Assistive Chessboard

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1 Introduction

1.1 Objective

Chess is a game played by over 600 million players [1], however it can be quite difficult for a fresh player to learn. A common method for learning is to utilize online resources but this negates the experience and flexibility of playing with a physical board. Another option is to play with a friend on a real board, perhaps using an online guide as an aide, but this can be distracting. While a friend may be a great source to learn from, playing with a friend might not be an option available at all times and resorting to an online neglects the experience of a real board.

Our solution is to design and build a chess board that can be this link between a physical board and an educational source by having it assist new players. The board will help guide a new player by having an RGB LED under each board square that will light up according to valid and invalid moves for the selected piece, pieces under threat, as well as a variety of other useful information. By giving visual aids to the new player, they will be able to see the basics of the game more easily, as 83% of what is learned is through the sense of sight [2].

1.2 Background

Currently, there do exist electronic chess sets that teach players of possible moves, but with the downfall of being pricey. One such example is the Excalibur King Master III [3], which states the move list on the LCD screen, but is small and not as intuitive. Meanwhile our chess board will give live feedback in the form of visual aids that result in a similar end goal.
By highlighting the move list onto the physical board, the player can see the possible moves more prominently.

This shows that there is indeed a product space for an assistive chessboard that is cheaper and more visually stimulating such as ours. By incorporating LEDs into our design, we are able to communicate information to new players much easier. With a visual guide right on the board, a new player will be able to improve their grasp of the game with less effort as they do not have to actively seek such information; it is all displayed clearly before them and in the flow of the game.

Compared to virtual chess guides and tutorials found online, our solution allows a player to experience a game on an actual board. From personal experience as a unskilled player, it is easier to scope out a physical board than one online. The physical interactivity of a real board can allow a player to feel more comfortable as their moves are not hindered by a computer interface. Our product solution combines the pros of a physical board with the broad assistive abilities of computer chess.

1.3 High-Level Requirements

- Chess board must be able to detect where every piece is and what each piece is by the use of the individual hall-effect sensors placed under each board square.
    - **a.** Must be able to located a piece and distinguish accurately its type for any piece centered within 0.125 inches of the center of the board space
- Chess board must be able to individually control each RGB LED under each chess board square to give an appropriate signal:
    - **a.** LEDs will be lit/unlit in an indistinguishable amount of time (<100ms [4])
    - **b.** LEDs will only light up the correct potential moves/board spaces in danger
    - **c.** The correctly placed LED will flash red if an invalid move is made with 50% duty cycle at 1 Hz
- Chess board must be able to send game move history over Bluetooth to a connected device for data logging
    - **a.** Must be able to communicate with a device within 10 ft
    - **b.** Minimum data size (2 bytes per move - average game is 40 moves [5] - 80 bytes on average must be transmitted)

2 Design

2.1 Block Diagram

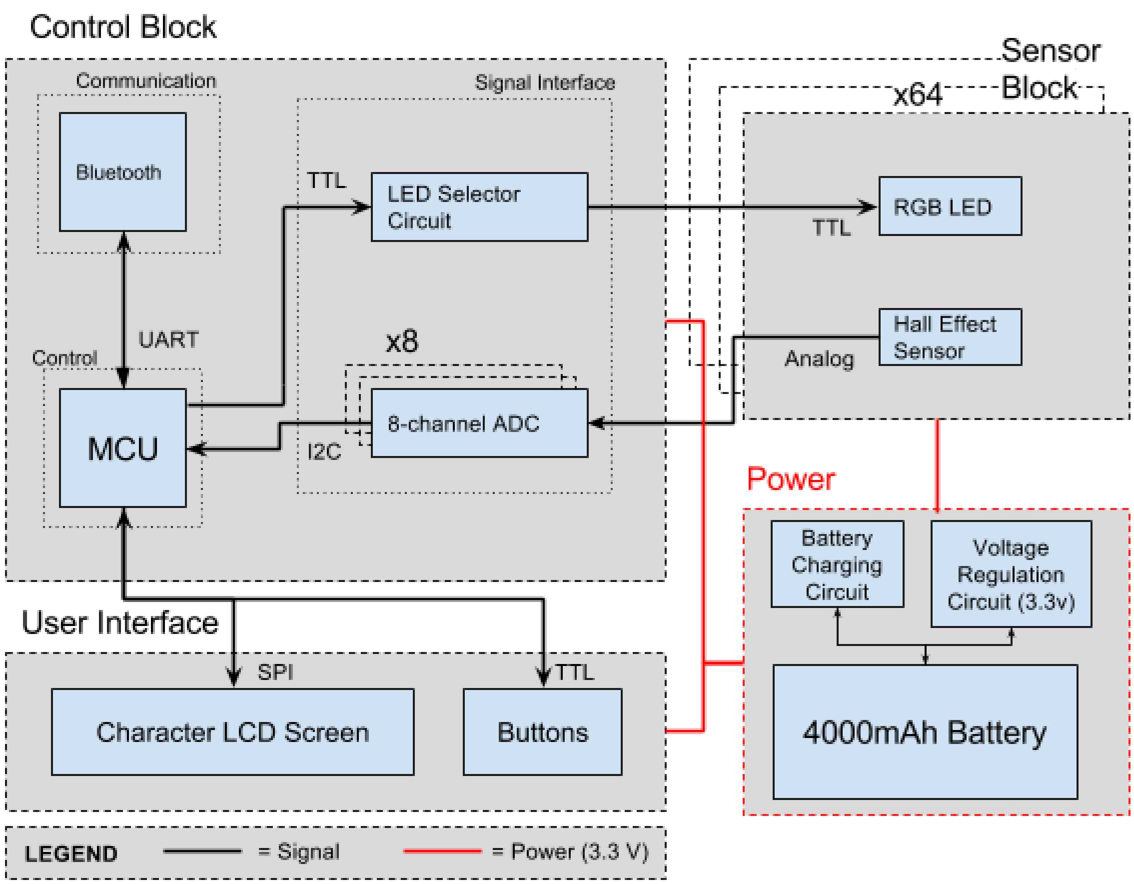

Figure 2.1.1: Block diagram

2.2 Physical Design

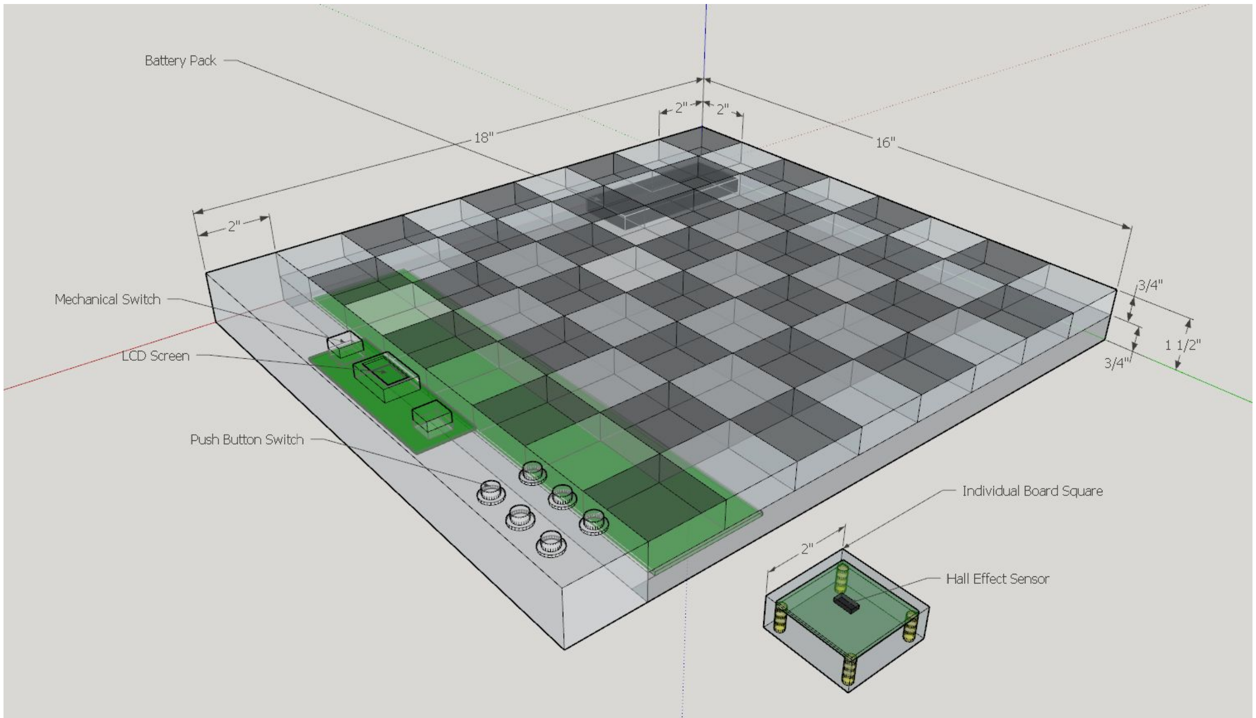

Figure 2.2.1: CAD drawing

2.3 Block Descriptions

2.3.1 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).

Justifications: While most of the Control Block is straight-forward, as it is composed of just a few discrete ICs, some design decisions had to be made on the LED Selector Circuit. Three options were considered here: a system using only shift registers, using only demultiplexers, or a combination of the two methods.

The shift register method functioned by having one 24-bit shift register assigned per row. It would have a parallel output connected to each of the 24 LED connections for that row (3 color connections per LED, 8 LEDs per row). Every time an LED needed to be updated for that row, the MCU would cycle in 24 new signals to the shift-register. To control this, the MCU would need 2 outputs per shift register for a total of 16 outputs. The main reason that this method was rejected is that it forced each LED on each row to be refreshed at once and required a full 24 clock cycles to do so.

The demultiplexer circuit uses 33 demultiplexers and 196 latches to allow the MCU to individually select each LED, assign its 3 RGB values, and lock them in until it needs to be changed again. This process only requires 2 clock cycles to change an LED value and does not require a whole row to be updated at once. The 10 required MCU outputs is less than the shift register method and there are fewer components activated for a single LED making the process is quicker. The major downside to this circuit is the large number of ICs that required which increases the difficulty of soldering and is more expensive. It also requires a larger PCB to contain each component which can also increase cost.

To help mitigate this cost while maintaining a level of control, a combination of the two methods was explored. Like the demultiplexer method, a single 1-8 demultiplexer is used to select the row for the MCU output to go. Then, like the shift register version, there is a 24-bit shift register that holds the signal for each color channel of each LED in that row. The number of MCU output signals is reduced to 6 (1 for the signal, 3 for the row select, 1 for the clock, and 1 for a asynchronous reset). This method is also inspired by industry standard LED controllers which operate as a series of selectable shift registers in a similar fashion [6]. Despite the longer refresh time for the LEDs in a row, there are fewer components and fewer MCU outputs to manage which reduces price, PCB size, and sources of error.

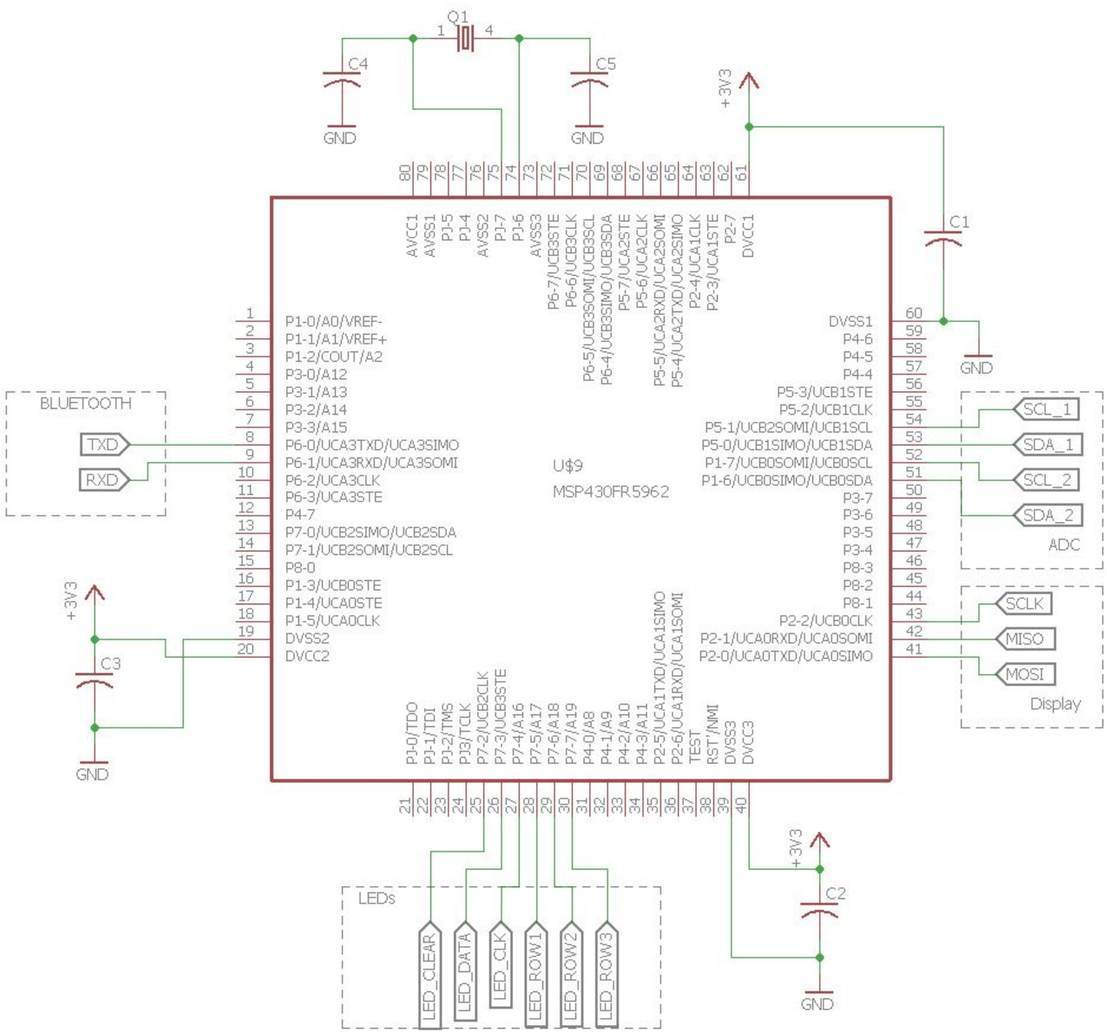

Figure 2.3.1.1: MCU circuit diagram

- **MCU:** The MCU (Microcontroller Unit) 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 signalling functions by TTL signalling 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.
    - <u>Supporting Documents:</u>
        i. **Part Information:** Texas Instruments' MSP430FR5962 [7]
            - Selected for 3.3V operating mode
            - 128KB FRAM
            - Low power: 118 μA/MHz
            - I2C, UART, and SPI interfaces

        ii. **High-Level Program State Diagram:**

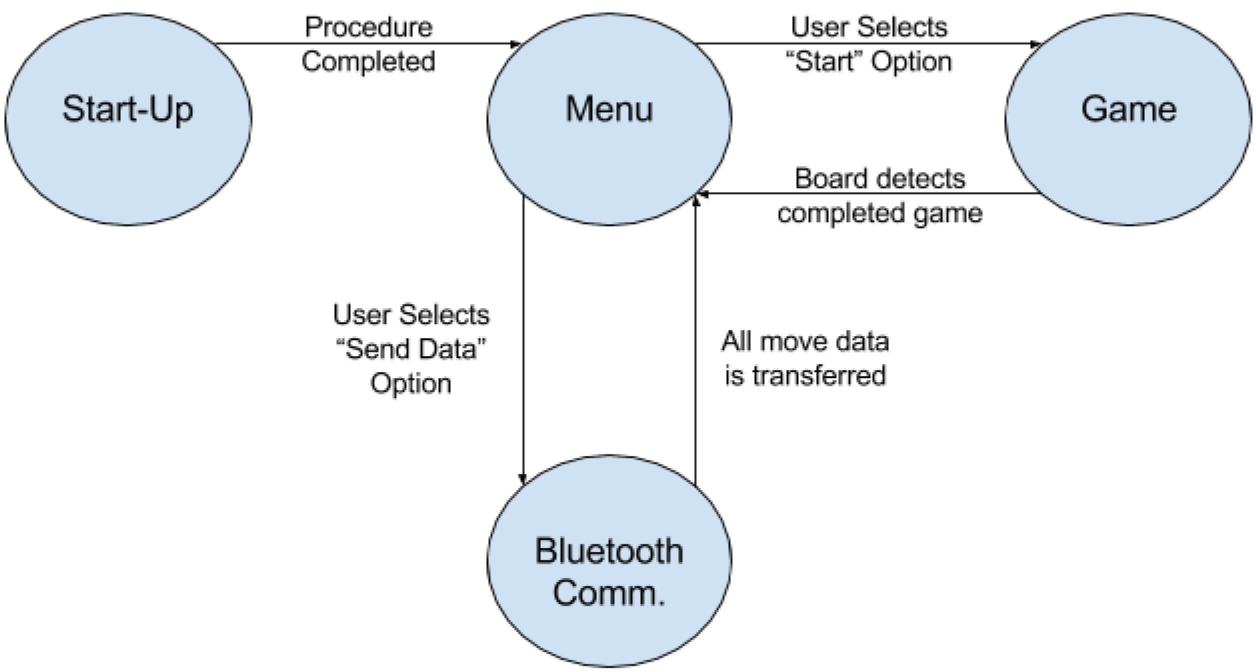

Figure 2.3.1.2: High level state diagram for MCU program operation

- **Start-Up:**
    - Wait for MCU chip start-up
    - Initialize FRAM block for game state and move storage
- **Menu:**
    - Send display information to LCD display
    - Read user input from buttons
    - Sets clock setting
    - Control movement to game/communication states

- **Bluetooth Communication:**
    - Controls Bluetooth connection protocol
    - Sends last stored game move data
- **Game:**
    - Starts and manages the chess clock
    - Routinely reads Hall-effect sensors and updates board state in memory
    - Check for differences in board state and store them as moves in FRAM
    - Send signal to update the LEDs on the board

iii. Program Flowcharts for Game Operation:

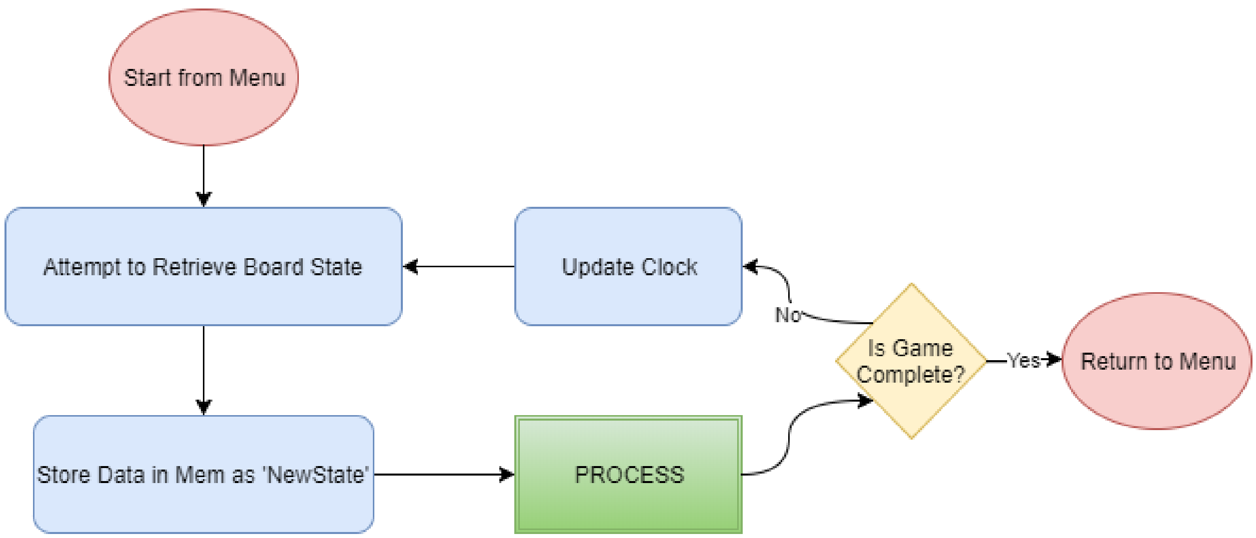

Figure 2.3.1.3: Game Operation Flowchart

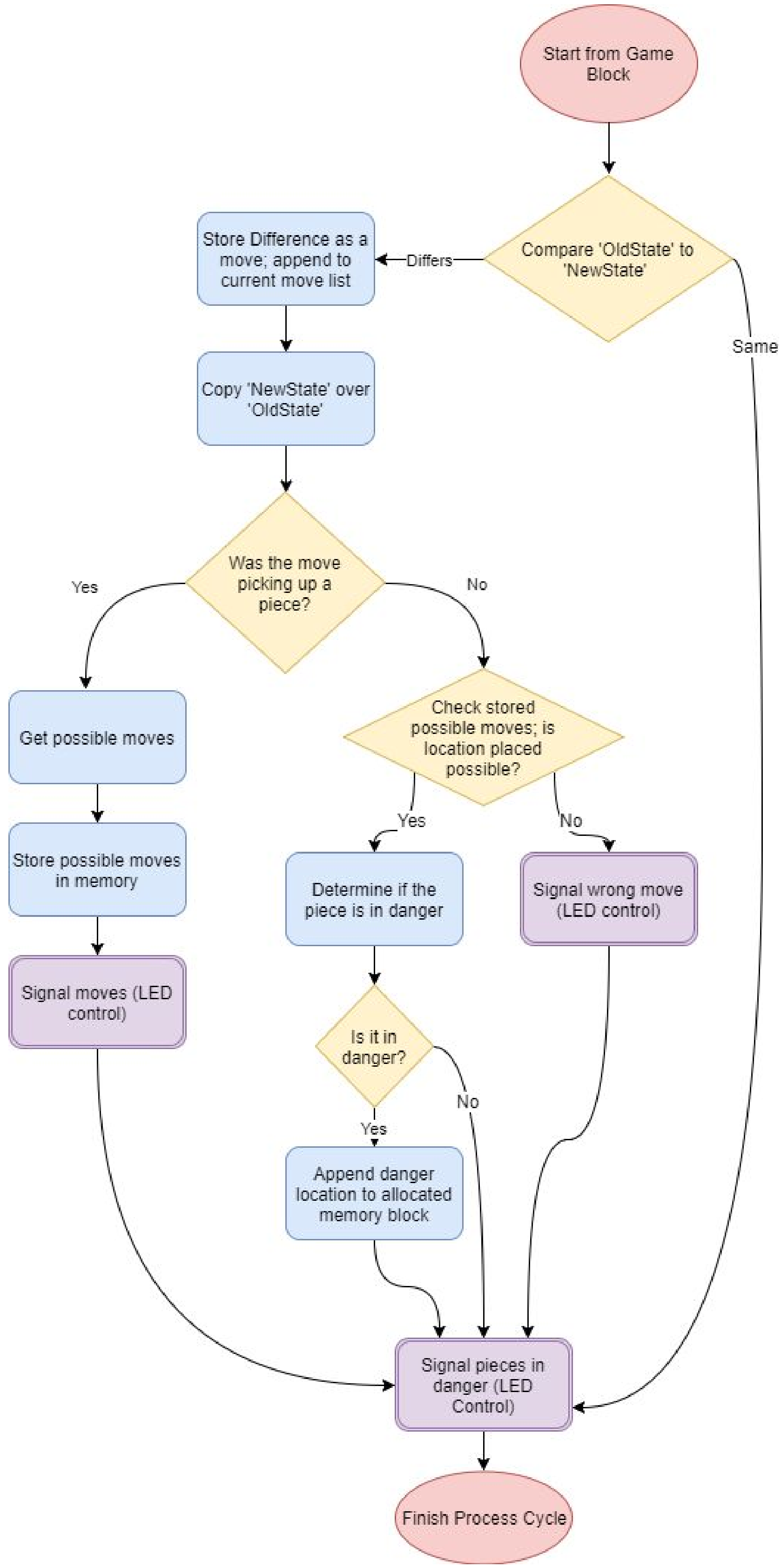

Figure 2.3.1.4: Process Block Flowchart

iv. Software State Diagram for Menu Control

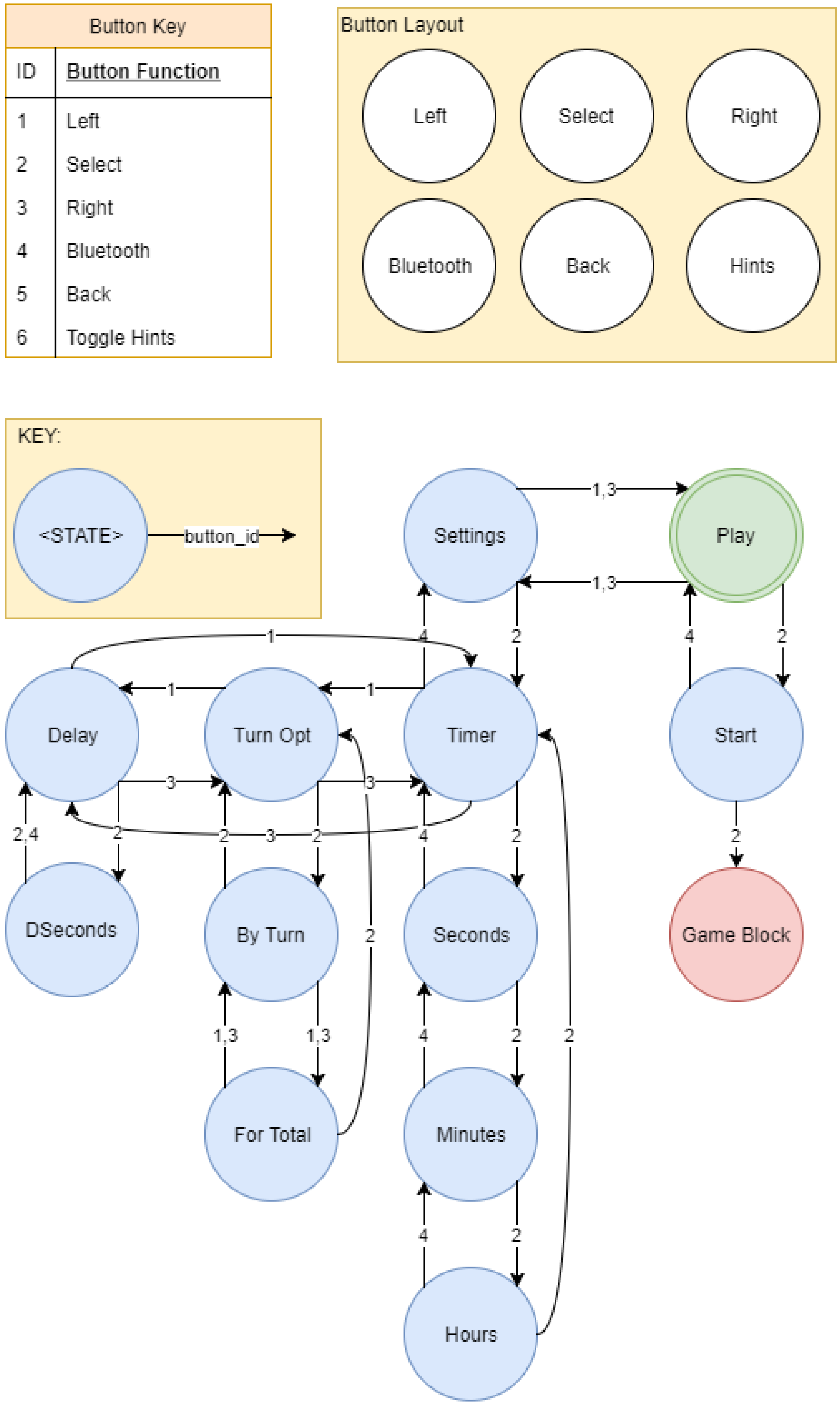

Figure 2.3.1.5: State Diagram for Menu operation

State	Output
Play	LCD=”Play”
Settings	LCD=”Settings”
Start	LCD=”Start \ Game?”
Timer	LCD = “Timer \ Settings”
Turn Opt.	LCD = “Turn \ Settings”
Delay	LCD = “Delay \ Settings”
Seconds	LCD = “HH:MM:SS”; Button(left) increases SS, Button(right) decreases
Minutes	LCD = “HH:MM:SS”; Button(left) increases MM, Button(right) decreases
Hours	LCD = “HH:MM:SS”; Button(left) increases HH, Button(right) decreases
By Turn	LCD = “Time by \ Turn”
For Total	LCD = “Time for \ Total”
DSeconds	LCD = “00:00:SS”; Button(left) increases SS, Button(right) decreases
Game Block	LCD = “HH:MM:SS”; MCU runs Game Block, LCD shows clock

Table 3.1.1.1: Menu State Outputs

Requirements	Verification
1. Can transmit data over UART to Bluetooth module 2. Can transmit data over SPI 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

- **Bluetooth:** The Bluetooth module (HC-06) is responsible for managing the connections and data transfer to a Bluetooth enabled device. This will facilitate the transfer of game data so that it can be stored and referenced by some other device at a later time.
    - Supporting Documents:
        - i. **Part Information:** HC06[8]
            - Easy to use
            - Has a connection range of 10 ft
            - UART interface with a variable baud rate

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 2. Connect Bluetooth module to MCU and ensure communication 3. Test Bluetooth module with commonly used phones to ensure data transfer

- **ADCs:** 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 will be eight, 8-bit 8-channel ADCs, one per row of sensors on the board. Each ADC will take the 8 sensor outputs of its row as its input.

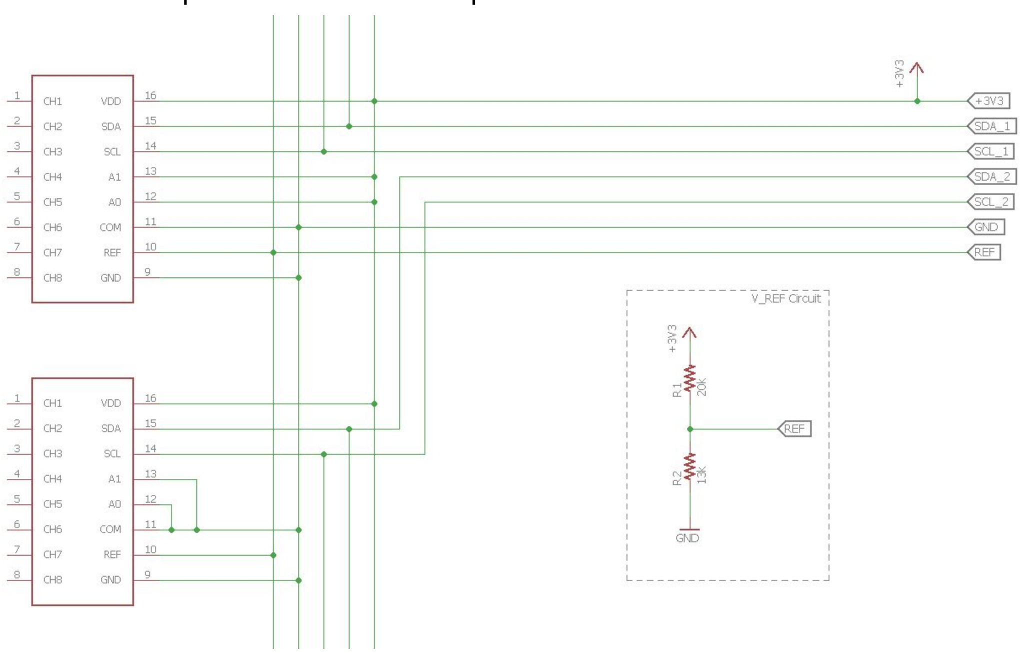

Figure 2.3.1.6: ADC circuit diagram

- Supporting Documents:
    i. **Part Information:** ON Semiconductor's NCD9830 [9]
        - Selected for 3.3V operating mode
        - Low power: max draw of 350μA
        - 8 Input Channels
        - 8-Bit output with V_{REF}~2V: ~8mV resolution

Requirements	Verification
1. At least 10mV input voltage resolution 2. I2C communication with MCU of speeds of at least 400 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 2. Connect ADC to MCU and ensure data communication

- **LED Selector Circuit:** 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 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.
    - Supporting Documents:
        i. **Part Information:** ON Semiconductor's MC74HC238A Demultiplexer [10]
            - Selected for 3.3V operating voltage
            - 1 input to 8 outputs
        ii. **Part Information:** Texas Instruments' SN74HC164 8-bit Shift Register [11]
            - Selected for 3.3V operating voltage
            - Parallel output capabilities
            - Low price at $0.325/device

iii. Circuit Example:

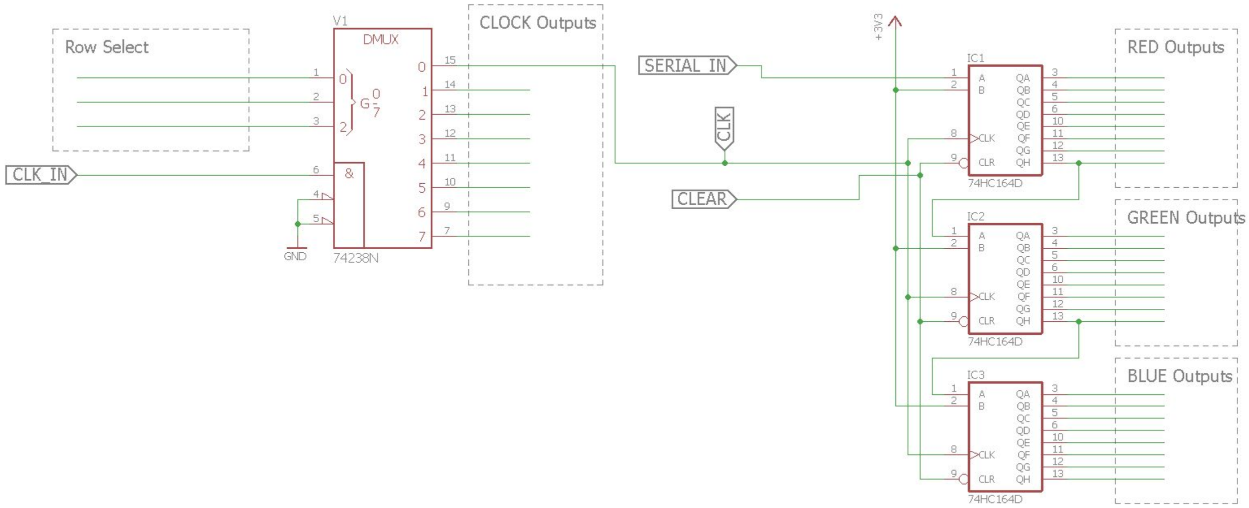

Figure 2.3.1.7: Circuit diagram for one row of LED selection

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

2.3.2 Sensor Block

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.

Justifications: When deciding on the sensing method for this block, a few different systems were considered. These system 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.

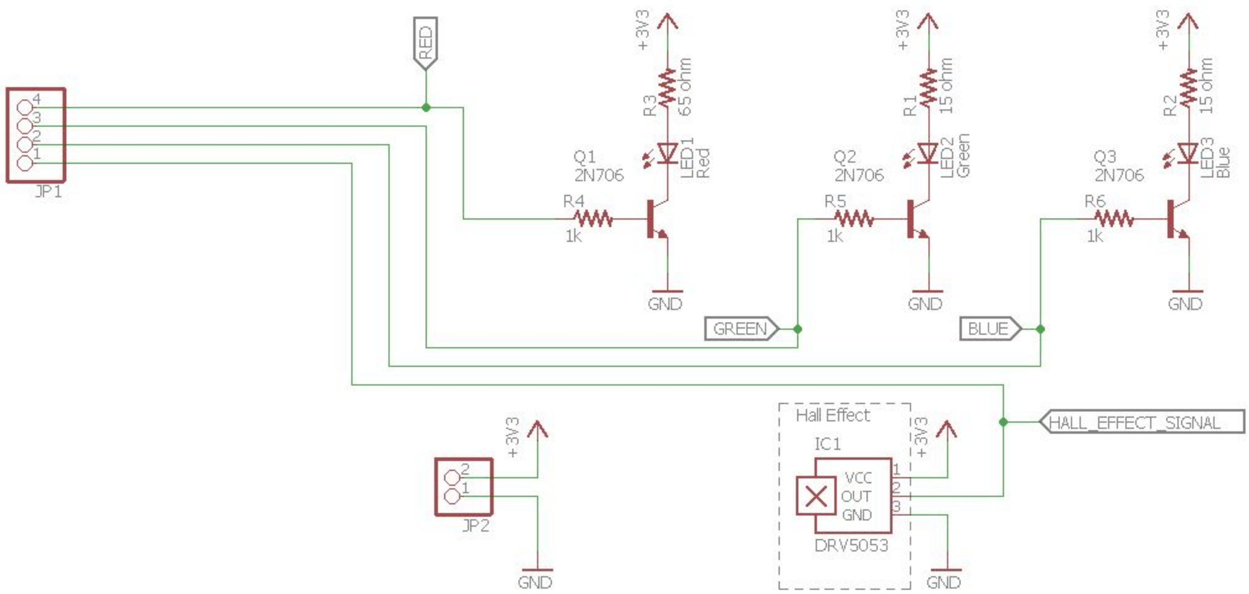

Figure 2.3.2.1: Sensor board circuit diagram

- **Hall-Effect Sensor (x64):**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.
    - Supporting Documents:
        i. **Part Information (Hall-Effect Sensor):** Texas Instruments' DRV5053OA Hall-Effect Sensor[12]
            - Selected for 3.3V operating mode
            - Low current draw of 2.7mA
            - Analog output voltage in range of 0.2-1.8V
            - Linear relation between V_{OUT} and B-field

ii. **Part Information (Magnets):** CMS Magnetics' N42 1"x1/32" Neodymium Rare Earth Disc Magnet [13]

- Selected for low cost: $0.58 per magnet
- Thickness tolerance of +/-0.002" which is in range of maximum +/-0.0062" (see section 2.4 Tolerance Analysis)

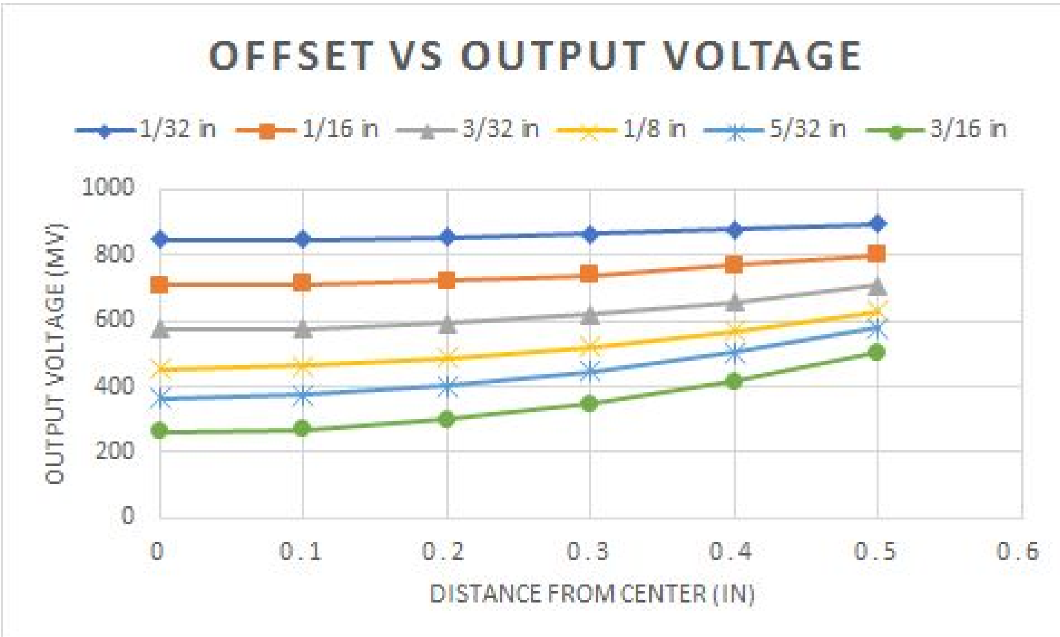

Figure 2.3.2.2: Output voltage of each magnet thickness compared to distance from center of the sensor [14]

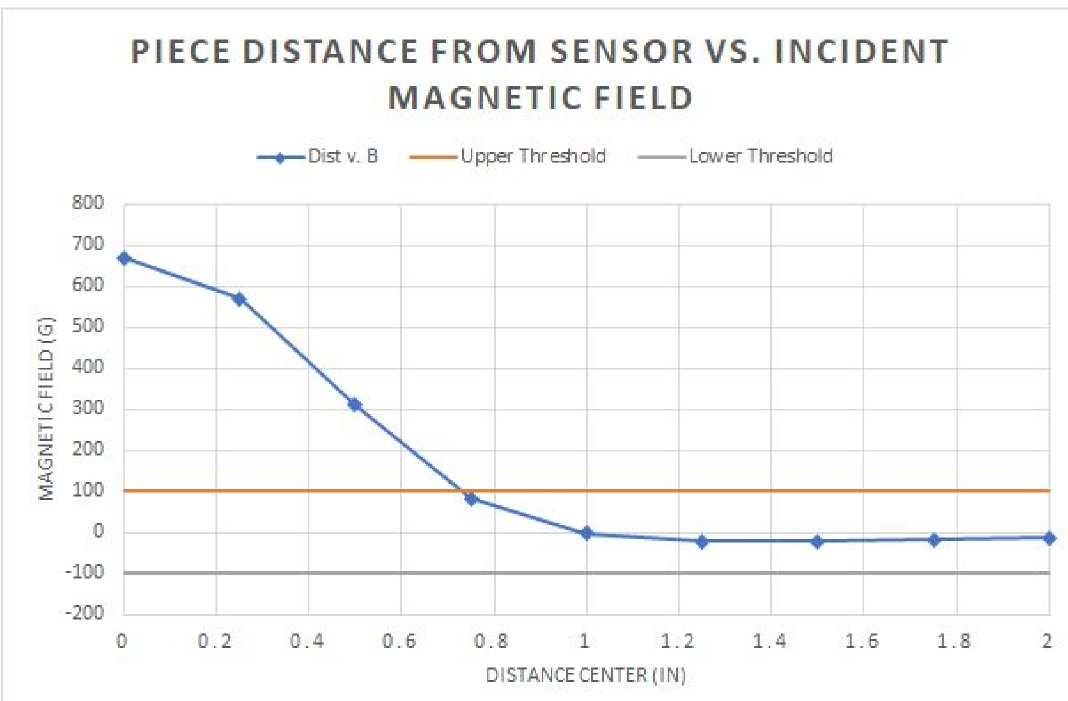

Figure 2.3.2.3: Magnetic field of strongest magnet as a function of distance from sensor; shows that interference between adjacent board spaces is negligible (board space centers are 2" apart)

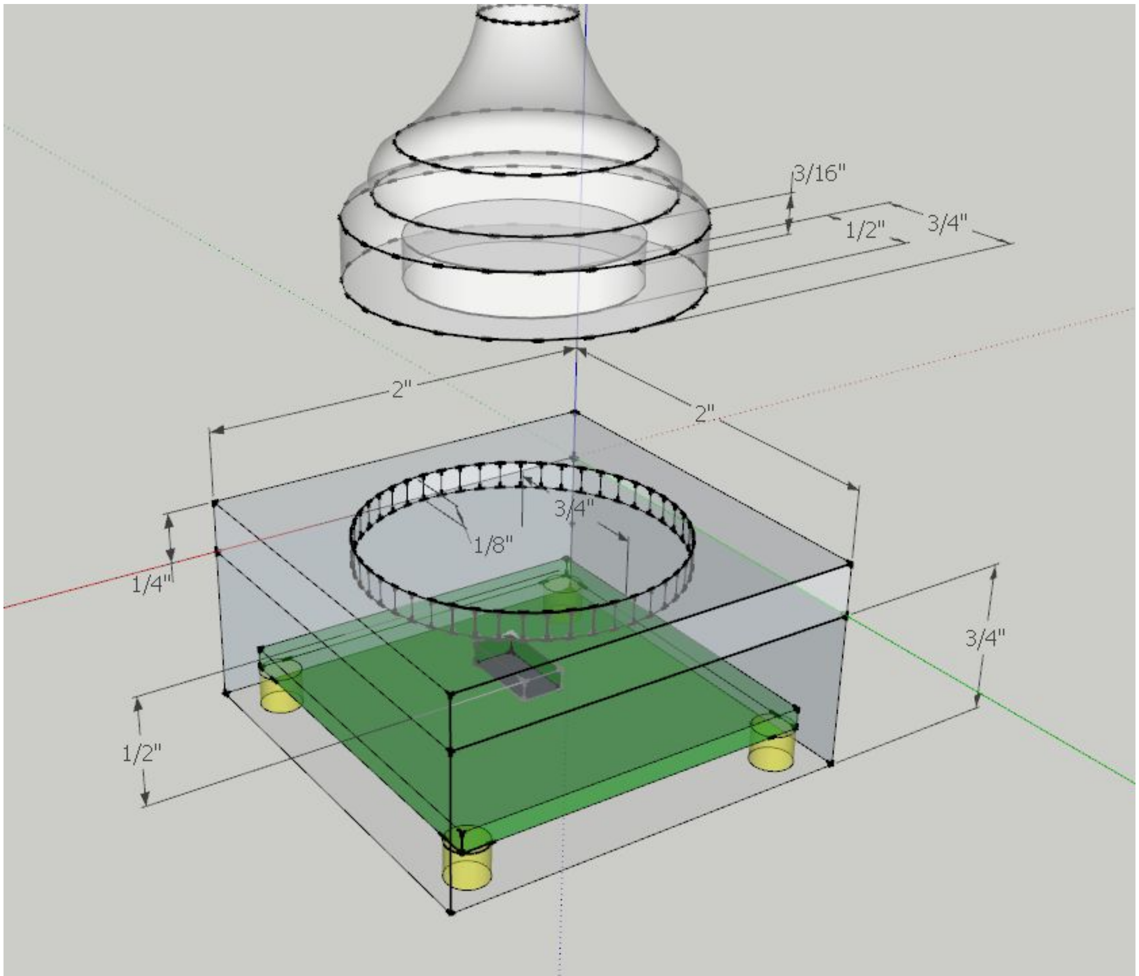

Figure 2.3.2.4: Physical depiction of sensor interaction

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}
3. Linear relationship between magnetic flux and output voltage
    a. Output matches within +/-50mV of expected value per magnet strength
	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

- **RGB LED (x64):** 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.
  - Supporting Documents:
    - i. **Part Information (LED):** Chanzon's 5mm RGB LED [15]
      - Selected for cheap price: $0.0896/LED
      - 3 color individually controllable analog color channels
    - ii. **Resistor Calculations**
      - Example calculation for red LED

$$R = (V_{DD} - V_{LED}) / I_{LED}$$

$$R = (3.3\ V - 2.0\ V)/(20\ mA)$$

$$R = 65\ \Omega$$

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

2.3.3 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).

- **Character LCD Screen:** The character LCD screen will operate at 3.3 V, and have a backlit 8x2 character space. The screen will be used to display the chess clock and an options menu to a user.
  - Supporting Documents:
    - i. **Part Information:** Newhaven Display's 0208AZ-FSW-GBW-33V3 [16]
      - Selected for 3.3V operating mode
      - 16 characters provide plenty for basic menu options
      - Backlit to provide easy legibility
      - SPI communication for interfacing with MCU

Figure 2.3.3.1: Example image of LCD display

Requirements	Verification
1. Can receive SPI 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

- **Buttons:** 6 general buttons + 2 higher accuracy switches that will allow the user to interact with the board settings. The 6 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.
    - Supporting Documents:
        i. **Part Information(general button):** uxcell’s Momentary Push Button Switch [17]
            - Selected for price at $0.53 each
            - Surface mountable on the chess board enclosure
        ii. **Part Information(mechanical switch):** Cherry’s MX Blue Keyswitch [18]
            - Tactile feedback so the user knows when it has been pressed
        iii. Physical Diagram

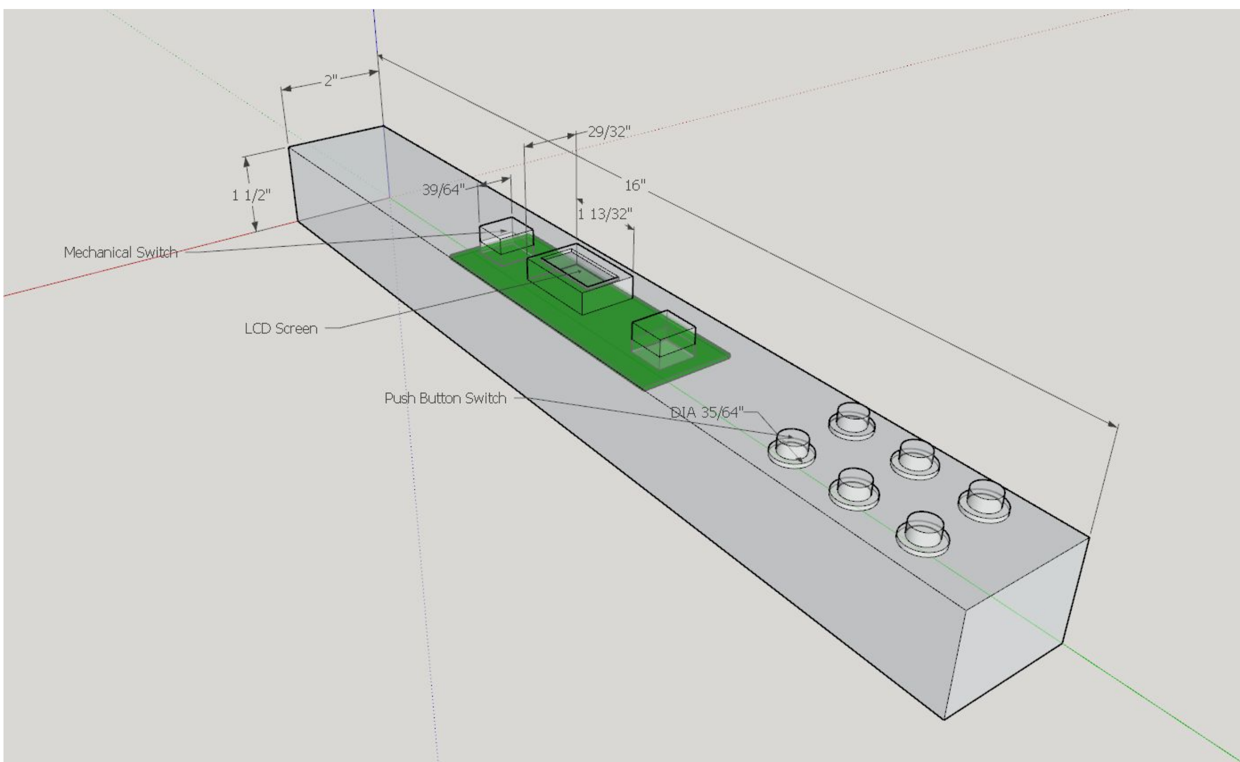

Figure 2.3.3.2: Physical depiction of switch and LCD layout

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

2.3.4 Power

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 4000mAh 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.

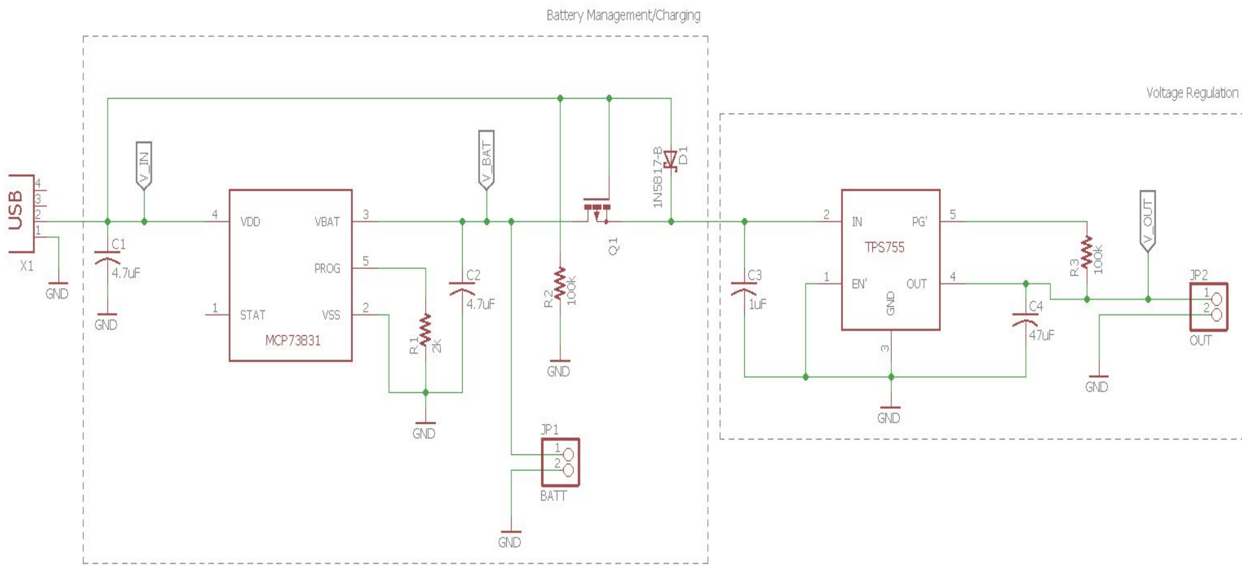

Figure 2.3.4.1: Power block circuit diagram

- **Batteries (x2):** Rechargeable battery to power whole board
    - Supporting Documents:
        i. **Part Information:** SparkFun's 18650 2600 mAh Li-Ion battery [19]
            - Provides sufficient battery capacity for 4+ hours of usage
            - Charging circuit is readily available
            - Allows for portability

ii. **Maximum Required Power Calculation:**

Part	Current Consumption
DRV5053 Hall Effect Sensor	2.7 mA * 64 = 172.8 mA
RGB LED	(20 mA * 3) * 64 = 3840 mA
NCD9830 8-bit 8 Channel ADC	(16.5 mA * 8) = 132 mA
MSP430 MCU	1.8 mA
HC06 Bluetooth Module	150 mA
Character LCD Screen	20 mA
Total	**4316.6 mA**

Table 2.3.4.1: Current consumption table

- **Likely power usage:** we estimate an average of 8 concurrent active LEDs with an average of 2 color channels active each. This leads to an estimated normal operating current consumption of **796.6 mA**

Requirements	Verification
1) Maintains a voltage level above 3.5V 2) Has a charge capacity of greater than 4000 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

- **Charging Unit:** Acts to allow the battery to be charged. Will contain a power jack to allow the battery to be charged from a wall plug.
  - Supporting Documents:
    i. **Part Information:** Maxim's MAX1551 Charger IC [20]
      - Provides safety measures for overcharging
      - Consumes minimal power when not charging

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

- **Voltage Regulator:** Regulates the voltage output to the rest of the circuit at 3.3V and provides over-load safety features.
    - Supporting Documents:
        i. **Part Information:** Texas Instruments' TPS755 Low Dropout Voltage Regulator [21]
            - Selected for :
                - Low dropout voltage
                - Provides a steady 3.3V output from a Li-ion battery
                - Can provide a maximum output of 5A

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

2.4 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 2.4.1

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 (º)	$B_{INCIDENT}$(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 2.4.1: 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 2.4.2

$B_{INCIDENT}$ 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 2.4.3

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 2.4.4

Where “n” corresponds to the n-th sized magnet when ordered by size. From table 2.4.1, $\mathbf{V_{THRESH}}$ **= 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 $\mathbf{V_{THRESH}}$ by 2 gives us the maximum output voltage range around $\mathbf{V_{OUT,IDEAL}}$ that each magnet’s magnetic strength is allowed to cause. Let this value be labelled as:

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

Equation 2.4.5

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

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

Equation 2.4.6

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 2.4.2: Relation between magnetic field strength and magnet thickness

As can be seen from table 2.4.2, 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 2.4.7

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 δ_{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.

3 Cost and Schedule

3.1 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 [22]	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.

3.2 Schedule

Date	Robert Kaufman	Rushi Patel	William Sun
10/9/2017	Buy parts; design user interface schematic and PCB layout	Finalize sensor block schematic and PCB layout	Coordinate completion of physical board with machine shop
10/16/2017	Order v1. Sensor and interface PCBs; Design power circuit schematic and layout	Design control block schematic and layout	Help with design; continue to communicate with machine shop
10/23/2017	Order v1. control block and power PCBs	Test and manage testing of v1. sensor PCB	Construct and manage construction sample of v1. sensing PCBs
10/30/2017	Update sensing block schematic and interface block schematic as needed; Order new boards	Test and manage testing of v1. control and power PCBs	Construct and manage construction of v1. control and power PCBs
11/6/2017	Update control block and power block schematic as needed; Order new boards	Test and manage testing of v2. sensor and interface PCB	Construct and manage construction of sample of v2. sensing PCBs
11/13/2017	Assist with testing and construction of remaining PCBs	Test and manage testing of v2. control and power PCB	Construct and manage construction of v2. control and power PCBs; construct remained of sensing PCBs
11/20/2017	Begin coding MCU; start final paper; start preparation of final presentation	Begin coding MCU; start preparation of final presentation	Begin coding MCU; start preparation of final presentation
11/27/2017	Operate physical testing of chessboard,	Continue coding and debug MCU; continue preparation of final	Continue coding and debug MCU; continue preparation of final

	bluetooth, and user interface; continue preparation of final presentation	presentation	presentation
12/4/2017	Prepare and Demonstrate	Prepare and Demonstrate	Prepare and Demonstrate
12/11/2017	Complete Final Paper and Present	Complete Final Paper and Present	Complete Final Paper and Present

4 Ethics and Safety

The biggest concern for our project, in terms of ethics and safety, will come from the battery type we select. Most lithium-ion batteries (most likely choice for us) are generally safe but the charging circuit must be properly designed to prevent overcurrent or charging the battery beyond safe levels. In the event of overcharging, the battery cathode can breakdown, leading to increase in cell pressure, and eventually venting with flame [23]. In order to protect ourselves, we will follow the ECE 445 General Battery Safety document [24], as well as use ICs designed to handle and regulate charging and discharging as per Section 2.3.4. To protect users, warnings will be placed on the product to inform of potential hazards due to a lithium-ion battery being used. This will fulfill the IEEE Code of Ethics Conduct #1 [25].

Another safety concern is the amount of current that could be used at one possible point. Having all the components on and running at one time will require a current of 4 A, therefore we chose a voltage regulator that limits the maximum current draw to 5 A. A current of 100 mA to 200 mA is deemed fatal, and current over 200 mA can be fatal if immediate attention is not given [26]. To ensure consumer safety, all the circuitry will be completely enclosed to prevent any potential contact to live connections. In doing so, the IEEE Code of Ethics Conduct #1 and #9 will be fulfilled, as have accepted responsibility in ensuring the safety and welfare of the public, and taken measures to avoid the injury of others.

The safety risks in magnets will be mitigated by ensuring that the housing for each piece is safeguarded from causing harm to the user. For example, a common problem when dealing with magnetic objects is having skin being pinched between objects, which would result in harm to the user. This will be mitigated by having lower strength magnets and housing the magnets in a safe way. Using the IEEE Code of Ethics Conduct #9, the primary factor driving the decisions for the housing will be the safety of users.

Our driving purpose for the project stems behind IEEE Code of Ethics Conduct #5. By improving the way the public perceives the role of technology in games, we can build a modern way to learn and play classic games. Many people are hesitant to incorporate technology into “the way things are done”, but, being shown how technology can be included to not only improve the way games are played but also can be completely non-disruptive to the traditional feel, the public perception of technology can be revised.

Other ethical issues we will handle include non-discriminatory practices and having a cohesive team according to IEEE Code of Ethics Conducts #8 and #10. We will operate as a team in a non-discriminatory way, assigning work fairly and assessing progress only on quality. We will treat everyone that we interact with through the work on this project fairly. We will also work together with our TA to ensure that we are delivering the best possible product that we are capable of and that each team member's ideas are considered and implemented.

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