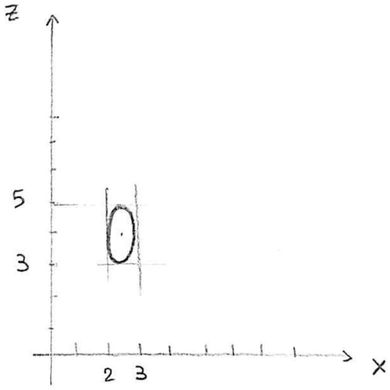


SOFT IRON DISTORTION
- NO SPHERICAL shape (ELLIPSOID)

ESEMPIO







XMAX = 3
XMIN = 2
$OFF_X = (3+2)/2 = 2.5$ centro
$SCALE_X = (3-2)/2 = 0.5$ raggio x

YMAX = 8
YMIN = 1
$OFF_y = (8+1)/2 = 4.5$
$scale_y = (8-1)/2 = 3.5$

ZMAX = 5
ZMIN = 3
$OFF_z = (5+3)/2 = 4$
$scale_z = (5-3)/2 = 1$

AVERAGE $= (0.5 + 3.5 + 1)/3$ raggio medio

$X_{calibrato} = \dfrac{X - OFF_X}{scale_x} \cdot Average$ (x sensitivity x sensitivity adjustment)