H.A.L.O
Hall-effect Array for Live Observation

Magnetic Field Imaging

Divide and Conquer Document
EEL4914 - Senior Design 1
Group 18

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Chapter 1: Project Description

1.1 Background and Motivation

Magnetic fields are present in nearly all electrical systems, but measuring and visualizing them often requires specialized equipment. In fields like electrical engineering, understanding magnetic fields is incredibly important. Traditional methods, such as single-point measurements or bulky sensors, can be quite expensive and don't provide a dynamic view of the magnetic environment.

One way to overcome these limitations is through the use of Hall effect sensors. These sensors generate a voltage that's proportional to the magnetic field they detect, offering a reliable and cost-effective way to measure magnetic fields. However, while Hall effect sensors are great for pinpoint measurements, there's still a significant need for a system that can map these fields in real time across a larger area.

This project aims to address this by creating a system that uses a 12x12 array of Hall effect sensors to generate a color-coded map of the magnetic field that refreshes at 60 Hz. By visualizing the magnetic field in real time, this system will provide users with a much deeper understanding of magnetic field behavior, especially in complex systems with oscillating magnetic fields. This can be especially useful in industry and for research, where it's vital to monitor the magnetic fields of electronics to prevent electromagnetic interference (EMI). Some potential applications for this system include monitoring power systems, detecting anomalies in machinery, or assessing sensor performance in different environments.

Our motivation behind this project comes from the need for a cost-effective, user-friendly way to study and visualize magnetic fields. With its practical applications ranging from industry and research labs to educational use, users will be able to engage more effectively with the concept of magnetism.

1.2 Existing Products & Technologies

To better guide our project design, we analyzed two existing systems that align with our objectives and give insights into effective design strategies. These projects serve as useful references, helping us understand other design approaches and areas for improvement.

The first project, "A Magnetic Imager Tile" [1], uses an 8x8 array of Hall-effect sensors to visualize magnetic fields. This system detects field polarity but does not measure the field's intensity. Data is transmitted using the I2C protocol to a laptop which displays the magnetic field. One of the key improvements we hope to make is transitioning from I2C to SPI for data transmission. SPI has higher bandwidth and lower latency, which is crucial since we want the refresh rate to be 60Hz. Also, this project relies on a development board and laptop to visualize the field. We hope to eliminate the need for external components by implementing a microcontroller chip and onboard LCD touchscreen to make the system function independently.

The second project, “A High-Resolution Magnetic Field Imaging System Based on the Unpackaged Hall Element Array” [2], has a different approach. It uses an array of 256 Hall-effect sensors attached to a motorized rail system to scan and render a high-resolution image of magnetic fields. Our project differs in that we aim to provide continuous real-time visualization rather than a static scan. However, we will incorporate data storage, allowing users to save static images or video recordings of 30 seconds or less of the magnetic fields onto an SD card. The motorized rail system is also a valuable concept that could be integrated into future iterations of our design.

By analyzing these existing projects, we aim to combine their strengths to create a system capable of high-speed magnetic field visualization.

1.3 Overview of Project Goals

The primary goal of this project is to develop a real-time magnetic field visualization system that can detect and display magnetic field strength using an array of Hall effect sensors. By providing a clear visual representation, we hope to make magnetic field analysis more accessible and user-friendly. The visual representation will be comprised of a heat map of the magnetic field where different gradients correspond to different field strengths.

We want to create a compact, lightweight, and reliable device that can be used by engineers, researchers, and educators working with electronics. The device should be easy to use in a variety of environments, primarily in classrooms and laboratories, while maintaining high accuracy and responsiveness.

Goals:

- Display a visualization of the strength of a magnetic field relative to space and frequency
- The system should be lightweight and portable
- The device should be low-cost
- Magnetic field data must be captured by the sensors and transmitted to the MCU
- Implement a user-friendly interface for visualizing magnetic fields
- Create a standalone system with an integrated touchscreen for ease of use
- Implement effective shielding techniques to prevent electromagnetic interference
- Allow the system to be powered by a USB-C connection and lithium-ion battery
- The system should be able to store and export magnetic field data on an SD card

Stretch Goals:

- The system could be enhanced with automated scanning capabilities using motorized rails to analyze larger and more complex magnetic fields

Objectives:

- Hall-effect sensors must be properly calibrated for precise magnetic field detection
- The touchscreen interface should be user-friendly and provide real-time interaction
- EMI shielding techniques will minimize interference with the sensor array

- House the system in a durable 3D-printed enclosure
- The system operates independently, utilizing its own power source, built-in controls, and onboard display without relying on external hardware.

1.4 Project Features and Functionalities

Overall functionality

The overall functionality of the project will be to utilize Hall effect sensors to map magnetic fields and display them as a 2-dimensional heat map for intuitive readability. The device will also update the screen at a rate of 60 Hz to show any changes in the magnetic field in real time.

Sensor Matrix

The sensor matrix will be made up of 144 Hall effect sensors in a 12 by 12 configuration. We will be utilizing analog Hall effect sensors instead of digital ones because it will make visualizing the heat map more comprehensive and will allow for different field strengths to be represented instead of just having the sensors detect the presence or polarity of said field. When analog Hall effect sensors come into contact with a magnetic field the electrons and holes separate in them creating a voltage that is proportional to the strength of the magnetic field. The analog outputs of the sensors would feed into several multiplexers which would then feed into the analog-to-digital converter pins on the MCU.

MCU

The MCU will have built-in analog-to-digital converters which will allow us to take the analog data coming from the multiplexers and convert it to digital signals that can be processed by the MCU. The MCU will be reading the voltage value of the Hall effect sensors and assigning a field value to them. This information will then be transmitted to our display screen via SPI.

Display

The display will receive data from the MCU and show the 2D map of the field. It will be a colored display using red to represent a region of high intensity and green to represent a region of low intensity, dark red being the highest and light green being the lowest. The colors will work similarly to a weather radar showing the levels of rain using different colors to represent different intensity. The display will have 144 such regions that can change colors according to the Hall effect sensor from which it is receiving information. The display will have a refresh rate of 60 Hz which will allow for real-time updates from the sensors to show any changes in the magnetic field such as moving a magnet across its surface or rotating its polarity.

The display will be able to switch between mapping things such as the amplitude of the magnetic field, the frequency of the magnetic field, the polarity of the magnetic field or change to a display that shows the number associated with each color mT for field intensity, Hz for frequency, and 1 or -1 for field direction. The screen will display which view is currently being shown. These views will also display a guide to show the user what value each color and intensity of said color represents.

The display will be a touchscreen to allow for user inputs. The user will be able to use the screen to change between displays, choosing which graph they want to see and how they want the data to be presented. The user will be able to change if they are viewing a graph showing amplitude, frequency, direction of field, or the raw data values. The screen will also allow the user to save the data from the past 30 seconds to an SD card.

Memory Card Connection

The device will come equipped with an SD card capable of storing 32 GB of information. This SD card will be ejectable so that a user can download information from the device and view it on their laptop or other devices capable of reading an SD card. The MCU will automatically save the last 30 seconds' worth of data to the SD. If the user does not save the data then it will be overwritten. The user can choose when to save 30 seconds worth of data and will be able to save multiple instances. The SD card will contain the information that could have been displayed on the screen such as the amplitude graphs, frequency graphs, field direction graphs, and the raw data.

Software

The software for the project will be responsible for acquiring sensor data, processing it, and updating the visual heat map on the onboard LCD display in real time. The software will be designed to meet a 60 Hz display refresh rate while sampling a 12 x 12 sensor array (144 sensors) with sufficient accuracy and speed. The microcontroller firmware will be developed in C, utilizing the STM32's existing libraries for LCD display interfacing (via SPI), expediting the development and testing process.

SPI is chosen for its higher data throughput, full-duplex capability, and lower latency compared to I2C or UART, advantages that are critical for achieving a smoothly refreshing, real-time display. An ADC (most likely 12-bit) will be used to convert the analog signals from the Hall effect sensors (routed through multiplexers) into digital values. Each sensor in the array is sampled individually. Given the need for real-time performance, it is critical that both the ADC conversion rate and the MCU's clock speed are sufficient to complete all 144 sensor readings within 1/60th of a second.

Initial calibration routines should allow for programmable offset and gain adjustments per sensor to account for base interference and component variances. Although the exact calibration method will be refined after sensor integration on the PCB, a calibration routine will be included in the firmware to adjust for ambient noise and baseline offsets.

The raw ADC values should be directly mapped to a set of bins corresponding to intensity levels. Each bin is associated with a specific color, with 16-24 possible colors available to represent different ranges of magnetic field strength. The min and max sensor values will be determined either via calibration or dynamic scaling, ensuring that the bin sizes accurately represent the range of measured voltages. At this stage, minimal processing beyond binning and scaling is performed on the sensor data, as the main objective is to maintain a high refresh rate for the heat map. However, if future testing indicates that interpolation or smoothing is needed to enhance the visual representation, this functionality can be incorporated as an optional processing step before mapping values to colors. The values acquired from the ADCs at this stage are all that is required for the comprehensive development of the various graph types and display modes outlined in the display section above.

The software's main loop should be optimized to sequentially sample each sensor, process the ADC values, update the corresponding bins and values, save data to the SD card, and transmit the color-coded data to the display. The clock speed of the MCU should be configured to ensure that all sensor readings, storage operations, and display updates are completed within the time frame required for a 60Hz refresh rate. This approach guarantees that the heat map remains accurate and responsive to changes in the magnetic field. Data is sent from the MCU to the LCD via the SPI protocol. SPI is selected due to its high throughput, full-duplex operation, simplicity, and reliability. The MCU will use the binned ADC data to generate a color-coded heat map. Each sensor's ADC reading is mapped to one of the predetermined color bins. The display would be partitioned into 144 regions, each representing a sensor's reading, which together form the complete 2D visualizations of the magnetic field.

Early software testing will be performed using a reduced sensor array (potentially a 2 x 2 array on a breadboard) to verify the basic acquisition, calibration, and display update functionality before scaling up to the full array size. This phased approach should allow for early debugging and performance verification. Although we do not expect the need for a full user interface, a simple status and legend display on the LCD will be incorporated to indicate operational mode or diagnostic information.

1.5 Requirement Specifications

Parameter	Purpose	Value
Basic Features		
Resolution	Magnetic field mapping	≥ 12x12 resolution displayed on screen
Measured Dimensions	Area covered by the system	12cm & 12cm area
Field Intensity Range	Detect a range of magnetic field strengths	$\pm$ 10 mT
Refresh Rate	Provide real-time measurement updates	60 Hz sampling rate
Detection Distance	Accurately measure fields close to the sensor	≈ 1 cm
Price		< $250
Power		< 5W

Advanced Features		
Data Logging	Stored values for analysis	Saves 30 seconds of data
Stretch Goal Features		
Rail Motors	Automated scanning	125x125mm scanned field

Table 1: List of Requirements & Stretch Goals

Specification notes:
Items in Blue will be demonstrated on D-Day
For demonstration purposes, we will use a magnetic field source such as a permanent magnet, and hold it above the sensor matrix. The display will show a heat map showing areas of high intensity in red and areas of lower intensity in green. We will have the display show values at each sensor and compare this data with an external off-the-shelf device with the ability to measure magnetic fields to verify that our display is showing valid readings.

To demonstrate that the display is refreshing we will move the magnet across the sensor, further away from the sensor, and rotate the magnet causing the polarity to flip. The display will be refreshing in real time to accurately show how the field is changing. The display will also be able to show the refresh rate to confirm that it is refreshing at least 60 times per second.

To demonstrate the data logging feature, we will save a recording after 30 seconds to the onboard SD card and put it into another device to view the contents of the card. This will allow us to see the past 30 seconds of recorded data.

1.6 House of Quality

The House of Quality provides insights into the trade-offs between various engineering requirements in H.A.L.O. Many of these requirements are interconnected, meaning improvements in one area could come at the expense of another. For example, increasing the refresh rate of the magnetic field mapping system may demand higher processing power, which could lead to increased power consumption and have an impact on our battery life. Similarly, reducing the system's size would require components to be placed closer together, increasing the risk of electromagnetic interference, which could degrade overall performance. Understanding these relationships allows us to make better-informed decisions in our design to ensure we create a well-balanced system that meets technical and logistical goals.

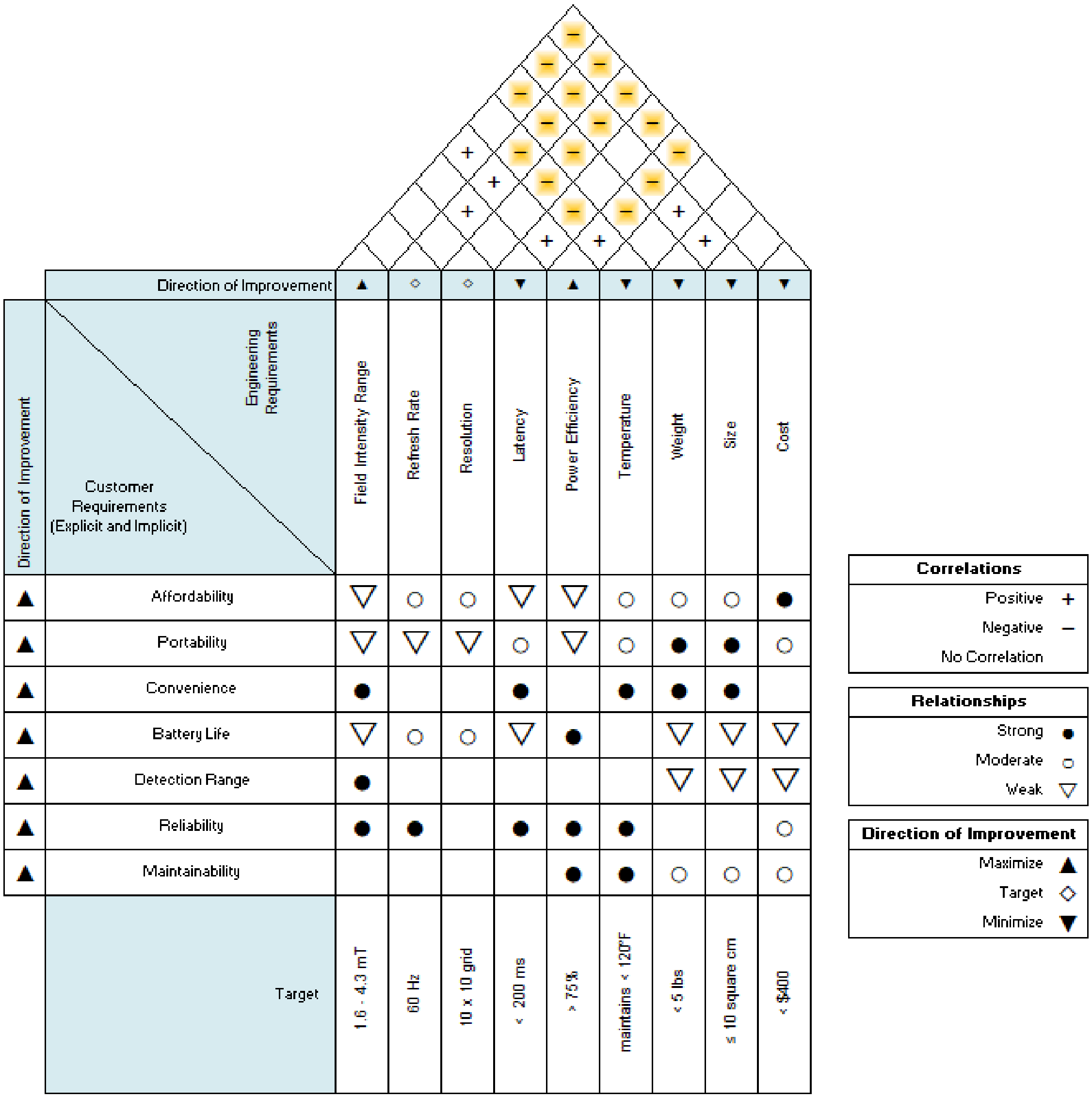


Figure 1: House of Quality Diagram

Chapter 2: Hardware Block Diagram

The H.A.L.O. system consists of two primary PCBs: the Sensor PCB and the Main PCB. The Sensor PCB houses the Hall-effect sensor array, which is used for measuring magnetic fields, as well as the multiplexer (MUX), analog-to-digital converter (ADC), binary counter, and decoder that work together to process and address the sensor readings. The Main PCB handles the system's power, processing, and output. It features a microcontroller (MCU), which manages tasks such as data acquisition, processing, and user interface interactions. The power subsystem includes a USB-C port for charging, a 3.7V lithium-ion battery, a battery management chip, and 3.3V/5V voltage regulators to ensure stable voltage across the system. Additionally, the Main

PCB is equipped with an SD card connector for data storage and is connected to a touchscreen LCD display for real-time visualization of the magnetic field data. To minimize magnetic interference and optimize overall system performance, the Sensor and Main PCBs are connected via a flexible printed circuit (FPC).

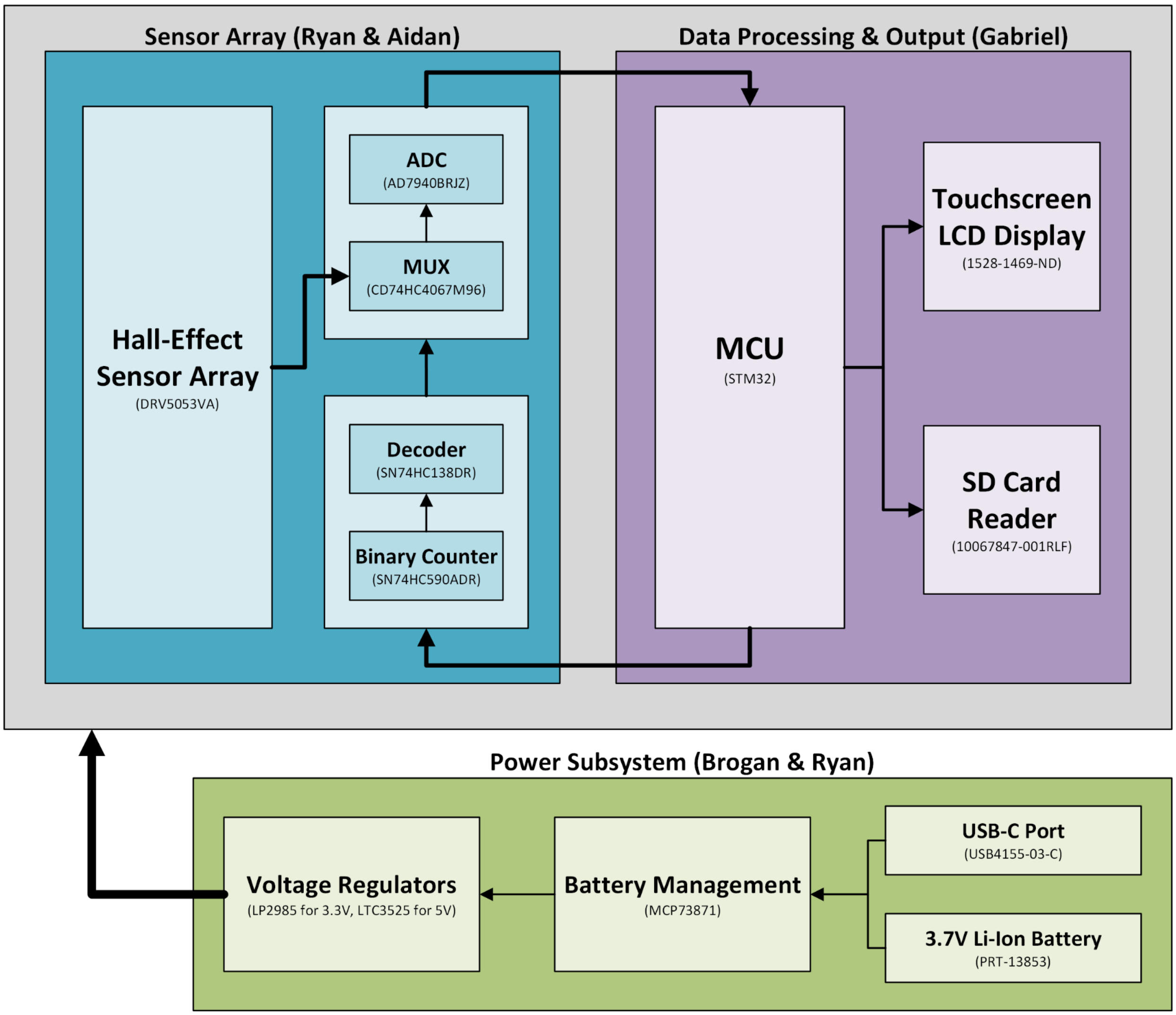
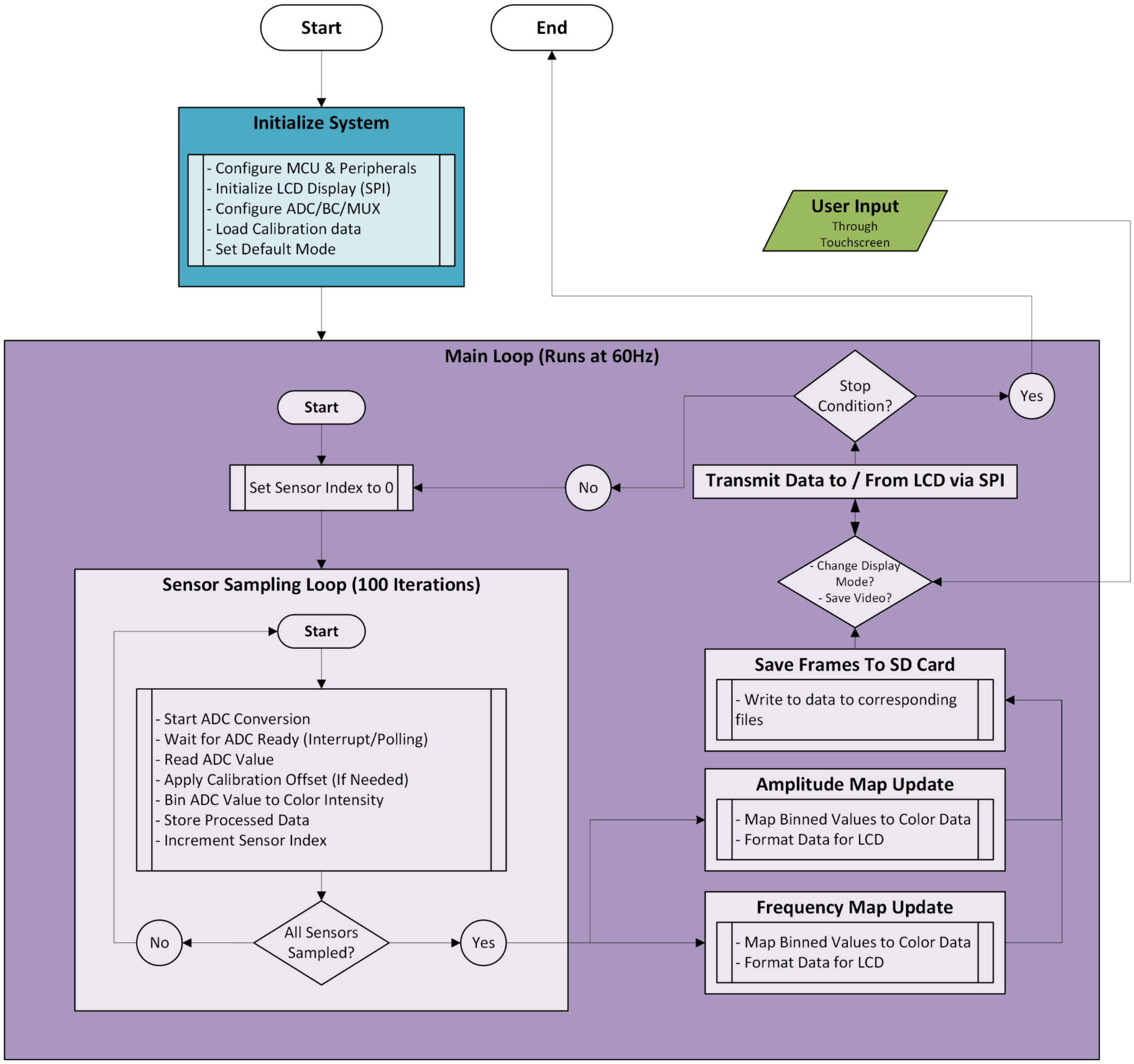


Figure 2: Hardware Block Diagram

Chapter 3: Software Flow Chart



Chapter 4: Budget & Financing

Component	Name	Price	Quantity
Electrical			
Hall-Effect Sensors	DRV5053VA	$0.55	144

STM32 Microcontroller	STM32F103C8T6	$6.08	1
Linear 3.3V Regulator	LP2985-33DBVR	$0.48	1
Switching 5V Regulator	LTC3525ESC6-5#TRPBF	$6.75	1
3.7V Lithium-Ion Battery	PRT-13853	$5.50	1
Battery Management Chip	MCP73871	$2.51	1
USB Type C Port	USB4155-03-C	$1.61	1
16:1 Multiplexer	CD74HC4067M96	$0.58	9
Analog-to-Digital Converter	AD7940BRJZ	$13.52	1
8-Bit Binary Counter	SN74HC590ADR	$0.48	1
3-to-8 Decoder	SN74HC138DR	$0.26	2
Memory Card Connector	10067847-001RLF	$2.00	1
Touchscreen LCD Display	1528-1050-ND	$24.95	1
Flat-Flex Cable	0150150233	$2.02	2
Misc Components		~$20.00	
Mechanical			
3D-Printed Housing	ABS Filament	$10.00	
Shielding Metal (Optional)	Mumetal Foil		
Total		**$182.86**	

Table 2: Bill of Materials

The total estimated budget for this project is $179.78. This estimate accounts for all necessary components, with some flexibility for potential adjustments or additional expenses. While the budget does not currently include spare parts, we plan to order extra Hall-effect sensors and other critical components to mitigate the risk of damaged or defective parts. Given the high number of sensors in our design, we will be sure to test each unit before integrating them into our PCB to ensure they function reliably. If unexpected changes must be made, we will be sure to look at cost-effective alternatives or adjust our component selection to stay within a reasonable budget.

Chapter 5: Project Milestones

Item	**Start Date**	**End date**	**Anticipated Duration**
Brainstorming	1/10/25	1/16/25	1 week
Divide and Conquer (D&C) Report	1/16/25	1/23/25	1 week
Divide and Conquer (D&C) Group Meeting	1/27/25	1/27/25	1 day
Update and upload D&C report onto group website	2/1/25	2/6/25	< 1 week
Parts selection	2/7/25	2/15/25	1 week
Acquire parts	2/7/25	3/10/25	Around 1 month*
Initial PCB design	2/16/25	3/2/25	2 weeks
Breadboard prototyping	3/11/25	4/14/25	1 month
Midterm Report	3/16/25	3/23/25	1 week
Midterm Report Group Meeting	3/26/25	3/28/25	1 day
Update and upload midterm report onto group website	3/28/25	4/3/25	1 week
SD1 Final Report & Mini Demo Video	4/15/25	4/23/25	1 week

Table 3: Senior Design 1 Milestones

Item	**Start Date**	**End date**	**Anticipated Duration**
Finalize Design and Parts Inventory	05/12/2025	05/14/2025	2 days
PCB Assembly	05/14/2025	05/28/2025	2 weeks
Finalize Firmware Development	05/28/2025	06/25/2025	4 weeks

Integration Testing	06/25/2025	07/02/2025	1 week
System Optimization	07/02/2025	07/09/2025	1 week
Final Testing and Validation	07/09/2025	07/16/2025	1 week
Final Documentation and Presentation	07/23/2025	07/30/2025	1 week

Table 4: Senior Design 2 Milestones

Appendix

[1] Jansen, Peter. "A Magnetic Imager Tile." Hackaday.io, 29 July 2017, https://hackaday.io/project/18518-iteration-8/log/64376-a-magnetic-imager-tile.

[2] Cai, Jiangwei, et al. "A High-Resolution Magnetic Field Imaging System Based on the Unpackaged Hall Element Array." *Applied Sciences*, vol. 14, no. 13, 2024, p. 5788. https://doi.org/10.3390/app14135788.

[3] S. Akka and M. Missous, "Design of a portable, two dimensional magnetometer, using 2 dimensional quantum Hall effect sensor array, optimised for low magnetic field applications," The 10th IEEE International Symposium on Electron Devices for Microwave and Optoelectronic Applications, Manchester, UK, 2002, pp. 177-182, doi: 10.1109/EDMO.2002.1174951. keywords: {Sensor arrays;Magnetometers;Hall effect devices;Design optimization;Magnetic sensors;Voltage;Data acquisition;Spinning;Magnetic fields;Magnetic switching},

[4] N. Fischer, J. Kriechbaum, D. Berwanger and F. Mathis-Ullrich, "Compliant Hall-Effect Sensor Array for Passive Magnetic Instrument Tracking," in IEEE Sensors Letters, vol. 7, no. 3, pp. 1-4, March 2023, Art no. 2500404, doi: 10.1109/LSENS.2023.3250971. keywords: {Sensor arrays;Sensors;Magnetic sensors;Bending;Target tracking;Magnetic flux;Shape;Magnetic sensors;passive magnetic sensing;flexible sensors;Hall-effect sensors;magnetic tracking;self-sensing;wearable sensors},