CheckMATE

Final Report

IGEN 430 Group 7

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1 Executive Summary

CheckMATE (**M**echanically **A**rticulated **T**abletop **E**xperience) is a modern chessboard that merges the tactile, over-the-board (OTB) chess experience with the connectivity and convenience of online play. With automatic piece identification and articulation, it offers real-time synchronization with online platforms for a seamless and immersive experience. The system is designed to retain the classic feel of chess while incorporating the advantages of modern technology.

The board follows standard tournament specifications (530 mm × 645 mm × 80 mm, with 50 mm squares), creating a familiar and comfortable environment. Custom pieces match tournament-standard dimensions and weights. Each piece includes embedded magnets and NFC (near-field communication) tags for precise tracking, with felt pads to reduce noise and friction. A dedicated area accommodates up to 32 captured pieces.

The user interface draws inspiration from traditional chess clocks and is positioned opposite the gantry's 'dead zone.' A large rocker switch enables intuitive turn signaling, while a 7 inch HDMI touchscreen provides easy navigation of features such as starting, loading, and resetting games. Visual cues and alerts support smooth, uninterrupted gameplay.

Piece movement is handled by a compact H-Bot gantry system, optimized for minimal height and footprint. Driven by two NEMA 17 stepper motors and controlled via GRBL firmware on an Arduino Uno, the gantry moves pieces at speeds up to 450 mm/s, with an average move time of around 2 seconds. The end effector includes a 20 kg electromagnet for secure piece manipulation and an NFC reader to verify piece type and placement.

Move tracking is managed by four custom PCBs (printed circuit boards) embedded beneath the playing surface. Each PCB houses 16 Hall-effect sensors and associated electronics to ensure signal integrity. With built-in multiplexers, the system can poll all 64 squares at approximately 1 kHz.

The entire system is powered via a USB-C laptop charger connected to a 20 V PD trigger. Onboard buck converters step down voltages to 5 V and 6.8 V for system components. Designed for extended use, the system consumes a maximum of 25 W and includes active cooling with a heatsink and fan.

At its core, **CheckMATE** is powered by a Raspberry Pi 5 running custom software developed primarily in Python. This platform coordinates hardware control, game logic, and user interaction, enabling a streamlined and flexible system architecture.

By integrating precise mechanics, robust electronics, and an intuitive interface, **CheckMATE** delivers a rich, responsive experience that enhances both in-person and online chess play. This system bridges the gap between tradition and technology and creates an advanced product that appeals to chess enthusiasts of all levels

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3 Introduction and Problem Definition

3.1 Objectives

The CheckMATE objective is to design and develop a chessboard incorporating automatic piece detection and articulation, allowing users to engage in online and over-the-board (OTB) chess games. A core tenet of the project is to ensure the board offers a seamless and intuitive experience, where the integration of technology does not detract from the traditional feel of the game. CheckMATE aims to bridge the gap between online and physical chess - bringing the best of both into one seamless experience.

In addition, the system should provide a highly responsive interaction, accurately replicating the sensation of manually moving pieces across the board. This includes ensuring that the automatic articulation of the pieces mimics the smooth, deliberate motions typical of traditional gameplay. The design should be discreet, meaning that the technology and mechanisms used to automate piece movement should not be immediately apparent, preserving the classic visual appeal of the chessboard.

Furthermore, the product should incorporate only minimal modifications to the traditional chessboard layout and structure. These modifications are focused on enhancing the functionality of the board without altering the essential design that players have come to expect. Ultimately, the aim is to create a product that combines the tradition of chess with modern technological convenience, ensuring that the game's core experience remains intact while introducing new possibilities for both online and in-person play.

3.2 Users

The popularity of chess has increased in recent years due to the COVID-19 pandemic, along with media such as the TV series *The Queen's Gambit* and an increased presence on streaming platforms such as *Twitch* and *YouTube* [1]. The vast majority of chess games occur online, with the largest service provider, *Chess.com,* hosting 11 million daily active users as of April 2023 [2].

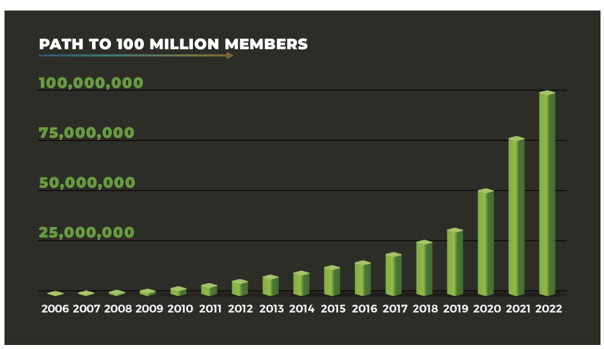

Figure 1 - Chess.com membership by time

While chess is gaining popularity, the option to play "over the board" (OTB) using a physical chess set remains limited. Currently, OTB play is often confined to clubs or games with family and friends, both of which have constraints.

The primary users of the CheckMATE system are chess enthusiasts who enjoy the convenience of online play but value the tactile experience of a physical board. This includes casual players, streamers, and competitive players who want a more immersive way to engage with online chess services. CheckMATE is also well-suited for content creators, coaches, and chess clubs seeking a modern tool for interactive training, analysis, or live demonstrations. Its intuitive interface and seamless synchronization with online services make it accessible to players of all skill levels, from beginners to titled professionals.

3.3 Needs

Through considering the online chess experience and stakeholder consultations with the *UBC Chess Club*, the following needs were identified:

Integration with Online Platforms - Can use and interact with the various pre-existing online services, such as ranked play, puzzles, game analysis, coaching, etc.

User-Friendly Setup and Compatibility - Must be simple to set up and intuitive to use.

Automatic Piece Articulation - Any moves not made in person (such as by an online opponent or engine) are done automatically.

Automatic Move Recognition and Recording - Must track piece positions and list of moves played.

Visual and Sensory Experience Comparable to OTB Play - Replicates the sensation and ‘feel’ of using a traditional chess set, with similar dimensions, piece weight, board size, etc.

Automated Board Reset and Piece Setup - Can automatically reset to the starting position.

Extended use - The system must be capable of sustained, reliable performance over long durations - both during individual chess matches and across the product’s overall lifespan.

3.3 Constraints

Size and Form Factor
CheckMATE must maintain a form factor consistent with traditional tournament-style chess sets. The board dimensions, square size (50 mm), and overall footprint should ensure familiarity for players, while individual pieces should match standard weights and dimensions. This ensures comfort and compatibility for users accustomed to OTB play and avoids disrupting muscle memory or spatial expectations.

User Operation and Experience

The system's operation must not interfere with the natural flow of a chess game. Inputting moves, whether manually or through automated articulation, should be intuitive and unobtrusive. Transitions between board interactions and online synchronization, both ‘board-to-online’ and ‘online-to-board’, must occur smoothly and without perceptible delays. Additionally, mechanical noise from the articulation system must be minimized to preserve the quiet, focused atmosphere typical of in-person play. Any distractions - visual, auditory, or physical - should be kept to a minimum to maintain the authenticity of the OTB experience.

Online Connectivity
CheckMATE must support stable, real-time integration with major online chess platforms such as Chess.com and Lichess. The system should synchronize moves with low latency and remain consistently connected throughout gameplay. In the event of connection loss, the system must recover gracefully by automatically reconnecting and resuming the game state without user intervention or data loss.

Technical and Mechanical Requirements
The piece articulation system must reliably reach all 64 squares on the board and accommodate off-board positions for up to 32 captured pieces. The mechanism should be durable, capable of withstanding frequent movement over prolonged periods without a decline in precision or reliability. Additionally, the system should be modular to allow for easy servicing or upgrades where necessary. The system should use only metric M2 or M3 socket head screws, and No. 8 square-drive button head wood screws.

3.4 Quantitative Design Requirements

The design requirements for the project are driven by user needs, project constraints, and the limitations and goals associated with the IGEN 430 project and the proposed DAID deliverables. Each requirement is categorized for clarity and numbered for reference throughout this document.

Category	Specification	Requirement No.	Status/Performance
Budget	< $1000	01	The Final Budget was increased to $1,150
Board Dimensions	< 500 mm x 600 mm x 150 mm	02	610 x 685 x 70 mm
Square Size	50 mm x 50 mm	03	Achieved
Approx Chess Piece Dimensions	King: 9.5 cm, Queen: 8.5 cm, Bishop: 7 cm, Knight: 6 cm, Rook: 5.5 cm, Pawn: 5 cm	04	Achieved
Articulation Speed	< 5 seconds per standard move	05	Achieved - 2 seconds per move
Piece Articulation Accuracy	The piece deviation is < 0.5 × diameter from the square center (25mm)	06	Achieved - Piece deviation is ~4 mm
API/Engine Response Time	< 2 seconds	07	Achieved
Tracking Refresh Rate	> 1 Hz	08	Achieved - 1 kHz
Piece Coupling Distance	< 2 cm or as required for coupling	09	Achieved
Power Consumption	< 50 W	10	Achieved - 20 W load, 8 W idle

System Voltage	12V	11	The original requirement was scrapped; the final system uses 20 V, 6.8 V and 5 V
Peak Amperage	< 5 A	12	Achieved - 1.8 A under load

Table 1 - Design Requirements

Board Dimensions: These board dimensions were set to restrict the size from being excessively larger than a traditional chess board. This ensures the product is convenient to manipulate and store. While the final product was larger than anticipated, the intent and original goal of a 'standard chess set' was still met.

Square Size: This is the lower bound of standard tournament square size, which was selected to limit the overall dimensions of the board. This requirement was fully satisfied.

Piece Dimensions: Piece dimensions follow standard sizing, with progressive height increments from pawn to king. Slight variations might be present when accommodating for any additional hardware. This requirement was fully satisfied.

Articulation Speed & API/Engine Response Time: Time is a key parameter in the game of chess, so excessively slow articulation or response times from the online API or integrated engine limit the ability of the board-using player unfairly. By ensuring rapid movement and response times, the experience is as seamless as possible.

Articulation Accuracy: Without accurate articulation, moves made by the board might be ambiguous and detract from the gameplay experience. That said, human placement is never going to be perfect and thus perfect placement of pieces is not required. Getting within the aforementioned distances mimics human play and saves articulation time.

Tracking Refresh Rate: Similar to articulation timing, detecting input moves is a key method of interaction for the board and needs to be detected rapidly for smooth gameplay. The polling rate of the sensors must be sufficiently fast to capture all moves.

Power Consumption: The entire system should not exceed 50 W. This ensures an economical use of power throughout the various sub-systems.

System Voltage: The system operates at a nominal voltage of 12 V, offering a balance between motor performance and embedded design considerations. As noted, this requirement was deemed overly restrictive. The final power architecture uses 3 separate voltages and performs better than an entirely 12 V system would. See Appendix G for details.

Peak Amperage: To safeguard the embedded circuitry, the peak amperage is limited to a maximum of 5 A under stressed operating conditions. This ensures an additional safety margin during the PCB design process.

4 Introduction

4.1 Literature/Technical Review

Existing Products

In the past 50 years, several existing products have offered functionalities similar to the proposed CheckMATE board. In the late 1970s, *Fidelity Electronics* released the first electronic chess board capable of detecting and tracking moves using a built-in chess engine [3]. In 2021 *PhantomChess* received crowdfunding totalling 2 Million USD by promising a board with automated piece articulation and online connectivity that allows users to play with online opponents [4]. They never delivered on their promise. In 2022 *Square Off* released a similar product to the market which can be bought for 550 USD [5]. These products demonstrate the market interest in integrating physical chess boards with online play; however, they also highlight challenges such as product failures and high costs that make them inaccessible to a broader audience.

5 Safety

5.1 Problem Areas and Safety Issues

Due to the nature and scale of the project, CheckMATE does not present significant immediate safety risks; however, several potential hazards have been identified and are addressed in Appendix A. The primary concerns include pinch points associated with the moving mechanical gantry, the risk of electrical discharge to or from circuit components, and potential choking hazards related to small detachable parts. Additional considerations involve software and API security to prevent unauthorized access or unintended system behavior.

All team members involved in the project completed IGEN shop safety training before accessing shared workspaces. This included instruction on the safe operation of power tools and the proper use of personal protective equipment (PPE) for various tasks. Most of the construction work was electrical and was performed with careful adherence to standard safety protocols, minimizing risk during assembly, testing, and operation.

6 Methods & Design

6.1 Engineering Calculations

Note: Complete calculations are found in Appendix B.

Stepper Motor Torque

The total torque that the motors will have to supply was calculated using a selected acceleration of 10 m/s^2 (typical to high-speed 3D printers) [6], as well as the mass and geometries of the belt and bearing system, and a safety factor of 3. Since the system is being driven by two motors, the individual motor torque is given by:

$$2\tau_{motor} = \tau_{system} = 3\,(0.348\,kg \times 10\,m/s^2) \times 0.00637m$$
$$\tau_{motor} = 0.0333\,Nm$$

Mechanical Force Requirement

Given an upper estimate for piece mass (50 g), and static friction coefficient $\mu_s = 0.29$ for felt on wood, the horizontal force required to push a piece on the board was estimated as follows:

$$f = 0.29 \times 0.05\,kg \times 9.81ms^{-2} = 0.1422\,N$$

Magnetic Coupling Distance

The magnetic coupling distance (r) can be estimated based on the required force (f), permanent magnet volume (V), and permanent magnet remnant magnetization (B_r), and electromagnet moment (m=NIA). Given the specifications of the electromagnet, as seen in Appendix C, a number of turns was estimated as 1,209. Given these values, the magnetic coupling distance was estimated as:

$$r = \left[\frac{3\times4\pi\times10^{-7}H/m(0.2134\,Am^2)(0.0873\,Am^2)}{4\pi\times0.1422N}\right]^{1/4} = 0.0222\,m$$

While this is an estimate based on a number of assumptions, this is consistent with the current range of design dimensions, and consistent with the observed coupling distance of ~1.5 cm, when considered an ideal value.

6.2 Experimental Methods

Magnet Testing

To properly specify permanent magnet size and strength for the chess pieces, thorough testing of several magnet sizes was performed. Details of magnet testing can be found in Appendix D. Magnets were tested for piece-to-piece coupling, electromagnet coupling distance, and electromagnet-adjacent piece coupling, as seen in Figure 2.

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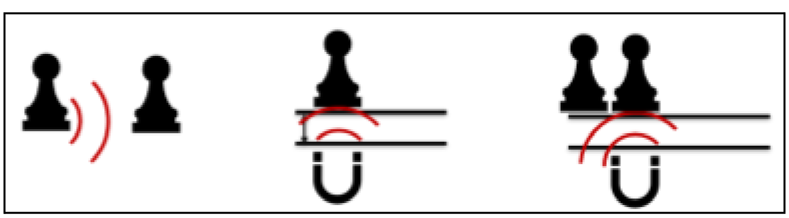


Figure 2 - Diagram of piece-to-piece coupling, electromagnetic coupling, and adjacent piece coupling

Minimum Piece-to-Piece Coupling Distance

A custom 3D printed radius measurement tool was used to determine the minimum coupling distance between two chess pieces with various magnet sizes. One piece was fixed at the center, while the other was moved closer until magnetic coupling occurred. Since pieces must pass side by side without coupling, a maximum coupling radius equal to or less than the piece diameter is required. This test ruled out the two strongest magnets due to excessive coupling distance. The two weakest magnets passed, while the mid-strength magnet showed inconsistent results, leaving its viability uncertain.

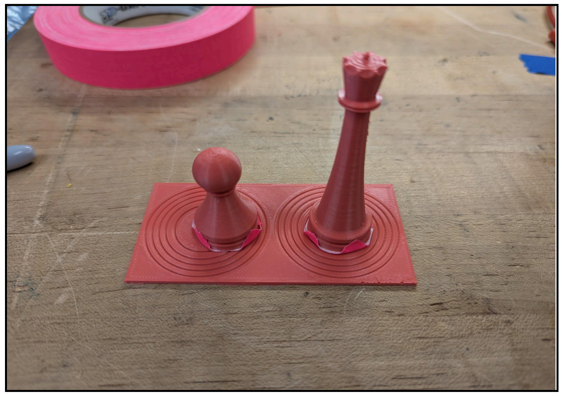


Figure 3 - Piece-to-Piece Coupling Test

Electromagnet Coupling Distance

A custom 3D printed step tool was used to measure the minimum coupling distance between the end-effector electromagnet and a chess piece magnet. The three remaining magnet sizes were tested by coupling a 10 kgf electromagnet at varying distances and oscillating it to simulate gantry motion. Coupling strength was evaluated based on tracking performance under high acceleration. Reliable tracking occurred at 10 mm, 8 mm, and 6 mm for the largest, mid-sized, and smallest magnets, respectively. Additional tests confirmed that only the largest magnet occasionally coupled to adjacent pieces, while the smaller two did not.

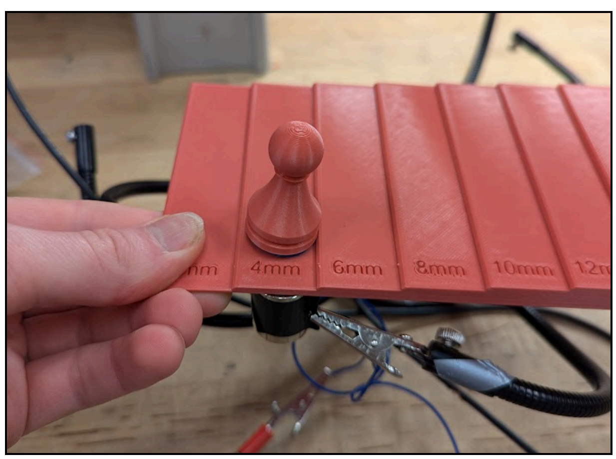


Figure 4 - Electromagnet Coupling Distance Test

Unpowered Electromagnet Coupling Distance

To verify that the unpowered electromagnet could pass beneath the populated board without interacting with piece magnets, a similar test was conducted with the electromagnet powered off. For all magnet sizes, interaction only occurred at distances much shorter than the minimum powered coupling distance, confirming that the unpowered electromagnet would not cause interference.

Permanent Magnet Coupling, Failures

To assess the viability of using an articulated permanent magnet instead of an electromagnet, and to further evaluate each magnet size for use in the chess pieces, all five original magnet sizes were tested in a 5x5 matrix, evaluating each as the gantry magnet against each piece magnet. Coupling distance, piece-to-piece coupling, and adjacent-piece interference were recorded. The two largest magnets were confirmed to be disqualified, and the mid-sized magnet was ruled out due to coupling issues. Of the remaining two, the magnet with the greater reliable coupling distance was selected for use in the pieces.

Heat Testing

To evaluate heat generation, the electromagnet was powered for 30 minutes, during which its temperature rose from 22 °C to approximately 31 °C - an acceptable increase, as this scenario exceeds the demands of even the most intensive use case (rapid bot-vs-bot play).

The full CheckMATE system was operated continuously for over 8 hours. At the end of this period, the electronics stack and CPU temperatures were measured at approximately 45 °C and 50 °C, respectively, both within their defined thermal limits.

Hall Effect Sensor Testing

To select a Hall effect sensor model, five sensors were tested for vertical sensing distance and horizontal sensing radius using the 3D printed step and radius tools. The chosen sensor demonstrated a vertical sensing range of up to 13 mm and a radial range of up to 6 mm.

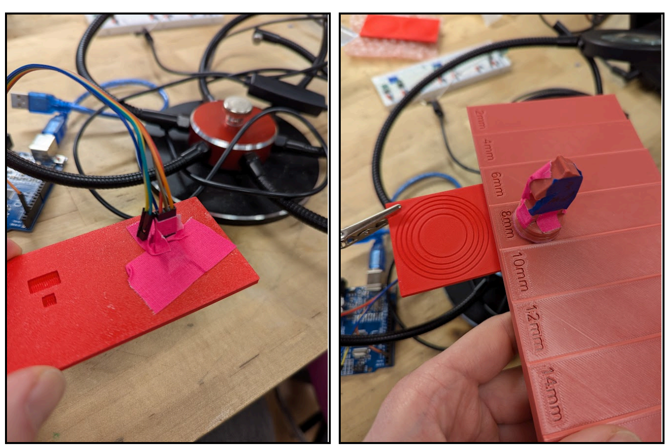


Figure 5 - Hall Effect Range Test

NFC Sensor Testing

The NFC sensor was tested with tags embedded in chess pieces. Initial tests showed interference from the metal gantry rail beneath the reader, as well as the piece magnet directly adjacent to the NFC tag. Adding a spacer between the magnet and tag in the pieces, and a ferrite sheet between the reader and rail resolved these issues. The reader successfully detected tags within ~3 cm above the sensor, confined to the projection of the square antenna. This confirmed reliable sensing within each square without detecting adjacent pieces.

Top Playing Surface Finish

To achieve a high-quality finish on the top playing surface, a laser-etched plywood prototype was tested with various treatments, including epoxy resin, polyurethane, and wood stain. Application methods were varied, with a focus on optimizing epoxy resin techniques.

The prototype was divided into multiple sections, each finished using different combinations, seen in Figure 6. The best results were obtained with two or more coats of epoxy resin, with sanding between layers. A final wet sanding to 800-grit produced a smooth, durable, and visually appealing surface.

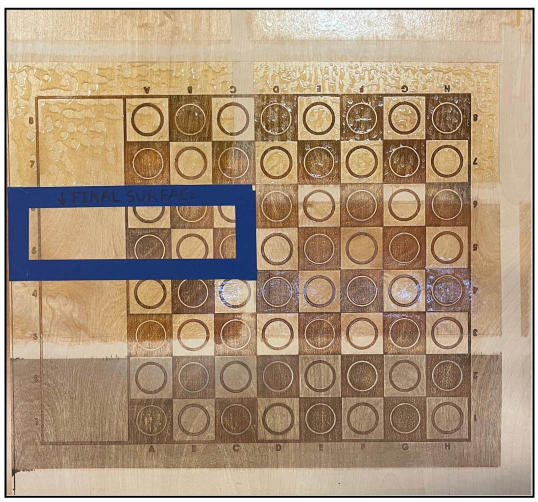


Figure 6 - Prototype Playing Surface with Final Finish in a Blue Square

End-Effector EM/Signal Interference

It was observed that when the end-stop and NFC signal lines to the end-effector were routed parallel to the unshielded electromagnet power lines, switching the electromagnet on and off induced significant voltage in the end-stop signal lines. This interference consistently resulted in peak-to-peak voltages exceeding 11 V, well above the 5 V logic level of the end-stop inputs, causing the gantry motion to halt unexpectedly. Several mitigation strategies were tested, including the addition of a 22 µF capacitor to the end-stop line. However, this measure only slightly reduced the voltage spike, bringing it down to approximately 10 V peak-to-peak.

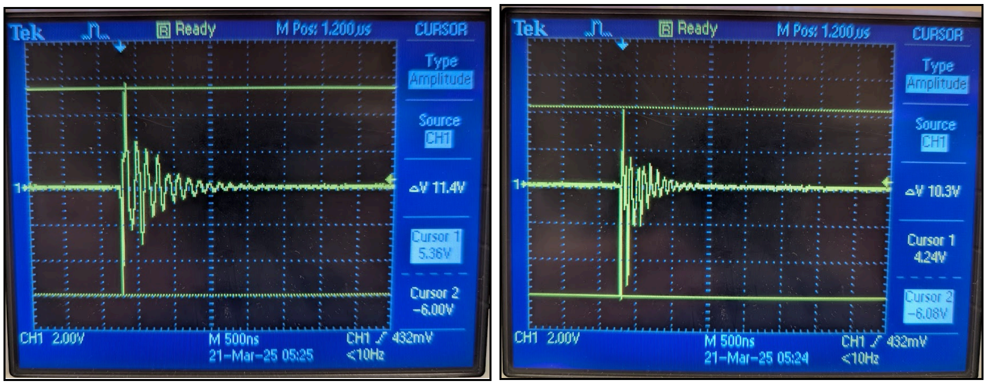


Figure 7 - Oscilloscope capture without capacitor, with 22 µf capacitor

Given the time constraints and the results of the electrical testing, shielding the end-effector signal lines was determined to be the most reliable solution. As a result, the design was revised to replace the unshielded ribbon cable with a shielded multi-conductor cable to minimize electromagnetic interference.

6.3 Material Selection

The FIDE Handbook states, "Chess pieces should be made of wood, plastic or an imitation of these materials" and "boards made of wood, plastic or card are recommended." [7] To be consistent with this, and to meet the requirement of a visual and sensory experience comparable to OTB play while also meeting the strength and durability requirements, the material selection is as follows:

Game Surface: Laser-etched ¼-inch Baltic birch plywood, finished with a clear epoxy resin coating to enhance durability and provide a smooth, high-quality playing surface with minimal wear over time.

Chess Pieces: 3D printed using PETG (Polyethylene terephthalate glycol) with a 0.2 mm layer height for precision. Each piece includes embedded neodymium magnets for reliable magnetic coupling, NFC tag for piece recognition, and felt bottoms to minimize friction and noise during movement.

Exterior Structure: Constructed from more ½-inch Baltic birch plywood, chosen for its strength, aesthetic appeal, and consistency with the top surface.

Interior Structure: Made from high-infill 3D printed PETG with increased wall loops to ensure superior mechanical strength, particularly in load-bearing or moving components of the articulation system. PLA (polylactic acid) 3D printed material was considered due to its printability, however, PETG was chosen for its superior mechanical properties.

User Interface (UI) Enclosure: 3D printed in PLA, with careful attention to surface finish and print orientation to achieve a refined visual appearance for external features.

6.4 Final Design Evaluation

The design evaluations of the various subsystems within CheckMATE, along with their corresponding design requirements, are summarized in this section. The numbered headings reference specific requirements outlined in Table 1, each relevant to the design and function of the associated subsystem. It is important to note the significant overlap in design requirements across subsystems, as these components were developed to work in close coordination. Achieving the overall design goals required seamless integration and collaboration between mechanical, electrical, and software elements.

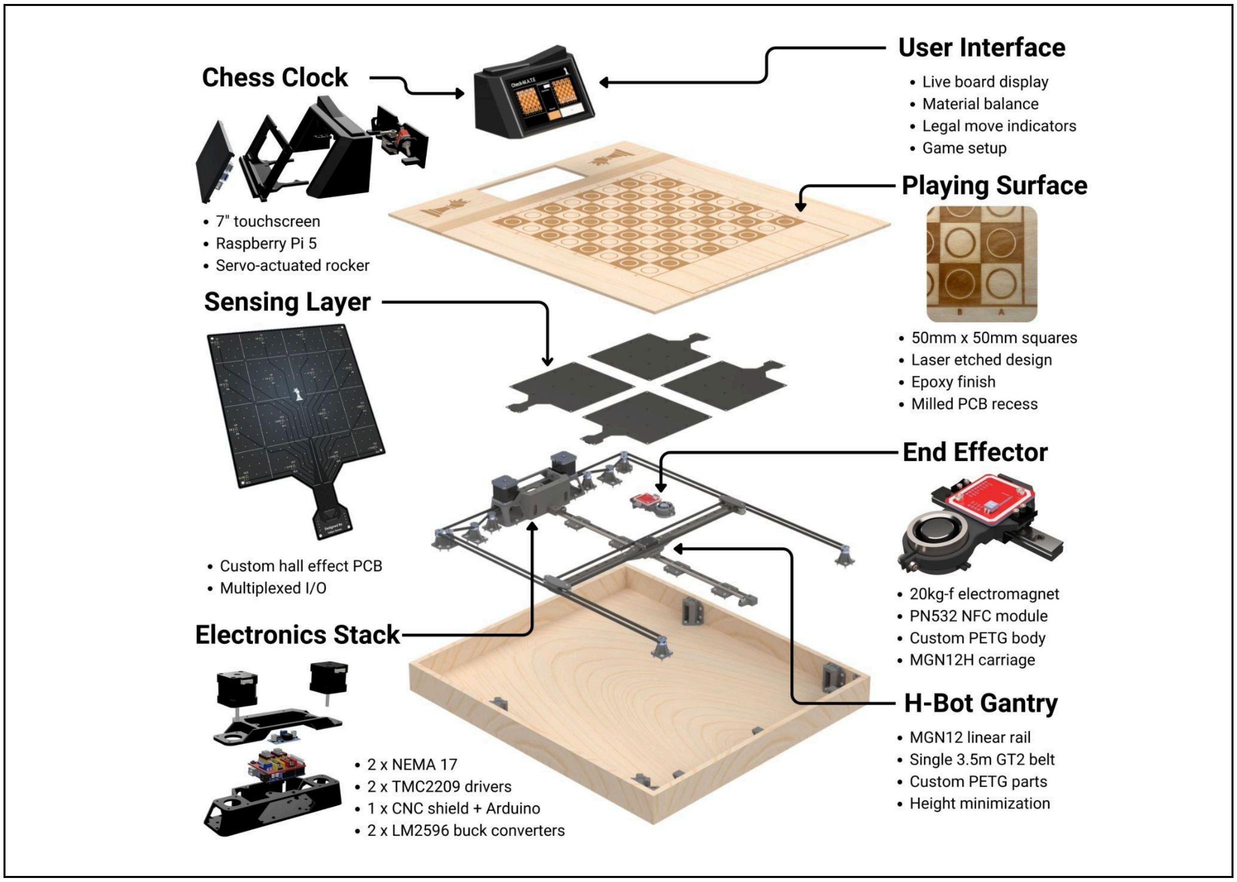


Figure 8 - Final Design Subsystem Overview

General Project Setup and Use
From a general use perspective, the board is powered on through a single USB-C connector, making it very easy to start to use. On boot, the main control program is executed, launching the user directly into the main menu, making setup very easy and rapid. This device could be used by anyone, including children, without any specific instruction, fulfilling most of the project needs. While the API interaction is still in development, a local Stockfish engine provides unlimited gameplay opportunities for a user without any dependency on internet connection. Overall, this satisfies all critical design needs.

Playing Surface - Design Requirements 1, 2, 3, 9

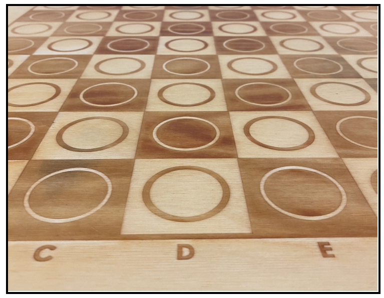


Figure 9 - Photograph of Playing Surface

- The final playing surface is constructed from laser-etched Baltic birch plywood, finished with multiple coats of epoxy resin and sanded to 800-grit to reduce friction between the surface and the chess pieces. This finish enables smooth piece articulation while preserving the traditional visual appeal expected of a standard chess set.
- The laser etching is aligned with the 50 mm square size requirement, providing clear visual cues for accurate piece placement and reinforcing the familiar layout of conventional boards.
- The playing surface is 6.5 mm thick and features milled recesses to house the embedded PCBs. This thickness was selected as an optimal balance, providing sufficient rigidity to support structural integrity while remaining thin enough to allow the required magnetic coupling between the gantry's electromagnet and the chess pieces.

Case/Structure - Design Requirements 1, 2

- The exterior structure and base are constructed from 12.5 mm thick unfinished Baltic birch plywood, providing a rigid and durable enclosure that aligns with the project's budget constraints. The natural wood grain also contributes to the traditional aesthetic expected of a high-quality chessboard.
- Interior structural components were 3D printed using PETG, selected for its balance of mechanical strength and cost-efficiency. These components support the internal mechanisms while keeping manufacturing costs low.
- To maintain visual consistency, two additional top panels were fabricated to cover the user interface (UI) area. These panels match the finish and material treatment of the main playing surface, preserving the polished, unified appearance.

H-bot Gantry - Design Requirements 1, 2, 5, 6, 10, 12

- With a top speed of 450 mm/s and acceleration of 500 mm/s^2, the gantry is capable of moving pieces around the board within the time constraints defined by the design requirements.
- The system's compact form factor - with a height of 45 mm and a footprint of 530 mm × 645 mm ensures compliance with size requirements while preserving the familiar appearance of a traditional chess set.
- The gantry's reachable work area effectively covers all 64 squares (each 50 mm), along with a dedicated dead zone sized to accommodate up to 32 captured pieces.
- To reduce upfront costs, the system was built using minimal off-the-shelf components (see BOM in Appendix H). The majority of parts were custom 3D printed in PETG, chosen for its balance of low cost and mechanical durability.

- Control is achieved via custom GRBL firmware running on an Arduino Uno, which receives G-code commands over a serial connection from a Raspberry Pi 5. This configuration enables precise, low-latency motion control across the system.
- Path planning for piece movement is calculated in Python as part of the main program. Chess moves in notation <start square><end square> are mapped to the corresponding square coordinates from the gantry's perspective, then custom g-code commands are made, the first of which is a movement to the absolute coordinates of the start square, activation of the electromagnet, relative movements to the end square, then deactivation of the electromagnet. Examples of specific scenarios like captures and more explanation can be found in Appendix E. The code is sufficiently optimized to meet timing requirements.
- For scenarios like captures, the gantry coordinates of a captured piece are passed to a function that deals with moving pieces to the dead zone located past the 'a' file on the board and organising them based on colour and order captured. While the least movements for the gantry would have been to move the captured piece to the dead zone then move the capturing piece into the square, a sequence of movements was instead used to give the capture a much more intuitive appearance for the user, closely mimicking a human doing the same capture. This sequence involves moving the capturing piece close, offsetting the captured piece, moving the capturing piece to the final square, and then sending the captured piece to the dead zone. This does take longer than required for a standard move, but has been optimized to be minimally invasive to playing experience in demonstrations conducted.

End Effector - Design Requirements 1, 6, 9, 10, 11

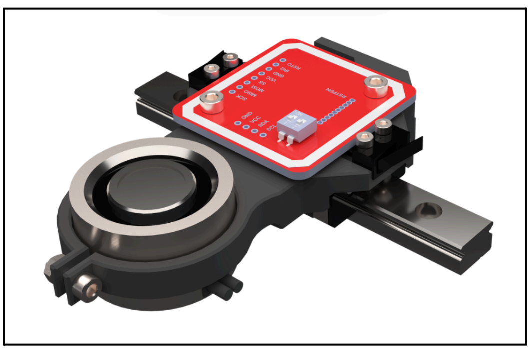


Figure 10 - End Effector Render

- The end effector consists of a 20 kgf electromagnetic and NFC reader, along with the x-axis limit switches mounted to a PETG chassis on an MGN12H carriage. It is specifically designed to minimize the height of the unit, being ~25 mm tall. Detailed information on the end effector can be found in Appendix I.
- Enables adjustability of electromagnet position to optimise magnetic coupling
- The NFC reader enables piece identification by scanning NFC tags present within each piece, allowing the system to verify piece placement and to start games from unknown positions, enhancing the user experience.
- Cables are tensioned using spring-loaded cable tensioners, preventing snagging and improving overall system reliability.

Piece Design - Design Requirements 4, 6, 9

- Pieces are custom-designed and 3D printed in black and white PETG. Piece dimensions and weight are consistent with tournament-style piece dimensions.
- 9.5 mm d x 1.6 mm h neodymium permanent magnet allows accurate piece articulation without piece-to-piece or end-effector to adjacent-piece coupling.
- Felt with static friction coefficient of ~0.29 allows silent, smooth and reliable piece articulation
- A low center of gravity was achieved by printing the pieces with a large number of bottom shell layers, increasing stability and allowing for faster acceleration without toppling. Additionally, internal features are used to increase the strength and durability of pieces across thinner cross-sections.

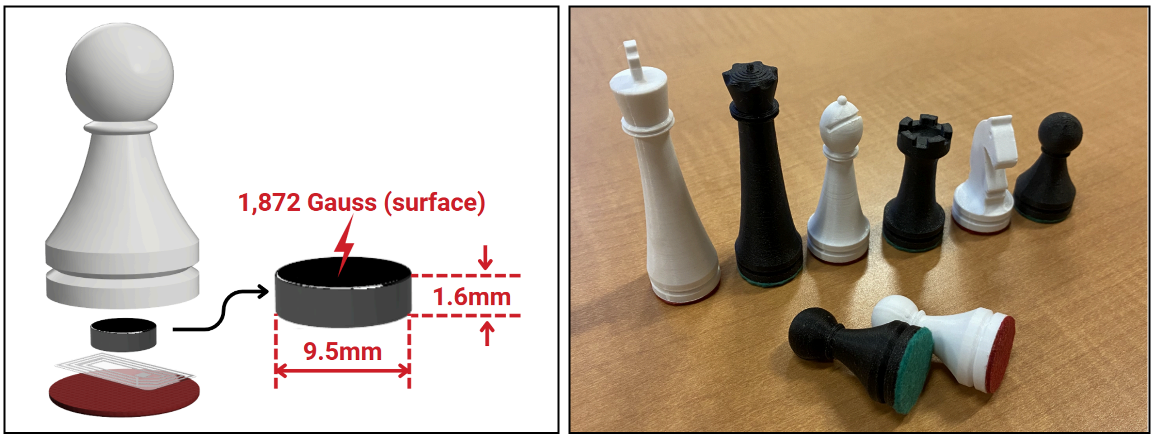


Figure 11 - Piece Design

Sense Layer - Design Requirements 1, 3, 8, 10, 11

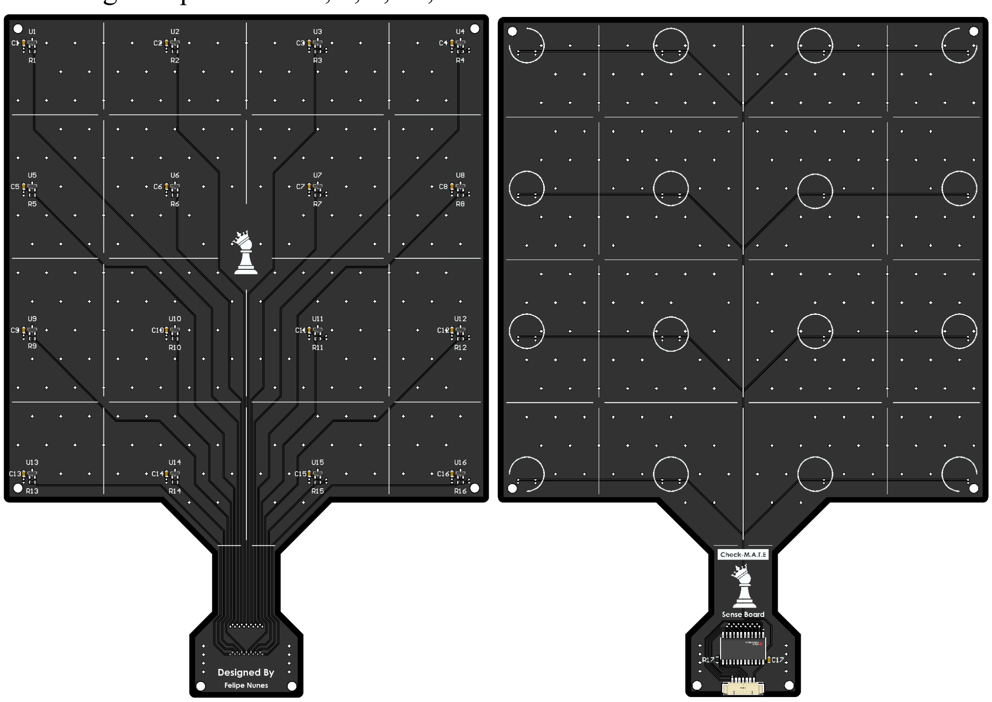


Figure 12 - Sense Board Front and Back View

- The Sense Layer is composed of four Sense Boards consisting of 16 Hall Effects each; the signal lines route into a multiplexor that encodes the individual lines to be accessible with four multiplexer inputs and one output (see Appendix F for electrical schematic).
- The board is fitted with a Molex Picoblade connector that mates to the Pi 5 with a Molex Cable assembly.
- Integrated hard-coded mappings of hall effect to chess squares.
- Piece detection is achieved by polling Hall Effect states at 1 kHz and registering overall board states on change.

User Interface - Design Requirements 1, 7, 10, 11, 12

Figure 13 - UI Render

- The user interface includes a 7-inch HDMI touch screen and a rocker switch for signaling active turn. Designed to mimic the look and feel of a traditional chess clock, the rocker can be used manually where desired or automatically articulated along with gameplay. The UI serves multiple purposes, allowing the user to select game type form the main menu, and showing live game data like current board state from either player's respective perspectives, past move list, material possession bar and a dedicated area to show which pieces had been captured, organised to match the physical layout.
- One of the key attributes of mid-game display when playing against the board is the legal move indication and icon indicators for things like check and checkmate. When it is the player's turn, and a piece is lifted, the legal moves for that piece are highlighted on the display, green for valid move to empty square, and red for valid capture. This is a fantastic aid for players less familiar with the rules of chess and serves as an indicator for when a move execution is understood correctly by CheckMATE's sensing layer.
- UI hardware is powered via onboard regulated 5 V and 6.8 V rails, and has been tested for stable power draw within the 5 A peak current limit.

Firmware - Design Requirements 5, 8

The open-source GRBL firmware was chosen to control the H-Bot gantry due to its robust performance in managing complex motion control tasks [8].

- Its adaptability enabled the repurposing of the coolant enable pin to control a transistor circuit for the electromagnet.
- A bespoke configuration file was implemented, tailored to the unique kinematics of the H-Bot gantry.
- The firmware was compiled with reference to the source code and the custom configuration to achieve a build that further optimizes performance.
- Compliant interface to receive serially transmitted G-Code commands from host Pi 5.

Software - Design Requirements 7
Github Repository: CheckMATE

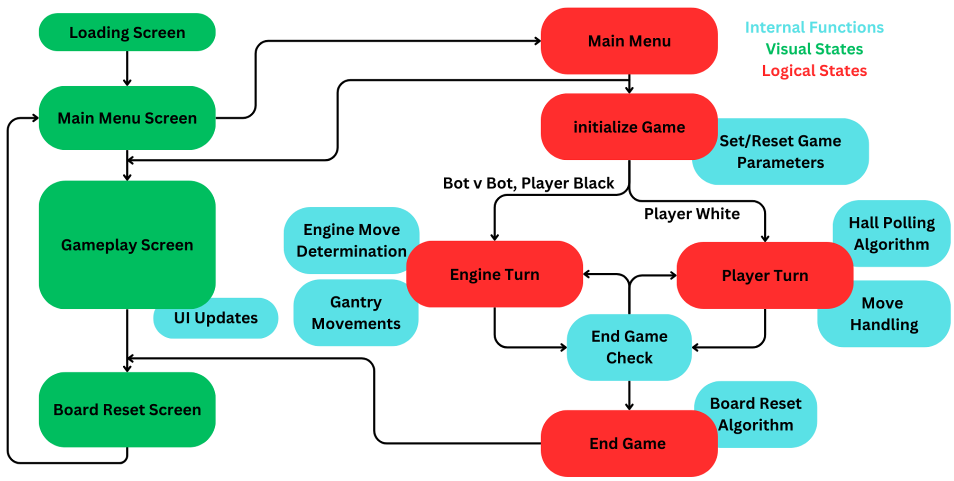


Figure 14 - Software Process Flow

- The software architecture used for this project was a custom-implemented state machine, with two main process flows, one for the logical control of the system and the other for UI elements.
- All UI elements were developed utilizing *Kivy*, a graphical framework made for Python which offers powerful visuals, transitions, and hierarchical based widget implementation [9]. By leveraging built-in elements like buttons, images, and labels, but by leveraging custom elements a completely unique and functional visuals, like a chessboard, can be created. Exact examples of this can be found on CheckMATE's Github under */checkmate/screens/custom_widgets.py*.
- To keep the UI responsive, it was run on a separate thread to the backend logic, so any events that take computational power or when polling for moves requires high-frequency looping. However, this separation prevents backend events from directly updating the screen, so an observer-notifier methodology was implemented, where calling a function to notify observers indicated to the main thread to refresh all registered observers via cross-thread communication and callbacks.
- The backend logic was established from a Python file called *control_system.py*, in which all other logical classes were referenced and initialized. By using this global object, all other elements for functionality could reference conveniently without needing to instantiate again. This was critical for things like gantry control, where multiple subsystems needed direct control of the gantry from a single serial connection.

- Contained in this control system is a state machine which transitions from a main menu, to initialize a game based on passed parameters, then to either a player turn state or board turn state, transitioning between as required based on game type. By using the *transitions* python library, a trigger function, a source state, a destination state, and concurrent functions can be set [10]. This allows for state transitions to not only be very controlled, but have repetitive functions, like updating UI elements, be done automatically.
- Chess logic was largely handled by the *python-chess* module by Niklas Fiekas [11]. This module supports integrating binary chess engines, as well as an object called chess.Board, which tracks game state, flags specific activities like captures and handles all legal move evaluations. This was instrumental to the success of the project, as the workload for implementing an equivalent system would have been on-par with all the software for CheckMATE.
- The on-board chess engine was Stockfish V17, built specifically for the Pi 5 architecture [12]. Response times were artificially slowed to allow for piece movement, but the response time was under 0.1 s, crushing the design requirement of two seconds.

6.5 Technical Drawings

Technical drawing were made for various subsystems using various CAD tools

- Mechanical parts and assemblies were designed with SolidWorks. Technical drawings of the various mechanical systems are as follows:
    - Gantry Assembly Diagram/BOM: Appendix H
    - End Effector Assembly Diagram/BOM: Appendix I
    - Overall System Assembly: Appendix K
- Electrical CAD was conducted using Altium:
    - Please find the associated schematic in Appendix F
- Lastly, helpful overviews and diagrams were created using Canva
    - Power and Electrical Architectures: Appendix P
    - Electrical Wiring Diagram: Appendix G

7 Project Planning

7.1 Cost/Budget

The initial project budget was $1,000 (CAD) and increased to $1,150 following consultations with course instructors. Of the total budget, $258 was used for prototyping, which includes shipping and customs, various consumables, and ultimately unused parts. $888 was used for the final system, with the cost of each subsystem shown below. A detailed cost breakdown across the entire project can be found in Appendix L.

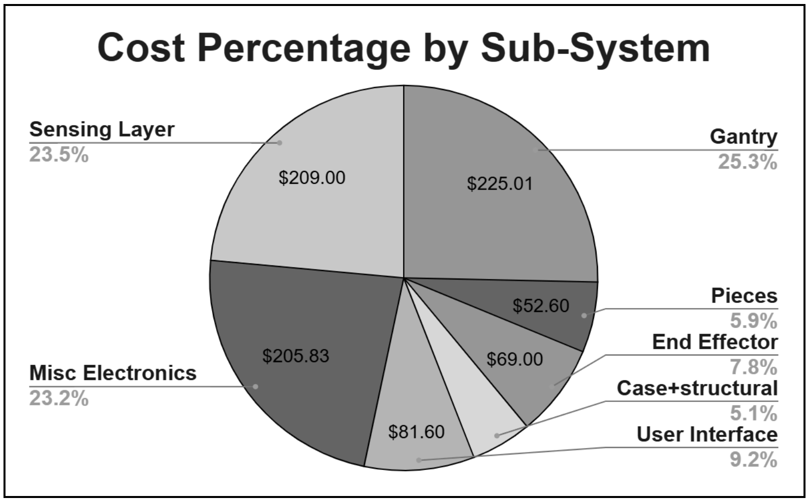


Figure 15 - Cost Percentage by Sub-System

7.3 Responsibility Distribution and Accomplishments

Team Member	Primary Responsibilities	Key Accomplishments
Ryan Brown	Control system software, user interface, USB-C advocate	Robust state machine program control, 99% successful piece movement, edge case handling, custom piece design, intuitive & responsive user interface, functional rocker switch design, one-cord power solution
Felipe Diaz	Top surface design and manufacturing	Aesthetic, smooth and professionally finished playing surface that minimized distance between pieces and electromagnet leading to reliable piece movement.
Felipe Nunes	PCB design, firmware, electrical hardware, software	Sense Board design and validation, hardware abstraction layers, electrical enclosure cabling and wiring Stepper motor + driver selection, GRBL build, software modules.
Jordan Bennett	Magnet and sensing testing, mechanical design, assembly	Piece magnet testing and selection, EM selection, cable management, end effector design, Hall effect and NFC testing, general assembly
Jackson Mills	Mechanical engineering of gantry, end effector and overall structure. DAID poster	Functional gantry and end-effector design, meeting speed, size, precision and longevity requirements. Informative CAD drawings and assemblies. The entire system is built with 3 types of fasteners.

Table 2 - Responsibility Distribution and Accomplishments

7.4 Project Plan vs. Delivery

Overall, the project progressed as expected, with the majority of design requirements successfully met within the planned timeline. The final product remains true to the original vision, and no major redesigns or subsystem overhauls were required during development. A detailed summary of planned versus completed deliverables, including estimated timelines and completion status, are in Appendix M. The team is highly satisfied with the outcome. A video showcasing the system in operation, as well as an award received, are included in Appendix N and Appendix O, respectively.

8 Socio-Economic Design Assessment

8.1 Social Impact of CheckMATE

Prior to the advent of online platforms, chess was inherently a social game, requiring players to be physically present with one another. The goal of this project is to recapture that sense of in-person connection while addressing situations where co-located play is no longer possible. For example, consider a grandparent and grandchild who have long bonded over games of in-person chess. As the grandparent ages, they may experience reduced dexterity or mobility, making it difficult to interact with physical pieces. CheckMATE enables them to continue playing by using a digital device, such as a tablet, to make moves remotely. Meanwhile, their counterpart can still engage with a physical board. This hybrid approach offers a more immersive and meaningful experience than having both players interact solely through digital devices. Even in fully offline mode, the ability to physically interact with a simulated player encourages physical movement and critical thinking.

8.2 Economic Impact of CheckMATE

CheckMATE aims to revitalize the largely stagnant chess market. Traditional boards rarely require replacement, limiting consumer demand outside of luxury or handcrafted options. CheckMATE introduces a new category of interactive, hybrid boards that merge physical and digital play, providing a compelling reason for users to upgrade. This opens opportunities for recurring engagement, software features, and accessory ecosystems - reinvigorating interest and innovation in a mature industry.

8.3 Disposal Plans

As CheckMATE is a fully functional and refined product, there are currently no plans for disposal. However, in the event that disassembly or decommissioning becomes necessary, the following disposal strategy will be implemented to ensure responsible and sustainable practices:

- **Electronic Components:** All electronic parts will be carefully removed and stored for potential reuse in future projects. Custom PCBs will be disposed of as electronic waste and sent to certified recycling facilities. Any cables deemed unsuitable for reuse will also be recycled accordingly.
- **Mechanical Components:** Fasteners and other mechanical hardware will be organized into their respective storage kits for future use. The gantry hardware will be taken apart and preserved as functional spare parts for future projects.

- **Wooden Elements:** The plywood used for the structure will be repurposed as scrap wood. Due to its aesthetic finish and durability, the epoxy-coated playing surface may be retained and reused as a traditional chessboard.
- **3D Printed Parts:** All PETG and PLA 3D printed components will be sorted and sent for recycling following local plastic recycling guidelines.

This disposal plan aligns with the team's desire to pursue the future development of this project and its commitment to responsibly dispose of components that can't be reused.

9 Conclusions & Recommendations

Conclusion

Overall, the CheckMATE capstone project was a strong success, meeting key design goals, delivering a fully functional self-playing chessboard, and demonstrating real potential for future development. The team's interdisciplinary collaboration resulted in a polished, innovative product that successfully merges classic chess gameplay with modern engineering. It is a testament to the chemistry and drive within the team that progress was able to be made continuously through the term at an ever-increasing rate. There were many design decisions made early in the project that led to easier integration and more advanced features. All members of the project are extremely proud of what they were able to put together for Design and Innovation Day, and the results can be seen below.

Figure 16 - Best IGEN Team♥ (as voted by others)

That said, having completed this project, several potential avenues for future development have emerged. Based on observations made throughout the design and implementation process, these opportunities present both potential benefits and implementation challenges—but each could contribute to an even more refined and capable system in a future iteration.

- **Wall-mounted H-Bot rails**: Alternative design to minimize gantry thickness, simplify cable routing and improve overall rigidity. Both CAD and physical prototypes were developed and showed significant promise but were ultimately rejected due to uncertainty of their performance relative to the functional existing system. With more time (and budget), such a system could benefit the performance and form factor of the gantry system.

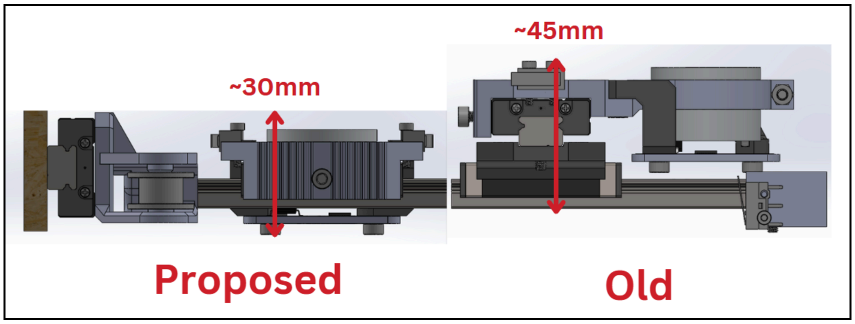


Figure 17 - Comparison Between Rail Layouts

- **LED indicators on squares:** Include LED indicators within the PCB, with light pipes mounted to the playing surface to give the user visual cues regarding legal piece moves, piece detection, check, checkmate, etc. Similar to the functionality of the UI but with improved ease of use.

- **Sense Board 3.0:** Design the Sense Board such that instead of relying on hall effects, each square has an associated antenna that can read each piece's NFC tag. Practical considerations would include radio-frequency implementation, electromagnetic interference, and effective read radius and frequency. This would eliminate the need of mounting the NFC module to the End Effector and moving underneath the respective piece to perform a scan.

- **Predictive Gantry Positioning :** To further optimize response time and enhance system performance, a predictive positioning algorithm could be implemented using the onboard chess engine. By analyzing the current game state and forecasting the most probable next moves, along with potential responses to those moves, the system can estimate a "center of gravity" for the most likely future move locations. The gantry's end effector could then be repositioned to this predicted region while awaiting the opponent's move, thereby minimizing travel distance when the actual move is confirmed. This predictive idle positioning reduces average move latency, particularly during fast-paced games or when move patterns are more predictable (e.g., during openings or endgames).

- **Open-Source Project, Commercialization:** Based on feedback from stakeholders and early-stage users, the CheckMATE team is currently evaluating two potential paths forward: releasing the project as an open-source initiative or pursuing commercialization. This decision is being made with careful deliberation, and no final determination has been reached at this time. While the team acknowledges the project's strong commercial potential, it also recognizes the scope and complexity of such an endeavor. Successfully bringing the system to market would require substantial investment in manufacturing, software refinement, user experience development, and long-term support infrastructure.

10 Appendices

Appendix A - Health and Safety Mitigation

Electrical System	
Risk	***Mitigation Strategy***
Electric shock for users	Make sure electrical connections are secure, ensure proper battery storage, charging and treatment Only operate CheckMATE indoors or in a dry environment, and prevent spillage of liquids onto board
Magnetic fields may pose a danger to those relying on ICD (pacemaker) [13], as well damage to magnetic-sensitive materials such as magnetic storage	Recommend users relying on ICD to talk to a doctor before using CheckMATE Do not operate close to magnetic-sensitive materials such as magnetic hard drives, tapes, devices etc.
Gantry System	
Risk	***Mitigation Strategy***
Moving components and pinch points	Ensure the board only operates while the top playing surface is properly in place Users should not open game board Ensure the gantry motion area is clear before operating tests or calibration of gantry Limit strength of motors past requirement for functionality Ensure use of gantry end-stops
Small Pieces	
Risk	***Mitigation Strategy***
Potential choking hazard for children and animals	Ensure pieces are sufficiently large to be difficult to swallow, recommend a minimum age range (eg. 3+)
Construction	
Risk	***Mitigation Strategy***
Power tool hazards	Ensure all participants have received necessary training on all tools and spaces used When operating power tools, operator should not be alone

Hazardous chemicals and fumes	Ensure all participants have received necessary training on all hazardous materials Ensure proper ventilation and PPE is used
Electronics assembly hazards	Ensure all participants have received necessary training on all tools and spaces used Routinely check electrical components for defects Use non-leaded solder and smoke absorber fans A second qualified individual must inspect all high-powered electrical circuits before they are energized and be present during the process
Other	
Risk	***Mitigation Strategy***
Wireless Connectivity and Privacy	Use secure and well-established API endpoints, store personal API keys in private environments

Table 3 - Health and Safety Mitigation

Appendix B - Calculations

Stepper Motor Torque

The total torque that the motors will have to supply is given by:

$$\tau_{system} = SF \times F \times r = SF \times (m \times a) \times r$$

As stated previously, speed is paramount for a seamless user experience, hence an acceleration of 10 m/s^2 was chosen (typical to high-speed 3D printers) [6]. Moreover, the motors will be fitted with a standard GT2 20 tooth pulleys with 2mm spacing, having a radius of 6.37 mm ($r = \frac{C}{2\pi} = \frac{2mm \times 20}{2\pi}$ = 6.37 mm). A safety factor of 3 was chosen to account for friction, angular inertia, and misalignment.

The overall mass of the end-effector is composed of several discrete components as follows:

$$m_{system} = m_{rail} + m_{magnets} + m_{servos} + m_{NFC}$$

$$m_{system} = 290\,g + 30\,g + 18\,g + 10\,g = 348\,g$$

Since the system is being driven by two motors, the individual motor torque is given by:

$$2\tau_{motor} = \tau_{system} = 2\,(0.348\,kg \times 10\,m/s^2) \times 0.00637\,m$$

$$\tau_{motor} = 0.0333\,Nm$$

Mechanical Force Requirement

Assuming an upper estimate for the mass of the largest chess piece (king) to be 50 g (rounded up to add a safety margin for the additional downward force from the electromagnet), and static friction $\mu_s = 0.29$ for felt on wood, using f = μ × N where N (normal force) = m × g, the force required to push a piece was calculated:

$$f = 0.29 \times 0.05\,kg \times 9.81ms^{-2} = 0.1422\,N$$

Magnetic Coupling Distance

The magnetic coupling distance (r) can be estimated based on the required force (f), magnet volume (V), and remanent magnetization (B_r).

Note: This estimation assumes the magnets are point dipoles, and the distance between the magnets is sufficiently large.

$$m = \frac{B_r V}{\mu_0} \qquad m = NIA \qquad V = \pi r^2 h \qquad F = \frac{3\mu_0 m_1 m_2}{4\pi r^4}$$

Rearranging for r: $$r = \left(\frac{3\mu_0 m_1 m_2}{4\pi f}\right)^{1/4}$$

Applying known values, including size of permanent magnet in each piece (9 mm d x 3.5 mm h), electromagnet specifications, and B_r (estimated at 1.2 T) [14]. While the number of turns of the electromagnet is unknown, it can be estimated from the geometry and electrical specifications, as seen in Appendix C. Estimated gauge of turns 28 AWG, wire diameter ~0.43 mm, coil height = 16.8mm, coil width = 17.4 mm − 4.05 mm = 13.35 mm. By estimating the number of vertical and radial turns, the number of total turns can be estimated:

$$T_V \sim \frac{16.8\ mm}{0.43\ mm} = 39 \qquad T_R \sim \frac{13.35\ mm}{0.43\ mm} = 31 \qquad T \sim T_V T_R = 39x31 = 1{,}209$$

$$m_1 = \frac{1.2T\times\pi\times(0.0045m)^2\times0.0035m}{4\pi\times10^{-7}H/m} = 0.2134\ Am^2$$

$$m_2 = 1{,}209 \times 0.2\ A \times \pi(0.010725\ m)^2 = 0.0873\ Am^2$$

$$r = [\frac{3\times4\pi\times10^{-7}H/m(0.2134\ Am^2)(0.0873\ Am^2)}{4\pi\times0.1422N}]^{1/4} = 0.0222\ m$$

With the specified values, a coupling distance is approximated to be around 2.2 cm. While this is an estimate based on a number of assumptions, this is consistent with the current range of design dimensions, and consistent with the observed coupling distance of ~1.5 cm, when considered an ideal value.

Appendix C - Electromagnet Specification Sheet

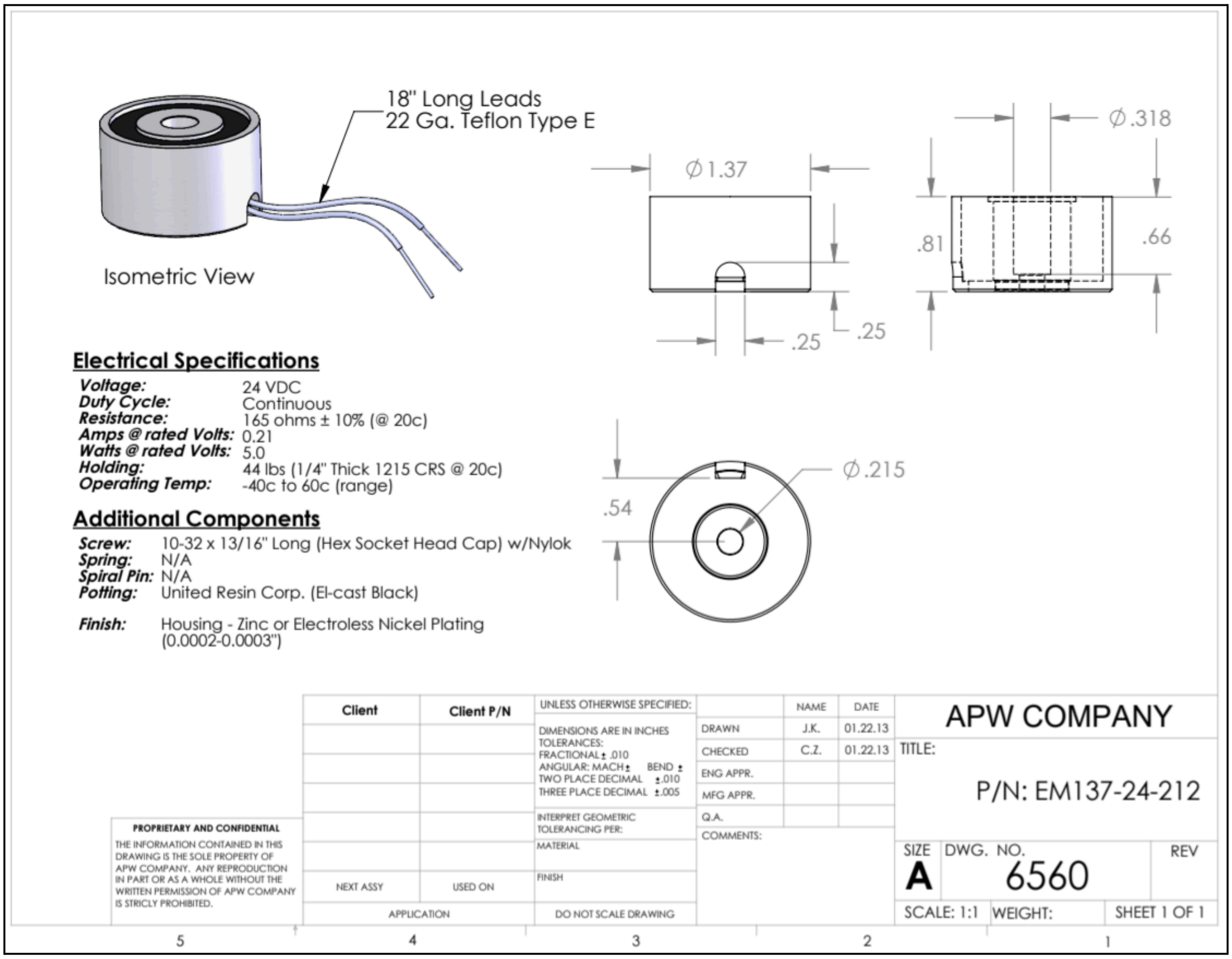


Figure 18 - Electromagnet Datasheet [15]

Appendix D - Magnet Testing Results

Introduction

This testing is to evaluate five sizes of neodymium permanent magnets for use in automatic, magnetic piece articulation in the CheckMATE system.

Magnet Types and Sizes

Magnet Type	**A**	**B**	**C**	**D**	**E**
Height (in)	0.375	0.25	0.125	0.063	0.236
Diameter (in)	0.375	0.375	0.375	0.375	0.197
Surface Gauss (G)	5,117	4,584	3,212	1,872	Not provided

Table 4 - Piece magnet sizes

Coupling Failure Types

CF1 (Coupling failure 1) = Magnetic coupling between side-by-side pieces
CF2 (Coupling failure 2) = Magnetic coupling between end effector and adjacent pieces

Test 1 - Minimum Piece-to-Piece Coupling Distance

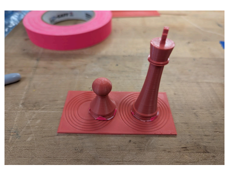
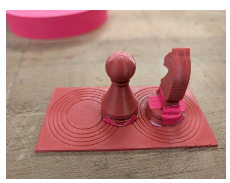
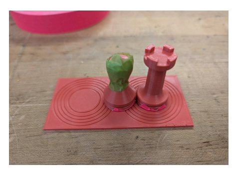
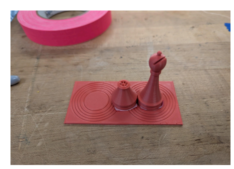
A - 0.375 in	**B** - 0.25 in	**C** - 0.125 in	**D** - 0.063 in	**E** - 0.394 in
40.5 mm + 17.5mm	38 mm + 15mm	27.75mm +4.25mm	< 23 mm OK	< 23 mm OK
				

Table 5 - Piece-to-piece coupling distance testing

RADIUS	11.5	15	17.5	20	22.5	26.5	29
DIAMETER	23	30	35	40	45	53	58
D. Eff	23	26.5	29	31.5	34	38	40.5

*** Piece diameter = R + 23mm/2 = R*11.5mm

Result: Coupling no problem for **D**, **E**. Coupling Failure 1 (CF1) **A**, **B**, (intermittent **C**) - repulsive coupling between pieces at piece diameter distance. **Eliminate A, B due to piece-to-piece coupling.**

Test 2 - EM Coupling Distance - Manual

Tested with 10 kgf articulating electromagnet (full power)

	C - 0.125 in	**D** - 0.063 in	**E** - 0.394 in
Reliable tracking	8mm, CF1, CF2	6mm	4mm
Intermittent tracking	10mm, CF1, CF2	8mm	6mm

Table 6 - EM coupling distance testing

Result:

- **C** allows reasonable tracking 8-10mm - could work at 10 with low enough acceleration NOTE: experiences coupling failure 1 and some instances of coupling failure 2.
- **D** in piece, reasonable tracking 6-8mm, could work at 8 with low enough acceleration.
- **E** in piece, reasonable tracking 4-6mm, could work at 6 with low enough acceleration.

Test 3 - UNPOWERED EM - Minimum No-Coupling Distance

Pieces pulled with unpowered electromagnet to test coupling with unpowered EM core.

Piece Magnet	**C** - 0.125 in	**D** - 0.063 in	**E** - 0.394 in
Min no-coupling dist (10g)	8 mm	4 mm	2 mm
Min no-coupling dist (5g)	6 mm	4 mm	2 mm

Table 7 - Unpowered electromagnet coupling distance

Result: Combined with Test 3, indicates that piece coupling with unpowered EM core is **no issue** (Min. unpowered no-coupling distances < min powered coupling distance)

Test 4 - PM Coupling, Decoupling Distances, Coupling Failures

TEST for magnet tracking (coupling) distance, magnet decouple distance, coupling failure using permanent magnet in end effector.

EE Magnet, Piece Magnet

GT = Good Tracking, NT = No Tracking, CF1 = Pieces Couple, CF1=EE pulls adjacent piece,

	A - 0.375 in	**B** - 0.25 in	**C** - 0.125 in	**D** - 0.063 in	**E** - 0.394 in
2Tiny	GT=4 NT=10	GT=6 NT=12	CF1	CF1	CF1
Puck	GT=6	GT=8	CF1	CF1	CF1

	NT=12	NT=14			
Mid	GT=8 NT=14	GT=10 NT=16	GT=14 GT=18 CF1	CF1	CF1
Fatboi	GT=10 NT=16	GT=14 NT=18-20 Edge of CF2	CF1, CF2	CF1, CF2	CF1, CF2
BFM	GT=10-12 NT=16	GT=14 NT=18	CF1, CF2	CF1, CF2	CF1, CF2

Table 8 - PM testing matrix

RESULT:

- **D** piece magnet with **A** in EE gives around 14mm.
- **E** piece magnet with **A** or **B** in EE has similar response to **D** in piece and **C** in EE >> Good piece tracking at 10 mm, no tracking (decoupling) at 16 mm. Reasonable tracking of **A**/**E** at 12 mm
- **A** with **E** a bit better tracking at 10 mm than **B**
- 6 mm articulation of PM on EE is adequate
- No coupling failures with either of these 3 combinations

Final Results

A, **B**, **C** eliminated due to piece-to-piece coupling, end-effector to adjacent-piece coupling, too strong coupling causing increased friction
D provides stronger magnetic coupling at adequate board depth than **E**, thus is the selected piece magnet.

Appendix E - Final Design Evaluation Supporting Information

Piece Path Planning

The basics for piece path planning are as discussed in the main body, where a move in the notation "e2e4" is split into a start square and end square, which can be correlated to the square coordinates in the gantry's reference. From there, the difference in coordinates is used to find the relative displacement in the x and y direction. This was then fed into the serial command function, which took a list in the form of absolute position, then a series of relative movements. The purpose for this notation is to allow for complex movements to be generalised in such a way that things like captures are not dependent on board location, as well as manual strings of movements being clear to understand. This works very well for cases like linear piece movement, which will only occur when there are no obstructions for the piece. Where this approach needs some logic added is with game events like knight movement, which traditionally follows an "L" shape, castling and captures.

Knight Mechanics

The knight movement is the only movement in the game that is not linear in the sense that it is neither parallel to an edge nor perfectly diagonal. Additionally, a human player traditionally lifts the knight over top of other pieces to complete its movement, which is not possible in this case. To accommodate this type of movement, the design choice of pieces' diameter be less than the gap between two pieces was leveraged. By making an 'S' motion, a knight can be slid between pieces to get to its final position. The direction taken is relative to the direction of displacement calculated by the start and end square. A diagram showing this movement can be seen below

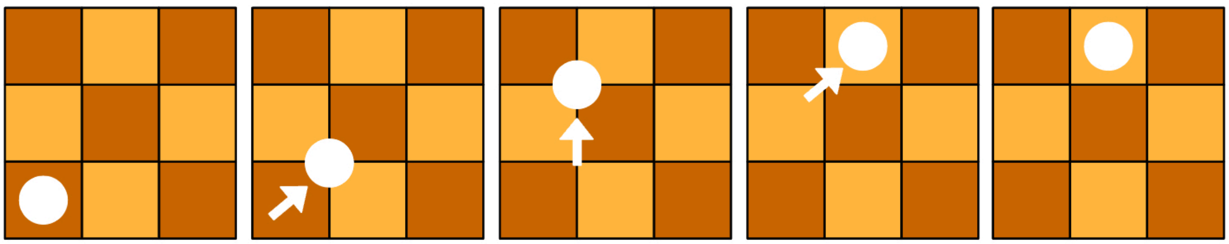


Figure 19 - Knight movement

Capture Mechanics

As only one piece can be moved at a single time, special care is taken when the board captures a piece. This process can be seen by the steps shown in the figure below:

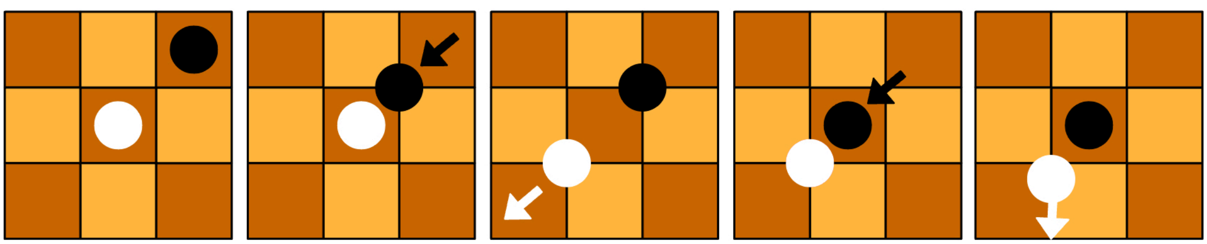


Figure 20 - Capture mechanics

This capture mechanic works for pieces coming from all directions, where the sign of the dx and dy for the capturing piece is used to account for which direction the captured piece should go. Where this runs into issues is lateral captures in the same rank, where the captured pieces would end up not on one of the inter-rank edges and thus not have a clear path to the dead zone, or if the capture happened on one of the outer squares, where the gantry cannot reach the outer edge. In these cases, the captured piece moves in a different direction, one specified depending on the location of the end square as well as the incoming direction of the capturing piece. This ensured all pieces were ready to be taken to the dead zone, and all pieces would remain within the electromagnet's reachable area.

Castling Mechanics

Castling is another situation where multiple pieces need to move for a single chess move, and it is especially complicated because using only the start square and end square is not enough to determine if it is a castle. Luckily, the python-chess module has a flag for when a move is a castle, so by checking its status and the end square, the system knows what movement needs to happen. The figure on the right shows the castling process, which is to first move the rook to its final position, then slide the king around along the edge to get to its final resting position. A key parameter here is depending on if it is king-side or queen-side the amount of spaces moved by the rook changes, and if it is white or black the displacement in the gantry x direction is different to keep the pieces away from the outer edge of the board.

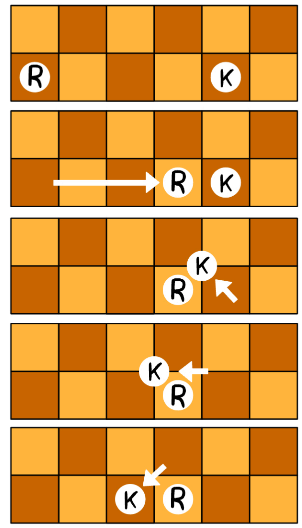


Figure 21 - Castling procedure

Appendix F - Sense Board Electrical Schematic

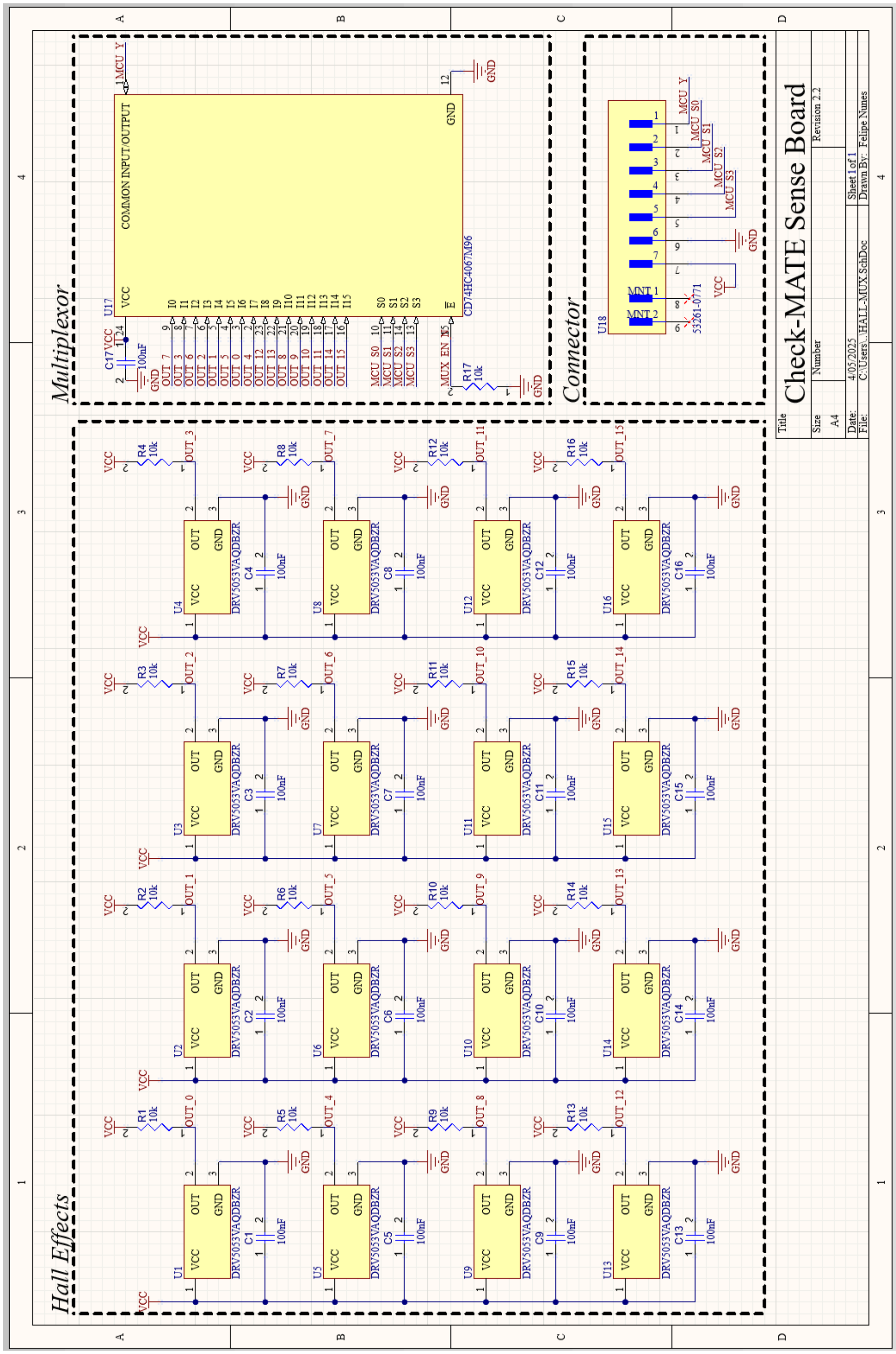


Figure 22 - Sense board electrical schematic

Appendix G - Electrical Overview

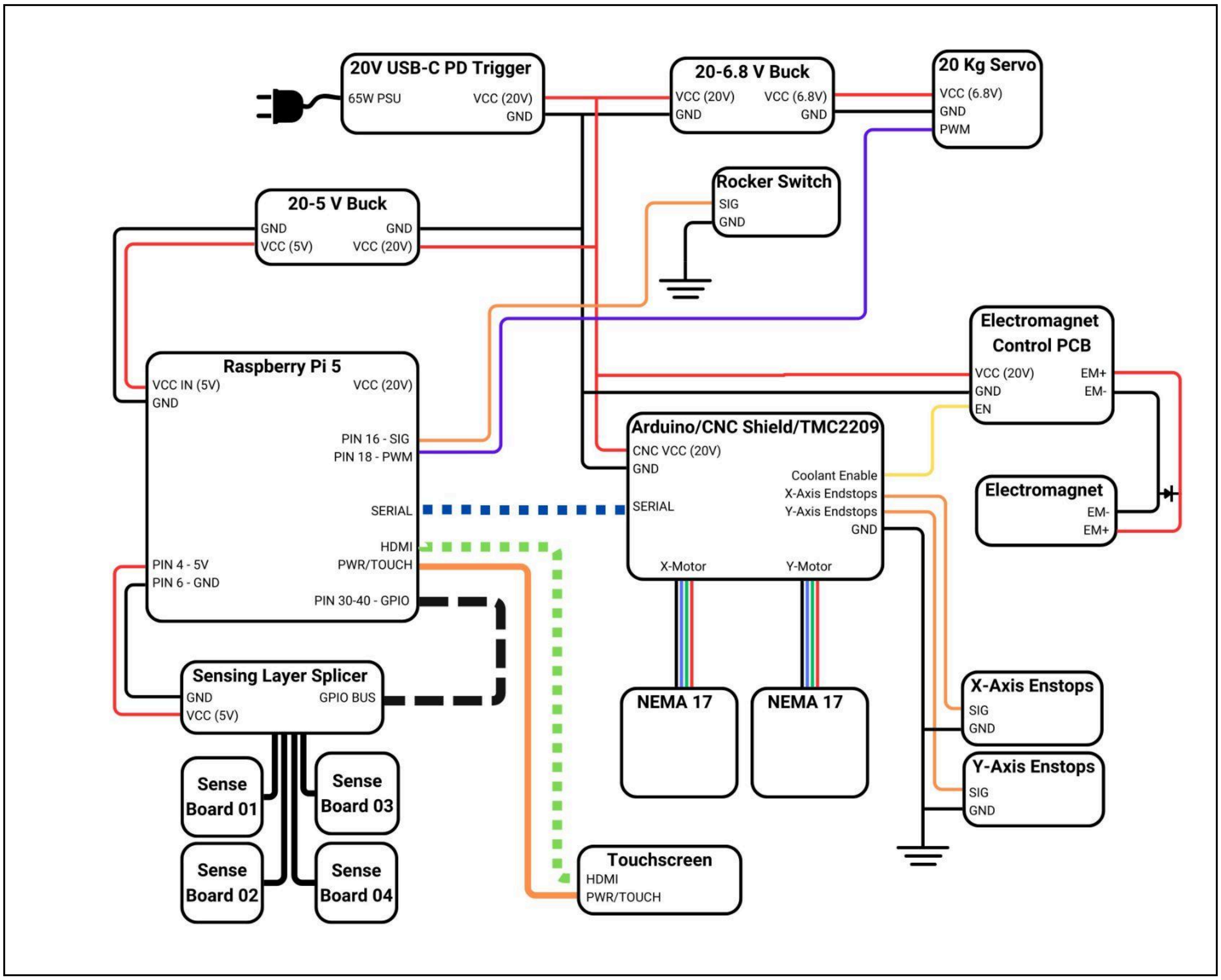
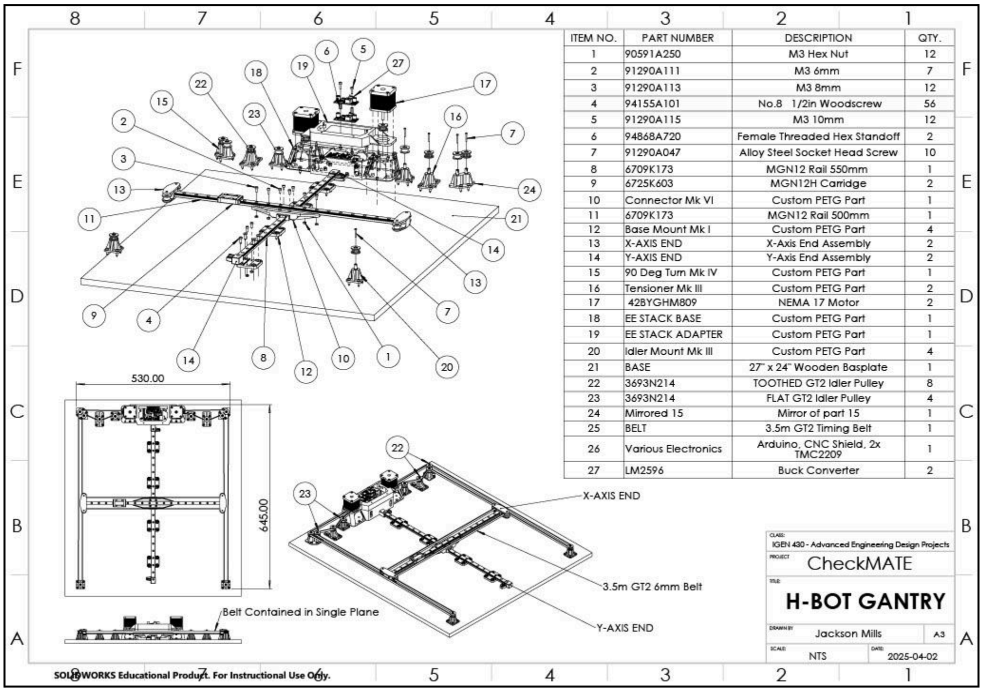


Figure 23 - Electrical overview

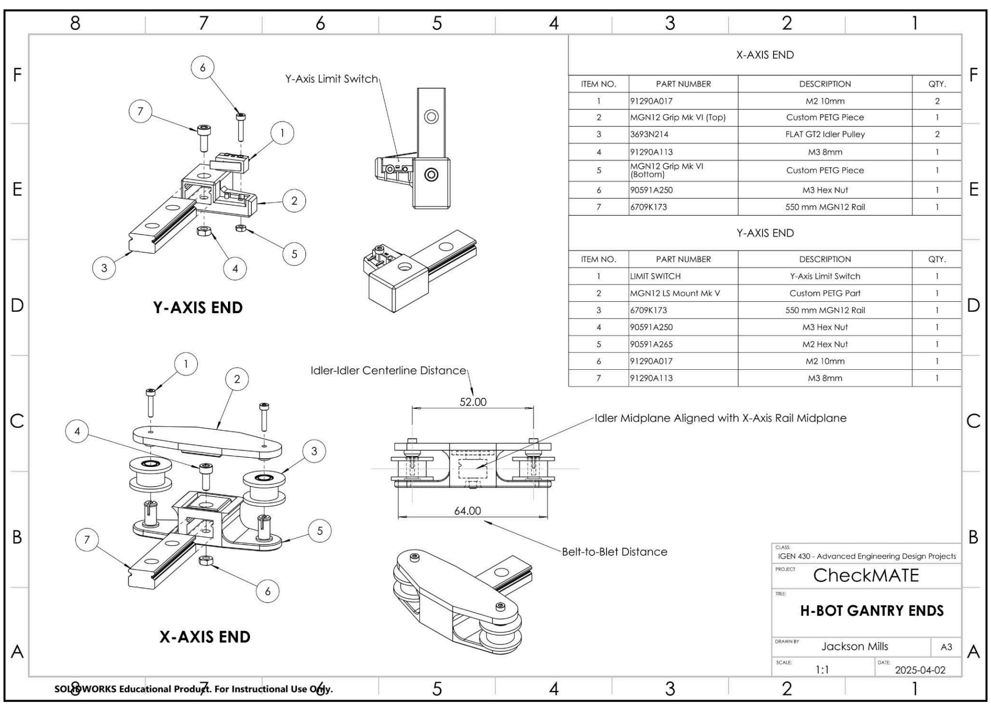
Appendix H - Gantry Assembly Diagram and BOM



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	90591A250	M3 Hex Nut	12
2	91290A111	M3 6mm	7
3	91290A113	M3 8mm	12
4	94155A101	No.8 1/2in Woodscrew	56
5	91290A115	M3 10mm	12
6	94868A720	Female Threaded Hex Standoff	2
7	91290A047	Alloy Steel Socket Head Screw	10
8	6709K173	MGN12 Rail 550mm	1
9	6725K603	MGN12H Carridge	2
10	Connector Mk VI	Custom PETG Part	1
11	6709K173	MGN12 Rail 500mm	1
12	Base Mount Mk I	Custom PETG Part	4
13	X-AXIS END	X-Axis End Assembly	2
14	Y-AXIS END	Y-Axis End Assembly	2
15	90 Deg Turn Mk IV	Custom PETG Part	1
16	Tensioner Mk III	Custom PETG Part	2
17	42BYGHM809	NEMA 17 Motor	2
18	EE STACK BASE	Custom PETG Part	1
19	EE STACK ADAPTER	Custom PETG Part	1
20	Idler Mount Mk III	Custom PETG Part	4
21	BASE	27" x 24" Wooden Basplate	1
22	3693N214	TOOTHED GT2 Idler Pulley	8
23	3693N214	FLAT GT2 Idler Pulley	4
24	Mirrored 15	Mirror of part 15	1
25	BELT	3.5m GT2 Timing Belt	1
26	Various Electronics	Arduino, CNC Shield, 2x TMC2209	1
27	LM2596	Buck Converter	2

Figure 24 - H-Bot gantry exploded view

High-res version: Linky



X-AXIS END

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	91290A017	M2 10mm	2
2	MGN12 Grip Mk VI (Top)	Custom PETG Piece	1
3	3693N214	FLAT GT2 Idler Pulley	2
4	91290A113	M3 8mm	1
5	MGN12 Grip Mk VI (Bottom)	Custom PETG Piece	1
6	90591A250	M3 Hex Nut	1
7	6709K173	550 mm MGN12 Rail	1

Y-AXIS END

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	LIMIT SWITCH	Y-Axis Limit Switch	1
2	MGN12 LS Mount Mk V	Custom PETG Part	1
3	6709K173	550 mm MGN12 Rail	1
4	90591A250	M3 Hex Nut	1
5	90591A265	M2 Hex Nut	1
6	91290A017	M2 10mm	1
7	91290A113	M3 8mm	1

Figure 25 - H-Bot gantry ends exploded view

High-res version: Linky

Appendix I - End Effector Assembly Diagram and BOM

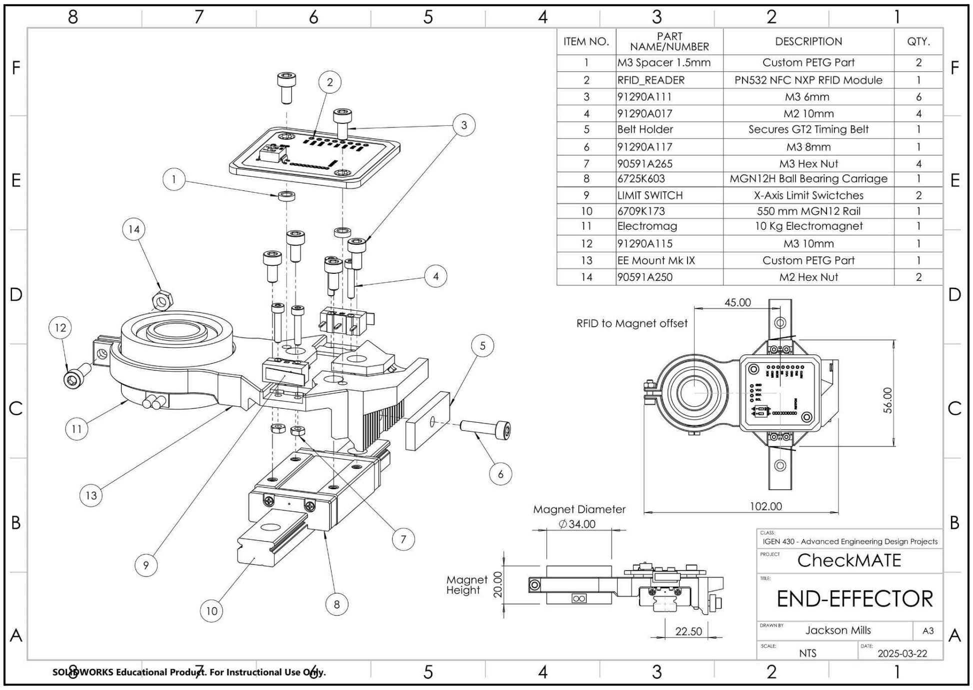


Figure 26 - End effector exploded view

High-res version: [Linky]()

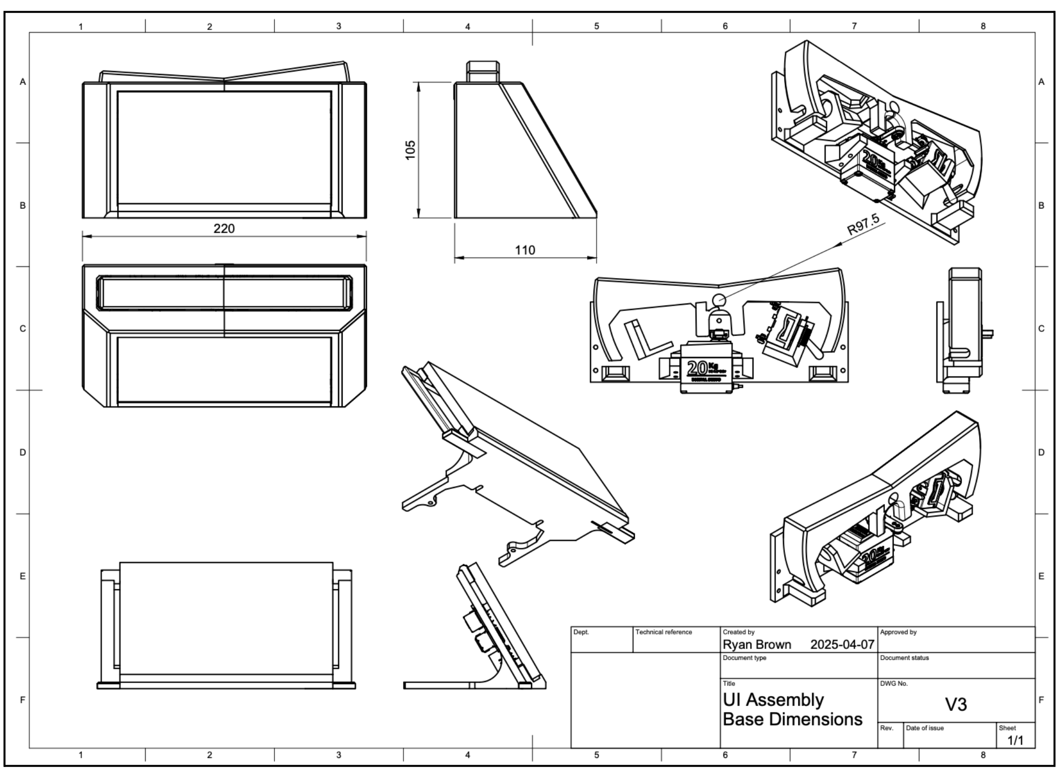


Figure 27 - UI exploded view

Appendix J - Piece Design

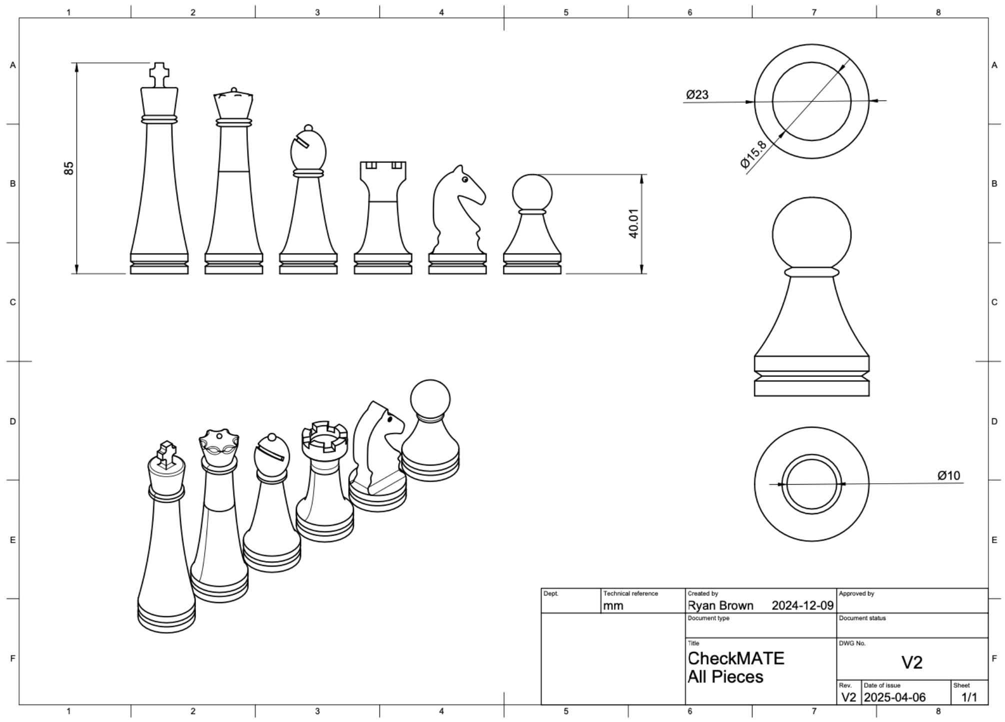


Figure 28 - Piece drawings

Pieces were designed using references found online for general style, however, each one is completely custom designed by members of the team. Specific geometry was used to ensure the diameter of the base is small enough such that pieces can fit between each other, but the stability of the pieces is not severely impacted. Of note, the knight proved a particularly difficult design to re-create, but the two-dimensional version created initially as a placeholder proved to be a clear indicator of piece type and added a certain charm to the lineup, so it was kept.

Appendix K - System Overview

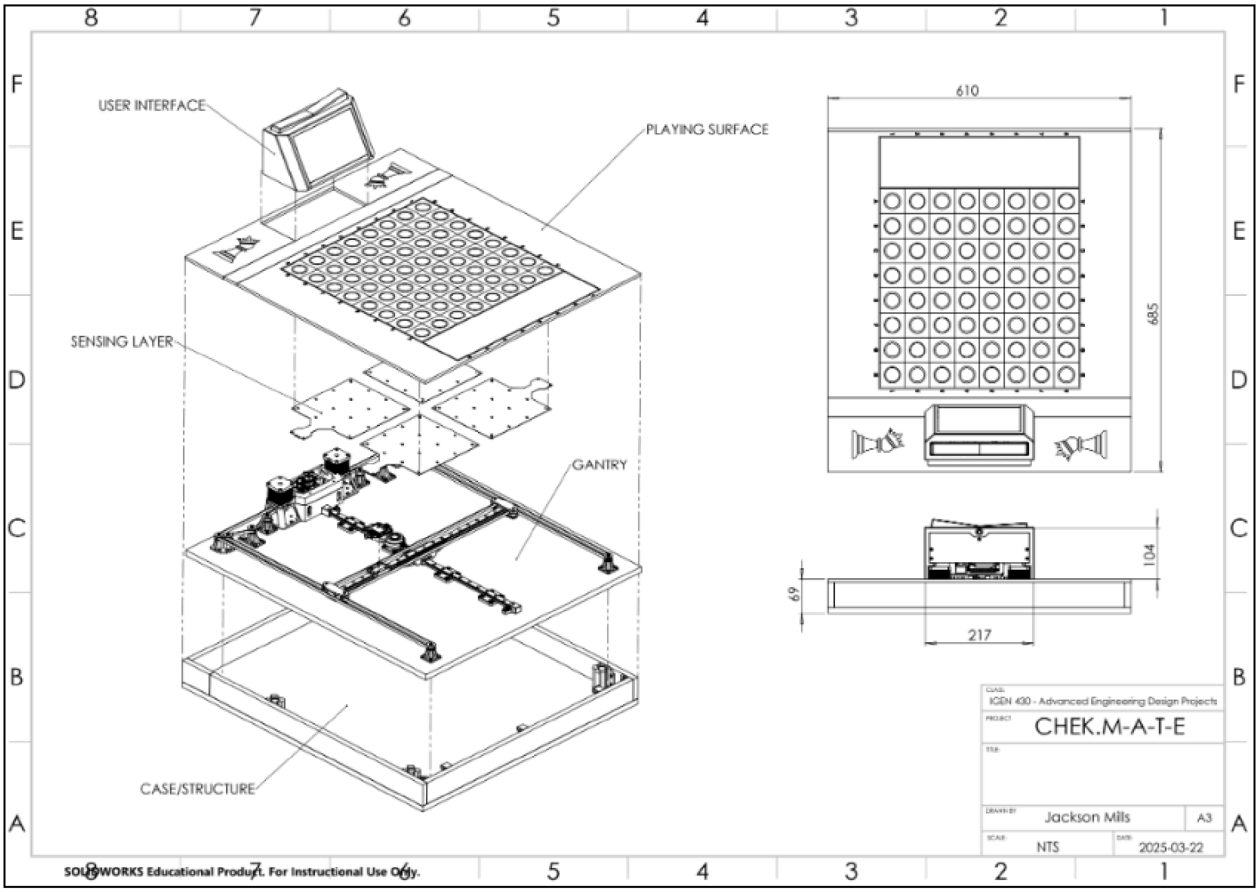


Figure 29 - System overview drawing
High-res version: [Linky]

Appendix L - Cost/Budget

					received
Check MATE Budget			Overall Cost:	$1,146.84	Shipping
			% of budget remaing:	0.27%	Not Ordered
Subsystem	**Part**	**Qty**	**Cost per**	**Cost**	**Status**
Gantry	MGN12H 550mm linear rail	1	$35.00	$35.00	received
	MGN12H 600mm linear rail	1	$32.00	$32.00	received
	6mm GT2 Timing Belt (3.5r	1	$11.99	$11.99	received
	2x NEMA 17	2	$41.51	$83.02	received
	GT2 Idlers	1	$10.00	$10.00	received
	GT2 Pulleys	1	$10.00	$10.00	received
	Filament	1	$20.00	$20.00	received
	CNC Shiled	1	$3.00	$3.00	received
	Stepper Drivers	2	$0.00	$0.00	received
	Wooden Base	1	$20.00	$20.00	received
			Total:	$225.01	19.57%
Pieces	RFID Tags	50	$0.40	$20.00	received
	Neodymium magnets	40	$0.45	$18.00	received
	Felt pads	32	$0.05	$1.60	received
	Filamet	1	$5.00	$5.00	received
	White Gorilla Glue	1	$8.00	$8.00	received
			Total:	$52.60	4.57%
End Effector	RFID reader	1	$15.00	$15.00	received
	Ferrite Sheet	1	$8.50		received
	Filament	1	$5.00	$5.00	received
	Limit Swicthes	2	$2.00	$4.00	received
	Electromagnet	1	$45.00	$45.00	received
			Total:	$69.00	6.00%
Case+structural	Baltic Birch (1/4in)	1	$15.00	$15.00	received
	Baltic Birch (1/2in)	1	$20.00	$20.00	received
	Filament	1	$10.00	$10.00	received
			Total:	$45.00	3.91%
User Interface	Rocker switch	1	$2.00	$2.00	received
	Screen	1	$52.60	$52.60	received
	Rocker Servo	1	$22.00	$22.00	received
	Filamet	1	$5.00	$5.00	received
				$81.60	7.10%
Misc Electronics	Hall effect 10x	1	$10.39	$10.39	received
	Multiplexors 10x	1	$22.46	$22.46	received
	Reed Switches	1	$25.98	$25.98	received
	Copper wire	1	$18.69	$18.69	received
	Battery/Power Mnagement	1	$100.00	$100.00	received
	Electromagnets	1	$16.62	$16.62	received
	Multiplexers	1	$11.69	$11.69	received
			Total:	$205.83	17.90%
Prototyping Cost	Many belts	2	$11.90	$23.80	received
	Various Shipping/Customs	1	$30.00	$30.00	N/A
	Prototyping Filament	1	$30.00	$30.00	received
	2 xPico, RFID reader, ferro	1	$50.00	$50.00	received
	Prototyping rail	2	$40.00	$80.00	received
	Spare 500mm rail	1	$45.00	$45.00	received
			Total:	$258.80	22.50%
Sensing Layer	PCB Manufactring	1	$30.00	$30.00	received
	PCB shipping/customs	1	$70.00	$70.00	received
	Hall Effects	1	$70.00	$70.00	received
	Capacitors	1	$5.00	$5.00	received
	Resistors	1	$4.00	$4.00	received
	Cables	1	$30.00	$30.00	received
				$0.00	received
			Total:	$209.00	18.17%

Figure 30 - CheckMATE Budget

Link to High-Res Image: [Linky]

Appendix M - Project Plan vs. Delivery

Task	Assign To	Planned Deliverable	Start Date	End Date	Status
Mechanical Articulation Feasibility	Jack, Jordan, Diaz	Definitive evidence of trial and reports on results, planned next steps	Sept 25, 2024	Oct 25, 2024	Evidence of high potential, design to follow
EM Articulation Feasibility	Jordan, Diaz, Nunes	Definitive evidence of trial and reports on results, planned next steps	Sept 25, 2024	Oct 25, 2024	Tested in lab, feasibility disproven
End Effector PM/EM Feasibility	Jordan	Definitive evidence of trial and reports on results, planned next steps	Sept 25, 2024	Oct 25, 2024	Tested in lab, EM ruled out, PM selected
Magnetic Sensor Matrix Prototype	Jack, Ryan	Chessboard with unknown piece tracking	Sept 25, 2024	Nov 10, 2024	4x4 prototype built, functioning LEDs
API Access and Control	Nunes	Game played via API calls external to online application	Sept 30, 2024	Oct 12, 2024	Access achieved; can play via terminal
Custom User Interface	Ryan, Nunes	Visual representation of chessboard digitally, interactive pieces	Sept 30, 2024	Oct 18, 2024	V1 Complete, graphic board, moving pieces
Gantry Specifications	Jack, Nunes	Gantry BOM determined and ordered	Nov 5, 2024	Dec 3, 2024	Planned, parts ordered
User Interface Physical Design	Ryan	User interface BOM and parts ordered	Nov 12, 2024	Dec 3, 2024	Planned, parts ordered
Board Design and CAD	Jack, Ryan	Full CAD of board and pieces for presentation and analysis	Nov 15, 2024	Dec 3, 2024	CAD complete and presented
Computer Vision Prototype	Diaz	Mockup and feasibility of accuracy scoring using a computer vision system	Nov 10, 2024	N/A	Rejected due to efficacy of existing sensing methods
End Effector Design	Jack, Jordan	End Effector designed in CAD, various prints require iteration	Nov 28, 2024	Mar 18, 2025	Design finalized

H-Bot Firmware	Nunes, Jack	GRBL Firmware integration	Dec 1, 2024	Feb 8, 2025	GRBL Compatibility confirmed
Gantry Prototype Assembly	Jack	Assembled crude H-bot gantry	Jan 14, 2025	Jan 30, 2025	Confirmed feasibility of H-Bot design, identified flaws of current system.
Hall Effect Testing	Jordan, Nunes	Determine Hall effect model and range	Feb 5, 2025	Feb 12, 2025	Model selected, range specified
Piece Magnet Testing	Jordan	Selecting optimal permanent magnet for pieces	Jan 27, 2025	Feb 5, 2025	9 mm d x 3.5 mm h neodymium magnet selected
End Effector Prototype Assembly	Jack, Jordan	Assemble prototype end effector	Jan 22, 2025	Feb 1, 2025	Identified flaws of current design, determined potential solutions
UI Prototype Development	Ryan	Custom screen and widget design and interaction	Oct 27, 2024	Apr 2, 2025	Flagged and remediated bugs
Overall Prototype Assembly	All	Integration of existing prototype systems	Feb 2, 2025	Feb 15, 2025	Finalized and documented
NFC Testing	Jordan	Confirm operation of NFC and sensing range	Feb 27, 2025	Apr 1, 2025	Confirmed operational range satisfactory
PCB Design	Nunes	Design, validation and ordering of sensing layer PCB	Feb 10, 2025	Mar 1, 2025	PCB design complete, ordered.
Prototype top Surface	Diaz	Design and manufacturing of top playing surface & testing of finishes	Mar 1, 2025	Mar 21, 2025	Manufactured surface and found ideal surface finish process
Final CAD	Jack, Ryan	Drawings, Renders and BOMs of various sub-systems	Mar 14 2025	Apr 1 2025	Finalized and documented
Cable Routing	Jordan, Jack	Implement End Effector cable routing	Mar 10, 2025	Apr 3, 2025	Tensioned cable solution implemented
Final Gantry Assembly	Jack	Construction of final gantry, mounted to final baseplate.	Mar 18, 2025	Mar 19, 2025	Mounted all gantry components to the final baseplate with proper spacing, verifying functionality for final deliverable

End Effector Signal Isolation	Jordan, Jack	Determine solution for cable routing which avoids EM/signal interference	Mar 18, 2025	Mar 20, 2025	Use shielded signal cable
Final End Effector Assembly	Jack, Nunes	Assembled end-effector design, including electrical connections	Mar 19th 2025	Mar 19th 2025	Assembled and debugged the final iteration of the end effector.
PCB Assembly	Nunes, Jack	5 fully assembled boards (front and back)	Mar 16, 2025	Mar 16, 2025	Assembled and validated solder joints with respect to each component
Integration of all subsystems	All	Functional operation of all working systems	Mar 16, 2025	Apr 2, 2025	Validated integration of assemblies and debugged software interfaces
Final Top Surface	Diaz	Smooth, visually appealing top surface, with milled PCB recesses	Mar 10, 2025	Apr 2, 2025	Smooth and aesthetic top surface that minimizes the distance between pieces and electromagnet
Final Piece Assembly	Jordan, Jack	Printed pieces, install magnet, spacer, NFC tag, felt	Mar 24, 2025	Apr 3, 2025	Pieces completed and tested, NFC tags programmed
Software Development	Nunes, Ryan, Diaz	Functional, bug-free software to drive the functionality of CheckMATE	Oct 26, 2024	Apr 3, 2:05 pm 2025	Functional, semi-bug-free software that implements all desired features
DAID	All	Final presentation of entire system to the public	Apr 3, 2025	Apr 3, 2025	Generated substantial interest
Final Report	All	Final Report to satisfy IGEN requirements	Apr 5, 2025	Apr 6, 7:52 pm 2025	Submitted

Table 9 - Project plan vs. delivery (to date)

Appendix N - Video of Operation

CheckMATE Youtube Link

Appendix O - IGEN Award

Figure 31 - IGEN 430 Award

Appendix P - Power and Control Architecture

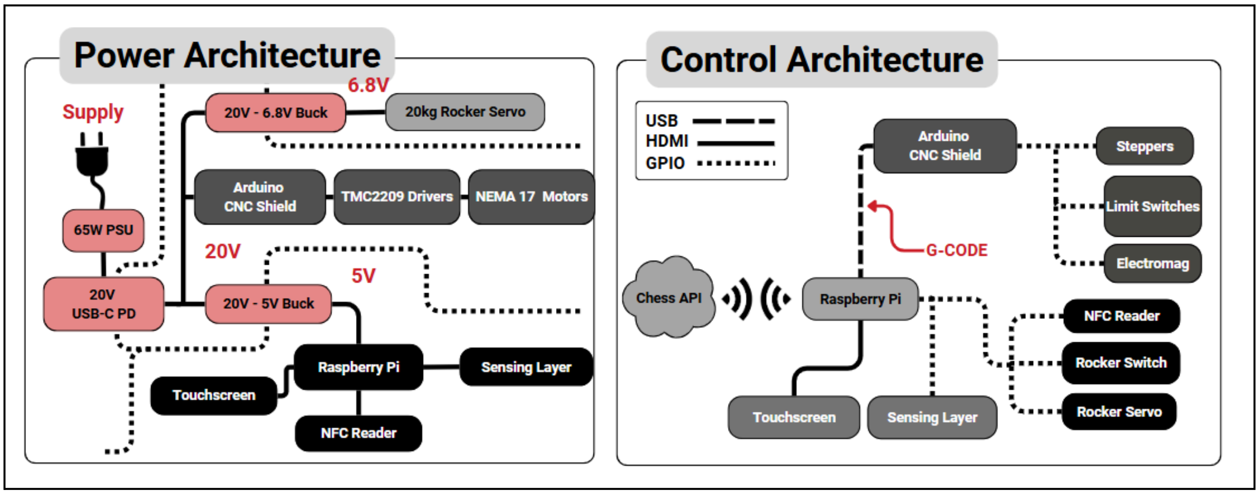


Figure 32 - Power and control architecture

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