HANOI UNIVERSITY OF SCIENCE AND TECHNOLOGY

PROJECT I

DESIGN A NAVIGATION SYSTEM FOR A PERMANENT MAGNET USING A HALL SENSOR ARRAY

MAJOR: CONTROL ENGINEERING AND AUTOMATION

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CHAPTER 1: OVERVIEW

1.1. General introduction to the topic

1.1.1. Research motivation

Magnetic navigation has emerged as a transformative technology with significant applications in both medical and industrial domains. In the medical field, the use of magnetic systems for guiding endoscopic devices is revolutionizing minimally invasive procedures. By enabling precise control over small, flexible instruments, magnetic navigation reduces patient trauma, shortens recovery times, and enhances procedural accuracy. Similarly, in industrial applications, magnetic navigation is vital for tasks requiring high precision, such as robotic assembly lines and automated inspection systems.

Despite its potential, achieving precise magnet positioning presents numerous challenges, particularly in medical contexts. The dynamic and complex environment inside the human body demands exceptional accuracy and reliability in tracking the magnet's position. External magnetic interference, sensor noise, and the need for real-time response further complicate the process. These challenges necessitate advanced techniques and robust systems for effective implementation.

Hall sensors play a vital role in facing with these challenges by enabling real-time magnetic field detection. Their high sensitivity and compact form factor make them ideal for applications requiring accurate position tracking. By utlizing a Hall sensor array, it becomes possible to map the magnetic field distribution and estimate the position and orientation of a magnet with high precision. This characteristic is crucial for achieving reliable and efficient magnetic navigation in complex environments.

1.1.2. Concept Overview

Hall sensor technology is based on the Hall effect, which occurs when a magnetic field perpendicular to a current-carrying conductor induces a voltage across the conductor. This voltage, known as the Hall voltage, is proportional to the strength of the magnetic field and can be used to measure magnetic field intensity and direction. Hall sensors are widely utilized for their sensitivity, compact size, and reliability in detecting magnetic fields, making them suitable for precise position tracking in applications like magnetic navigation.
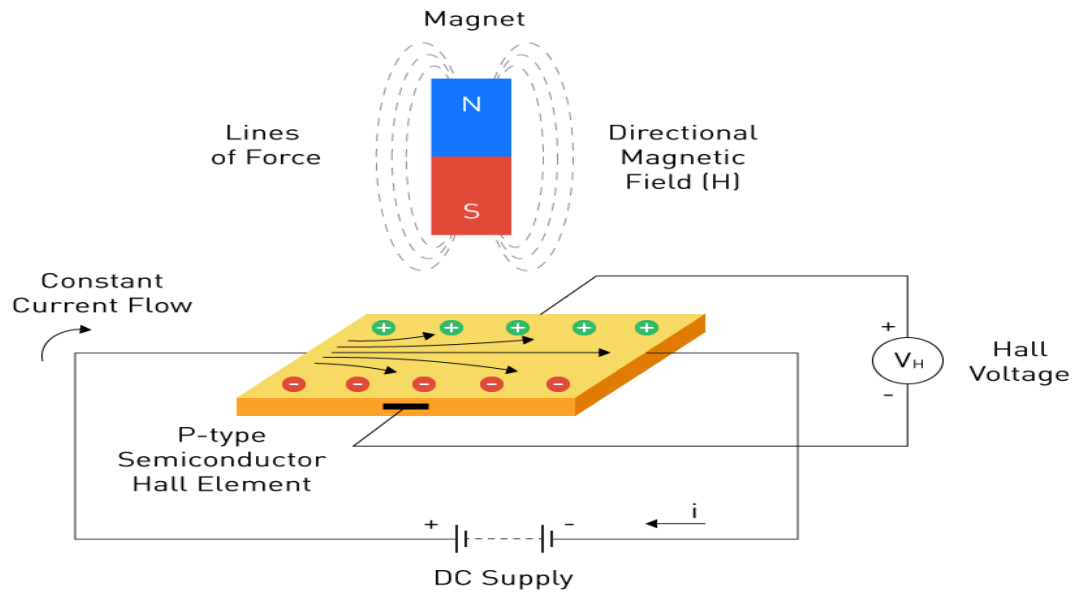
Figure 1.1 Hall effect

Magnetic navigation involves solving two relatable problems: the forward problem and the reverse problem.

- Forward problem: This problem involves calculating the magnetic field generated by a magnet at specific points in space, given its position and orientation. Using mathematical models, such as the magnetic dipole equations, the field can be calculated for any location, allowing for the reverse problem which requires the comparison from initial calculated values and them obtained from Hall sensors.
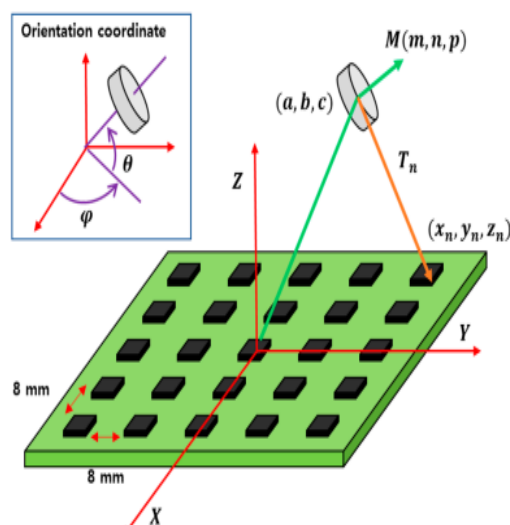
Figure 1.2 Forward problem

- Reverse problem: This involves using magnetic field measurements from a Hall sensor array to estimate and infer the position and orientation of the

magnet. It is an inverse problem that requires advanced optimization algorithms to make comparison between the sensor data and initial calculated values obtained from the forward problem. Solving the reverse problem is crucial for real-time navigation and control of the magnet.

By combining Hall sensor technology with robust algorithms, it is possible to create an efficient and accurate magnetic navigation system, enabling precise control in both medical and industrial applications.

1.2. Approach and Challenges

1.2.1. Approach

This project follows a structured approach to design and implement a magnetic navigation system using a Hall sensor array. The first step is to choose a suitable sensor for this project after making a research from completed previous research.

The next step focuses on algorithm development. The forward problem, which calculates the magnetic field at specific points based on the magnet's position and orientation, is modeled using magnetic dipole equations. By contrast, the reverse problem, involving position estimation from sensor data, is addressed using optimization algorithms implemented in Python. These algorithms are shifted for efficiency to ensure processing capabilities.

A custom PCB design for the Hall sensor is created using Altium Designer. The layout considers factors such as signal integrity, noise minimization, and compactness to achieve precise magnetic measurement result. After the design phase, experimental trials are conducted to calibrate the sensor array and optimize its performance.

Data acquisition is managed through the use of multiplexers (MUX), which sequentially read signals from the sensors. This reduces the number of required ADC pins on the microcontroller, optimizing the system's hardware requirements. The acquired data is stored in the microcontroller's memory and subsequently processed to estimate the magnet's position.

For intial trials, we will deploy a 3x3 array of Hall sensors arranged in a grid configuration. This setup enables the precise capture of the magnetic field's spatial distribution, essential for accurate position tracking. These trials examine the accuracy of the system under controlled conditions, providing insights into potential improvements in the array configuration.

Finally, the sensor data and algorithms are integrated into a navigation system. Extensive testing ensures that the system accurately tracks and navigates the magnet, meeting the project's goals for precision and reliability.

1.2.2. Challenges

Developing a magnetic navigation system presents several technical and practical challenges that must be overcome. One of the primary issues is that the magnetic range of currently available sensors in the market is relative small compared to the required range we need for further applications in the future.

Besides, the sensor noise and environmental interference can also be a significant concern. Hall sensors are highly sensitive to external magnetic fields and electrical noise, which can degrade the accuracy of measurements.

Another significant challenge lies in solving the reverse problem. This requires handling high-dimensional, non-linear optimization problems, which are computationally intensive. Efficient algorithms and well-optimized code are essential to ensure that the system processes data and estimates the magnet's position in real time without delays.

Calibration of the sensor array also poses difficulties. Variations in sensor sensitivity, alignment, and environmental conditions can introduce errors in position estimation. A systematic calibration process is necessary to normalize sensor outputs and maintain accuracy across the entire array.

The PCB design for the sensor array adds another layer of complexity. Balancing the need for a compact design with effective signal routing and noise reduction is a demanding task. Proper placement of sensors, traces, and components must account for both electrical and mechanical constraints.

Finally, managing large volumes of sensor data and integrating it with the system's algorithms is critical. Ensuring low-latency data flow and seamless interaction between hardware and software is essential for the system's overall performance.

By systematically addressing these challenges, this project aims to create a robust and efficient magnetic navigation system capable of performing reliably in real-world applications.

1.3. Contribution of the Project

This project offers significant contributions in the design and development of a magnetic navigation system using a Hall sensor array. By addressing both theoretical and practical aspects, it provides a comprehensive framework for precise magnet tracking and control.

One of the primary contributions lies in the innovative application of Hall sensor technology to solve the reverse problem of magnet navigation. The project integrates a 3x3 Hall sensor array with advanced optimization algorithms to accurately estimate the position and orientation of a permanent magnet. This method not only ensures high precision but also enhances real-time response, which is critical in dynamic environments such as medical applications.

Another key contribution is the design and implementation of a custom PCB for the Hall sensor array. Using Altium Designer, the project incorporates noise reduction techniques and efficient signal routing to achieve a compact and robust circuit. This PCB serves as a reliable platform for experimental trials and practical deployment, bridging the gap between theoretical modeling and real-world applications.

On the software side, the project develops and validates algorithms for solving both the forward and reverse problems of magnetic field analysis. These algorithms, implemented in Python, demonstrate high computational efficiency

and can be adapted for other magnetic navigation systems. By tackling challenges such as non-linear optimization and sensor data processing, the project sets a foundation for future research in similar domains.

The project also makes a notable contribution to experimental methodologies. By calibrating and optimizing the Hall sensor array through systematic trials, it establishes best practices for setting up and validating magnetic navigation systems. The findings from these experiments provide valuable insights into sensor placement, data acquisition techniques, and array configuration.

Beyond technical advancements, the project contributes to the broader fields of medical robotics and industrial automation. Our furture aim is to make a complete embeded and controllable endoscope capsule robot system in medical field where the Hall sensor array will play a vital role in addressing navigation problem.

CHAPTER 2: LITERATURE REVIEW

2.1. Basics of Magnetic Navigation

Magnetic navigation involves the use of magnetic fields to control and track objects, offering a non-invasive and precise method for positioning in various applications. It leverages the fundamental properties of magnets and the interactions between magnetic fields and sensors to achieve accurate spatial control.

2.1.1. Magnetic Fields and Principles

Magnets generate magnetic fields, which are vector fields surrounding the magnet. The strength and direction of these fields depend on the magnet's shape, size, and material properties. A magnetic field can be mathematically described using the concept of a magnetic dipole, where the field lines emanate from the north pole and curve back into the south pole.

The behavior of a magnetic field is governed by the laws of electromagnetism, including Ampère's law and Gauss's law for magnetism. These principles are used to predict the distribution and intensity of the magnetic field in space, providing the foundation for navigation and tracking systems.
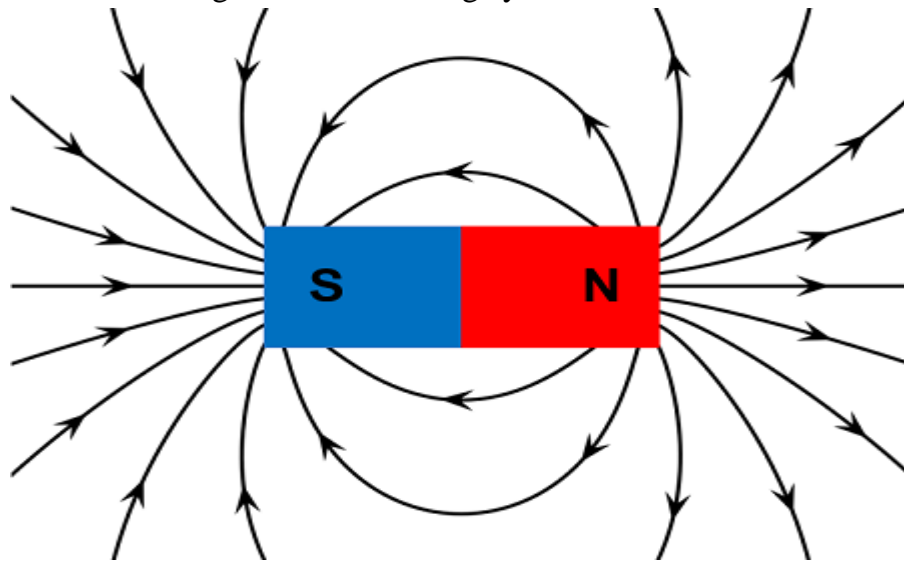
Figure 2.1 Magnetic field of a permernant magnet

2.1.2. Role of Magnetic Dipoles in Navigation

Magnetic dipoles, such as permanent magnets, are fundamental to magnetic navigation. They exhibit a magnetic moment, a vector quantity representing the strength and orientation of the magnetic source. The dipole moment determines the interaction of the magnet with external fields and the field it produces.

In magnetic navigation, the magnet's dipole field is analyzed to determine its position and orientation relative to the surrounding environment. This analysis requires solving the forward problem, which calculates the magnetic field at

specific points, and the reverse problem, which estimates the magnet's position based on measured field data.
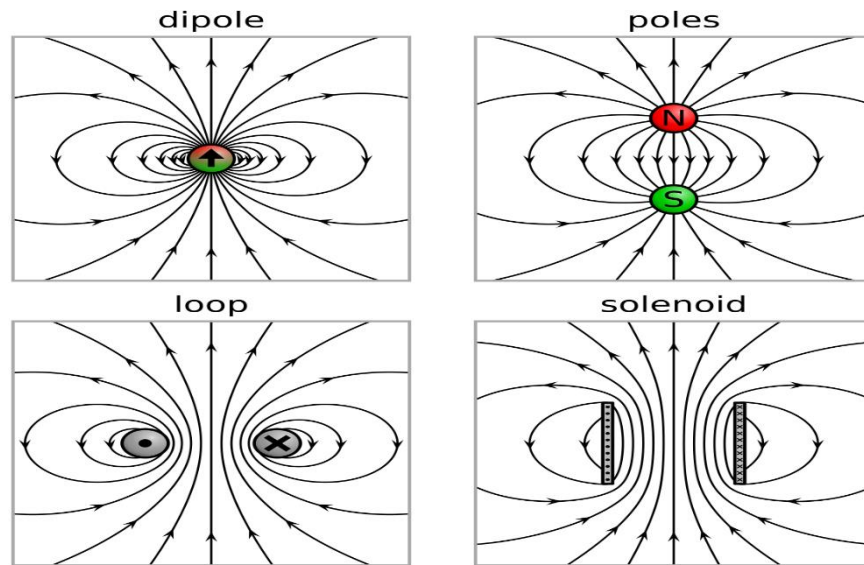
Figure 2.2 Magnetic field dipole

2.1.3. Hall Sensors in Magnetic Navigation

Hall sensors play a pivotal role in magnetic navigation by detecting and measuring the magnetic field. These sensors operate based on the Hall effect, which generates a voltage proportional to the magnetic field's strength when a current flows through the sensor.

In a navigation system, an array of Hall sensors is deployed to map the magnetic field across multiple spatial points. This data is then processed to infer the magnet's position and orientation. The high sensitivity, compact size, and reliability of Hall sensors make them an ideal choice for real-time magnetic tracking applications.

Figure 2.3 Hall effect sensor

2.1.4. Applications of Magnetic Navigation

Magnetic navigation is widely used in medical, industrial, and robotics applications. In the medical field, it enables the precise control of endoscopic tools, improving the safety and effectiveness of minimally invasive surgeries. In industrial settings, magnetic navigation supports automated systems for object manipulation and inspection.
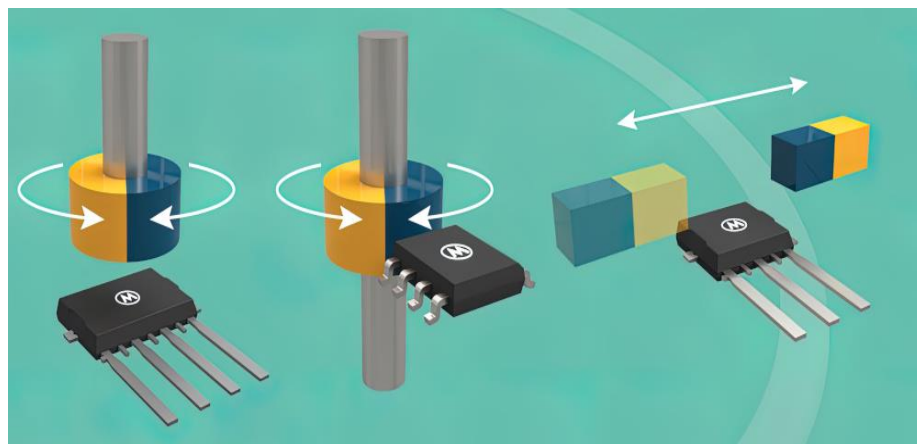
By combining the principles of magnetism with advanced sensing and computational technologies, magnetic navigation systems achieve high accuracy and reliability, making them indispensable in modern engineering and technology domains.

2.2 Theoretical background

2.2.1 Forward problem

The forward problem involves calculating the magnetic field at a given sensor position, provided parameters comprising the position (x,y,z), orientation (α,β) and dipole moment m of the magnet. This problem is going to address 5 degrees of freedom which make it easier to solve. The magnetic field at any sensor location is determined using the dipole field equation:

$$\mathbf{B} = \frac{\mu_0}{4\pi r^5} \left[3(\mathbf{m} \cdot \mathbf{r})\mathbf{r} - r^2\mathbf{m} \right]$$

where:

$\mathbf{m}$: magnetic dipole moment

$\mathbf{r}_{sensor}$: position vector of the sensor

$\mathbf{r}_{dipole}$: position vector of the magnet (dipole)

$\mathbf{r} = \mathbf{r}_{sensor} - \mathbf{r}_{dipole}$: vector from the dipole to the sensor

μ_0: Permeability of free space

From the equation above, we will write code in Python which is used due to its high popularity and simplicity. The code of the forward problem is presented as below:

```python
import numpy as np
import math

w0 = 4 * np.pi * (10**(-7))

def tinhtutruongtai1diem(x, y, z, alpha, beta, sensorposition):
    m = 1
    mx = np.cos(beta) * np.cos(alpha) * m
    my = np.cos(alpha) * np.sin(beta) * m
```

```python
        mz = m * np.sin(alpha)
        m_vecto = np.array([mx, my, mz])

        ss_vecto = np.array(sensorposition)
        vitri = np.array([x, y, z])
        r_vecto = ss_vecto - vitri
        r = np.linalg.norm(r_vecto)
        a = np.dot(m_vecto, r_vecto)
        tuso = w0 * (3 * a * r_vecto - (r**2) * m_vecto)
        mauso = 4 * np.pi * (r**5)
        B_vecto = tuso / mauso
        B = np.linalg.norm(B_vecto)

        return B

sensorposition = [(i, j, 0) for i in range(10) for j in range(10)]
sensorposition = np.array(sensorposition)

x = 1
y = 2
z = 3
alpha = np.radians(90)
beta = np.radians(0)
p = np.zeros((10, 10)

for i in range(10):
    for j in range(10):
        p[i, j] = tinhtutruongtai1diem(x, y, z, alpha, beta, sensorposition[i * 10 + j])

print(p)
```

Here, this section of the report focuses on the theoretical computation of the magnetic field **B** produced by a magnetic dipole at a grid of sensor positions. The primary goal is to model the field values at each sensor in a 10×10 grid using known dipole parameters.

The magnetic field **B** at a sensor position is computed using the tinhtutruongtai1diem function. The function models a magnetic dipole located at position (x,y,z) and orientation angles α, β. The dipole's magnetic moment m is decomposed into Cartesian components:

$$m_x = m \cos(\beta) \cos(\alpha), \quad m_y = m \cos(\alpha) \sin(\beta), \quad m_z = m \sin(\alpha)$$

where m=1 is assumed to simplify calculations.

The relative position vector **r** between the dipole and a sensor is given by:

$\mathbf{r}=\mathbf{r}_{sensor}-\mathbf{r}_{dipole}$, $r=|\mathbf{r}|$.

The magnetic field vector B is calculated using the following equation:

$$\mathbf{B} = \frac{\mu_0}{4\pi}\frac{1}{r^5}\left[3(\mathbf{m}\cdot\mathbf{r})\mathbf{r}-r^2\mathbf{m}\right]$$

where $\mu_0=4\pi\times10^{-7}$ T. Finally, the magnitude B is derived as the norm of **B**.

A 10×10 grid of sensors is defined on the z=0 plane. Each sensor's position is represented as a point (i,j,0), where i and j range from 0 to 9. This array contains all sensor coordinates needed for calculating the magnetic field.

The dipole's position and orientation are initialized as:

- x=1, y=2, z=3: The Cartesian coordinates of the dipole.
- α=90°, β=0°: The dipole's orientation in spherical coordinates.

The angles α and β are converted to radians using np.radians to match the input requirements for trigonometric functions. The magnetic field at each sensor is calculated sequentially. The results are stored in a 10×10 matrix p. The computation proceeds as follows:

Loop through each sensor position in the grid. Pass the sensor's position and dipole parameters to tinhtutruongtai1diem. Store the resulting magnetic field magnitude B in the corresponding entry of matrix p.

Finally, the matrix p is printed, displaying the computed magnetic field values at each sensor. These values represent the theoretical magnetic field magnitudes in the 10×10 grid.

The resulting matrix provides a spatial distribution of the magnetic field, which can be used for visualization or further analysis.

2.2.2 Reverse problem

This problem focuses on modeling and optimizing the magnetic field produced by a dipole at specified sensor positions. The goal is to utilize optimal algorithms which compares measured values with calculated results from the forward problem and sequentially adjust the model parameters to minimize the error. The optimization identifies the dipole's position and orientation that best fits the measured data.

The code written in Python is presented as below:

```python
import numpy as np
from scipy.optimize import minimize


#cost function
def cost_function(params, sensorposition, B_meas):
```

```python
    x, y, z, alpha, beta = params
    B_cal = np.zeros((10, 10))
    for i in range(10):
        for j in range(10):
            B_cal[i, j] = tinhtutruongtai1diem(x, y, z, alpha, beta, sensorposition[i * 10 + j])
    cost = np.sum((B_meas - B_cal) ** 2)
    return cost

sensorposition = [(i, j, 0) for i in range(10) for j in range(10)]
sensorposition = np.array(sensorposition)

#B_mea: obtain from sensors
B_meas = np.random.rand(10, 10)

#x = 1
#y = 2
#z = 3
#alpha = np.radians(90)
#beta = np.radians(0)

x = float(input("Nhập giá trị cho x: ")
y = float(input("Nhập giá trị cho y: ")
z = float(input("Nhập giá trị cho z: ")
alpha = float(input("Nhập giá trị cho alpha: ")
beta = float(input("Nhập giá trị cho beta: ")

B_cal = np.zeros((10, 10))

for i in range(10):
    for j in range(10):
        B_cal[i, j] = tinhtutruongtai1diem(x, y, z, alpha, beta, sensorposition[i * 10 + j])

bandau = [x, y, z, alpha, beta]
p = cost_function(bandau, sensorposition, B_meas)
print("Initial cost:", p)

#optimization function
```

```
result = minimize(cost_function, bandau, args=(sensorposition, B_meas),
method='BFGS')
x_opt, y_opt, z_opt, alpha_opt, beta_opt = result.x

print(f"x_opt: {x_opt}")
print(f"y_opt: {y_opt}")
print(f"z_opt: {z_opt}")
print(f"alpha_opt: {alpha_opt}")
print(f"beta_opt: {beta_opt}")
```

A cost function is used to minimize the error between the calculated magnetic field values B_cal and the measured magnetic field values B_meas. The cost function sums the squared differences:

$$\text{Cost} = \sum_{i,j} \left(B_{\text{meas}}[i,j] - B_{\text{cal}}[i,j] \right)^2 ,$$

where B_cal is computed at each sensor position using the dipole model. This function is essential for evaluating the fit between the theoretical model and experimental data.

To simulate the sensor setup, a 10×10 grid of sensors is created on the Oxy plane. Each sensor position is represented as a point (i,j,0), where i and j range from 0 to 9. The simulated sensor positions are stored in a structured array for further calculations.

Because the system is not totally completed, random values are generated to simulate the measured magnetic field values B_meas, which serve as real experimental data.

The program initializes the magnet's position (x,y,z) and orientation (α,β) using user-provided values that are possibly choosen. These values are passed to the tinhtutruongtai1diem function to compute the initial magnetic field B_cal at each sensor position. The initial cost is calculated by comparing B_cal with B_meas.

The optimization process uses the scipy.optimize.minimize function with the BFGS algorithm. In numerical optimization, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is an iterative method for solving unconstrained nonlinerar optimization problems. Like the related Davidon-Fletcher-Powell method, BFGS determines the descent direction by preconditioning the gradient with curvature information. It does so by gradually improving an approximation to the Hessian matrix of the loss function, obtained only from gradient evaluations (or approximate gradient evaluations) via a generalixed secant method.

The initial parameters (x,y,z,α,β) serve as the starting point, and the cost function guides the minimization. The optimization adjusts the dipole parameters to reduce the cost function iteratively.

The result of the optimization provides the best-fit $:x_{opt}$, y_{opt}, z_{opt}, α_{opt}, β_{opt} which describe the dipole's position and orientation that align most closely with the measured data.

CHAPTER 3: HARDWARE DESIGN

3.1 Hall sensor

To ensure optimal performance of the magnetic navigation system, the Hall sensor selection process is guided by key categories that match the project's requirements. These categories address the technical, environmental, and financial aspects of the sensor's operation and suitability.

3.1.1 Measurement Signal

The required signal is the magnetic field generated by a permanent magnet. The sensor must accurately detect and measure the magnetic field intensity across a large. This range ensures compatibility with the dipole fields generated by the permanent magnet in the navigation system while allowing some margin for unexpected field variations or positioning errors.

3.1.2 Environmental Conditions

The system will operate in normal room temperatures ranging from 20°C to 30°C, a stable and controlled environment with minimal temperature variation. The sensor must maintain its accuracy and reliability within this range, without requiring additional temperature compensation circuitry or calibration.

3.1.3 External Interference

To minimize noise and ensure the accuracy of magnetic field measurements, the operational environment is expected to have limited external magnetic distractions. While interference from nearby electronic devices and stray magnetic fields is not significant, the sensor should still provide robust performance against minor perturbations to ensure consistent readings.

3.1.4 Measurement Range

The sensor must handle magnetic field intensities up to 130 mT with high accuracy. This range is chosen to cover typical field strengths encountered in the system where the magnetical magnitide of the control structure may raise to 25 mT. Moreover, we need to ensure that there is no saturation or loss of sensitivity in high-field regions because it would lead to a failure in calculation.

3.1.5 Sensitivity

High sensitivity is critical for precise detection and tracking of the magnetic field. Sensitivity values should be as small as possible, enabling the sensor to detect minute changes in field strength. This feature directly impacts the system's ability to estimate the magnet's position and orientation with high accuracy.

3.1.6 Cost and Affordability

Given the project's constraints and the potential for scaling the system, the selected sensor must be cost-effective without compromising essential features. Affordable sensors that meet the technical criteria are prioritized, ensuring the feasibility of the system for prototyping and potential mass production.

These categories provide a comprehensive framework for evaluating and selecting the most suitable Hall sensor. By focusing on these criteria, the project ensures that the chosen sensor will deliver the desired performance while maintaining cost-effectiveness and adaptability to the intended operating environment.

To select the most suitable Hall sensor for the magnetic navigation system, a detailed comparison of various sensors from existing research was conducted. The selection criteria included measurement range, sensitivity, and compatibility with the project's requirements. Research papers detailing sensor performance in magnetic tracking applications were analyzed to assess each sensor's suitability. Here is the table of sensors that we did research.

Paper	Sensor	Range	Sensitivity
A 3-axis magnetic sensor array system for permanent magnetic tracking [1]	AK09912 (digital) 9 sensor 0.5m x 0.5m	±4.9 mT	0.15 µT/LSB
Geometric compensation for the rotating of magnetometer array during magnetic tracking [2]	LSM303D (digital) 9 sensor	±0.2 mT	8 µT/LSB
		±0.4 mT	16 µT/LSB
		±0.8 mT	32 µT/LSB
		±1.2 mT	47.9 µT/LSB
A new tracking system for 3 magnetic objectives [3]	HMC1043 (analog) 16 sensor, cubic Substitution	±0.6 mT	1 (mV/1000 µT)
Locating intra-body capsule object by 3-magnet sensing system [4]	HMC1053 (analog) 32 sensor on 8 PCB	± 0.6 mT	1 (mV/1000 µT)
Automated Bowel Polyp Detection Based on Actively Controlled Capsule Endoscopy: Feasibility Study [5]	DRV5055A4 (analog) 6 x 6 sensors	±169 mT	12.5 mV/1000 µT
3-D Localization Method for a Magnetically Actuated Soft Capsule Endoscope and Its Application [6]	A1302(analog)		1.3 mV/100 µT
Robotic Localization Based on Planar Cable Robot and Hall Sensor Array Applied to Magnetic Capsule Endoscope [7]	WSH202 (digital) 25 sensor 34cm x 34 cm		
Design and Optimization	HMC5883L	±0.81 mT	0.073 µT/LSB

|			
Strategy of Sensor Array Layout for Magnetic Localization System [8]	(digital) 8 sensor 20×20 cm^2	8	
Generating Rotating Magnetic Fields With a Single Permanent Magnet for Propulsion of Untethered Magnetic Devices in a Lumen [9]	A1301 (analog)		25 V/T
Low-Latency Tracking of Multiple Permanent Magnets[10]	LSM9DS1 iNEMO inertial modules (STMicroelectronics) 4x4 sensor	±0.4 mT	1.6 µT /LSB
		±0.8 mT	3.1 µT /LSB
		±1.2 mT	4.7 µT /LSB
		±1.6 mT	6.2 µT/LSB
Real-Time Pose Detection for Magnetic Medical Devices[11]	CYP15A		
The Calibration of 3-Axis Magnetic Sensor Array System for Tracking Wireless Capsule Endoscope[12]	HMC1053 (analog)	±0.6 mT	1 (mV/100 µT)

Table 3.1 Sensor research
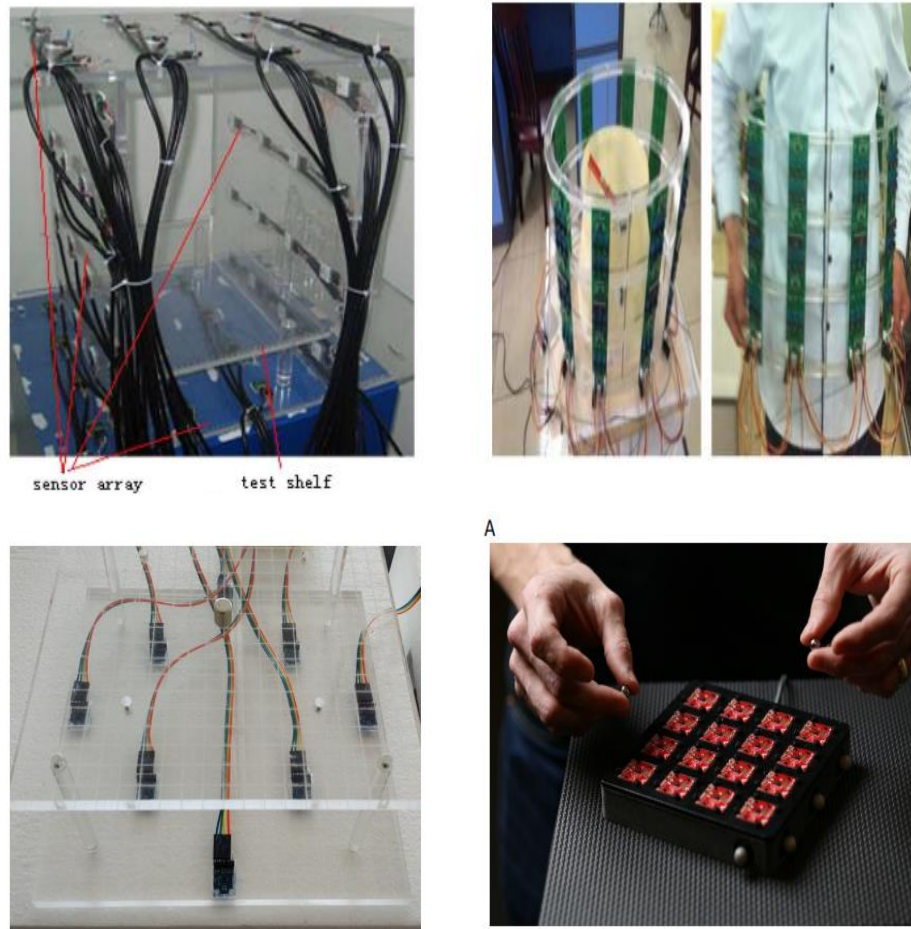
Figure 3.1 Existing research

After evaluating various Hall sensors based on the defined selection criteria, the DRV5055 was chosen as the most suitable sensor for this project.

The DRV5055 device is a linear Hall effect sensor that responds proportionally to magnetic flux density. The device can be used for accurate position sensing in a wide range of applications. TI provides us 2 packages of this sensor. Here is the figures of 2 types of packages.
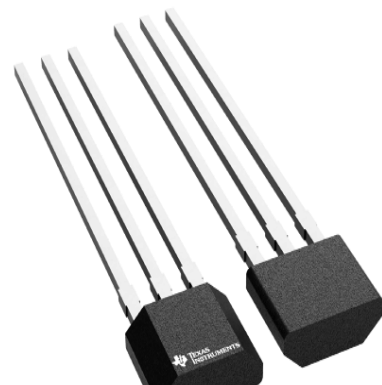

Figure 3.2 SOT-23

Figure 3.3 TO-92

The device operates from 3.3-V or 5-V power supplies. When no magnetic field is present, the analog output drives half of V_{CC}. The output changes linearly with the applied magnetic flux density, and four sensitivity options enable maximal output voltage swing based on the required sensing range. North and south magnetic poles produce unique voltages. Magnetic flux perpendicular to the top of the package is sensed, and the two package options provide different sensing directions. The device uses a ratiometric architecture that can eliminate error from V_{CC} tolerance when the external analog-to-digital converter (ADC) uses the same V_{CC} for its reference.
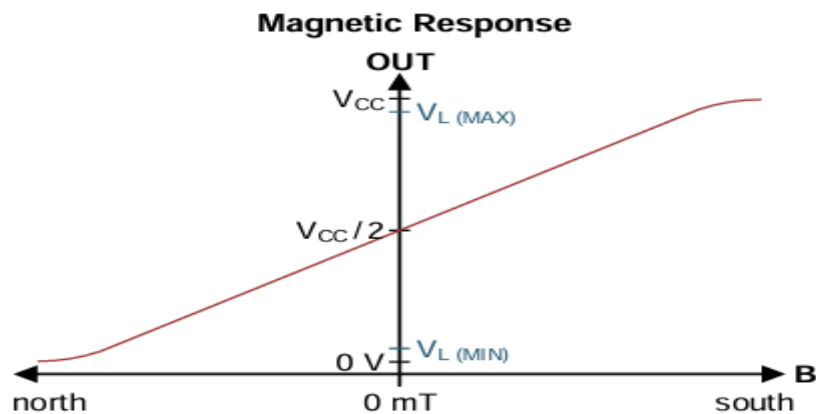
Magnetic Response

Figure 3.4 Characteristic line

Below are the reasons that support the decision:

The DRV5055 is specifically designed to measure magnetic fields with a wide dynamic range of up to 169 mT, which comfortably exceeds the project requirement of 130 mT. This ensures accurate detection of the magnetic field generated by the permanent magnet without risking saturation, even at higher field intensities.

The DRV5055 performs reliably within normal operating temperatures ranging from -40°C to 125°C, far surpassing the project's required range of 20°C to 30°C. This margin ensures stable performance in the intended environment and provides flexibility for future use in varying conditions.

The analog output of the DRV5055 is inherently robust against minor magnetic interference due to its stable design and good signal-to-noise ratio. This feature ensures accurate readings even in the presence of small external magnetic distractions, aligning well with the project's controlled environmental conditions.

The sensor's range of ±169 mT comfortably accommodates the magnetic field strengths encountered in the project. This range ensures reliable performance without the risk of exceeding the sensor's limits, providing a balance of accuracy and versatility for the system.

The DRV5055 offers a sensitivity of 12.5 mV/mT, allowing it to detect subtle changes in the magnetic field. This high level of sensitivity supports the project's need for precise position and orientation estimation, enhancing the overall accuracy of the navigation system.

At a price range of $0.5 per unit (from Taobao), the DRV5055 is highly cost-effective compared to other sensors with similar performance. This affordability makes it ideal for prototyping and potential scaling while maintaining high quality.

Hall sensor DRV5055 was selected for this project due to its superior range, sensitivity, and robustness in the specified environmental conditions. Its cost-effectiveness further reinforces its suitability, ensuring that the project remains technically and financially viable. By integrating the DRV5055, the magnetic navigation system is well-equipped to deliver accurate and reliable performance.

3.2 Microcontroller STM32

3.2.1 STM32F103xx

The STM32F103xx medium-density performance line family incorporates the high-performance Arm® Cortex®-M3 32-bit RISC core operating at a 72 MHz frequency, high-speed embedded memories (Flash memory up to 128 Kbytes and SRAM up to 20 Kbytes), and an extensive range of enhanced I/Os and peripherals connected to two APB buses. All devices offer two 12-bit ADCs, three general purpose 16-bit timers plus one PWM timer, as well as standard and advanced communication interfaces: up to two I^2Cs and SPIs, three USARTs, an USB and a CAN.

The devices operate from a 2.0 to 3.6 V power supply. They are available in both the –40 to +85°C temperature range and the –40 to +105 °C extended temperature range. A comprehensive set of power-saving mode allows the design of low-power applications.

The STM32F103xx medium-density performance line family includes devices in six different package types: from 36 pins to 100 pins. Depending on the device chosen, different sets of peripherals are included, the description below gives an overview of the complete range of peripherals proposed in this family.

These features make the STM32F103xx medium-density performance line microcontroller family suitable for a wide range of applications such as motor drives, application control, medical and handheld equipment, PC and gaming

peripherals, GPS platforms, industrial applications, PLCs, inverters, printers, scanners, alarm systems, video intercoms, and HVACs.
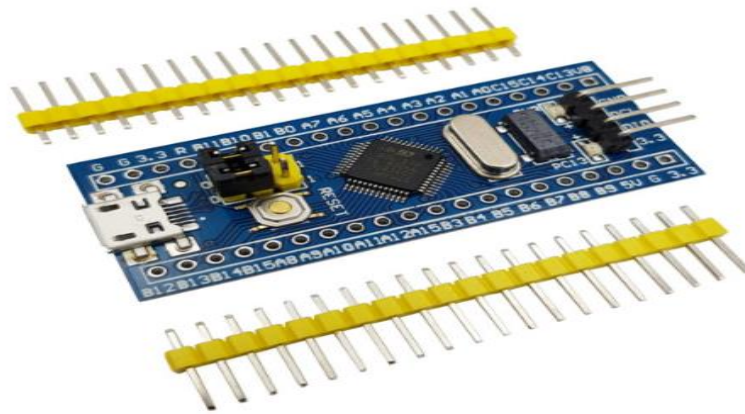
Figure 3.5 STM32F103C8T6

3.3 ADC MUXTIPLEXOR

3.3.1 74HC4067

The 16-Channel Analog Multiplexer 74HC4067 is used to expand analog or digital communication pins. It functions as a 16-to-1 switch, allowing multiple input signals to be connected to a single output channel by selecting the appropriate address bits. This is particularly useful for microcontrollers with limited analog or digital pins that need to interface with multiple devices. The circuit is built with high-quality components and precise manufacturing, ensuring durability and reliability.
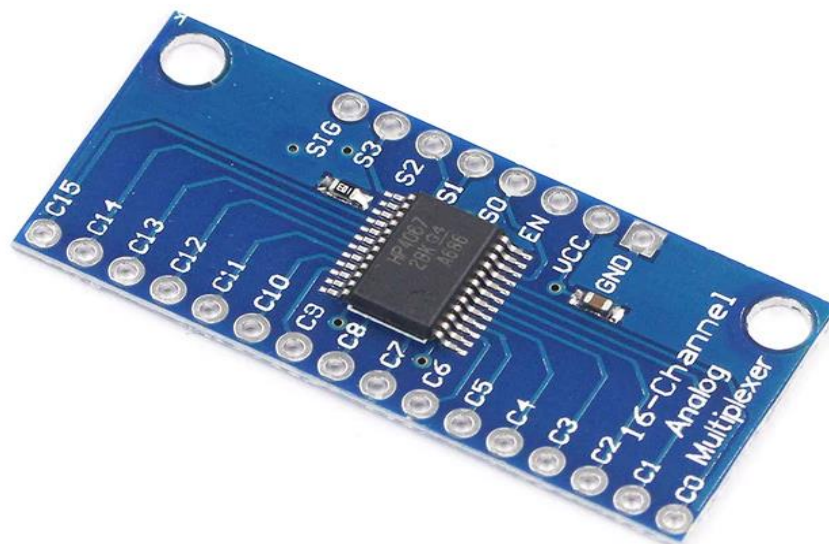

Figure 3.6 74HC4067

CHAPTER 4: NEXT STEPS

4.1 Trial

To evaluate the performance of the DRV5055 sensor, experiments will be conducted to measure the magnetic field along the z-axis in a controlled laboratory environment. The measurements will be carried out in the ITIMS Laboratory, which is equipped with advanced instrumentation for precise magnetic field analysis.

4.1.1 Setup

A standard magnetic field sensor, the Lakeshore 425 Gaussmeter, will be used as the reference for comparison. The Lakeshore 425 Gaussmeter is a high-performance instrument designed for precise measurement of magnetic fields. Manufactured by Lake Shore Cryotronics, a global leader in magnetic and cryogenic measurement solutions, the 425 model is widely recognized for its accuracy, reliability, and ease of use in both research and industrial settings.

Figure 4.1 Lakeshore 425

Lakeshore 425 will directly measure the magnetic field at the same positions, providing reference data for comparison. The magnetic field values obtained from the DRV5055 will be compared with the reference values from the Lakeshore 425. Parameters such as precision, accuracy, linearity, and response time of the DRV5055 will be examined. The comparison will focus on key performance metrics, including:

- Precision: The consistency of the DRV5055 measurements across multiple trials.

- Accuracy: The closeness of the DRV5055 measurements to the reference values obtained from the Lakeshore 425.
- Linearity: The ability of the DRV5055 to provide proportional outputs over the tested range.
- Noise Performance: The level of signal noise in the DRV5055 outputs compared to the reference sensor.

To carry out the trials in ITIMS, a custom mechanical structure was designed using SolidWorks and fabricated using a 3D printer. This structure ensures precise alignment and positioning of the measurement components, enabling accurate magnetic field measurements.

Solidworks is a powerful 3D CAD software used for designing and modeling complex mechanical systems with precision and efficiency. Its intuitive interface and advanced tools enable the creation of detailed designs for prototyping and manufacturing.

3D printing complements SolidWorks by transforming digital designs into physical models, offering a rapid and cost-effective way to validate and test prototypes.

In this project, SolidWorks was used to design a custom structure for holding the gaussmeter Lakeshore 425 probe and magnet. The design was then fabricated using a 3D printer, ensuring precise alignment and flexibility for conducting controlled magnetic field measurements. This combination significantly streamlined the development and testing process, enhancing the overall efficiency and accuracy of the setup. The structure is presented in the figure below:
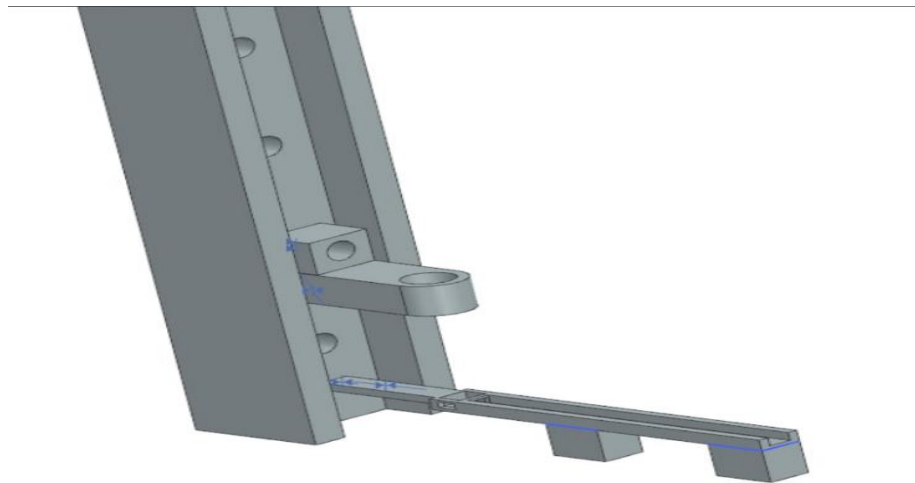

Figure 4.2 Measurement structure in ITIMS

4.1.2 Trial steps

The structure includes a secure holder for the probe of the Lakeshore 425 gaussmeter, ensuring its stability during measurements. The holder's dimensions and design were optimized to match the probe's shape and size, preventing unwanted movements or vibrations.

A bar is integrated into the structure to hold the magnet. The bar is capable of moving vertically along a 25 cm range to simulate different distances between the magnet and the sensor. The vertical movement of the bar can be adjusted in precise 5 cm steps, allowing for consistent and repeatable measurements at distances of 0 cm, 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm.

This setup enables systematic measurement of the magnetic field magnitude along the z-axis at various distances. The stable and adjustable design ensures that external disturbances and alignment errors are minimized, leading to reliable data collection.

The measurements collected using the Lakeshore 425 probe at different distances will be compared with the outputs of the DRV5055 Hall sensor, providing critical insights into the sensor's accuracy and precision across varying magnetic field intensities. This setup is crucial for validating the DRV5055's performance under controlled laboratory conditions.

4.2. Sensor Module Design

Altium Designer is a professional software widely used for designing printed circuit boards (PCBs). It integrates advanced tools for schematic capture, PCB layout, and simulation, enabling engineers to create precise and reliable designs for electronic systems. In this project, Altium Designer was utilized to design the module for the chosen sensor, DRV5055.

From the typical schematic provided by the manufacturer, we proceed to design the module circuit for the sensor. The PCB design of sensor is given as below:
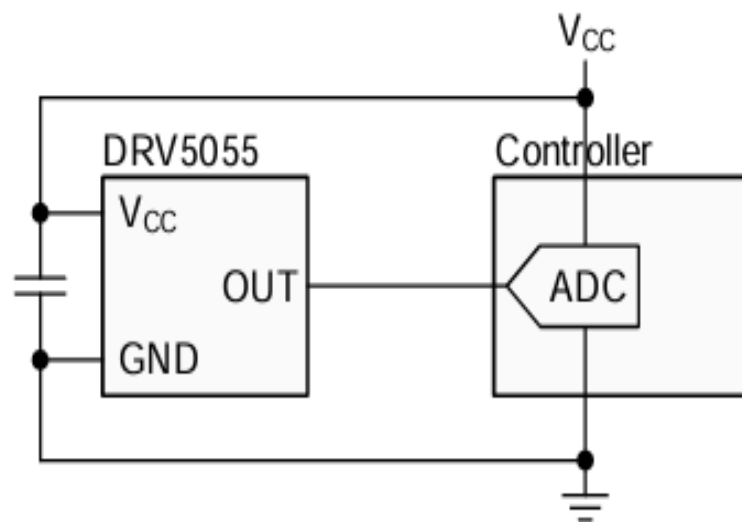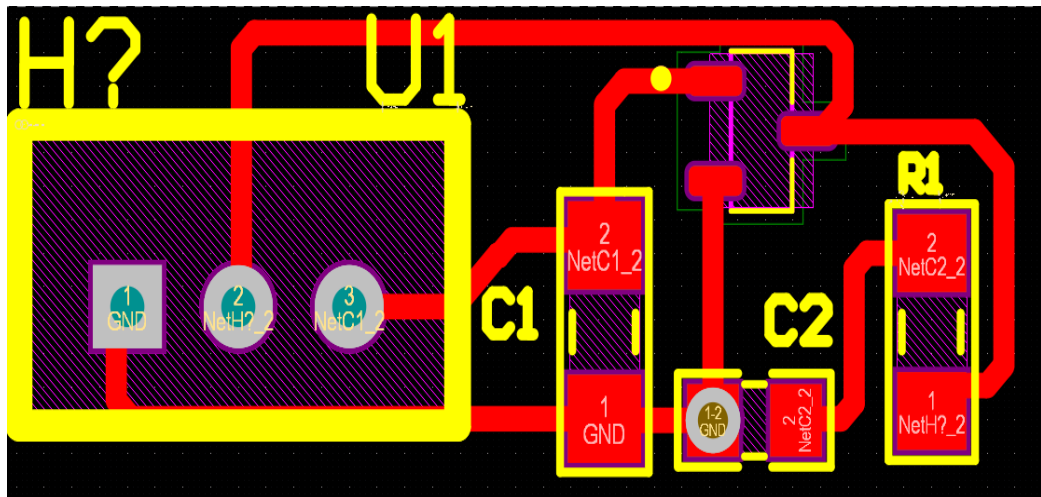

Figure 4.3 Typical schematic
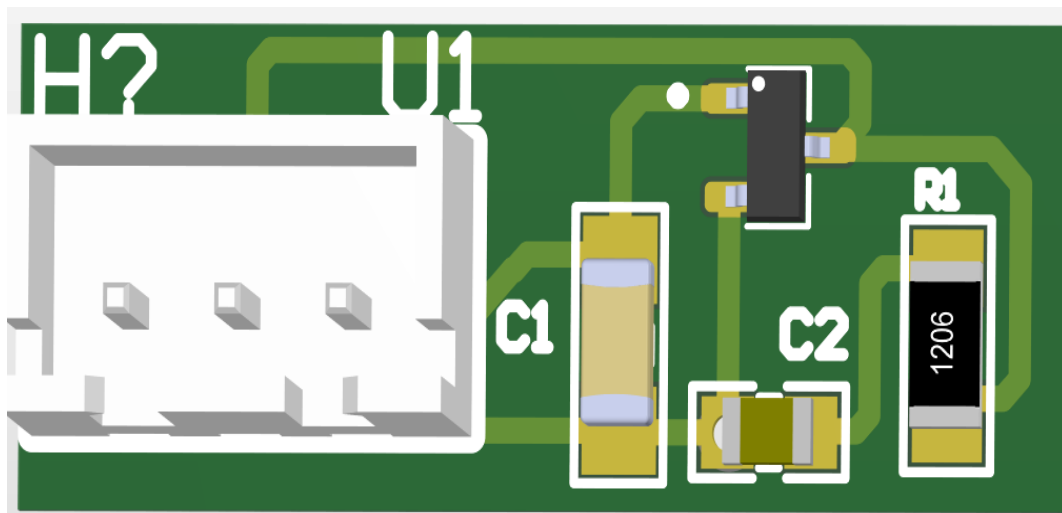
Figure 4.4 PCB design in Altium Designer

Figure 4.5 3D view PCB

4.3 Completing the system

After completing the design and fabrication of the sensor module, the next phase of the project will focus on determining the optimal configuration for the sensor array. This involves iterative experimental trials to evaluate and refine the arrangement of the sensors, ensuring maximum accuracy and reliability in magnetic field detection.

The experiments will begin with a basic 3×3 array configuration. This initial setup provides a manageable framework for evaluating the performance of the system while minimizing complexity. The sensors will be arranged in a uniform grid, with equal spacing between adjacent sensors.

Key objectives of the initial trials include:

- Assessing the sensitivity and coverage of the 3×3 array.

- Identifying potential issues such as overlapping sensor signals or insufficient resolution in field measurements.
- Establishing baseline performance metrics, including position and orientation accuracy.

Following the initial trials, the sensor array configuration will be adjusted manually to explore alternative arrangements. These adjustments may include:

- Changing the Spacing: Increasing or decreasing the distance between sensors to optimize field resolution and reduce noise.
- Testing Non-Uniform Layouts: Experimenting with non-grid configurations, such as hexagonal or radial patterns, to improve the system's ability to track fields with varying gradients.

For each configuration, the system's performance will be evaluated based on the following criteria:

- Accuracy: The closeness of the calculated magnetic field values to the reference measurements.
- Precision: The consistency of sensor readings across multiple trials.
- Coverage: The ability of the array to detect magnetic fields across the entire region of interest without blind spots.
- Signal Noise: The level of interference or noise affecting sensor outputs.

The goal of these trials is to identify the array configuration that provides the best balance of accuracy, precision, and coverage while minimizing noise. This optimal configuration will form the foundation for the final implementation of the magnetic navigation system, ensuring reliable and robust operation.

By systematically evaluating and refining the sensor array, the project will achieve a highly efficient design tailored to the specific requirements of magnetic field detection and navigation.

CHAPTER 5: CONCLUSION

5.1 Conclusion

This project successfully demonstrates the design and implementation of a navigation system for a permanent magnet using a Hall sensor array, with a focus on optimizing precision and reliability. The study began with a detailed exploration of the principles of magnetic field measurement, the forward and reverse problems, and the criteria for selecting appropriate sensors. The DRV5055 Hall sensor was chosen based on its sensitivity, range, and cost-effectiveness, ensuring its suitability for the project requirements.

To validate the system, a custom mechanical setup was designed in SolidWorks and fabricated using a 3D printer, allowing precise control and measurement of magnetic fields in a laboratory environment. Comparative testing with the standard Lakeshore 425 gaussmeter provided insights into the accuracy and precision of the sensor array. Further, trials with various sensor configurations demonstrated the feasibility of achieving optimal magnetic field detection and navigation.

The results of this project contribute to advancements in magnetic navigation technologies, particularly for medical and industrial applications. The approach outlined here serves as a foundation for future developments, including scaling up the sensor array, improving data acquisition algorithms, and enhancing real-time performance.

5.2 Limitations

Despite the achievements of this project, several limitations were identified that could impact its performance and scalability. The accuracy of the magnetic field measurements is highly dependent on the precise alignment and spacing of the sensors in the array, as even minor misalignments can lead to errors in field mapping. Additionally, the sensitivity of the DRV5055 Hall sensor, while sufficient for the specified range, may not accurately capture extremely weak magnetic fields, which could be a limitation in applications requiring ultra-high precision. Environmental factors, such as external magnetic field interferences or temperature variations beyond the tested range of 20–30°C, also pose challenges to the system's reliability.

Furthermore, scaling the sensor array beyond the current 3×3 configuration to larger arrays could introduce complexities in wiring, data acquisition, and microcontroller processing capabilities. Lastly, the process of manually testing different sensor configurations is time-consuming and may not fully explore all potential optimal arrangements. Future work should address these limitations by improving sensor calibration, implementing environmental shielding, automating configuration processes, and exploring advanced sensors or microcontrollers to enhance system performance.

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