

Accurate Pick and Place Arm

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1 Introduction

1.1 Problem

Automation is becoming more common in manufacturing, laboratories, and many other industries. Robotic arms are often used for tasks that involve picking up and moving parts because they can work continuously and repeat the same motion many times. As these systems are used for smaller parts and more complicated tasks, accuracy and repeatability become much more important. Even a small positioning error can cause a part to be placed incorrectly, damage a component, or cause problems later in the manufacturing process.

Accurate pick-and-place robots are also becoming more important in laboratory environments. Labs may use robotic systems to move samples, handle containers, or perform repetitive procedures where consistency is important. In these situations, a robot needs to be able to return to the same position and handle objects without damaging them. Better accuracy can help reduce human error and make automated systems more reliable.

This problem also relates to safety and public welfare. Robots can take over repetitive or potentially dangerous tasks that would normally be done by a person, such as working around machinery, chemicals, or other hazardous equipment. However, the robot itself also needs to be accurate and predictable so that it does not damage equipment or create additional safety risks. In areas such as medical or laboratory automation, poor positioning could also affect the quality of testing or research.

There are also economic and environmental reasons to improve the accuracy of robotic systems. A more accurate robot can reduce defective parts, wasted material, and the amount of rework needed during production. This can lower manufacturing costs while also reducing material and energy waste. As labor costs increase and companies continue to automate more processes around the world, reliable robotic systems are becoming increasingly valuable.

1.2 Solution Overview

The goal of this project is to design and build an accurate pick-and-place robotic arm and demonstrate its performance using a chessboard. Moving chess pieces provides a simple way to test whether the arm can repeatedly identify specific locations, pick up objects, and place them accurately in a controlled environment.

The baseline demonstration executes a predefined sequence of source-to-destination moves on a chessboard. The overhead camera identifies the pieces and establishes their positions relative to the board; calibration transforms these locations into robot coordinates for inverse kinematics. The arm picks up each specified piece, transports it above neighboring pieces, and releases it upright in the specified destination square. The OLED displays the source square, destination square, sequence progress, and any fault. The baseline requires no interactive move selection or autonomous chess opponent.

The software will be structured to support a C++ chess engine and eventual human-versus-computer play. In the baseline, a predefined move provider supplies source and destination squares to the same motion interface that a chess engine would later use. Legal-move validation, human-turn recognition, chess clocks, captures, castling, promotion, and endgame handling are extension features. They are not required to pass the baseline demonstration, and successful predefined moves establish manipulation capability rather than proof that a complete autonomous game has been implemented.

At a high level, our goal is to avoid the complexity and cost associated with traditional multi-joint robotic arms, where every additional degree of freedom requires another motor, sensor, and control system. Instead, we plan to use a simpler and more elegant mechanical architecture designed specifically around the requirements of the task.

The arm will consist of two links that provide planar motion across the x-y plane, while the end-effector moves vertically along the z-axis to pick up and place chess pieces. On the electrical side,

custom PCBs will integrate sensors such as magnetic encoders and Hall-effect sensors to accurately determine joint position and provide reliable feedback for the control system.

The software stack will tie the entire system together. Closed-loop PID controllers will provide precise joint positioning, while a computer vision pipeline will identify chess pieces and determine their locations on the board. These positions will then be converted into robot coordinates and passed through the inverse kinematics system to determine the joint commands required to move the end-effector to the desired location.

Our contribution is the integration of custom power, sensing, communication, user-interface, and electromagnet-control circuitry with camera calibration, kinematics, motion sequencing, and custom mechanics. Purchased QDD100 actuators provide rotary actuation; their internal motor control is distinguished from the STM32 supervisory firmware and the Jetson perception and planning software. Two nominal 250 mm planar links and a separate vertical axis provide the three translations needed for the baseline task.

1.3 Visual Aid

Predefined chess-piece transfer demonstration

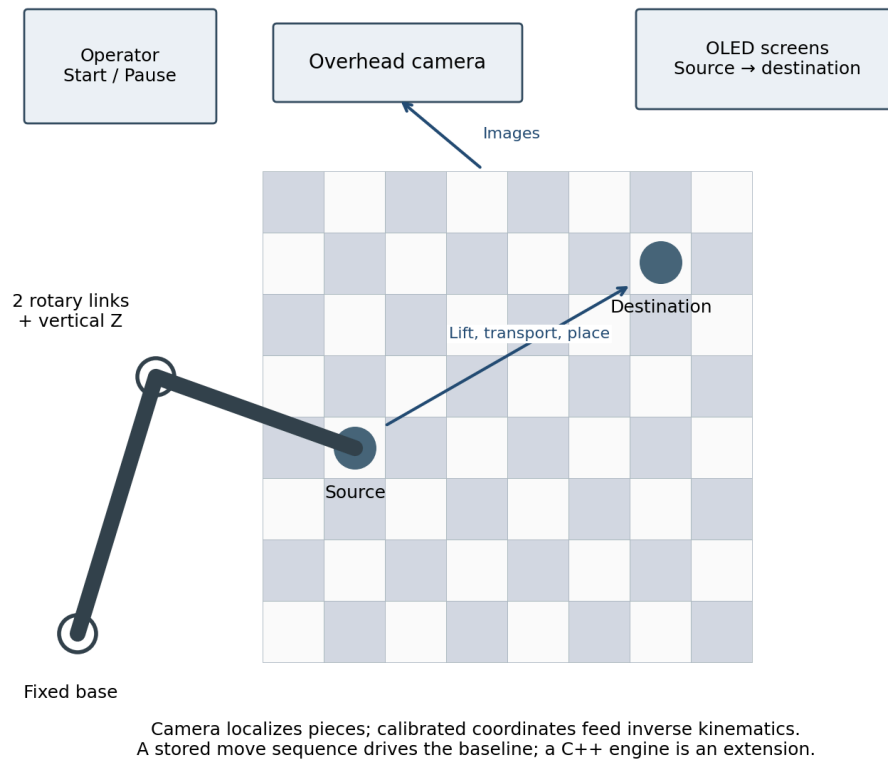


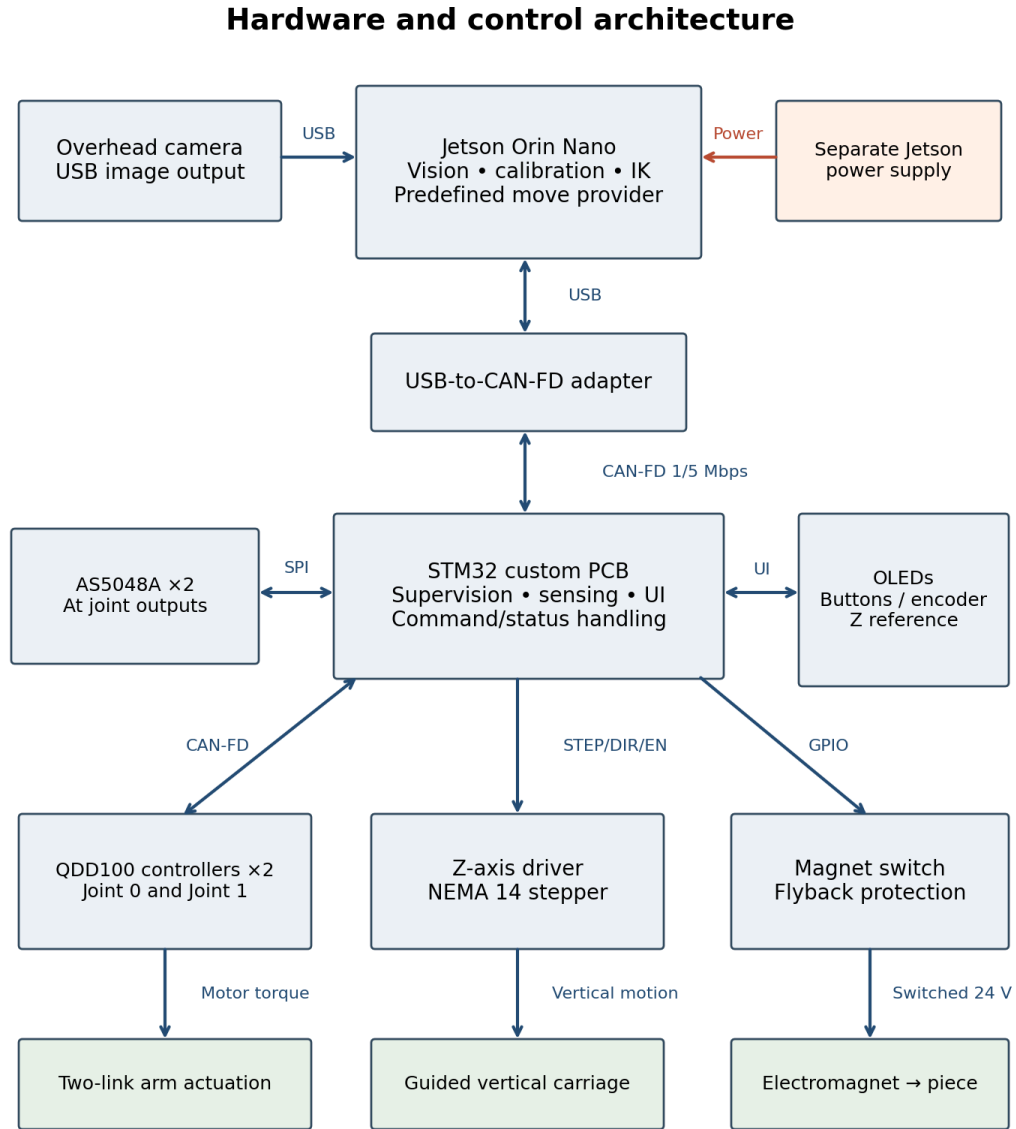
Figure 1: Predefined chess-piece transfer in its operating context.

1.4 High Level Requirements

- HLR-1: After settling at a commanded target, the end-effector shall have a horizontal radial positioning error of no more than 3.0 mm, measured in the chessboard plane. Vertical positioning is verified separately under the Z-axis requirements.
- HLR-2: The vision system shall identify chess pieces with at least 90% overall recall on the labeled verification set. A correct identification requires the correct piece type, color, and occupied square.
 - $\text{Recall} = \text{True Positives} / (\text{True Positives} + \text{False Negatives})$
- HLR-3: The robotic arm shall successfully complete at least 90 of 100 predefined pick-and-place attempts. Success requires pickup of the intended piece, transport without dropping the piece or disturbing neighboring pieces, and release upright in the intended destination square without manual intervention. The test set shall cover all six piece types, both colors, and near, central, and far board locations. Failed pickups, drops, collisions, incorrect destinations, and manual interventions count as failed attempts.

2 Design

2.1 Block Diagram & Preliminary Mechanical Drawing



Power: protected 24 V → actuators / Z driver / magnet; regulated 5 V and 3.3 V → logic.
Logical interfaces shown; final schematic defines CAN segmentation, termination and stop circuit.

Figure 2: Control architecture, interfaces, and physical outputs.

Vertical transport clearance and nominal geometry

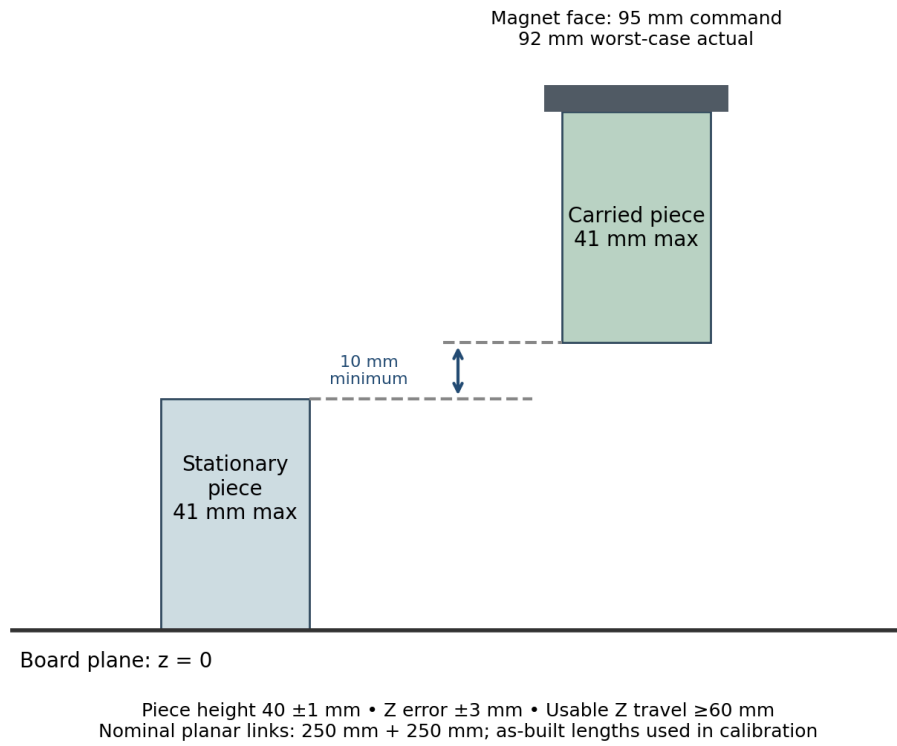


Figure 3: Nominal geometry and worst-case vertical clearance.

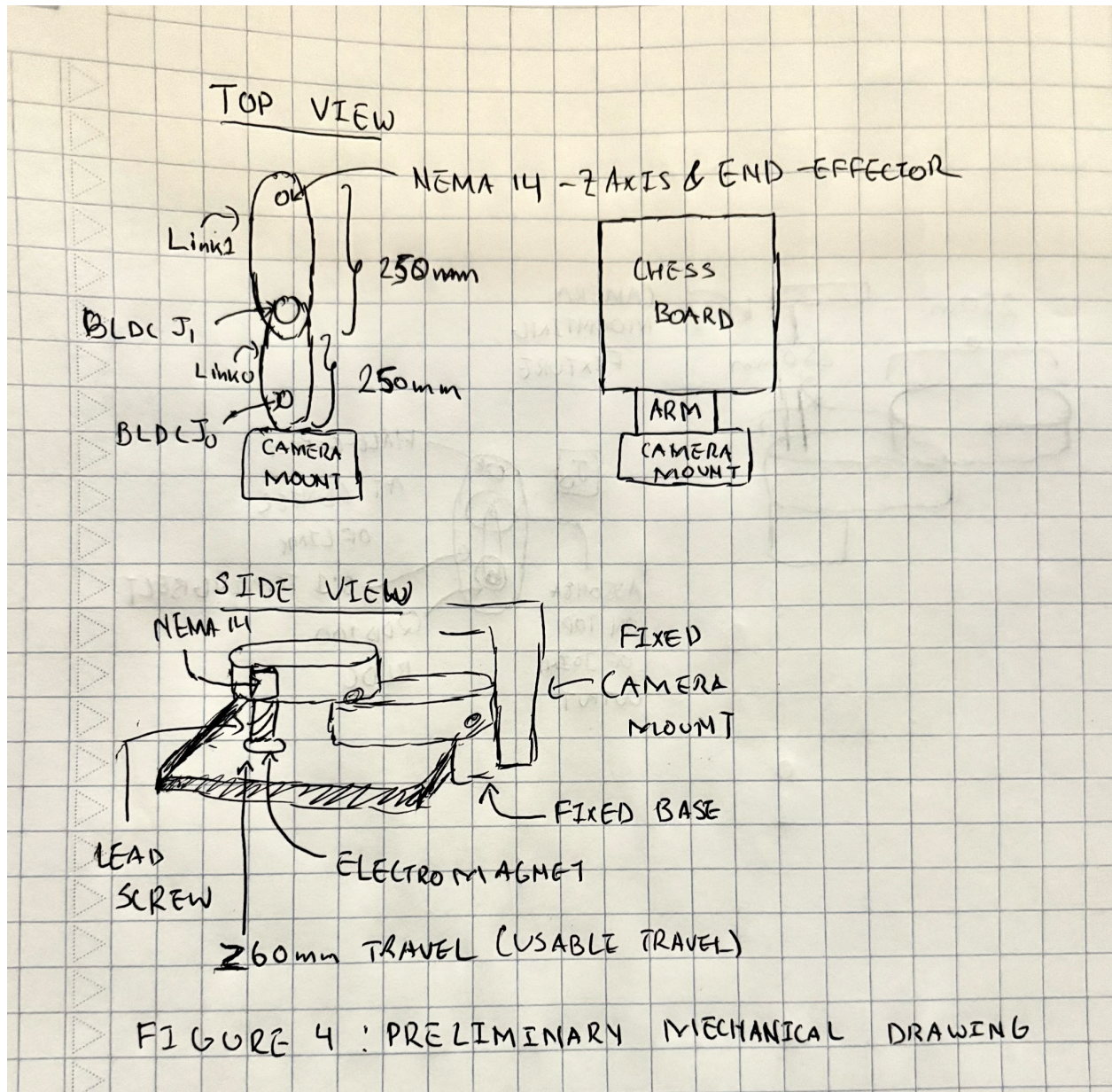


Figure 4: Preliminary Mechanical Drawing

2.2 High Level Block Diagram Explanation

Joint 0 and Joint 1 use QDD100 BLDC actuators to position two 250 mm links in the board plane. Separate AS5048A encoders mounted at the joint outputs measure the delivered joint angles. A NEMA 14 stepper drives the Z mechanism, which provides at least 60 mm of usable travel. Custom chess pieces have equal nominal height, 40 ± 1 mm including the flat magnetic pickup surface. The electromagnet attaches at the top. The commanded transport height is 95 mm above the board, or 55 mm above the nominal pickup height.

The Jetson Orin Nano connects by USB to a USB-to-CAN-FD adapter. The adapter exchanges commands and status with the STM32 custom PCB over CAN-FD. The STM32 commands both QDD100 controllers over CAN-FD, reads the separate output encoders, controls the Z-axis driver and electromagnet switch, and handles the OLEDs and physical controls. Status returned to the Jetson includes command completion, joint feedback, input events, and faults; the message interface also accommodates future turn-change events.

At startup, the robot validates sensor readings, loads calibrated joint offsets, and establishes the Z reference before motion is enabled. An absolute angular reading does not by itself establish the geometric zero of a joint. The Jetson verifies the board and the next predefined source and destination, transforms camera observations into robot coordinates, and calculates joint targets. The STM32 supervises execution and reports completion or a fault. The next move begins only after placement and board verification succeed.

Each of these subsystems will be described in more detail below, with tolerance analysis and subsystem requirements

2.3 Mechanical Subsystem

Mechanical Subsystem Explanation

The mechanical subsystem is responsible for positioning the end-effector over the chessboard and moving it vertically to pick up and place pieces. It consists of Joint 0, Joint 1, the Z-axis, the end-effector, and the camera mount. These components must work together to keep the end-effector within the project's 3 mm positioning requirement.

Joint 0 receives commanded angles from the software subsystem and provides encoder feedback to the controller. It must maintain approximately $\pm 0.10^\circ$ positioning accuracy, have less than 0.10° of mechanical backlash, include an encoder or reference sensor, and use bearings to support the arm loads rather than relying only on the motor shaft. This joint will use a QDD100 BLDC actuator whose motor controller receives position commands and returns feedback over CAN-FD.

Joint 1 uses the second QDD100 actuator and coordinates with Joint 0 to position the end-effector in the board plane. Both QDD100 controllers receive commands from the STM32 over CAN-FD. The two separate AS5048A sensors are mounted at the joint outputs, after the actuator transmissions. Actual settled output-angle error shall be within $\pm 0.10^\circ$ for each joint under the tested payload and from both approach directions. This total joint-angle requirement includes the effects of sensing, calibration, control, and transmission reversal observed at the output.

The Z-axis uses a NEMA 14 stepper, a lead screw, and a guided carriage. Usable travel shall be at least 60 mm, with the mechanism positioned to reach both the piece pickup surface and the 95 mm transport height relative to the board. The maximum vertical positioning error is ± 3 mm. The magnet mount includes axial compliance for gentle contact with the 40 ± 1 mm piece tops. The combined contact-height accommodation must cover at least 8 mm, spanning the piece-height and Z-position uncertainties; the available spring stroke and contact force must be verified before pickup tests. Lateral compliance and payload deflection are included in the horizontal error budget.

The electromagnet contacts a flat, centered, magnetically attractable surface on the top of each custom chess piece. All pieces have a total height of 40 ± 1 mm. Visible type and color markings surround the pickup surface so the camera can distinguish the pieces when the arm is parked outside its view. Pickup shall tolerate a radial horizontal offset of 3 mm. Holding and release performance will be tested on the actual piece materials and top geometry, rather than inferred from a magnet rating measured against a different steel target.

The camera mount holds the overhead camera in a fixed position relative to the chessboard and robot. Because the vision system depends on this relationship, the mount should limit camera translation to approximately 0.5 mm and angular movement to about 0.1° after calibration.

The two rotary axes provide planar positioning while the separate Z-axis provides pickup and overflight clearance. The nominal link lengths are 250 mm each. As-built joint-center distances, encoder offsets, and tool offsets must be measured and used in calibration. If a link dimension changes, the drawing, kinematic parameters, reachable workspace, and error analysis must all be updated together. A dimensional change is not absorbed silently into the positioning tolerance.

Mechanical Subsystem Requirements

- Joint 0 shall reach commanded positions within $\pm 0.10^\circ$.
- Joint 1 shall reach commanded positions within $\pm 0.10^\circ$.
- Mechanical backlash at each rotary joint shall be $< 0.10^\circ$.
- Z-axis positioning error shall be ≤ 3 mm.
- The end-effector shall tolerate within 3 mm pickup misalignment.
- Camera mount displacement shall remain < 0.5 mm after calibration.

Table 1. Mechanical requirements and verification

Requirement	Verification
Horizontal radial end-effector positioning error ≤ 3.0 mm	Equipment: Calibrated XY grid with 1mm markings using a ruler/caliper. Procedure: Command the robot to move to the markings. Test at least nine locations including the center, edges, and corners, with three repetitions from both approach directions and the heaviest piece attached. Measure the End-Effector position and calculate: $error = \sqrt{(\Delta x)^2 + (\Delta y)^2}$ Pass: ≤ 3 mm for every trial Results: Record the target, measured values, approach direction, payload, repetitions, reference uncertainty, and calculated error in the units of the requirement.
Joint 0 & Joint 1 reach angular positions within $\pm 0.10^\circ$	Equipment: Independent rotary encoder or angular measurement system with resolution $\leq 0.02^\circ$. Procedure: Command Joint 0 and Joint 1 to at least 5 positions distributed across its operating range. Measure the actual angle after the joint settles. Test each position while approaching from both rotational directions and repeat 3 times Pass: Absolute angular error plus reference uncertainty $\leq 0.10^\circ$ on every command Results: Record the target, measured values, approach direction, payload, repetitions, reference uncertainty, and calculated error in the units of the requirement.
Mechanical backlash at Joint 0 and Joint 1 shall remain below 0.10° throughout their required ranges of motion.	Equipment: Dial indicator with ≤ 0.01 mm resolution and rigid mounting fixture. Procedure: Place the indicator tangentially against the arm at a measured radius R from the joint. Approach the same commanded position from clockwise and counterclockwise directions and measure the displacement difference Δx. Calculate backlash using $\theta_b = \tan^{-1}(\Delta x/R)$. Test at least 3 positions on each joint. Pass: Backlash must be $< 0.10^\circ$ for every measurement. Results: Record the target, measured values, approach direction,

	payload, repetitions, reference uncertainty, and calculated error in the units of the requirement.
The camera mount shall remain within 0.5 mm of its calibrated position and within 0.10° of its calibrated orientation during normal robot operation.	Equipment: Dial indicator with ≤ 0.01 mm resolution and an angular measurement device or laser pointer and measured projection distance. Procedure: Record the initial camera position and orientation after calibration. Operate the arm through at least 50 representative movement cycles. Return the robot to its starting position and measure camera translation and angular orientation. Pass: Translational displacement must be < 0.5 mm and angular displacement must be $< 0.10^\circ$. Results: Record initial and final measurements and calculated displacement in a table.
M-3: The Z-axis shall provide at least 60 mm usable travel and ± 3.0 mm vertical positioning accuracy. Pieces shall be 40 ± 1 mm tall including the pickup surface. At the commanded 95 mm magnet-face transport height, clearance between the carried piece and every stationary piece shall be at least 10 mm. Usable travel must include the contact and loaded transport positions, including compliance.	Equipment: Digital caliper or height gauge with resolution ≤ 0.5 mm and the tallest chess piece used in the final system. Procedure: Measure the total usable Z-axis travel from its lowest to highest operating position. Measure every piece height, including its pickup surface. Command at least five Z positions across the usable range, approach from both directions, and repeat three times with the heaviest piece attached. Measure the actual loaded magnet-face height, including compliance, rather than motor steps alone. Place the tallest chess piece on the board and move the end-effector carrying a piece to its transport height. Measure the minimum clearance between the carried piece/end-effector assembly and the tallest stationary piece. Pass: Usable travel must be at least 60 mm; every piece must measure 39–41 mm; loaded Z-position error must be at most 3.0 mm; and measured transport clearance must be at least 10 mm throughout the path. Results: Record travel, commanded/measured positions, error, and measured clearance in a table

2.4 Electrical and PCB Subsystem

Electrical Subsystem Explanation

The electrical subsystem connects the mechanical hardware to the software and is responsible for power distribution, motor control, sensing, communication, end-effector control, and the user interface. These components must provide reliable feedback and control so the robot can meet the 3 mm positioning and 90% pick-and-place success requirements.

Power Distribution will take power from a laboratory power supply and distribute it throughout the robot. The primary bus will provide 24 V for the motor drivers and electromagnet, while regulators will generate 5 V and 3.3 V for sensors, PCBs, the OLED, and other low-voltage electronics. The Jetson will use a separate wall power supply and communicate with the robot through CAN. A rocker switch will provide main system power or enable control.

The STM32 receives joint-target commands from the Jetson through the USB-to-CAN-FD adapter and commands both QDD100 controllers over CAN-FD [1]. The nominal bus timing is 1 Mbps arbitration and 5 Mbps data. The Z stepper is controlled separately through its driver interface; it is not described as a CAN actuator. The PCB requires a CAN-FD transceiver for each implemented CAN segment. Physical segmentation, termination placement, node addresses, and the exact adapter must be captured in the final schematic and interface table.

Two AS5048A absolute magnetic encoders measure the rotary-joint output angles and connect to the STM32 through SPI. Their 14-bit output resolution is a component property, not a guarantee of $\pm 0.10^\circ$ assembled joint accuracy [2]. Magnet alignment, installation error, sensor nonlinearity, zero offsets, and filtering must be included in calibration and independently verified. Reference sensors establish or check known positions. Z homing establishes the vertical coordinate origin; Z encoder feedback is not assumed unless it is included in the final hardware.

End-Effector Control will switch an electromagnet used to pick up the chess pieces. Because the electromagnet requires more current than a microcontroller output can provide, a MOSFET or similar

switching circuit will control it from the 24 V power rail. The circuit must also include protection against inductive voltage spikes when the electromagnet is turned off.

The baseline OLED screens display the source and destination squares, sequence progress, readiness, pause status, and faults. Physical controls start the predefined sequence, request a pause, and reset a fault only after its cause is cleared. Their exact mapping is documented with the PCB input assignments. Turn-change inputs, difficulty selection, and chess-clock displays are reserved for the autonomous-chess extension.

The electrical design separates high-level computation from hardware supervision and sensing. The Jetson is used for tasks such as computer vision, chess logic, and overall system coordination, while the STM32 handles communication with the motors, sensors, and other hardware. CAN-FD was selected as the main communication interface because it allows the controller to exchange joint commands and feedback with multiple devices over a single network while providing enough bandwidth for the required control and sensor data. Absolute encoders and reference sensors are used to improve repeatability and provide reliable joint-position information needed to meet the 3 mm positioning requirement. A 24 V rail powers the motors and electromagnet, while regulated 5 V and 3.3 V rails supply the lower-voltage electronics and sensors. The electromagnet is controlled through a separate switching circuit because its current requirement is higher than what the microcontroller can directly provide, while also allowing protection against inductive voltage spikes

Electrical Requirements

- The assembled 24 V distribution shall remain within 22.8–25.2 V at loads from 0 to 10 A, including downstream converter input current.
- The 5 V rail must provide at least 2 A and the 3.3 V rail at least 1 A.
- The assembled motor-power path shall complete the loaded switching and motion test in E-2 without reset, unintended outputs, or damage.

- The implemented CAN-FD network shall exchange command and feedback messages at 1 Mbps arbitration and 5 Mbps data; application-message loss shall be no more than 1% over the verification run.
- The assembled electromagnet switching stage shall complete all 50 loaded on/off cycles in E-2 and remain within the selected voltage and temperature limits.
- Each button input shall be distinguishable and detected within 100 ms in every verification trial.
- The user-interface rotary encoder shall be debounced so that false counts are no more than 1% of total detected counts during operation.

Table 2. Electrical requirements and verification

Requirement	Verification
The 24 V rail shall remain within 22.8–25.2 V while supplying up to 10 A continuous load. The regulated 5 V rail shall supply at least 2 A, and the 3.3 V rail shall supply at least 1 A, while remaining within $\pm 5\%$ of their nominal voltages.	Equipment: DMM, oscilloscope, and adjustable electronic load. Procedure: Test each rail at 0%, 25%, 50%, 75%, and 100% of its specified output load. At full load, operate for ten minutes and record minimum and maximum voltage and component temperatures. Repeat with the other rails loaded and during representative motor and magnet switching. Account for downstream regulator input power within the total 24 V bus load. Record oscilloscope bandwidth and probe placement. Pass: 24 V remains 22.8–25.2 V, 5 V remains 4.75–5.25 V at 2 A, and 3.3 V remains 3.135–3.465 V at 1 A. Results: Record voltage and current at each load point in a table.
E-2: The assembled power and magnet-switching circuits shall complete 50 loaded switching cycles without MCU reset, unintended output transitions, or damage. Measured switching voltages and operating temperatures shall remain within the selected parts' documented limits. Current-rating margins are component-selection checks, not a	Equipment: Current probe and oscilloscope. Procedure: Measure the maximum motor current during representative arm movements and the steady-state electromagnet current while energized. Cycle the electromagnet on and off at least 50 times while observing the switching waveform for abnormal voltage spikes or faults.

substitute for this functional test.	Pass: All 50 cycles must complete without MCU reset, unintended output transitions, or component failure. Peak switch voltage and measured temperatures must remain within the selected parts' documented limits; record those numerical limits alongside the measurements. Verify current-rating margins separately as design-selection checks. Results: Record measured currents, required ratings, and switching-waveform observations.
The CAN-FD network shall operate at 1 Mbps arbitration and 5 Mbps data, with application-message loss $\leq 1\%$ during the verification run.	Equipment: CAN-FD analyzer or oscilloscope with CAN decoding and communication logging software. Procedure: Log at least 1,000 transmitted command and feedback messages on the implemented CAN-FD links while both rotary joints move and the electromagnet switches. Match sent and received application messages by identifier and sequence or timestamp. Separately record CAN error frames and retransmissions; do not equate a successfully retransmitted message with permanent application-message loss. Record transmitted frames, received frames, and detected CAN errors. Pass: Network operates at 1 Mbps/5 Mbps. At most 1% of unique transmitted application messages may be missing or invalid at the receiver after the 100 ms receipt deadline. Duplicate messages do not count as additional successes; retransmissions and CAN error frames are reported separately. Results: Record unique application messages sent, valid messages received by the deadline, missing/invalid messages, duplicates, CAN error frames, retransmissions, and loss percentage.
E-3: The assembled and calibrated rotary-output sensing path shall measure each joint angle within $\pm 0.05^\circ$ of an independent reference over the operating range. This sensing allocation is included within, not added to, the $\pm 0.10^\circ$ actual joint-position requirement.	Equipment: Encoder logging software, a rigid fixture, and an independently calibrated angular reference. Procedure: Use an independently calibrated angular reference with stated uncertainty no greater than 0.01°. Compare measured and reference angles at at least ten positions across each operating range, approaching from both directions and repeating three times. Repeat after ten minutes of powered operation. Record calibration version, reference uncertainty, and signed measurement errors. Pass: Absolute angular measurement error plus reference uncertainty must not exceed 0.05° at every tested position. Raw bit depth is not the pass criterion.

	Results: Record reference angle, calibrated sensor angle, signed error, approach direction, and measurement uncertainty for each trial.
All buttons shall be correctly detected by the controller within 100 ms, and rotary encoder noise filtering shall limit false encoder counts to $\leq 1\%$ of total detected counts during normal operation.	Equipment: Oscilloscope or logic analyzer and STM32 input/count logging software. Procedure: Press each button at least 20 times while measuring the delay between the electrical input transition and controller detection. Rotate the quadrature encoder through at least 1,000 valid counts while recording A/B signals and decoded counts. Compare the decoded sequence with the expected quadrature sequence and identify false counts. Pass: Every button press is detected within 100 ms and rotary encoder false-count rate is $\leq 1\%$. Results: Record button response times and calculate <i>False Counts Rate</i> = (<i>False Counts</i> $\div$ <i>Total Counts</i>)

2.5 Software Subsystem

Software Subsystem Explanation

The software subsystem coordinates the complete operation of the robotic arm from startup calibration through the completion of a chess move. It connects the camera, encoders, motor controllers, electromagnet, OLED display, buttons, and chess logic into one system. The software must support the three main high-level requirements by maintaining accurate robot positioning, correctly identifying chess pieces with at least 90% recall, and coordinating reliable pick-and-place operations.

Startup validates the rotary-output encoders, loads calibrated zero offsets, and establishes the Z reference before enabling motion. The Jetson calibrates the camera-to-board and board-to-robot transformations. Measured link lengths, tool offsets, and encoder offsets are stored as versioned calibration parameters. Verification uses independent reference locations not used to fit calibration. Missing or invalid data prevents entry to Ready and produces an OLED fault message.

The STM32 handles physical controls and OLED updates. Start begins the predefined move sequence only from Ready. Pause requests a controlled pause and preserves magnet energization while carrying a piece. Reset clears sequence state only after the fault cause is removed and the system is safe. OLED screens display source and destination squares before each move and update progress or fault status within 100 ms of the corresponding software event. Difficulty selection and chess clocks are extension features.

The Jetson identifies piece type, color, and occupied square from overhead images. Calibration converts observed pickup locations to physical coordinates for inverse kinematics. The actual piece pickup feature is localized; a square center is not assumed to locate a piece placed off-center. The destination is the calibrated square center. The arm parks outside the board view for recognition and placement verification. A missing source, occupied destination, ambiguous detection, or invalid calibration prevents execution.

The baseline sequence manager stores predefined source and destination squares and advances only after motion completion and post-placement verification. The sequence is prepared before the demonstration and uses reachable, unoccupied destinations. Every initiated attempt is logged, including failures. A C++ chess-engine adapter may later replace the predefined move provider without changing the source/destination interface.

The autonomous-chess extension will compare successive board observations, validate human moves, and request responses from a C++ chess engine. Optional 5+10 and 10+10 clocks, turn-change inputs, captures, castling, promotion, and terminal game states require additional handling and tests. These features do not gate baseline acceptance.

The kinematics block converts calibrated pickup coordinates and predefined destination squares into Joint 0 and Joint 1 targets, rejecting unreachable points, joint-limit violations, and collision paths. The motion sequence moves the robot above the selected piece, lowers the Z-axis, activates the electromagnet, raises the piece to a safe clearance height, moves to the destination square, lowers the piece, turns off the electromagnet, and returns to the camera-viewing position. Joint-position calculations must have enough numerical precision that software rounding contributes no more than 0.10 mm of end-effector error.

The STM32 supervises joint commands and reads the output encoders at intervals no greater than 20 ms. QDD100 controllers provide internal motor control; the 50 Hz minimum applies to student firmware supervision, not motor commutation. Completion requires measured rotary output-angle errors within $\pm 0.05^\circ$ for three consecutive valid updates, completion of the commanded Z move, and no active fault. With calibrated sensing error bounded by $\pm 0.05^\circ$, the corresponding actual settled output-angle error is bounded by $\pm 0.10^\circ$. Encoder-based convergence is checked independently during calibration and accuracy testing. Invalid targets, stale feedback, and movement timeouts prevent progression.

The STM32 energizes the electromagnet during pickup and transport and releases it after placement. Magnet command state is logged but does not prove physical attachment. A camera check after placement verifies the resulting occupancy. Actual pickup and release are scored in the 100-attempt

test. Automatic detection of a dropped piece during transport requires a separately specified sensor or observation method; it is not assumed from the magnet command alone.

The baseline state machine uses Calibrate, Ready, Verify Board, Approach Source, Pickup, Lift, Transport, Place, Verify Result, Complete, Paused, and Fault states. Movement states require acknowledged completion. Calibration failure, invalid board data, stale feedback, actuator fault, or timeout enters Fault. Fault handling requests a stop of current motion and inhibits new motion commands. Resume requires explicit operator action and valid state; reset never automatically restarts motion. Emergency stopping is independent of this software sequence.

The move-provider interface separates baseline verification from future gameplay. The predefined sequence and future C++ engine both produce source/destination pairs. The Jetson owns perception, coordinate conversion, and move selection; the STM32 owns hardware supervision and returns status. OLED updates and physical controls remain operational with the chess engine and clocks disabled.

Software Requirements

- The computer vision system must identify chess pieces with at least 90% recall.
- Startup calibration must successfully determine and store all required joint offsets before the main state machine can begin.
- Joint-control calculations must update at a minimum rate of 50 Hz.
- The software shall require measured output-angle error $\leq 0.05^\circ$ at each rotary joint for three consecutive valid updates before motion completion. Together with sensing error $\leq 0.05^\circ$, this supports actual settled error $\leq 0.10^\circ$.
- Kinematic and numerical calculations must contribute no more than 0.10 mm of end-effector positioning error.
- Start, Pause, and Reset inputs must be detected within 100 ms.
- Extension only: Player timers shall update at least every 100 ms and detect expiration within one update cycle.
- Extension only: Only the active player's timer may count down.

- Baseline: An invalid board state shall prevent the next predefined move. Extension only: An illegal human move shall prevent turn advancement.
- Motor, calibration, or end-effector faults must prevent the state machine from beginning the next operation.
- The electromagnet must remain activated while a chess piece is being transported, including if the system is paused while holding a piece.

Table 3. Software requirements and verification

Requirement	Verification
The computer vision system shall identify chess pieces with $\geq 90\%$ recall and correctly associate detected pieces with their corresponding chessboard squares.	Equipment: Overhead camera, completed chessboard setup, and a labeled set of known board configurations. Procedure: Capture images from at least 20 labeled board configurations containing all six piece types and both colors at near, central, and far board locations. Park the arm outside the board view and record camera height, lighting conditions, and image resolution. Use verification configurations that were not used to train or tune the classifier. Compare detected pieces and occupied squares against the known board states. Calculate: True Positive (TP): number of ground-truth pieces correctly identified by type, color, and square, using one-to-one matching False Negative (FN): number of ground-truth pieces without a correct matching prediction, including missed or misclassified pieces $\text{Recall} = (TP) / (TP + FN) * 100 \%$ Pass: Overall piece-detection recall must be $\geq 90\%$, and detected pieces must be assigned to the correct board squares. Results: Record true positives, false negatives, calculated recall, and incorrectly identified squares in a table.
S-1: The software shall validate rotary-joint calibration parameters and establish the Z reference before entering Ready. Invalid or missing calibration shall prevent baseline sequence execution.	Equipment: Robot, encoder/reference sensors, and software logging through the Jetson/STM32. Procedure: Power-cycle the system at least 10 times from different initial joint positions. Record calculated offsets and verify that the robot reaches its defined home position. Repeat the test with one reference sensor or encoder signal intentionally disabled.

	Pass: All 10 normal startup tests must complete calibration before entering the Ready state. A missing or invalid calibration signal must prevent the state machine from advancing. Results: Record startup attempt, calculated offsets, calibration status, and final state in a table.
Joint-control calculations shall update at ≥ 50 Hz, kinematic calculations shall contribute ≤ 0.10 mm of end-effector positioning error, and a joint movement shall not be considered complete until both measured rotary output-angle errors are $\leq 0.05^\circ$ for at least 3 consecutive supervisory updates, with the calibrated sensing requirement independently satisfied.	Equipment: Software timestamps/logging, encoder feedback, and known X-Y test coordinates. Procedure: Command at least 10 positions distributed across the chessboard workspace. Log control-loop timestamps, calculated joint angles, and encoder feedback. Use forward kinematics on the calculated angles and compare the resulting X-Y location with the requested position. Pass: The interval between consecutive completed control updates must not exceed 20 ms during the test; report the maximum interval, not only average frequency. Calculated numerical positional error must be ≤ 0.10 mm. The motion-complete flag requires measured rotary errors $\leq 0.05^\circ$ for three consecutive valid updates, valid Z completion, and no active fault. Inject a measured error above 0.05° and verify that completion remains false. Results: Record control frequency, target coordinates, calculated coordinates, numerical position error, and final joint error.
S-4: In baseline mode, user inputs and OLED source/destination, progress, and fault displays shall update within 100 ms. Invalid source or destination occupancy shall prevent the next predefined move. Chess clocks and legal-move validation are extension-only tests.	Equipment: Software timestamp logging, OLED, buttons/rotary encoder, and predefined legal and illegal board states. Procedure: Activate each user input at least 20 times and measure detection latency. In baseline mode, issue at least 20 source/destination or fault-display changes and measure visible OLED update latency. Present a missing source piece, occupied destination, and invalid board observation. Separately test chess clocks and illegal moves only if the autonomous-chess extension is implemented. Pass: Every baseline input and OLED update must meet 100 ms. Every invalid-board case must block the next move. Extension only: timer updates and expiration detection must meet 100 ms, only the active clock may decrease, and illegal moves must block turn advancement. Results: Record input latency, visible OLED update latency, source/destination status, and state-machine response. Record clock results separately only if the extension is implemented.
The software shall activate the	Equipment: Software logs, robot hardware, electromagnet, and

electromagnet only after reaching the pickup position, keep it activated throughout transportation, release it only at the destination, and prevent the next operation from beginning whenever a motor, calibration, movement, or end-effector fault is detected.	ability to inject or simulate system faults. Procedure: Perform the 100 predefined physical pick-and-place attempts specified in HLR-3 while logging robot state and electromagnet command. Record piece type and color, source and destination squares, pickup, transport, release, neighboring-piece disturbance, and any manual intervention. Count every initiated attempt, including aborted attempts, and do not replace failures with retries. During separate trials, introduce a motor fault, failed movement, calibration fault, and end-effector fault. Pass: At least 90 of the 100 attempts must satisfy every HLR-3 success condition. The electromagnet must remain activated continuously between pickup and placement during every successful move. Each injected fault must prevent progression to the next motion state and generate the appropriate fault state/display message. Results: Record state transitions, magnet status, injected fault, and software response for each trial.
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2.6 Tolerance Analysis

2.6.1 Vertical clearance

The critical vertical function is transporting one piece over another without contact. Piece height includes the metal pickup surface and is bounded by 39–41 mm. Let z_m be the actual loaded magnet-face height above the board, h_c the carried-piece height, and h_s the stationary-piece height. Clearance is

$$C = z_m - h_c - h_s. \quad (1)$$

The transport command is $z_{m,cmd} = 95$ mm. With a worst-case downward Z error of 3 mm and both pieces at their maximum 41 mm height,

$$C_{min} = 95 - 3 - 41 - 41 = 10 \text{ mm}. \quad (2)$$

This proves the required vertical clearance under the specified height and loaded-position bounds. At nominal 40 mm piece height, the commanded lift is $95 - 40 = 55$ mm. The Z assembly shall provide at least 60 mm usable travel, positioned to include contact and transport. This minimum is not proof that any 60 mm mechanism will fit: contact overtravel, axial compliance, end-stop reserve, and loaded deflection must fit the actual operating envelope. Increase travel if the implemented contact mechanism requires it. Verify clearance along the complete path with the tallest stationary piece and heaviest carried piece. The ± 3 mm bound applies to the loaded magnet face, including mount deflection.

2.6.2 Horizontal positioning

Let L_0 and L_1 be measured joint-center link lengths; θ_0 is the base-joint angle and θ_1 the relative elbow angle. In the calibrated robot frame,

$$x = L_0 \cos \theta_0 + L_1 \cos(\theta_0 + \theta_1), \quad (3)$$

$$y = L_0 \sin \theta_0 + L_1 \sin(\theta_0 + \theta_1). \quad (4)$$

A conservative bound follows from the chord-length inequality $2 \sin(|\delta|/2) \leq |\delta|$, with angular errors in radians:

$$e_{\text{joint}} \leq (L_0 + L_1)|\delta\theta_0| + L_1|\delta\theta_1|. \quad (5)$$

For $L_0 = L_1 = 250$ mm and each actual output-angle error $\leq 0.10^\circ = 0.00174533$ rad, $e_{\text{joint}} \leq 1.309$ mm. Actual output angle error includes the sensing, zero-calibration, control, and transmission effects observed at that joint. Encoder quantization and backlash are therefore not added again as separate endpoint terms.

Table 4. Horizontal error allocation

Contribution	Bound	Evidence required
Actual rotary-joint angle errors	1.309 mm	Independent loaded output-angle tests in both directions
Residual structure and geometry	0.500 mm	Combined link/tool calibration residual, bending, Z lateral play, and magnet-mount lateral motion
Vision to robot localization	1.000 mm	Independent physical target tests including camera drift and pickup-feature localization
Numerics and command quantization	0.100 mm	Forward kinematics of the transmitted joint commands
Total allocated error	2.909 mm	Conservative Error Sum

The allocation leaves 0.091 mm below the 3.0 mm requirement. It is a conditional design budget, not measured performance. Every allocation must be supported by its verification; resolution alone does not establish accuracy. The residual structure/geometry allowance is a combined limit, not 0.5 mm for each effect. Measurement uncertainty must be included in pass/fail decisions. If any bound cannot be met, revise the mechanics, calibration, or allocation and repeat the end-to-end test.

AS5048A output resolution is 14 bits [2]. Its ideal half-count angular quantization is $180^\circ/16384 = 0.01099^\circ$, corresponding to at most 0.144 mm for this two-link geometry. This is only the quantization contribution already contained within the actual joint-angle term; sensor nonlinearity and installation

effects require calibration. A hypothetical 400 mm board imaged across 800 pixels has average scale 0.5 mm/pixel. A radial two-pixel error would be 1 mm, whereas two pixels on each axis would be 1.414 mm radially. The design therefore verifies physical radial localization error directly rather than treating pixel count as an accuracy guarantee.

2.6.3 Kinematics and reachability

For a target (x,y) , define $c = (x^2 + y^2 - L_0^2 - L_1^2)/(2L_0L_1)$.

A target is geometrically reachable only if $-1 \leq c \leq 1$. Candidate elbow angles are:

$$\theta_1 = \pm \arccos(c), \text{ and } \theta_0 = \text{atan2}(y,x) - \text{atan2}(L_1 \sin \theta_1, L_0 + L_1 \cos \theta_1). \quad (6)$$

Reject infeasible commands and check board dimensions, base placement, joint limits, and link collision envelopes for every trajectory received. Use the measured link lengths in both calibration and inverse kinematics and re-evaluate these bounds after a mechanical change.

2.7 Integration Specification

Table 5. Baseline interface responsibilities

Interface	Direction and content
Camera to Jetson	USB images; board state, pickup-feature localization, and calibration processed on Jetson
Jetson to adapter	USB adapter carries CAN-FD traffic to and from STM32
Adapter to STM32	CAN-FD 1/5 Mbps; joint targets, command identifier, sequence state; return completion, feedback, input events, and faults
STM32 to QDD100 controllers	CAN-FD 1/5 Mbps; position commands and actuator feedback. STM32 is the motion-command authority
Output encoders to STM32	SPI; separate AS5048A measurements at Joint 0 and Joint 1 outputs
STM32 to Z driver	STEP/DIR/enable design interface; driver supplies motor phases. Reference input establishes Z home
STM32 to magnet switch	GPIO control to protected 24 V switching stage

UI to and from STM32	Buttons/rotary encoder inputs, OLED source, destination, status, and fault outputs. Display interface and addressing follow final module configuration
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Table 6. Baseline state transitions

State group	Completion condition	Failure action
Calibrate → Ready	Valid calibration and Z reference; Start accepted	Fault; inhibit motion
Verify Board → Approach Source	Source recognized, destination empty, path reachable	Reject move; display reason
Pickup → Lift	Contact sequence complete, magnet on, commanded Z state reached	Stop sequence; attachment is not inferred from command alone
Transport → Place	Loaded transport height reached; rotary and Z completion valid	Controlled stop request; no new target
Verify Result → next move or Complete	Source empty, intended piece at destination, neighboring occupancy unchanged	Record failed attempt; Fault
Paused or Fault → recovery	Explicit operator action, valid feedback, and safe physical state	No automatic restart

Pause, software fault, emergency stop, and total power loss are distinct conditions. Holding the magnet during Pause requires power; total power loss can release the piece. The physical design must contain a dropped piece and prevent uncontrolled Z descent. A software stop request alone does not prove emergency-stop performance.

3 Cost & Schedule

3.1 Weekly assignments

Table 7 assigns one primary deliverable to each member each week. Tasks are planned work, not completed results. The existing milestone dates are retained as integration targets. Optional chess-engine development proceeds only after baseline tasks are on schedule.

Table 7. Weekly work plan for fall 2026

Week	Ian	Michael	Nithin
Oct 5–11	Bench-test power, GPIO, and encoder interfaces	Finalize 40 mm piece and ≥ 60 mm Z geometry	Implement predefined move-provider and command logging
Oct 12–18	Complete electrical bench tests by Oct 14	Review PCB layout and release by Oct 16	Implement STM32 CAN-FD command/status handling

Oct 19–25	Bring up PCB and complete rail/interface tests	Assemble arm, Z axis, pieces, and camera mount	Integrate camera calibration and inverse kinematics
Oct 26–Nov 1	Calibrate output sensing and test magnet switching	Verify loaded joint, Z, and clearance requirements	Implement motion state machine and OLED status
Nov 2–8	Run timing, watchdog, and fault-injection tests	Measure structural residual and pickup offset tolerance	Complete baseline software verification by Nov 3
Nov 9–15	Integrate power, CAN, sensors, and UI	Check complete motion paths and guarding	Integrate vision-to-motion and post-placement checks
Nov 16–22	Log integrated electrical performance	Run 100-attempt physical acceptance with team	Analyze recall, endpoint error, and failure logs
Nov 23–29	Close electrical defects and prepare test evidence	Close mechanical defects and rehearse demonstration	Freeze baseline, organize logs, and prepare demo sequence
Nov 30	Support final demonstration and report electrical results	Support final demonstration and report mechanical results	Support final demonstration and compile software results

Table 8. Listed parts and estimated costs

Part & Name:	Quantity:	Link:	Manufacturer:	Total:	Description
PCB Fabrication	5	Link	JLCPCB	\$25	Fabrication of STM32 control PCB

OLED Screen	3	Link	EastRising	\$60.75	Source/destination, sequence progress, and faults
USB to CANFD Adapter	1	Link	Jhoinrch	\$19.99	Connects the Jetson to the STM32
CAN FD Transceivers: MCP2558FD	1	Link	Microchip Technology	\$1.06	Takes can controller inputs from stm32 and outputs them to can bus
Electromagnet	1	Link	AIRTAK	\$12.99	Picks up the chess pieces
Hall Effects	3	Link	ALLECIN	\$7.99	For reference and for zeroing our motors
Magnetic Encoder: AS5048A	2	Link	ams-osram	\$38.80	Absolute encoders for measuring rotary-joint output position
Rocker Switch	1	Link	Ace electronics	\$10.00	Powering On/Off the Game
Rotary Encoder	1	Link	Bourns Inc	\$2.69	Baseline Start/Reset selection. Difficulty is an extension

Buttons	2	Link	Dirvcp	6.69	Baseline operator inputs. Chess-clock use is an extension
LEDs: NeoPixel	1 (3m total)	Link	Adafruit	\$29.95	Display different color per turn
Logic Shifter: (74ahct125)	10	Link	Bridgold	\$7.99	To shift logic up to 5v for the NeoPixel LEDs
Nema 14	1	Link	StepperOnline	\$10.11	Motor for Z-joint
Stepper Driver	1	Link	Fabreeko	\$11.99	Drives the Stepper Motor that controls the Z-Joint
STM32G483 RET6	1	Link	STMicroelectronic s	\$11.60	Custom-PCB microcontroller
Jetson Orin Nano	1	Link	NVIDIA	\$230.99	For handling the higher level control system and software orchestration. From University Funding.
Luxonis Stereo Camera	1	Link	Luxonis	\$299.99	Camera needed for Piece Detection and Board state classifier. From University

					Funding.
QDD100s	2	Link	mjbots	\$800.00	BLDC Motors for j0 and j1, Received at discount through university funding.
Labor for Ian	\$20*2.5*100 H total	NA	NA	\$5000	Ian Work Price
Labor for Nithin	\$20*2.5*100 H total	NA	NA	\$5000	Nithin Work Price
Labor for Michael	\$20*2.5*100 H total	NA	NA	\$5000	Michael Work Price
Listed-cost subtotal:				\$16,529.54	

Table 9. Milestone schedule

Milestone:	Items Completed:	Who:	Date Final:
Electrical Components Testing On Devboard	All ordered Electrical Components must be tested	Ian Lead, Michael and Nithin Support	10/14/2026
PCB and DRC Pass	PCB schematic and	Michael,Ian, Nithin	10/16/2026

	layout finalized, team design review completed, DRC passed, and PCB order submitted		
Mechanical Prototype Done	Final CAD completed and all required mechanical parts printed/fabricated. Joint 0, Joint 1, Z-axis, end-effector, and camera mounting hardware ready for testing.	Michael Lead, Nithin and Ian Support	10/25/2026
Electrical Tests & Verification Passed	Electrical subsystem assembled and electrical verification tests passed, including power rails, sensors, motor interfaces, CAN communication, UI hardware, and PCB functionality.	Ian Lead, Michael, and Nithin Support	10/25/2026
Mechanical Tests & Verification Passed	Mechanical subsystem tests passed, including joint motion/accuracy,	Michael Lead, Nithin and Ian Support	10/28/2026

	backlash, Z-axis travel/accuracy, structural stiffness, and camera mount stability.		
Software Tests & Verification Passed	STM32 firmware and higher-level software tests passed. Verify communication, calibration, motor commands, kinematics, vision, chess logic, state machine, UI handling, and required software timing.	Nithin Lead and Ian Support	11/3/2026
Full System Integration Complete	Mechanical, electrical, firmware, and software systems fully integrated. The robot must perform through the complete stack.	ALL	11/16/2026
Final Demo Ready	Final debugging/refinement, collection of performance	ALL	11/30/2026

	data, and demonstration-ready system		
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These milestones supplement the weekly member assignments in Table 7. Each weekly deliverable is reviewed at the team meeting; delayed critical tasks are reassigned before optional chess-engine work proceeds.

4 Ethics

This project uses an autonomous robotic arm to identify and move chess pieces using computer vision, encoder feedback, closed-loop motor control, and an electromagnetic end-effector. Although chess is used as the demonstration, the system represents a general pick-and-place platform. Accurate robotic systems can improve public welfare by reducing repetitive manual work, improving consistency, and reducing damaged parts and material waste. Lower-cost automation can also make robotics more accessible to smaller organizations.

Relevant guidance includes the IEEE Code of Ethics [4], machinery guarding and anchoring principles in OSHA 29 CFR 1910.212 [5], and robot risk-reduction principles in ISO 10218-1:2025 [6]. ISO 10218-1 addresses industrial robots; it is used here as design guidance, without claiming certification or that every industrial requirement applies to this educational prototype. Applicable UIUC laboratory procedures must also be followed. The IEEE Code of Ethics is especially relevant because the team must protect user safety and honestly report technical limitations. Measured positioning accuracy, vision

performance, and pick-and-place reliability will be reported accurately, including any failures to meet project goals.

The main mechanical safety concerns are unexpected arm motion, pinch points at the rotary joints, and Z-axis movement near users. Joint 0 and Joint 1 use BLDC actuators, so software joint limits, workspace limits, a defined operating area, and an emergency stop will be used. Power will be removed before maintenance.

Electrical risks include short circuits, overcurrent, incorrect wiring, inductive voltage spikes, and overheating. The system will use overcurrent protection, properly rated wiring, regulated supplies, and flyback protection for the electromagnet. Software faults, calibration failures, encoder errors, CAN-FD communication faults, or motor faults will prevent the state machine from advancing. Testing will begin at reduced speed and restricted motion, with the emergency stop accessible at all times.

To reduce the risk of injury or equipment damage, the robot will be operated using a controlled safety procedure. Before powered motion tests, the team must document the emergency-stop circuit, measure stopping time and distance at the allowed speed and payload, and confirm that the guarded operating area contains the stopping envelope. Stop behavior must account for Z descent and loss of magnetic holding force; actuator disable alone is not evidence of a safe stop. Any mechanical adjustment, wiring change, or maintenance will only be performed after the system is powered off and disconnected. During operation, hands and tools must remain outside the robot workspace, especially near the rotary joints and Z-axis pinch points. Initial testing will be performed at reduced speed and limited joint travel before full-range operation is allowed. Before power-up, the electrical system will be inspected for loose connections, exposed conductors, damaged insulation, incorrect polarity, and possible short circuits. If the system detects a motor, calibration, vision, communication, or end-effector fault, the software will stop the current sequence and prevent further motion. The cause of the fault must be identified and corrected before the system is reset and operation resumes.

5 References

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