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

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***Abstract* — Magnetic field sensing systems are often large, expensive, and stationary, making them impractical for everyday use. H.A.L.O. (Hall-effect Array for Live Observation) directly addresses these limitations by providing a compact, battery-powered system capable of detecting and visualizing magnetic fields. The device captures magnetic field intensity in real time using an 8x8 grid of DRV5053VA Hall-effect sensors. These readings are multiplexed, digitized using a high-speed SPI ADC, and processed by an ESP32 microcontroller. Data is transmitted to a Raspberry Pi 4, which visualizes the field either as a heat map or a matrix of individual sensor readings on a touchscreen LCD. Data logging is also supported for saving magnetic field data to an external SD card. A 7.4V lithium-ion battery powers the system, which is regulated using buck converters and can be recharged using a dedicated charging IC. H.A.L.O. offers a functional portable solution for magnetic field observation in educational and research environments.**

***Index Terms* — Hall-effect Sensor Array, Magnetic Field Imaging, ESP32, Multiplexing, SPI ADC, Raspberry Pi, Embedded System, Battery Power, Magnetic Sensing**

I. Introduction

A. Background & Purpose

Magnetic fields are present in many physical systems, yet their invisibility to the naked eye makes it difficult to observe and understand without specialized tools. While devices such as Gaussmeters and Hall probes are available, they provide only single-point measurements and lack the ability to capture a broad view of the magnetic field structure. Other available solutions are often bulky, expensive, and not suited for portable use or real-time visualization.

Magnetic field visualization is seen in a variety of disciplines for a variety of usages. Educational applications see relatively simple approaches like magnetic shavings that help to approximate field lines. The engineering profession sees technology employed for visualizing the fields and their strengths at points in space created by systems and electronics. This analysis aids in testing and redesign. The medical field relies on magnetic field visualization for technologies like magnetic resonance imaging (MRI). These large machines allow for non-invasive viewing of crucial areas in a patient; however, these varied technologies tend to either lack sophistication or are extremely large, bulky, and unwieldy.

There is a clear need for a compact system that enables real-time magnetic field visualization. Such a tool would allow users to better understand field strength and distributions in an intuitive and interactive way, without requiring tedious repositioning or complex equipment. In the classroom, this could make magnetic concepts more tangible by revealing field patterns generated by everyday objects. In research environments, it could facilitate the investigation of new magnetic materials and electronic components such as sensors and voltage regulators. H.A.L.O. (Hall-effect Array for Live Observation) was developed to meet this need using a low cost, embedded platform based on analog sensors and microcontroller data processing.

The design centers on accessibility, modularity, and ease of use. The system's architecture includes a planar array of Hall-effect sensors, digital data processing, live display output, and onboard data logging. It is battery powered and fully self-contained, making it suitable for portable use without the need for any external infrastructure. By combining real-time sensing with intuitive feedback and visualization, H.A.L.O. provides a practical tool for observing magnetic fields in ways not readily available with conventional tools.

B. Magnetic Field Visualization

An integral aspect of this project is how H.A.L.O. will visualize the magnetic fields it detects. Both visualization methods will consist of an 8x8 grid of squares where each tile displays data corresponding to the measurement obtained by its respective Hall-effect sensor. H.A.L.O. will visualize the magnetic field in two distinct ways: a heat map and raw data.

The heat map is the most intuitive method for displaying the magnetic field. This method consists of displaying a color in each tile that corresponds to the value obtained by the Hall-effect sensor that tile obtained. Positive values will be shown using red, and negative values will be shown using blue. The larger magnitudes will have a darker shade, and the smaller magnitudes will have a lighter shade.

The other method of visualizing the magnetic field is directly displaying the values obtained from the Hall-effect sensors. There exists a linear relationship between the voltage produced by the Hall-effect sensor and the strength of the magnetic field, so after calibrating for the sensitivity of the Hall-effect sensor, the magnetic field strength can be displayed in Tesla at each tile in the visualization on the screen.

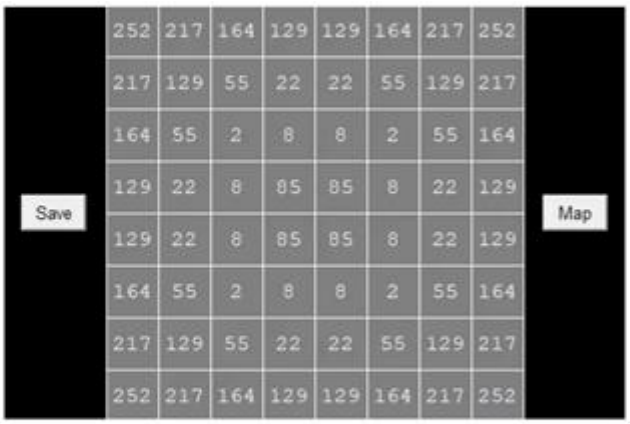

Fig. 1. Demonstration of Raw Data Method for Magnetic Field Visualization

II. SYSTEM COMPONENTS

To understand the functionality of the system, it is important to first define its major components. Each was selected through comparison and evaluation of tradeoffs in size, efficiency, cost, and other design constraints. The rationale behind these selections is discussed in detail throughout this section.

A. Magnetic Field Sensor

The DRV5053VA from Texas Instruments is a chopper-stabilized Hall-Effect sensor that provides a linear analog output voltage in response to magnetic flux density. This sensor operates with a supply voltage ranging from 2.5V to 38V, meaning it is a versatile option that can be used in various applications. The sensor’s chopper stabilized design modulates its signal at a high frequency to minimize noise and DC offset, meaning it is capable of maintaining high accuracy over a wide range of operating conditions.

In the absence of a magnetic field, the DRV5053VA outputs a voltage of 1V. When we expose the sensor to a magnetic field, the output voltage changes linearly, with the direction of the magnetic field influencing the voltage polarity. This sensor is available in models with varying sensitivities, including -45 mV/mT, -23 mV/mT, -9 mV/mT, +23 mV/mT, and +45 mV/mT. For our application, the ±9 mV/mT version will be the most suitable, as it provides a response to everyday magnetic fields such as desktop magnets or small electric motors.

One of the more notable features of the DRV5053VA is its capability to determine the polarity of an applied magnetic field. For this model, a south pole magnetic field decreases the output voltage below 1V, while a north pole magnetic field increases it above 1V. This polarity sensitivity is a great addition to this sensor, as we will also be able to observe the direction of magnetic fields.

This sensor also has excellent temperature stability, with its sensitivity only varying by ±10% over an operating temperature range of -40°C to +125°C. While it is not likely that our system will be exposed to extreme temperatures, it is helpful to note that this is a robust sensor that will not experience fluctuations when changing its surrounding environment.

The DRV5053VA is offered in a compact 3-pin surface-mount package, making it much easier to integrate into our custom PCB. Since our system involves integrating 64 of these sensors together, a compact packaging is crucial in minimizing the size of our PCB and simplifying routing.

In summary, the DRV5053VA Hall-Effect sensor offers a combination of high sensitivity, temperature stability, and ease of integration, making it an excellent choice for precisely measuring magnetic fields in our system. While it is important to mitigate interference when using this sensor, this limitation is minor compared to its significant advantages.

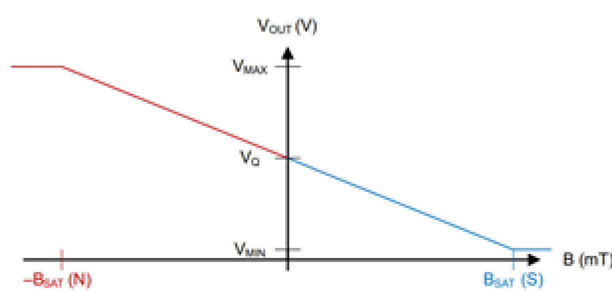

Fig. 2. Voltage and Tesla relationship for Hall-effect sensors

As can be seen in the above graph, the polarity of the magnetic field is determined by establishing a midpoint between the minimum and maximum saturation voltages seen by the Hall-effect sensor. The correct Tesla values can be ascribed to the voltage levels obtained from the Hall-effect sensor by using the sensitivity of the sensors and through testing. In theory, the minimum and maximum saturation voltages should correspond to –9 mT and +9 mT respectively.

B. Multiplexers (MUX)

The CD74HC4067/CD74HCT4067 is a high-speed 16-channel analog multiplexer/demultiplexer that allows a single analog or digital signal to be routed to one of 16 channels using 4 binary address inputs. It features low on-resistance typically 70 Ω at 4.5 V, fast switching ~13 ns, and break-before-make behavior to prevent channel shorting. The device operates over a wide supply voltage range, 2 V to 6 V for HC, 4.5 V to 5.5 V for HCT and supports both analog and digital signals across the full supply range. It includes an active-low enable pin to disable all channels and offers excellent signal integrity with a –75 dB off-channel isolation and up to 89 MHz bandwidth.

For the purpose of our project, we are using 4 16:1 MUXs with a fast switching speed so that we can cycle through all of the sensors quick enough to provide an adequate refresh rate. The select and enable lines are controlled by the MCU and that allows us to send the outputs from all of the sensors to the ADC one at a time.

C. Analog-to-Digital Converter

The ADS7883SDBVR developed by Texas Instruments is a compact, low-power, capacitor-based SAR analog-to-digital converter that delivers 12-bit resolution at speeds up to 3 MSPS. It uses a simple three-wire SPI interface. It operates from a single 2.7 V – 5.5 V rail, the device draws only a few milliamps at full speed and offers a power down mode for duty cycled operation, making it a good fit for our battery powered system. Its digital input pins tolerate levels up to 5.5 V regardless of the actual supply voltage, which simplifies mixed-voltage designs and relaxes power-up sequencing requirements. Housed in a tiny six-pin SOT-23 package and specified over the –40 °C to +125 °C range, the ADS7883 slots easily into space-constrained, wide-temperature applications that need fast, high-resolution data acquisition without sacrificing power budget.

The speed that this ADC operates at makes it a good choice for reading data from sensors and providing a fast refresh rate. Its small form factor also makes a good choice for a small electronic device like the HALO sensor array. With a 12 bit resolution, it provides enough accuracy to acquire meaningful sensor data to be displayed.

D. Microcontroller Unit (MCU)

The ESP32, developed by Espressif Systems, is a high-performance and low-power microcontroller with integrated Wi-Fi and Bluetooth connectivity. It features a dual-core Tensilica Xtensa LX6 32-bit processor, running up to 240MHz with 520KB of onboard SRAM. There are 34 general-purpose I/O pins with support for touch sensing and capacitive inputs, along with support for various communication protocols, including I2C, SPI, UART, CAN, and PWM. It’s also equipped with a 12-bit SAR ADC with up to 18 input channels. With an operating voltage of between 2.2V and 3.6V, the MCU is adaptable to a variety of applications.

The ESP32 is available in various form factors, most notably the surface-mount variant, the ESP-WROOM-32. There are various devkits available for the ESP32, with most offering USB support and advanced peripherals, as well as a RISC-V-based power-optimized variant. The ESP32 is extremely well-supported, with many of the most common development environments offering specific ESP32 IDEs including Arduino IDE, Espressif IDE, MicroPython, PlatformIO, as well as extensive Microsoft Visual Studio packages.

For the scope of H.A.L.O, the ESP 32 will be used to control the MUXs and ADC for retrieving raw voltage data from the sensors and converting it to magnetic field data before being sent to the Raspberry Pi to be displayed on the screen.

E. Raspberry Pi 4 & Touchscreen Display

Our system requires a responsive visual interface to render spatial data collected from the hall effect sensor array in real time. The selected display subsystem consists of a Raspberry Pi 4 Model B single-board computer, interfaced with a 5-inch capacitive touchscreen LCD (Liquid Crystal Display) panel through a MIPI DSI (Mobile Industry Processor Interface Display Serial Interface) flexible printed circuit (FPC) cable.

The Raspberry Pi 4B serves as the graphical processing and user interface host. It comes with a Broadcom BCM2711 quad-core ARM Cortex-A72 processor running at 1.5 GHz, 4 GB of LPDDR4 RAM, and I/O capabilities including full-size HDMI, USB 3.0, and a native MIPI DSI output. This DSI interface is used to drive the Hosyond 5-inch capacitive touchscreen LCD, which accepts video signals through a 2-lane MIPI DSI interface and connects through a 15-pin FPC (flexible printed circuit) ribbon cable. The display has a resolution of 800×480 pixels and features a capacitive touch sensor supporting multi-touch input. The FPC connection was chosen over HDMI for its compact profile and lower latency in transmitting display signals directly from the Pi's GPU to the LCD panel, resulting in smoother graphical updates and reduced wiring complexity within the final enclosure.

This display configuration was selected not only for its resolution and touchscreen capability but also because the Raspberry Pi supports running the Linux operating system natively, which provides an accessible platform for rapid GUI development using high-level languages like Python. The Raspberry Pi runs a customized Raspbian Linux operating system that boots directly into the GUI environment used by HALO. Unlike embedded microcontroller-based GUI systems, this setup enables much faster development and iteration because it has access to well-supported ecosystem of open-source libraries and hardware abstraction layers. Furthermore, this configuration simplifies integration with external peripherals, such as an SD card for data logging and a UART interface for communication with the sensor array subsystem.

F. Power Supply Unit

The circuit is supplied power via two 18650 button top lithium-ion batteries. The power is sent to two different regulators: one at 3.3 V and one at 5.0 V. Our circuit also utilizes an MP2615 battery management chip. This allows the system to be charged via a 12 V power input. This addition allows for charging via a wall outlet. This eliminates not only the need to constantly remove and insert batteries but also the need for a separate method of charging the batteries as that functionality is included in our system.

The 3.3 V and 5.0 V regulator circuits were both designed with TI's WEBENCH tool. The 3.3 V regulator uses an LM2576 switching regulator, and the 5.0 V regulator uses an LM2679 switching regulator. Using switching regulators for both step-down converters ensure a system with high electrical efficiency and all the benefits that come along with that, such as lower operating temperature and lower power consumption.

III. SYSTEM CONCEPT

To give a clear overview of H.A.L.O.'s functional structure, a hardware block diagram is included illustrating the major components of the system and how they interact. This diagram reflects the flow of data and power from the point of magnetic field detection to user feedback via the touchscreen interface.

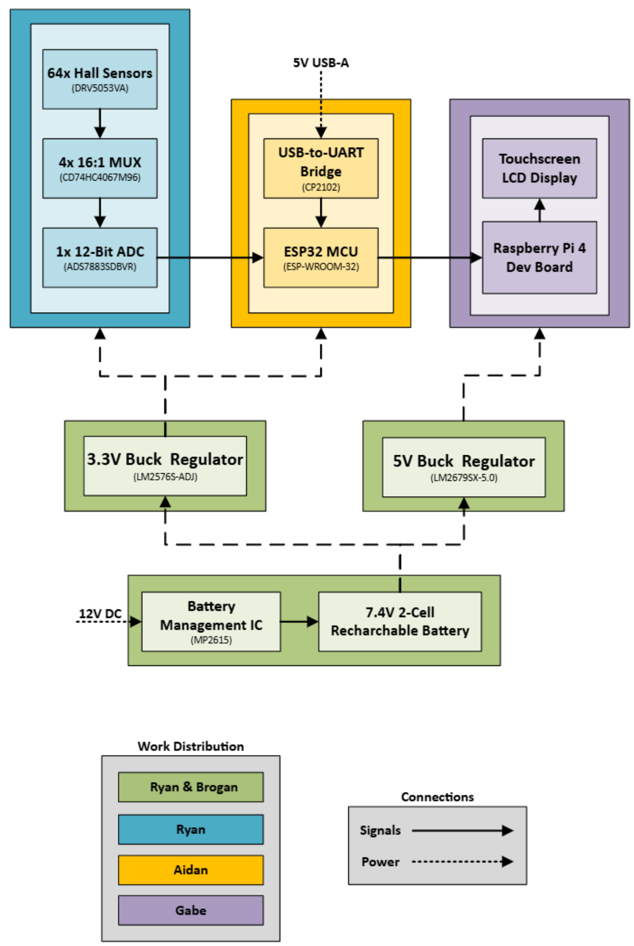

Fig. 3. Hardware Block Diagram & Work Distribution

The H.A.L.O. system is composed of several interconnected subsystems designed to operate together as a compact and self-contained magnetic field imaging device. At the core is an 8×8 array of DRV5053VA analog Hall-effect sensors, which detect local magnetic flux density. These sensors feed into four 16:1 analog multiplexers (CD74HC4067), which sequentially route one sensor output at a time to a single ADC for digitization.

A 12-bit ADS7883 SPI ADC samples the analog signal at high speed and delivers the data to an ESP32 microcontroller. The ESP32 handles MUX selection logic, data collection, and conversion of voltage values into calibrated magnetic field strength values. Once a full frame of 64 measurements is collected, it is transmitted to the Raspberry Pi 4 via UART.

The Raspberry Pi receives the sensor data and renders it in real time to a 5-inch capacitive touchscreen. Two visualization modes are supported: a numerical grid and a color-coded heatmap. Data can also be saved to an SD card for later analysis.

The entire system is powered by a 7.4V lithium-ion battery. This battery supplies power to two independent buck regulator circuits: a 3.3V regulator for the ESP32 and analog components, and a 5.0V regulator for the Raspberry Pi. Charging and power management are handled by an MP2615 battery management IC, allowing the system to recharge through a 12V input without removing the battery.

This architecture emphasizes modularity, efficient power use, and reliable data throughput, enabling H.A.L.O. to function as a fully portable and practical magnetic field imaging solution.

IV. Hardware Detail

Each subsystem introduced in Section II is expanded on here, with technical focus on performance, layout, and how the components are integrated.

A. Sensor Array and Multiplexing

The Sensor Array PCB forms the core of the system and contains 64 DRV5053VA Hall-effect sensors laid out in an 8×8 grid. Each sensor outputs a voltage that varies linearly with magnetic field strength. We chose the VA variant for its ±90 mV/mT sensitivity, which helps the system detect small changes in field intensity from things like permanent magnets or nearby current-carrying conductors.

To reduce the number of ADC inputs needed, the array is connected to four CD74HC4067 analog multiplexers. These 16-channel MUXs are addressed using shared 4-bit select lines, while the ESP32 handles enable signals independently for each chip to scan one quadrant at a time. This sequencing allows us to scan the full array using just one ADC channel. Switching timing was adjusted to ensure clean signal handoff between MUX channels.

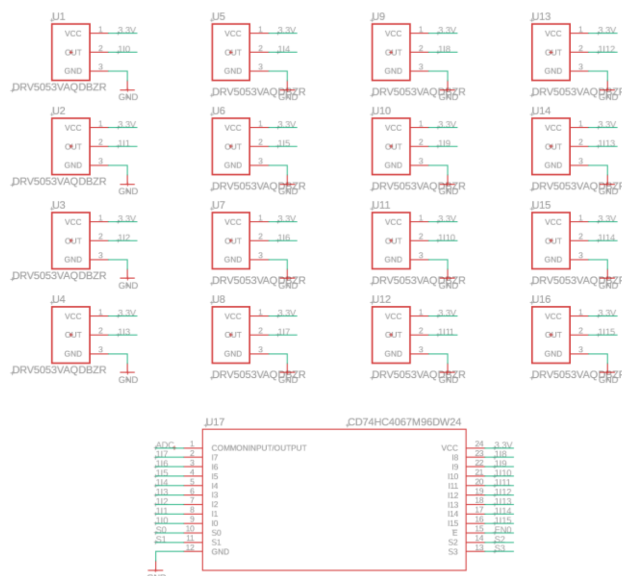

Fig. 5. Sensor Array & Multiplexer Schematic

The analog layout was carefully designed. Sensor outputs were routed with matched trace lengths to minimize skew, and a continuous analog ground plane was placed underneath to limit noise pickup and keep readings consistent.

B. Data Acquisition & Microcontroller Unit

The sensor voltages are read by a Texas Instruments ADS7883, a 12-bit SAR ADC with SPI output. It supports up to 3 MSPS, though our system runs at 1 MSPS for better consistency. The ADC’s small SOT-23-6 footprint made it easy to place close to the sensor array, reducing routing length. A dedicated chip select pin helps sync the ESP32's reads with MUX switching.

The ESP32-WROOM oversees managing the MUXs, polling the ADC, and sending all 64 sensor readings to the Raspberry Pi. It runs at 240 MHz and operates at 3.3V.

One core is dedicated to sensor scanning, while the other handles UART communication. We use a 921600 bps UART connection to ensure that data moves quickly enough to avoid GUI lag on the Pi.

Sensor data is buffered on the ESP32 until the full 8×8 matrix is scanned. Once the entire set is captured, it's sent to the Pi as one serial packet. This setup keeps latency low and makes debugging simpler by separating data collection from visualization.

C. Power Management

Power is handled by the Battery Management PCB, which holds two 18650 lithium-ion cells in series. The 7.4 V battery rail feeds into the MP2615, a charge management IC that supports USB-C and 12 V DC input. It manages charge current, battery protection, and thermal safety without needing external monitoring.

Two buck regulators step the 7.4 V rail down to the voltages needed by the rest of the system. A 3.3 V rail is generated by an LM2576 to power the ESP32, Hall sensors, and ADC. A 5.0 V LM2679 feeds the Raspberry Pi and its display. These were selected for their high current capacity and because they're easier to work with on prototyping boards. Design values for both circuits were generated using TI WEBENCH.

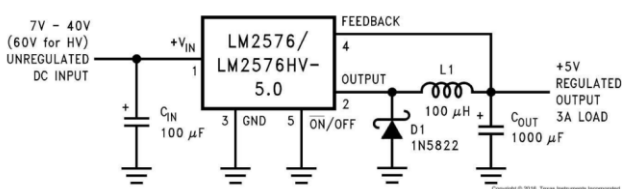

Fig. 6. 3.3V Regulator Schematic

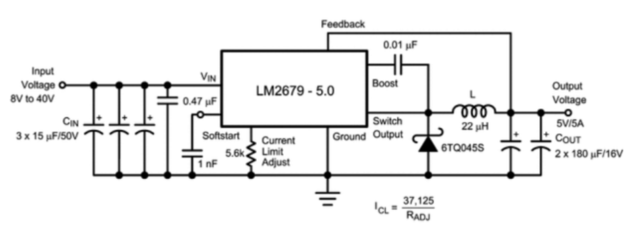

Fig. 7. 5.0V Regulator Schematic

Each regulator sits on its own PCB to keep noisy switching traces away from the rest of the system. This also simplifies troubleshooting and makes swapping out a regulator circuit easy if needed. The regulators are efficient and stay cool under load, which is important since there's no fan or active cooling in the system enclosure.

V. BOARD DESIGN

The H.A.L.O. system is implemented across five custom-designed PCBs: Sensor Array, ESP32, 3.3 V Regulator, 5.0 V Regulator, and Battery Management. Each board was designed in Fusion 360 with modularity, electrical separation, and ease of debugging in mind. Dividing the system into independent PCBs allowed for incremental testing during development and simplified fault isolation when troubleshooting.

All boards were fabricated as two-layer designs, with copper pours used for ground planes on both sides to reduce noise and provide low-impedance return paths. The Sensor Array PCB, in particular, required careful analog layout. It houses the 8×8 grid of DRV5053VA Hall-effect sensors and four CD74HC4067 analog multiplexers. Sensors were arranged with uniform spacing, and signal traces were routed to maintain consistent lengths and minimal crosstalk. Ground planes were maintained beneath all analog signal paths to reduce susceptibility to high-frequency noise.

The ESP32 PCB includes the ESP32-WROOM module, CP2102 USB-to-UART bridge, and associated support components. Trace routing prioritized short paths between the microcontroller, ADC, and multiplexer control lines. Sensitive signals were kept clear of switching power lines, and decoupling capacitors were placed close to the ESP32 and CP2102 to suppress transient noise.

Both regulator PCBs—3.3 V using LM2576 and 5.0 V using LM2679—were laid out with wide power and ground traces to support high current without excessive voltage drop. The design followed TI's WEBENCH recommendations for component placement, including proper feedback trace routing, thermal reliefs, and output filtering. These PCBs were also kept physically separate to prevent heat and switching noise from reaching the analog front end.

The Battery Management PCB contains the MP2615 charging IC, two 18650 lithium-ion cells, a USB-C connector, a 12 V barrel jack, and a rocker switch. High-current paths were routed with widened traces and minimal via transitions to avoid unnecessary resistance and heating. The charging IC was isolated from the data and sensor subsystems to prevent interference during fast charge and discharge events.

Headers were used for interconnections between all boards. Power and ground lines use thicker-gauge wires to reduce loss, while logic signals (UART, MUX select, ADC input) are routed using shorter 22 AWG jumpers. This physical separation improved layout clarity and reduced the likelihood of interference across subsystems. Overall, the board layout strategy was built around minimizing noise, isolating power delivery, and ensuring stable performance across all modules.

VI. Software

A. Raspberry Pi 4 Module

The HALO display application is implemented in Python using a custom-built graphical user interface. The application continuously receives sensor data from the ESP32 controller over a UART serial connection. This data represents the real-time output of an 8×8 array of Hall-effect sensors, multiplexed and digitized via external ADCs. Upon reception, the Python application parses the raw ADC values and stores them in a matrix structure representing the spatial grid. Two GUI modes are supported: a “Raw Value” view and a “Heat Map” view. In the Raw Value mode, each cell in the 8×8 grid displays its corresponding ADC value directly, providing immediate insight into numerical sensor outputs. In Heat Map mode, the matrix is rendered as a color-coded grid using a 16-bin color scale that spans a spectrum from deep blue (lowest value) to bright red (highest value), with intermediate colors representing mid-range values. This visualization provides a clear and intuitive representation of magnetic field intensity and polarity across the sensor plane.

While the GUI application currently operates with raw ADC values, future development will incorporate calibration routines to convert these readings into physical units of magnetic flux density (millitesla, mT). This will be achieved by mapping known magnetic field strengths to ADC readings using a linear or polynomial regression model, derived from the hall-effect sensors’ datasheet as well as through controlled calibration experiments. This enhancement will allow HALO to not only visualize field gradients but also report meaningful field intensities in engineering units, expanding its utility in quantitative analysis.

The display software operates in a continuous refresh loop, maintaining a target update rate of 30 frames per second. This is facilitated by Python's Tkinter library for GUI elements, combined with optimized numerical processing using NumPy for fast array operations. The interface also features interactive buttons for switching between GUI modes and, in the final version, will include a "Save" function. This feature will write the current sensor data to the Raspberry Pi’s internal storage, allowing users to log temporal snapshots of the field distribution for post-analysis. Each snapshot will be saved in a human-readable format such as JPEG, CSV or JSON, making it compatible with downstream tools such as MATLAB, Python pandas, or spreadsheet software.

The touchscreen aspect of the display is supported natively by the Raspberry Pi’s Linux kernel and configured via standard input device drivers. While currently only used for toggling the GUI mode, the touchscreen provides a future-proof avenue for additional interaction paradigms, such as region selection, snapshot viewing, or parameter input for advanced visualization control.

Significant attention was given to the responsiveness and performance of the display subsystem, as real-time interactivity is essential to the system's user experience. To minimize latency and maximize refresh rate, Python was selected as the development language because it is lightweight enough to run efficiently on the Raspberry Pi.

The following diagram shows the general processing that the Raspberry Pi employs to visualize the data. This includes reading sensor data from the ESP32, organizing these values into an array, rendering the heat map / raw value grid, handling touch input, and saving data.

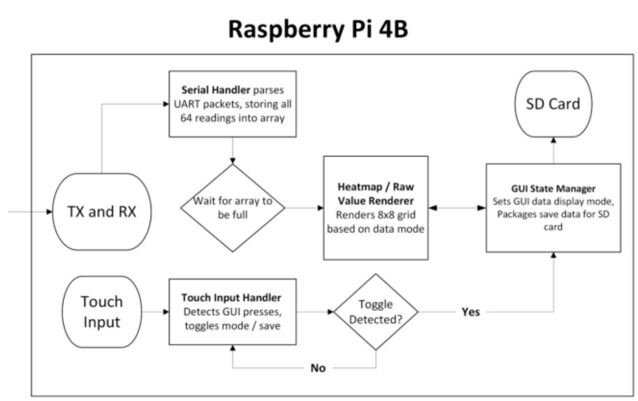

Fig. 8. Software Block diagram

To further optimize communication between the sensor controller and the display system, the UART link connecting the ESP32 and Raspberry Pi was configured to operate at an increased baud rate of 922600 bps. This ensured timely transmission of the full 64-value sensor matrix at each sampling interval, reducing the effective communication delay between the acquisition and rendering phases of the system. At lower baud rates initially tested, the round-trip time between data acquisition on the ESP32 and GUI update on the Pi introduced perceptible lag, particularly when toggling between display modes or observing transient magnetic events. By tuning the serial connection and parsing logic to operate asynchronously, these latencies were significantly reduced.

B. ESP32 Microcontroller

The ESP32 acts as the main controller for the entire system. It is responsible for the handling of data from the sensors to the Pi. We are using Arduino IDE to program the ESP32.

The code defines GPIO pins for S0-S3, EN0-EN3, CS and configures MISO and SCKL for SPI communication with the ADC. The enable lines allow the ESP to disable all of the MUXs except for one so that it can send analogue values to the ADC from one sensor at a time. Once the select lines have gone through all 16 channels, the next enable line will turn on the next MUX in the sequence. The ESP receives the digital values from the ADC and stores the values in batches of 64. The data will not transmit until the ESP has received a fresh batch of 64 values.

The ADCs sample rate is set to 1 MHz. The time for one read is 1 µs. The switching time for the MUX is ~50ns making the total read time for one sensor ~1.05 µs. The total read time for all of the sensors would be 67.4 µs including the on time of each MUX being ~50ns. Without any restrictions, the sensor array is being read at ~14 kHz, but due to screen limitations, this is limited to 10 Hz with a loop that waits to send the signal.

Before the data is sent to the PI, it is converted from voltage values to mT. Once all 64 values have been stored and converted, the data is sent to the PI via UART serial connection matching the baud rate of the PI at 921600 for a high speed connection. The sensor data is sent in order so that it can be displayed on the screen in the proper place.

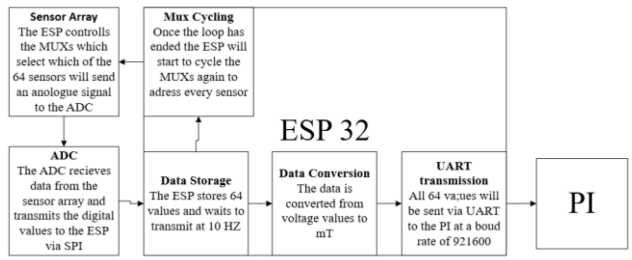

Fig. 9. ESP32 Data Flow Diagram

ACKNOWLEDGEMENT

The authors wish to acknowledge Dr. Piotr Kulik, Dr. Enxia Zhang, and Dr. Jaesung Lee for their time in reviewing and supporting this project

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