Assistive Chessboard

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Abstract

Our proposed project aimed to bridge the gap between the physical feel of a chessboard and intuitive player assistance. To do this, we chose Hall-effect sensors and LEDs as the method of sensing and displaying information. By placing both a Hall-effect sensor and a RGB LED underneath each board square, we identified individual chess pieces through varying magnetic strengths and relayed possible moves with a blue board square, invalid and threatened pieces with red squares, and current move by a green square.

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1. Introduction

Chess is a popular game played by millions of people [1], however it can be quite difficult for a new player to start learning. Utilizing online resources to learn takes away from the experience and feel of a physical board. Our project aimed to alleviate this problem by building a chessboard that links the physical aspect of a board with an interactive educational source to assist new players. By using Hall-Effect sensors and LEDs underneath each board square and chess pieces with different magnetic strengths, we are able to identify individual chess pieces and then relay moves to the player through the LEDs. Possible moves are displayed by blue board squares, and invalid and pieces under threat by red board squares. Overall, our project works as intended as all 12 piece types are identified correctly and the respective feedback is clearly displayed through the LEDs.

2. Design

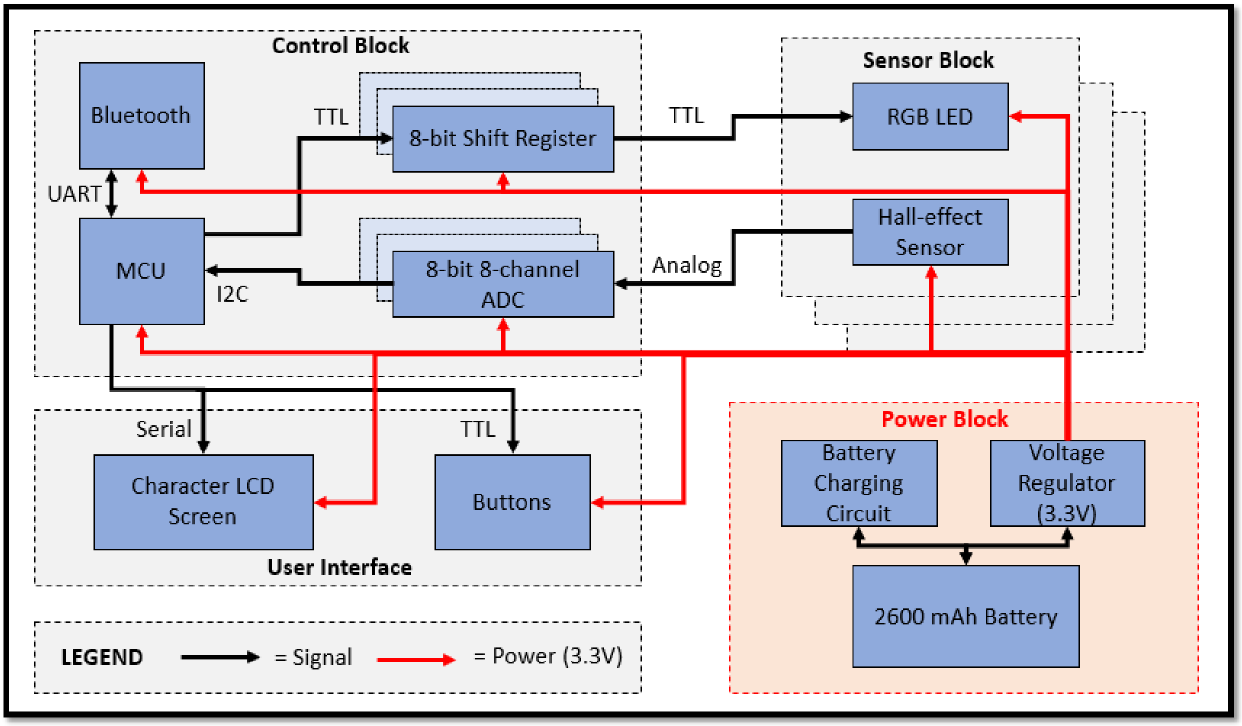

Figure 2.1: Block Diagram

2.1 Control block

The purpose of the Control Board is to manage the entire system. It takes in the analog signals from the sensor array and outputs signals for the LED lights. It also controls the LCD display and is interfaced with by the set of buttons in the User Interface block. Finally, the Control Board is responsible for managing the Bluetooth connection and sending game data through it to a connected device. The Control Board contains a MCU, a Bluetooth module, the LED selector circuit, and 8 8-channel ADCs (one per row of 8 sensor blocks).

While most of the Control Block is straightforward, the LED selector circuit was chosen from a system of only shift registers, only demultiplexers, or a combination of the two. The first method consists of 24 8-bit shift registers and two connections per row to the MCU. However, this method needed a full 24 clock cycles to refresh the LEDs along with a total of 16 connections to the MCU. The second option consists of 33 demultiplexers and 192 latches, and while only needing two clock cycles to change an LED and a total of 10 MCU outputs, would have been significantly harder to solder because of the sheer number of components.

Another LED circuit that was an option was a matrix LED selector. This circuit would have allowed us to daisy-chain each of the rows and columns for the LEDs and allowed for full PWM control of each LED. This option would require extensive coding for controlling each row and having a fast refresh rate to make the lights visually appealing. However, this option was not known to us until the design was finalized and was therefore not considered.

Therefore, we settled on a combination of the two previous methods. Three shift registers per row are used to hold the respective RGB color channel, a multiplexer is used to select the desired row, and six MCU signals (Three for the row, and one for the signal, clock, and asynchronous reset). Despite needing a longer refresh time for the LEDs, there are fewer components and MCU outputs, reducing both cost and sources of error.

2.1.1 MCU

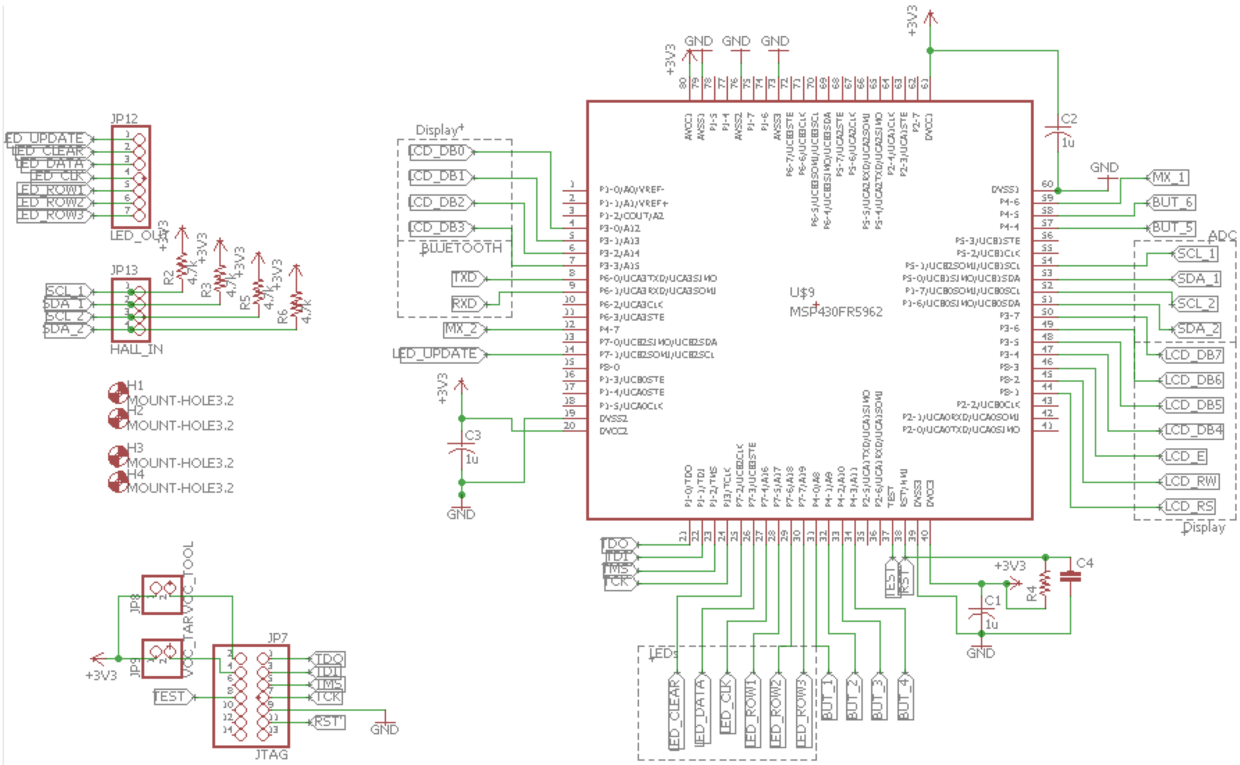

Figure 2.1.1.1: MCU board schematic

The Microcontroller Unit (MCU) stores and updates the board state in its flash memory. Using this it is able to output the appropriate LED signals to perform the board's signaling functions by TTL signaling to the LED selector circuit. It updates the board state by reading the digital sensor readings through an I2C communication from the ADCs. The MCU is responsible for temporarily storing the moves of a game in its flash memory and for sending that data to the Bluetooth module to be transmitted through an UART connection. Finally, the MCU must manage the chess clock settings and time by sending data to the LCD screen and reading inputs from the buttons through TTL signaling.

We used the TI MSP430FR5962 MCU [2] for this project. This MCU contains two I2C buses in order to communicate with ADCs as well as an UART interface for communicating with the Bluetooth module.

2.1.2 Bluetooth

The Bluetooth module is responsible for receiving game data from the MCU and wirelessly relaying the information to a mobile phone or a computer. The module is paired with a small app to display the current game status. This app can be further expanded to include past game move history and useful guides for the user.

The module we selected was the HC-06 Bluetooth module [3]. This module was selected for its relatively low cost as well the ease of sending raw data through Bluetooth, which is practical for sending chess game data.

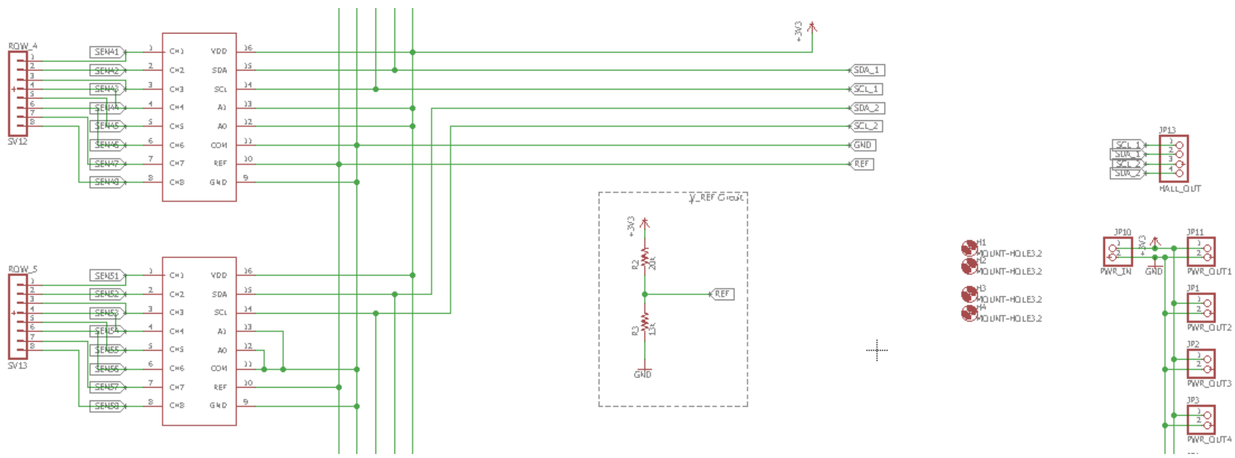

Figure 2.1.2.1: ADC circuit schematic with reference voltage circuit

2.1.3 ADC

The ADCs convert the analog hall-effect sensor outputs into a digital form that can be sent to the MCU over a single line through I2C communication. There are eight, 8-bit 8-channel ADCs, one per row of sensors on the board. Each ADC takes the 8 sensor outputs of its row as its input. This means that having a low power ADC was necessary since eight ADCs would be running at all times. Another aspect we had to consider was the output resolution which had to be appropriately small (see Appendix B).

The ADC we picked was ON Semiconductor's NCD9830 [4] which had a low current draw of 350 μA. The 8-bit output with 8 mV resolution fits our tolerance for discerning individual chess pieces apart, and has eight input channels for all the sensors in each board row.

2.1.4 LED Selector Circuit

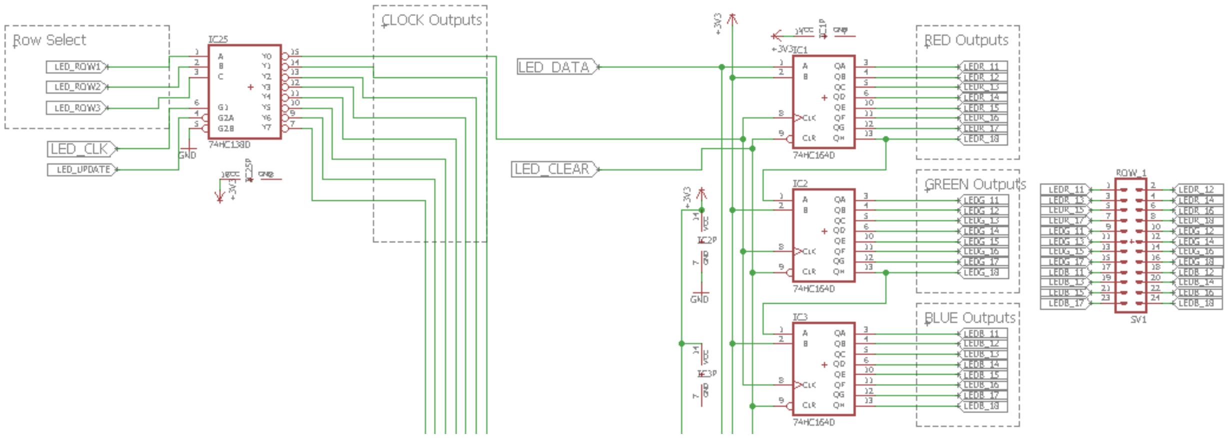

Figure 2.1.4.1: LED Selector circuit schematic

The purpose of the LED Selector Circuit is to allow the MCU to change the state of each color channel for all LEDs on the board. It consists of 24 8-bit shift registers and 1 1-8 demultiplexer. The shift registers are assigned 3 to a row of the board with each one representing one of the red, blue, and green inputs of the LEDs for that row. The output of the red shift register connects to the input of the green and the output of the green shift register connects to the output of the blue to form a 24-bit shift register. The parallel outputs of the shift registers are used to send the signal to the LEDs. The 1-8 demultiplexer acts as a row select for the MCU. When a LED signal needs to be updated on a row, the MCU sends the full 24-bits of that row to be cycled through again. The demultiplexer we selected was ON Semiconductor's MC74HC238A IC [5]. This IC allows the clock signal to propagate within our required timing requirements as well as allows the MCU to accurately select the shift register to modify. The shift register we selected was Texas Instrument's SN74HC164 [6] 8-bit shift register. This IC can provide 8 parallel outputs and is available for a relatively low cost.

2.2 Sensor Block

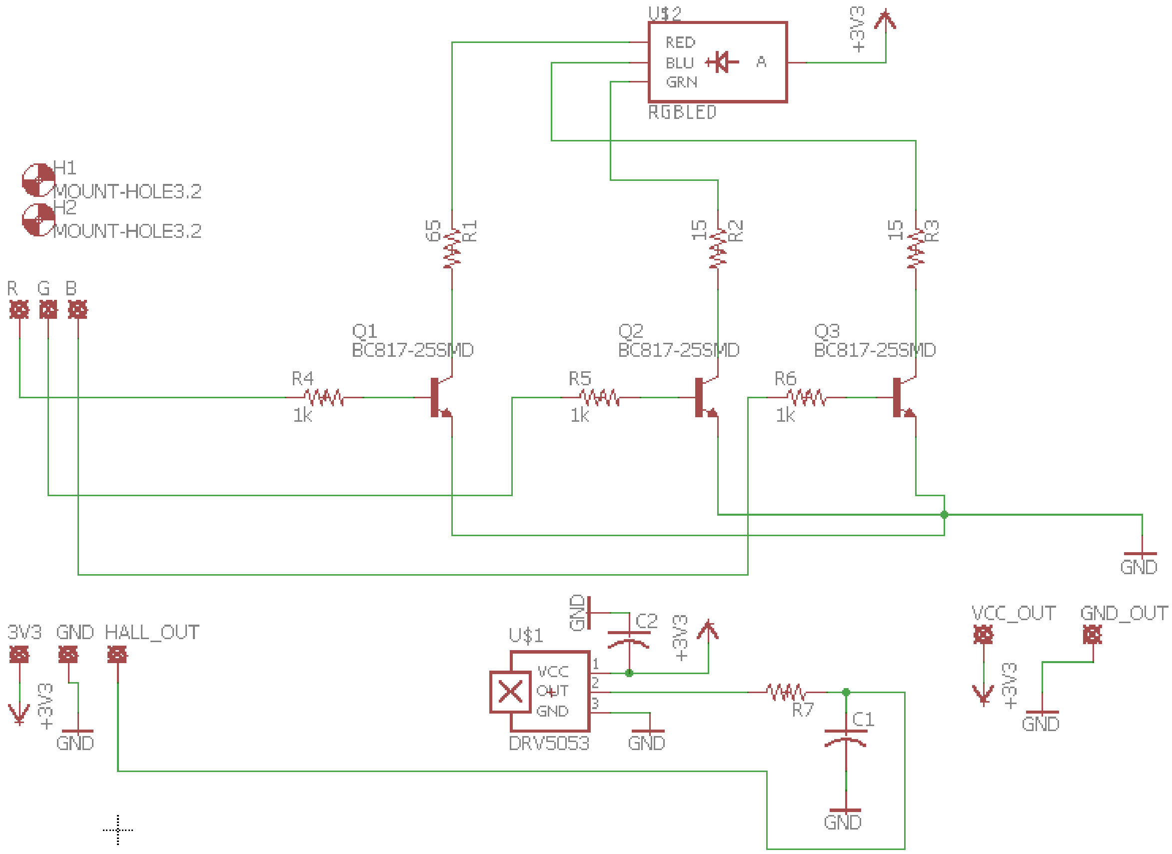

Figure 2.2.1. Sensor board circuit schematic

The Sensor Block is a 1 in. x 1 in. PCB that sits underneath each square on the chessboard. It contains a Hall-effect sensor and an RGB LED, along with control circuitry (i.e. transistors) for the LEDs. The connection to each board will be a 4-wire connection (3 for the RGB LED and 1 for the analog output of the sensor; all go to the Control Block) along with a 2-wire connection for the power and ground line that will be daisy-chained along each of the 8 rows. The purpose of the Sensor Block is to determine the board state and communicate hints to the player.

<u>Justifications:</u> When deciding on the sensing method for this block, a few different systems were considered. These systems included using RFID, capacitive touch, or varying resistance values.

The RFID idea worked by having a chip at the base of each piece as well as a reader under each board square. Ultimately this idea would have been too expensive and we were unsure of how to handle any interference between close pieces on the board.

The capacitive touch option would have worked along the lines of having metal pieces and metal board tiles. When the player would touch the piece and the piece would come in contact with the metal board space, a capacitive system would be created and we theorized that we could alter that by placing different strength capacitors in the pieces to alter the overall capacitance allowing piece identification. Not only were we unsure of the feasibility of piece identification, but this idea also required more expensive, custom, metal chess pieces.

The varying-resistor method was discarded as it required the pieces to be placed in a specific location and orientation in order to complete the circuit which we felt took too much away from playing chess and would leave connections to the circuitry exposed.

With these other options considered, we determined that the best compromise between cost, feasibility, and gameplay retention was to use the magnetic sensing option. With our current plan, the use of Hall-effect sensors and varying magnet levels allows the chess pieces to be oriented as desired. It requires no exposed circuitry to the surface of the board. Interference effects between close pieces are not an issue. The price is within our reasonable expectations and if used for bulk production would be in our desired range of keeping the overall board at a competitive price. The main negative of the magnetic sensing method is the requirement for the piece to be centered on the board space, removing a bit of the smoothness to the gameplay.

2 2 1 Hall-Effect sensor

The Hall-effect sensor will operate at 3.3V and be able to detect polarity of a magnetic field in order to detect whether a piece is black or white. It will also need to exhibit a linear relationship between output voltage and magnetic field strength in order to detect which of the six unique chess pieces a piece is.

The sensor we selected was Texas Instruments' DRV5053OA [7] Hall-effect sensor. This sensor has a very linear output in relation to the strength of the magnet field. The sensor outputs a steady level of 1V with no magnetic field, with a level between 1V and 0V as negative polarity and a level between 1V and 2V as positive polarity. The magnets that allowed for a practical division of piece types were CMS Magnetic' N42 1"x1/32" Neodymium Magnets [8]. These magnets are the exact size of the chess pieces, allowing them to be mounted underneath the pieces without being obstructive. These parts were also selected over other options for their low cost.

2.2.2 RGB LED

The RGB LEDs are responsible for signaling to the user based on the user's actions. When a piece is picked up, they will signal the possible moves that can be made with that piece. If the piece is placed in an invalid square, the LED will alert the user by flashing red on that square. The LEDs will be controlled by a transistor and resistor for each color that will receive an input from the Signal Interface block. The LEDs selected for this project were Chanzon's 5mm RGB LED [9]. They were selected for their low price as well as a bright light output which can be seen through the frosted acrylic. The LED requires 20mA current for maximum output. Therefore, an example calculation for the resistor required for the red LED which has drop voltage of 2V is:

$$R = \frac{V_{DD} - V_{LED}}{I_{LED}}$$

$$R = \frac{3.3\,V - 2.0\,V}{20\,mA}$$

$$R = 65\ \Omega$$

2.3 User Interface

The user interface serves to display outputs and take user inputs. It will feature an LCD screen that will show the chess clock as well as the menu for selecting different operation options (such as clock setting or hint toggling). We selected Newhaven Display's LCD Character Display [10] with an 8x2 backlit character space, which is more than enough for a menu and clock. GPIO communication also allows for easy interfacing with the MCU.

2.3.1 Buttons

Six general buttons and two higher accuracy switches that will allow the user to interact with the board settings. The six buttons will be used for "shift menu left", "shift menu right", "select", "back", "sync Bluetooth", and "toggle hints". The higher accuracy switches will be used for manual stopping of the chess clock, and will be more responsive so the user will know exactly when the switch is pressed. Uxcell's Momentary Push Button Switch [11] were a cheap option, and was surface mountable with general through-holes of the chessboard. Cherry's MX Blue Keyswitches [12] were selected for their prominent tactile feedback.

2.4 Power

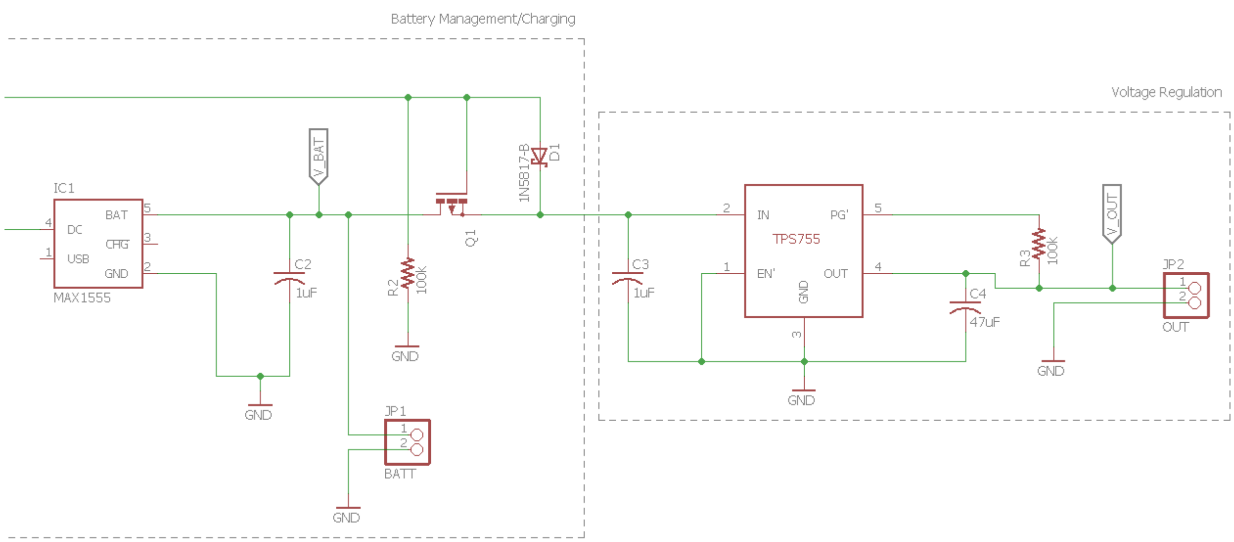

Figure 2.4.1. Power board circuit schematic

The maximum current draw of the board given the maximum draw from each component is a little under 4 A, therefore we need a battery solution that can provide at least 2400mAh to insure 1 hour of operation while realistically providing around 4+ hours of operation. The power block will also include a charging circuit and a voltage regulator.

The voltage regulator is responsible for taking either the USB or the battery as a voltage input and outputting a steady 3.3V for every component in the board. The regulator we selected was Texas Instruments' TPS755 Low Dropout Voltage Regulator [13]. This regulator is capable of outputting 3.3 V with a dropout voltage of 180 mV at an input voltage of 3.5 V. It is also capable of sourcing up to 5 A, which would allow the maximum current requirement.

The battery charging unit allows the Li-ion battery to be safely charged when a USB input is present. This includes a small circuit to disconnect the battery from load when it is being charged to allow for faster charging. The charging unit we selected was Maxim's MAX1551 Charger IC [14]. This unit is capable of safely charging a single-cell Li-ion battery with protections for overcharging. It also consumes minimal power when the battery is not being charged. The battery used was Sparkfun's 18650 2600mAh Li-ion battery [15]. This battery provided sufficient capacity to meet the operation time requirements.

3. Verification

3.1 MCU

The MCU was verified by running the chess logic code and verifying that the unit was capable of communicating with each of the modules through their respective interfaces. This was checked through the functional integration test and was recorded in a video.

3.2 Bluetooth

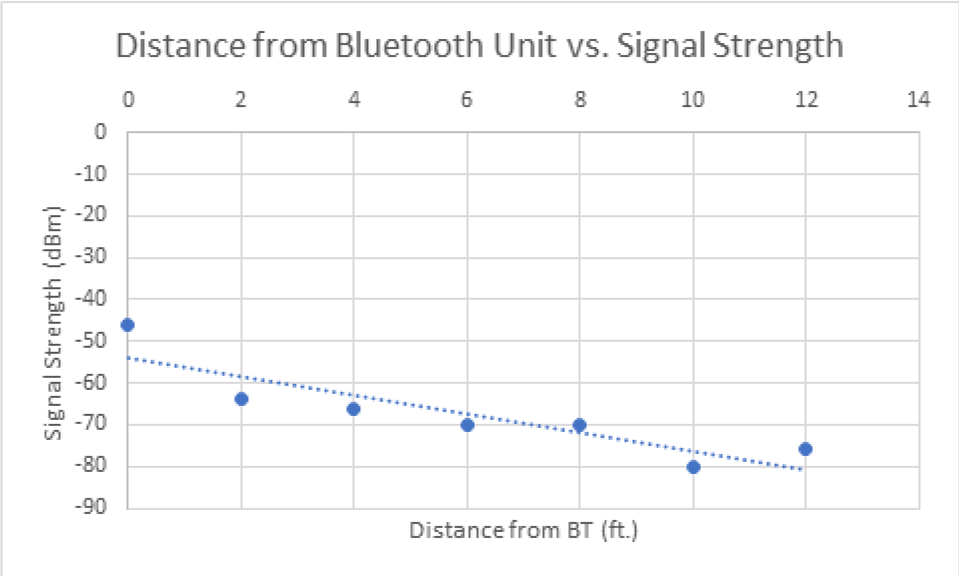

Figure 3.2.1: Bluetooth signal strength versus distance

3.3 ADC

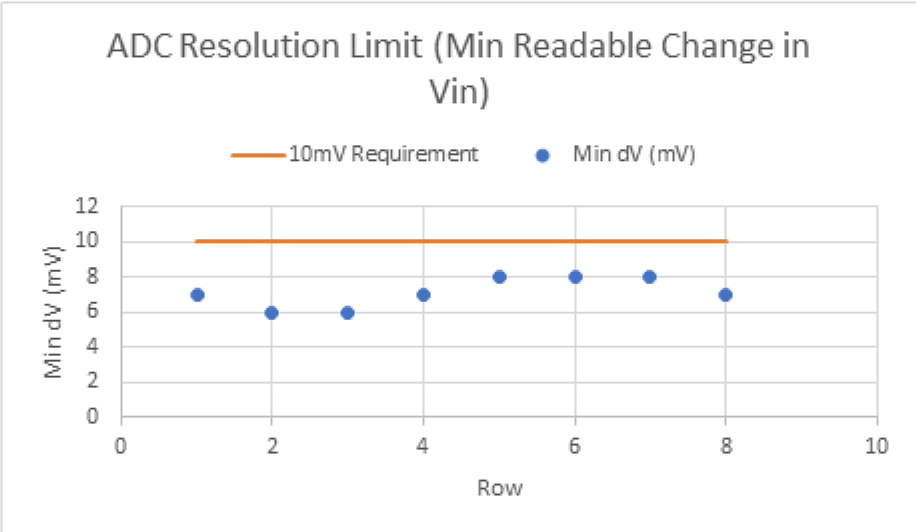

Figure 3.3.1: ADC resolution test

Each ADC was tested by increasing the input voltage by 1 mV until the digital reading by the MCU incremented, and the increment voltage was record resulting in Figure 3.3.1. The blue voltage readings are under the required 10 mV, showing that the ADC resolution is indeed high enough for our needs. This also shows that our ADC is able to communicate with the MCU, as the readings were received through the MCU.

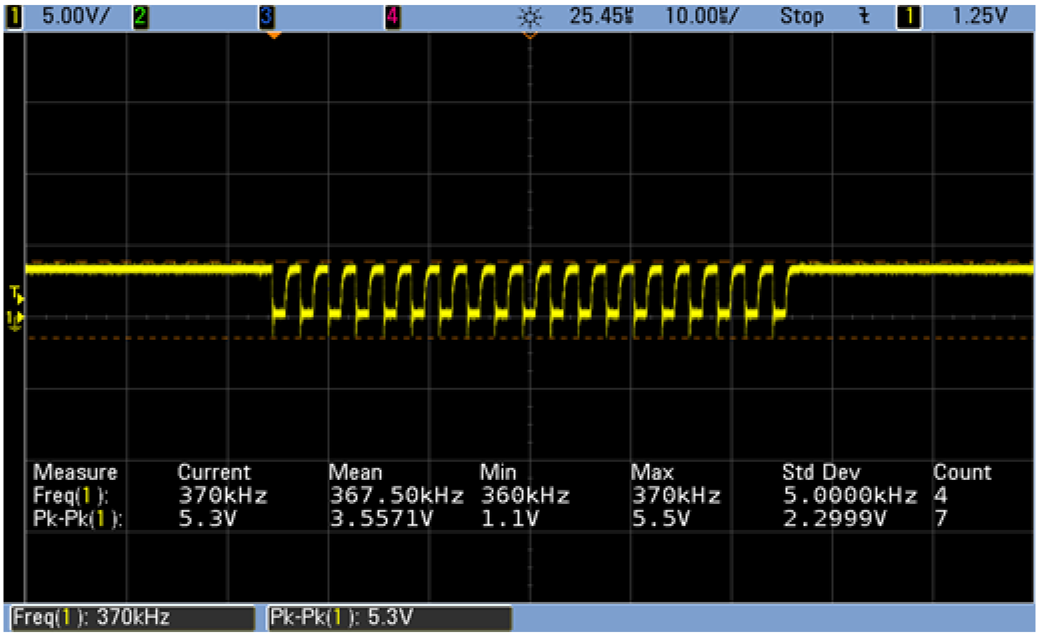

Figure 3.3.2: Oscilloscope Output of Clock Frequency

Figure 3.3.2 shows that the output from the ADC is above the required 100 kHz frequency required.

	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
Row 1	132	130	132	132	132	132	132	132
Row 2	132	132	132	130	130	132	132	132
Row 3	132	132	132	132	130	130	132	130
Row 4	132	132	132	132	131	132	133	132
Row 5	132	132	132	130	130	130	130	132
Row 6	132	132	132	132	132	132	132	132
Row 7	132	133	131	132	132	132	132	132
Row 8	132	132	130	130	132	132	132	130

Figure 3.3.3: ADC outputs from Hall-effect sensors

3.4 LED Selector Circuit

Row 1 In (V)	Row 1 Out (V)	Row 2 In (V)	Row 2 Out (V)	Row 3 In (V)	Row 3 Out (V)	Row 4 In (V)	Row 4 Out (V)	Row 5 In (V)	Row 5 Out (V)	Row 6 In (V)	Row 6 Out (V)	Row 7 In (V)	Row 7 Out (V)	Row 8 In (V)	Row 8 Out (V)
3.3	3.303	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.304	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.303	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.303	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.303	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.307	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.307	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.308	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.309	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.309	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
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3.3	3.309	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309
3.3	3.309	3.3	3.309	3.3	3.309	3.3	3.31	3.3	3.31	3.3	3.31	3.3	3.309	3.3	3.309

Row 1 In (V)	Row 1 Out (V)	Row 2 In (V)	Row 2 Out (V)	Row 3 In (V)	Row 3 Out (V)	Row 4 In (V)	Row 4 Out (V)	Row 5 In (V)	Row 5 Out (V)	Row 6 In (V)	Row 6 Out (V)	Row 7 In (V)	Row 7 Out (V)	Row 8 In (V)	Row 8 Out (V)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3.4.1: LED Selector On/Off Functionality

We tested each individual LED by sending a signal from the MCU to each LED color channel and measured the voltage at the pin. Figure 3.4.1 shows the voltage at each pin in on and off state. Figure 3.4.2 shows a frame from a visual test of signaling the LEDs on the board.

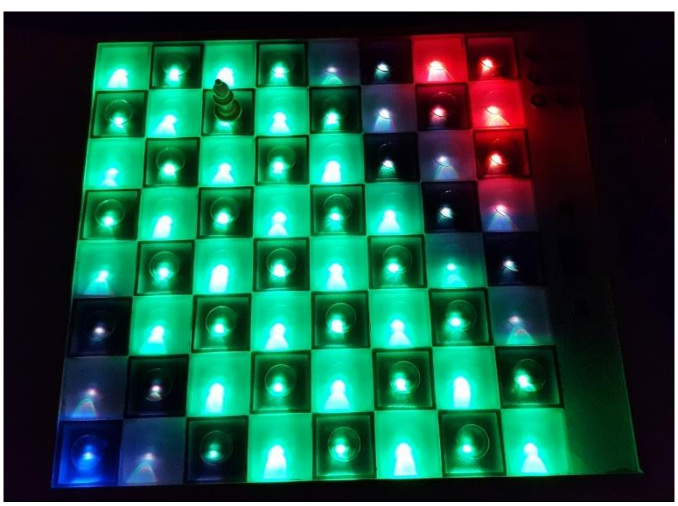

Figure 3.4.2: LED Selector Live Test

3.5 Sensor Block

3.5.1 Hall-Effect sensor

Minimum V_{OUT} (V)	Maximum V_{OUT} (V)
0.287	1.820

Figure 3.5.1.1: Testing the min/max value of the Hall-effect sensor

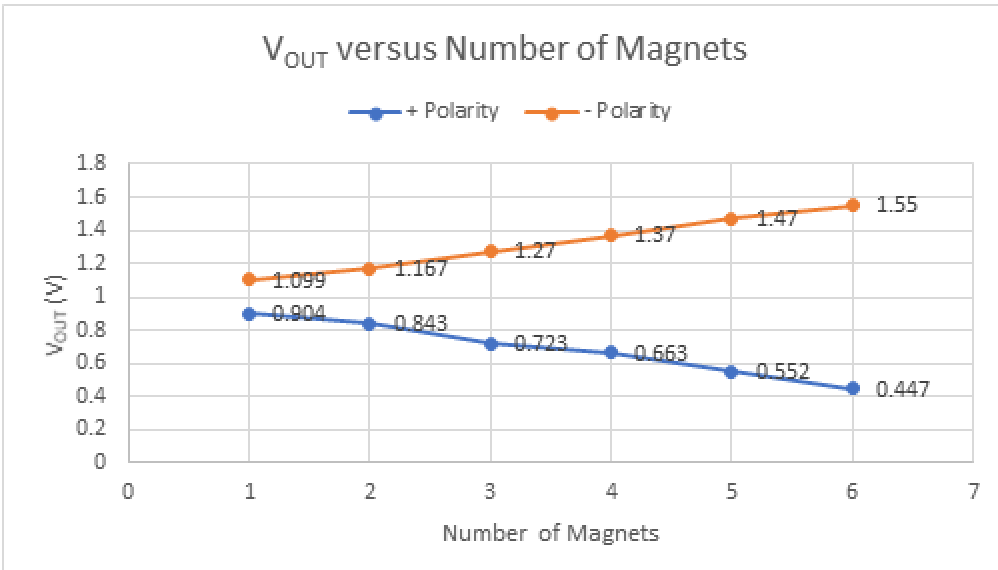

Figure 3.5.1.2: Linear relationship between magnetic strength and output

We obtained the data for figure 3.5.1.1 by placing a magnet as close as possible to the Hall-effect sensor, and then turned it over to test the other side.

3.5.2 RGB LED

See figure 3.4.2 for a test of LED visibility.

3.6 User Interface

3.6.1 LCD

The LCD screen was tested by writing data to it and verifying that the text was visible.

3.6.2 Buttons

The buttons were tested by connecting them to the MCU and verifying that the MCU could detect a button press.

3.7 Power

3.7.1 Batteries and Charging Unit

Figure 3.7.1.1: Image showing the output of the Li-ion battery

The power block needed minimal verification. The battery was tested for its output. The charging unit was tested to make sure it was safely charging the battery. The voltage regulator was tested for a steady output with both a battery as well as the USB input.

3.7.2 Voltage Regulator

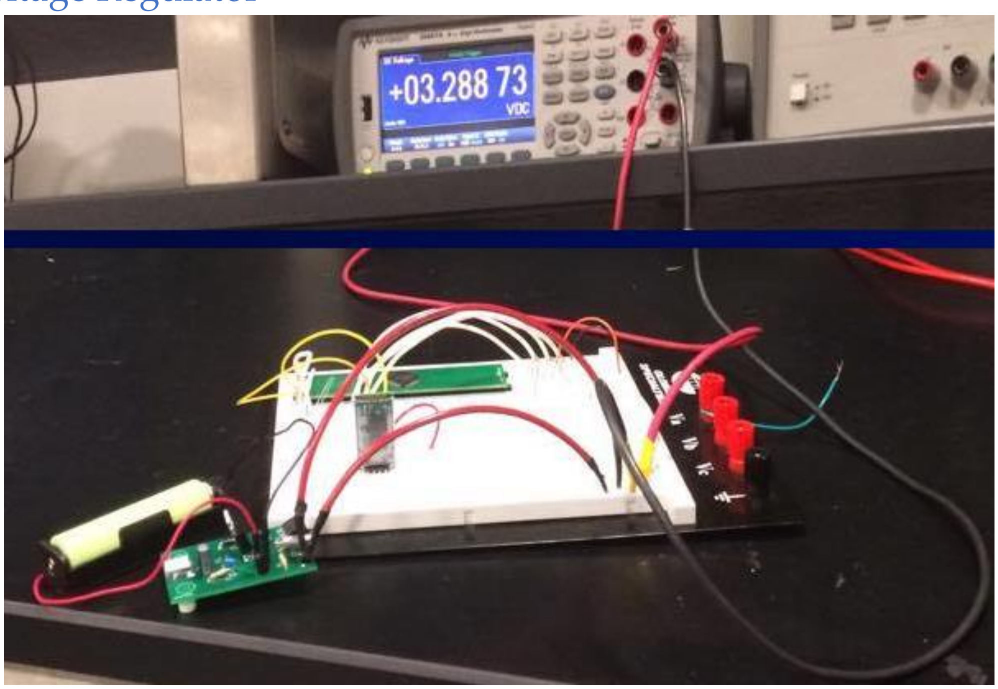

Figure 3.7.2.1: Image showing the output of the LDO voltage regulator

4. Cost Analysis

Our development costs are estimated at $32 per hour, 15 hours per week for three people. Over the semester, we approximate 13 weeks of work and verification time:

$$3 * \frac{\$32}{\text{hour}} * \frac{15}{\text{hour}} * 13 \text{ weeks} * 2.5 = \$46,800$$

Equation 3.1.1

Our prototype parts and manufacturing cost is estimated at $220 per board:

Part	Quantity	$/item (Prototype)	Total Cost (Prototype)	$/item (Bulk)	Total Cost (Bulk)
Body	1	20	20	5 [16]	5
Battery (SparkFun.com; 2.6 Ah 3.7V Li-ion)	2	5.95	11.9	5.95	11.9
Magnet (CMS Magnetics; N42 1"x1/32")	74	0.58	42.92	0.48	35.52
Battery Management IC (Mouser; MCP-73831T-2ACIOT)	1	0.6	0.6	0.42	0.42
LDO Voltage Regulator (Muser; TPS75533KTTT)	1	6.1	6.1	3.2	3.2
Momentary Push Button (Amazon.com)	6	0.536	3.216	0.536	3.216
Mechanical Switch (MechanicalKeyboards.com)	2	1	2	0.5	1
8-bit SR (Mouser; SN74HC164NSR)	24	0.39	9.36	0.108	2.592
Demultiplexer (Mouser; MC74HC238ADR2G)	1	0.281	0.281	0.078	0.078
Bronze Acrylic (Falken Design; 1/8")	32	0.098	3.136	0.098	3.136
White Acrylic (Falken Design; 1/8")	32	0.093	2.976	0.093	2.976
LCD Display (Digi-Key; 0208AZ-FSW-GBW-33V3)	1	9.8	9.8	7.056	7.056
Bluetooth Module (Amazon.com; HC-06)	1	8.99	8.99	8.99	8.99

Microcontroller (Mouser; MSP430FR5962IZVWR)	1	6.23	6.23	3.4	3.4
ADC (Mouser; MAX11603EEE+)	8	1.73	13.84	1.63	13.04
LED (Amazon.com; 5mm RGB 4 pin)	64	0.0896	5.7344	0.0896	5.7344
Hall Effect Sensor (Mouser; DRV5053VAQDBZR)	64	0.736	47.104	0.349	22.336
PCB (PCBWay; 1"x1" single layer)	64	0.24	15.36	0.0435	2.784
PCB (PCBWay; 4"x4" two layer)	1	5.6	5.6	0.865	0.865
Chess Set (Chesshouse.com; 1 1/4" base)	1	5	5	5	5
Total			$220.15		$138.24

Table 3.1.1: Price breakdown and total

Building only one prototype will yield a total development cost of $ 47,020.

5. Conclusion

Overall, our Assistive Chessboard design functioned as intended. The sensor blocks were able to accurately detect the varying number of magnets on the chess pieces and the LEDs clearly illuminated their respective board square. The control block was able to read the analog Hall-effect sensor output for each sensor, signal individual LEDs to illuminate a certain color, process the chess logic, and transmit data through Bluetooth. The user interface block was functional in that it provided an accessible control scheme to interact with the chessboard. Finally, our power block was able to regulate the voltage and current output to the circuit allowing the board to be powered by either battery or USB.

While completing this project, we made sure to adhere to proper ethical standards. Our biggest safety concern was our use of a lithium-ion battery but by adhering to the ECE 445 General Battery Safety document [17] we were able to handle them appropriately. Our power circuit had a safe charging chip and limited the current output to minimize risk. This helps cover the IEEE Code of Ethics #1 and #9 to make the product safe to use [18]. Other ethical issues we handled include non-discriminatory practices and having a cohesive team according to IEEE Code of Ethics #8 and #10 [18]. We did operate as a team in a non-discriminatory way, assigning work fairly and assessing progress only on quality.

While our final product did work, it was not without design, construction, and testing challenges along the way. One common issue that we suffered was the use of faulty footprints in out PCB layouts. Often resulting from failing to check the compatibility of a pre-made footprint, this led to severe delays as we had to fix and reorder our PCBs for our sensor boards and control board. Other issues that arose were inherent flaws with some of our design choices. The relatively high strength of the magnets meant the pieces were unwieldy, wanting to attract to each other. Our choice of LED selector circuit required intense wiring with us manually cutting and crimping over 600 wires leading to difficult construction and debugging process.

Aside from overlooked minor design flaws, there was also an unexpected behavior with the Hall-effect sensors on each sensor board. As more current flowed through the PCB that housed the sensor, the Hall-effect output would linearly increase (see Appendix C). Since each active LED channel drew 20mA and since eight sensor boards were daisy chained together, a maximum of 480mA could be flowing through a control board raising the Hall-effect output by as much as 43mV making that space incorrectly identify a piece. To overcome this for this prototype, we would turn off the LEDs for an imperceptible amount of time while quickly reading the ADC for that row to read the analog outputs in their unaffected states. In future work on this product, separating the LED and Hall-effect power traces could alleviate this issue.

In the grand scheme of this project, these issues did not prevent our Assistive Chessboard from functioning, however, these issues can be alleviated in future revisions to this product. By placing the Hall-effect sensors closer to the surface of the board, weaker magnets could be used, making the pieces less attracted to each other. More Hall-effect sensors could also be placed under each chess space to remove the need for each piece to be centered. Another option to eliminate the issues of unwieldy pieces would be to investigate and implement an alternative sensing method, such as pressure or capacitive touch. As discussed in section 2.1 for the alternative LED selector options, we could use a grid-based selector circuit instead to reduce wiring and necessary integrated circuits, helping to improve reliability.

Beyond optimizing the design, additional software function can be added to the existing product. Given the size and power of our microcontroller unit, we should be able to add more interactive and beneficial game options to the board. Additional teaching resources such as scripted AI skill challenges and even a full AI opponent with different difficulty levels could be implemented, helping a player train further. Using the already functioning Bluetooth connectivity, it is possible to make the application connected to the internet to allow wireless play allowing players to experience playing a physical game of chess with a friend while being separate.

6. Sources

[1] "Chess Redux: how many people play chess?", Chess News, 2017. [Online]. Available: http://en.chessbase.com/post/che-redux-how-many-people-play-che-. [Accessed: 03- Oct- 2017].

[2] "MSP430FR5962IZVWR Texas Instruments | Mouser Europe", Mouser Electronics, 2’017. [Online]. Available: http://www.mouser.com/ProductDetail/Texas-Instruments/MSP430FR5962IZVWR/. [Accessed: 06- Oct- 2017].

[3] 2017. [Online]. Available: https://www.olimex.com/Products/Components/RF/BLUETOOTH-SERIAL-HC-06/resources/hc06.pdf. [Accessed: 20- Oct- 2017].

[4] "NCD9830DBR2G ON Semiconductor | Mouser Europe", Mouser Electronics, 2017. [Online]. Available: http://www.mouser.com/ProductDetail/ON-Semiconductor/NCD9830DBR2G/?qs=xGcJQ%252bnsJwuRbKLXZSG0bw%3D%3D. [Accessed: 06- Oct- 2017].

[5] O. Semiconductor, "MC74HC238ADR2G ON Semiconductor | Mouser Europe", Mouser Electronics, 2017. [Online]. Available: http://www.mouser.com/ProductDetail/ON-Semiconductor/MC74HC238ADR2G/. [Accessed: 06- Oct- 2017].

[6] "SN74HC164NSR Texas Instruments | Mouser Europe", Mouser Electronics, 2017. [Online]. Available: http://www.mouser.com/search/ProductDetail.aspx?R=0virtualkey0virtualkeySN74HC164NSR. [Accessed: 06- Oct- 2017].

[7] Texas Instruments, “DRV5053 Analog-Bipolar Hall Effect Sensor,” DRV5053 Datasheet, May 2014 [Revised December 2015].

[8] “N42 1"x1/32" Neodymium Rare Earth Disc Magnet,” CMS Magnetics, Inc. [Online]. Available: http://www.magnet4sale.com/n42-1x1-32-neodymium-rare-earth-disc-magnet/. [Accessed: 06-Oct-2017].

[9] ”Chanzon 100 pcs 5mm RGB LED Diode Lights Tricolor (Multicolor Red Green Blue 4 pin Common Anode Clear DC 20mA/Color) Super Bright Lighting Bulb Lamps Electronics Components Light Emitting Diodes”, Amazon.com, 2017. [Online]. Available: . https://www.amazon.com/Tricolor-Multicolor-Lighting-Electronics-Components/dp/B01C19ENFK. [Accessed 03- Oct- 2017]

[10] Newhaven Display, “0208AZ-FSW-GBW-33V3 Character LCD Display”, 0208AZ-FSW-GBW-33V3 Datasheet, October 2011 [Revised June 2017]

[11] “uxcell Momentary SPST NO Red Push Button Switch”, Amazon.com, 2017. [Online]. Available: https://www.amazon.com/dp/B0094GP7SQ/

[12] Cherry, “MX Keyswitch”, MX Series Datasheet

[13] T. Instruments, "TPS75533KTTT Texas Instruments | Mouser Europe", Mouser Electronics, 2017. [Online]. Available: http://www.mouser.com/ProductDetail/Texas-Instruments/TPS75533KTTT/?qs=sGAEpiMZZMsGz1a6aV8DcPXeWoVS0FnzqFSLEFdrBZs%3D [Accessed: 06- Oct- 2017].

[14] "Maxim Integrated MAX1551 / MAX1555 Li+ Battery Chargers | Mouser Europe", Mouser.com, 2017. [Online]. Available: http://www.mouser.com/new/maxim-integrated/max1551max1555/. [Accessed: 06- Oct- 2017].

[15] L. (2600mAh), "Lithium Ion Battery - 18650 Cell (2600mAh) - PRT-12895 - SparkFun Electronics", Sparkfun.com, 2017. [Online]. Available: https://www.sparkfun.com/products/12895. [Accessed: 06- Oct- 2017].

[16] “Cost Estimator,” Injection Molding Cost Estimator. [Online]. Available: http://www.custompartnet.com/estimate/injection-molding/. [Accessed: 05-Oct-2017].

[17] “Safe Practice for Lead Acid and Lithium Batteries,” University of Illinois ECE445 Course Staff, 2016. [Online]. Available: https://courses.engr.illinois.edu/ece445/documents/GeneralBatterySafety.pdf. [Accessed: 5-Oct-2017].

[18] "IEEE IEEE Code of Ethics", Ieee.org, 2017. [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 03- Oct-2017].

Appendix A: Requirements and Verification

Control Block

MCU

Requirements	Verification
1. Can transmit data over UART to Bluetooth module 2. Can transmit data over serial connections to LCD display 3. Can store at least 1KB of past move data accurately in FRAM	1. Connect MCU with Bluetooth module and ensure functionality by sending known data package and comparing that to the data received by the Bluetooth connected device 2. Connect MCU with LCD to ensure functionality by sending a test string and comparing it to the output on the LCD 3. Store and read, ensuring no differences, game data 10 times to ensure data validity

Table A.1: MCU requirements and verification

Bluetooth

Requirements	Verification
1. Connection range of 10 feet 2. Can communicate with MCU with UART interface 3. Compatible with Bluetooth version 2.0 devices	1. Connect a Bluetooth device that is 1 foot away a. Move device outwards until it is 10 feet away b. Make sure it is connected the entire time 1. Connect Bluetooth module to MCU and ensure communication 2. Test Bluetooth module with commonly used phones to ensure data transfer

Table A.2: Bluetooth requirements and verification

Sensor Interface

Requirements	Verification
1. At least 10mV input voltage resolution through ADCs 2. I2C communication with MCU of speeds of at least 100 kHz	1. Using a variable voltage source, send 1V into pin CH0 and have the MCU retrieve the digital reading through I2C a. Increase the supplied voltage by 1mV and retrieve the digital reading again b. Continue increasing the supplied voltage by 1mV until the digital reading changes; the supplied voltage is the resolution, verify that it is under 10mV 1. Connect ADC to MCU and ensure data communication

Table A.3: Sensor interface requirements and verification

LED Selector Circuit

Requirements	Verification
1. Able to select each row individually 2. Ability to retain values between changes	1. Connect the demultiplexer module to the shift registers to ensure individual selection 2. Cycle through different values for each LED to validate functionality

Table A.4: LED selector circuit requirements and verification

Sensor Boards

Hall-Effect

Requirements	Verification
1. Analog output in range of at most 0V to 2.048V to ensure compatibility with ADC 2. Output voltage distinguishes polarity of magnet a. B-Field > B_{SAT} forces output of V_{OUT_MAX} b. B-Field < $-B_{SAT}$ forces output of V_{OUT_MIN} 1. Linear relationship between magnetic flux and output voltage	1. Place our strongest magnet on the sensor and read voltage output with a voltmeter; flip magnet and read voltage output again to read the opposite end of the V_{OUT} range 2. Use data from verification step 1 to verify that one polarity saturates at V_{OUT_MAX} and one at V_{OUT_MIN} 3. Place each of our 6 different strength magnets at 0.5 inches above the hall effect sensor and read the output voltage; verify output voltages matches expected values within noted error for each of the 6 different magnet strengths

Table A.5: Hall-effect requirements and verification

LEDs

Requirements	Verification
1. Each LED color must be visible under frosted acrylic 2. 3 independently controlled color channels	1. Power LED on while it is covered by acrylic sheet; visually judge visibility 2. Power only one color input pin at a time and visually verify that only the appropriate color is activated

Table A.6: LED requirements and verification

User Interface

LCD Screen

Requirements	Verification
1. Can receive communication from the MCU 2. Characters are visible	1. Connect the LCD to the MCU to ensure communication 2. Populate LCD with characters and verify it can be seen

Table A.7: LCD screen requirements and verification

Buttons

Requirements	Verification
1. Easily pressable buttons	1. Press the buttons and ensure that they are easily pressable

Table A.8: Button requirements and verification

Power

Battery

Requirements	Verification
1. Maintains a voltage level above 3.5V 2. Has a charge capacity of greater than 2600 mAh	1. Check the battery voltage with a voltmeter to ensure voltage level 2. Run the battery with a known load to ensure estimated charge capacity

Table A.9: Battery requirements and verification

Charging Unit

Requirements	Verification
1. Safely charges a single-cell Li-ion battery to full charge 2. Consumes minimal power (< 2mA) when battery is at full charge	1. Charge battery using the charger IC and run the battery capacity verification 2. Test the current into the charging IC when the battery is at full charge

Table A.10: Charging unit requirements and verification

LDO

Requirements	Verification
1. Outputs 3.3V ± 5% with an input of 3.7V 2. Provides an output current of 4A to ensure maximum load conditions	1. Check with voltmeter to ensure voltage output is within specifications 2. Use the regulator with a known load to ensure the maximum current capability

Table A.11: LDO requirements and verification

Appendix B: Tolerance Analysis

The Sensor Block is the most critical section of our design as it is provides the information required to ensure functionality of our chess board. As such, we need to be confident that our selection of Hall-effect sensors, ADCs, and magnets are capable of functioning together. We must also consider a range for mechanical error in the placement of each Hall-effect sensor in relation to the center of the indent of each corresponding board space. This mechanical error is based on our ability in construction precision and has been selected to be r_{OFFSET} = +/-0.125" in any direction from the center of the board space. Due to pricing and availability, there is less flexibility in selecting a different Hall-effect sensor and ADC. Therefore we will seek to discover the required thickness tolerance for the magnets used to identify the chess pieces.

For the price and analog functionality the TI DRV5053 Hall-effect sensor is the only reasonable part to use so we will consider this a static variable. We will be using the most sensitive version (the DRV5053OA) for our design since there is no price tradeoff for using a less sensitive version. The DRV5053OA features a -11mV/mT magnetic field to V_{OUT} relationship with a maximum of 5 mVpp output noise leading to a maximum $V_{OUT,ERR}$ of +/-2.5 mV [12].

We selected the Maxim NCD9830DBR2G as it was the cheapest 8-bit, 8-channel ADC that we could find. If it is proven to have insufficient accuracy, it could be replaced by a better ADC, but the rest of the tolerance analysis will show that a replacement is unnecessary. Since the V_{OUT} of the Hall-effect is in the range of 0.2V to 1.8V, we will be using the 2.5V internal reference voltage of the ADC to ensure the lowest voltage resolution possible. The Maxim NCD9830DBR2G datasheet notes that the maximum possible value for the 2.5 V_{REF} is 2.525V. Because the range of the digital output ranges from 0V to V_{REF}, we can find the voltage resolution by dividing $V_{REF,MAX}$ by the number of digital output options which is defined by $2^{\#\ of\ bits}$. Given the ADCs are 8-bits we get the following:

$$V_{RES} = \frac{V_{REF}}{2^8} = \frac{2.525V}{256} = 0.00986V$$

Equation B.1

The relative accuracy of the digital output is +/-0.5 LSB which equates to +/- V_{RES} therefore the $V_{DIG,ERR}$ = +/-4.93 mV.

Combining the maximum analog error with the maximum digital error, we arrive that the worst case voltage reading error is $V_{ERR} = V_{OUT,ERR} + V_{DIG,ERR}$ = +/-7.43 mV. This information will be used in conjunction with the magnetic strength values to arrive at the maximum thickness tolerance of our magnets.

Using the neodymium magnet magnetic field strength calculator found at KJMagnetics.com, a table of the magnetic field strength per magnet thickness is generated. For tolerance analysis, a worse case situation is considered where the x-offset of the sensor is set at r_{OFFSET} = 0.125″ and the y-offset is set at 0.5″ away from the surface of the magnet as guaranteed by the construction of our chessboard.

Size (n/32″)	B (G)	θ_y(°)	$B_{INCIDENT}$(G)	B_{IDEAL} (mT)	$V_{OUT,IDEAL}$(mV)
1	137.7	11.5	134.9356318	13.4935632	851.5708
2	264.5	10.7	259.9010847	25.9901085	714.1088
3	382	10.5	375.6033747	37.5603375	586.8363
4	487.4	10.9	478.6066766	47.8606677	473.5327
5	562.2	10.9	552.0571883	55.2057188	392.7371
6	657.2	10.7	645.7731299	64.577313	289.6496

Table B.1: Relation between magnet thickness to the ideal output voltage

The magnetic field in gauss is taken directly from the calculator as well as the angle from the y-axis. $B_{INCIDENT}$ is the strength of the magnetic field that passes perpendicularly through the Hall-effect sensor as that is what the sensor reads.

$$B_{incident} = B \times \cos\theta_y$$

Equation B.2

$B_{INCIDENT}$ is then converted from gauss to milli-Tesla since the Hall-effect sensor is specified milli-Tesla readings. The conversion ratio of 1 mT = 10 G is used. Finally, the ideal output voltage from the Hall-effect sensor is calculated using the specified sensitivity of -11mV/mT.

$$V_{OUT,IDEAL} = 1 - B_{IDEAL}(\mathrm{mT}) \times 11\left(\frac{\mathrm{mV}}{\mathrm{mT}}\right)$$

Equation B.3

To determine the maximum magnetic field threshold range for discriminating magnet sizes, the maximum difference between successive outputs must be found. This is done by the following:

$$V_{THRESH} = \min(\{V_{OUT,IDEAL}[n] - V_{OUT,IDEAL}[n-1] | n \in [2,6]\})$$

Equation B.4

Where "n" corresponds to the n-th sized magnet when ordered by size. From table 2.4.1, V_{THRESH} = 80.796 mV when taking the difference between the outputs for the 4th and 5th magnets (B=487.4G and B=562.2G respectively). Dividing V_{THRESH} by 2 gives us the maximum output voltage range around $V_{OUT,IDEAL}$ that each magnet's magnetic strength is allowed to cause. Let this value be labelled as:

$$V_{RANGE} = \frac{V_{THRESH}}{2} = \pm 40.398 mV$$

Equation B.5

Using V_{RANGE} and the previously determined V_{ERR} we can determine the worst case voltage range around $V_{OUT,IDEAL}$ that a magnet can cause. Let this be labelled as $V_{MAX\_RANGE} = V_{RANGE} + V_{ERR}$ = +/-32.966 mV. Using the specified Hall-effect sensitivity, this can be converted back into magnetic strength to give us a B_{MAX_RANGE} which will denote the maximum magnetic field strength difference away from ideal that a magnet is allowed to have.

$$B_{MAX\_RANGE} = \frac{V_{MAX\_RANGE}(\text{mV})}{11\left(\frac{\text{mV}}{\text{mT}}\right)} = \pm 2.997 mT$$

Equation B.6

To find the maximum magnet thickness tolerance, we must find the general relation between magnet thickness and magnetic field strength.

Size (n/32")	B (mT)	B(mT)/inch
1	13.49356318	431.794022
2	25.99010847	415.841735
3	37.56033747	400.6436
4	47.86066766	382.885341
5	55.20571883	353.3166
6	64.57731299	344.412336

Table B.2: Relation between magnetic field strength and magnet thickness

As can be seen from table B.2, the relation is not linear so to account for the worse case scenario, the largest field-to-thickness ratio, B-to-T_{MAX} = 431.794 mT/inch, will be used. Using this information and B_{MAX_RANGE} the worst case thickness tolerance can be determined:

$$\delta_{MAX} = \frac{B_{MAX\_RANGE}}{B - \text{to} - T_{MAX}} = \frac{\pm 2.997\text{mT}}{431.794\frac{\text{mT}}{\text{inch}}} = \pm 0.00694\text{inches}$$

Equation B.7

Given the worst-case scenarios of error, we need magnets with a guaranteed thickness of +/-0.00694".

If this value needs to be increased, the most immediate solution would be to allow less error in sensor placement. Calculated with the same methods, we determined that by allowing 0" if placement tolerance, the δ_{MAX}only increases to +/-0.00754. The other logical change we could consider is using a higher-bit or more accurate ADC. Finding an ADC with 0 LSB of error is unlikely so the only other option would be to use a higher bit ADC. For example, again using the same calculations and keeping all parameters the same except for bit size of the ADC, by using 10-bit output ADCs, a $\delta_{MAX}$of +/-0.00772" can be achieved. As it stands, we believe that the magnets we have selected will meet our thickness standard with a tolerance rating of +/-0.002", well within our +/-0.00694 range, but it is good to know our options if problems arise during construction and testing of our board.

Appendix C: Additional Data

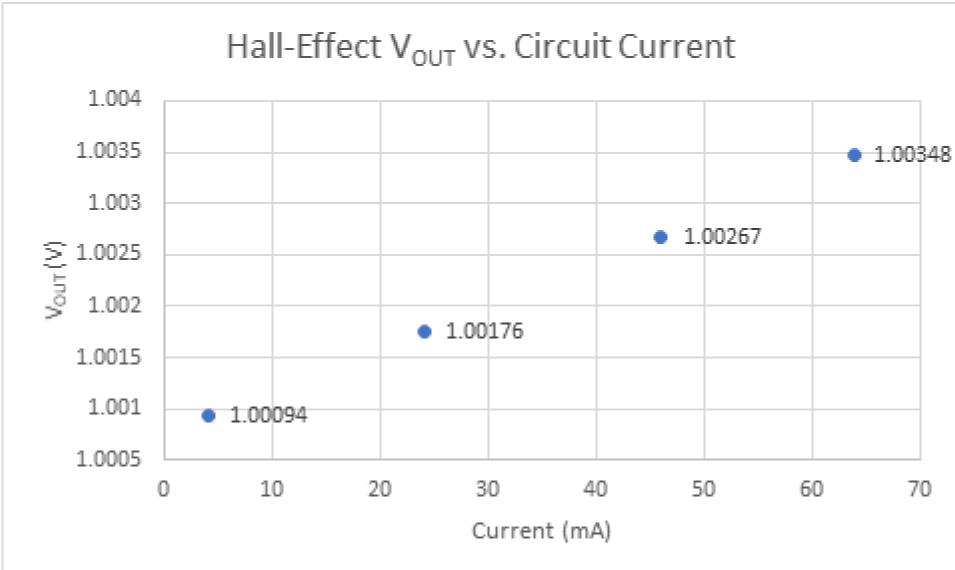

Figure C.1: Effect of current on Hall-effect sensor output

Appendix D: PCB Layouts

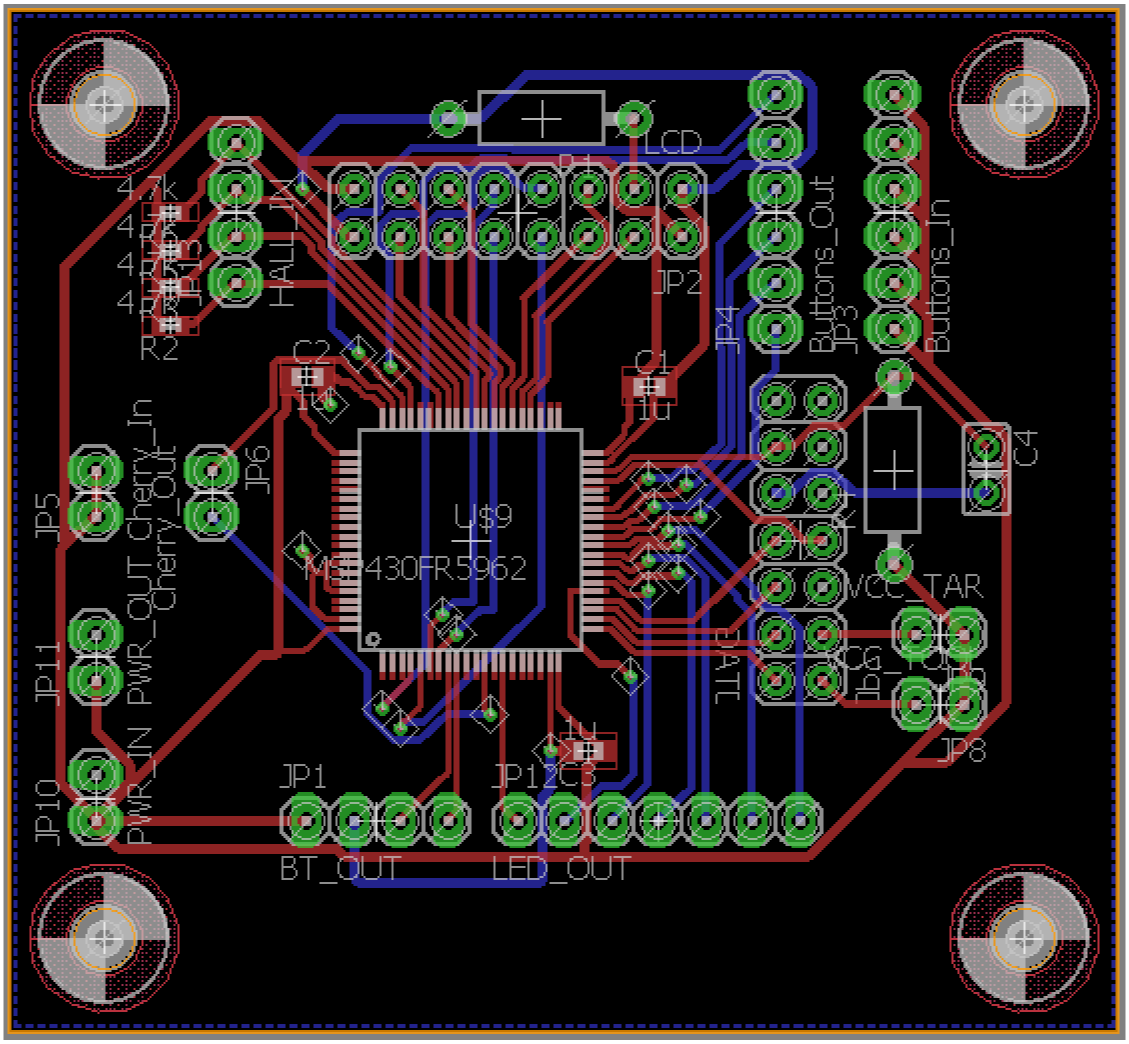

Figure D.1: MCU PCB

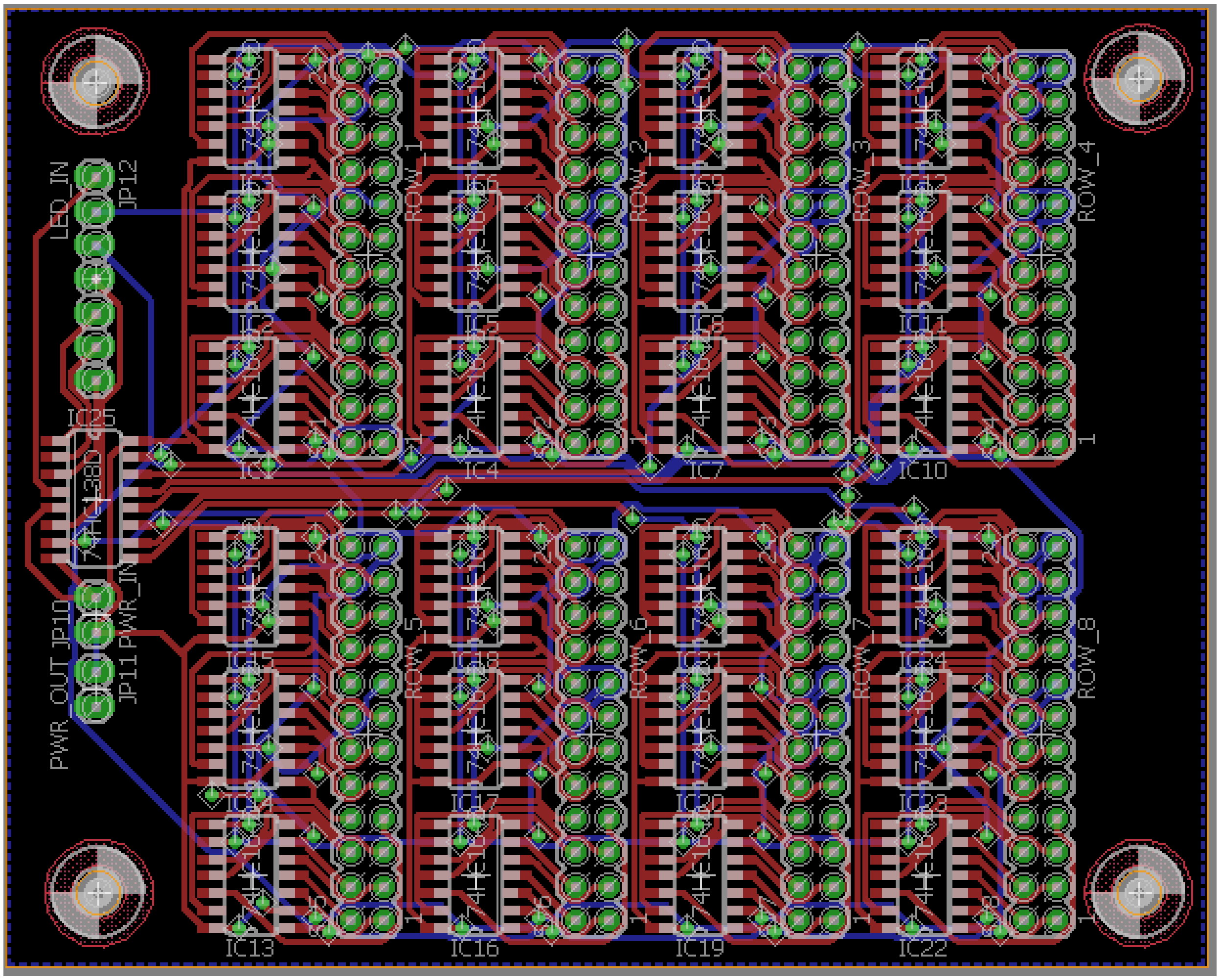

Figure D.2: Shift Register PCB

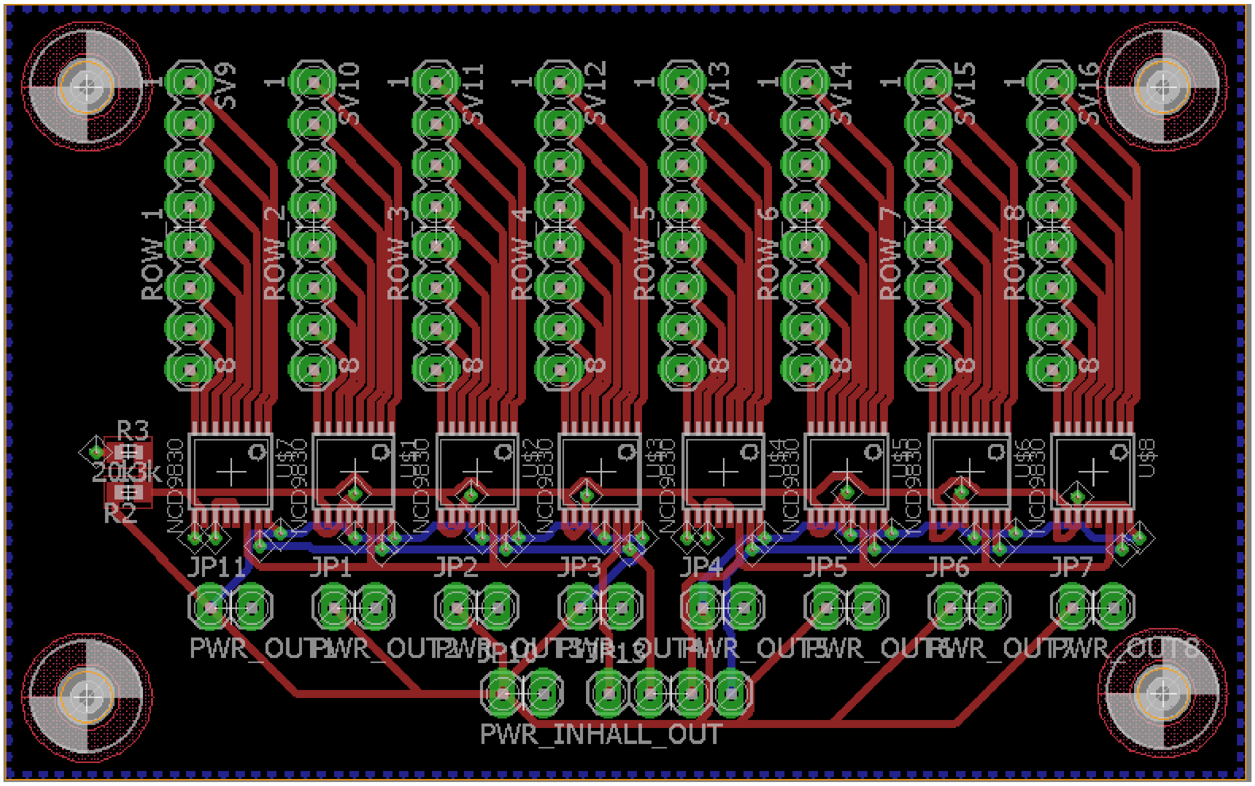

Figure D.3: ADC PCB

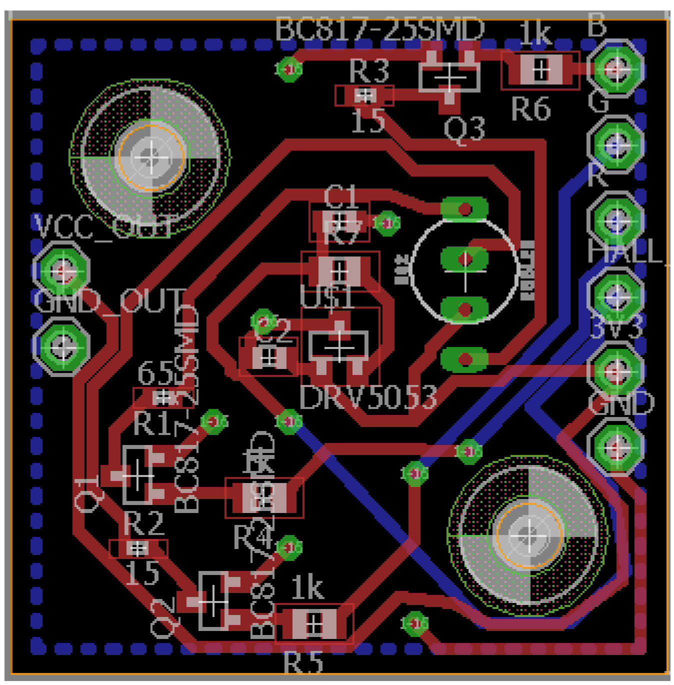

Figure D.4: Sensor Board PCB

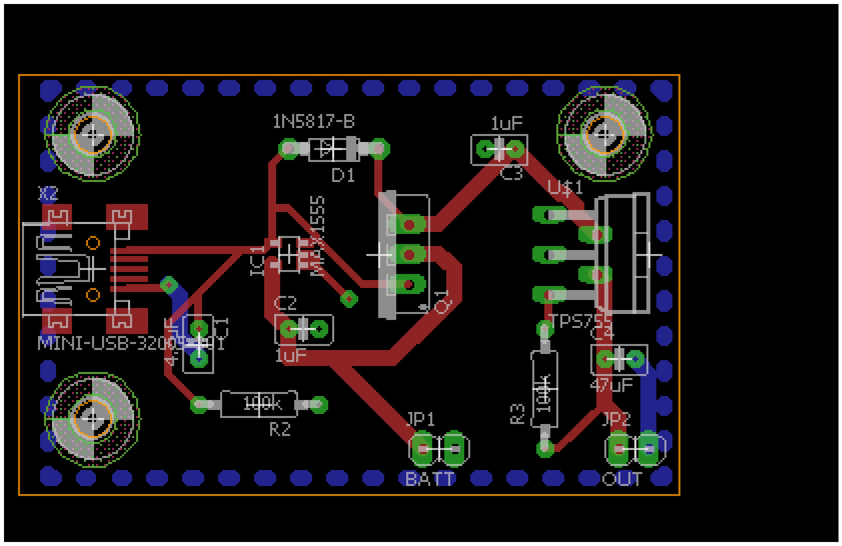

Figure D.5: Power PCB