

Air Hockey Playing Robot Project Proposal

ECE 445, Fall 2026

Group 32

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1.1 Problem

Air hockey requires a player to visually track a puck moving at speeds upwards of several meters per second, predict its trajectory, and physically intercept it, all in a fraction of a second. This task is trivial for a skilled human player, but presents a challenging robotics problem requiring tightly coupled low-latency perception and control when performed autonomously. This type of problem, where a system must perceive a fast-moving object and generate a precise physical response, is a long-standing benchmark in robotics research. Racket and paddle sports in particular have been used since the 1980s to push the limits of real-time perception to action pipelines, because they force a system to detect object position and velocity, predict future states, and command actuators to a target, all in milliseconds.

Recent high-profile results in table tennis show how difficult this remains even with substantial engineering resources: in 2025, Sony AI published a table tennis robot in *Nature* that could compete with elite human players¹, describing the underlying challenge as one that requires exceptional real-time sensing and control, with implications for AI systems operating in dynamic physical environments more broadly.

Air hockey compresses this same challenge into a smaller, faster, and more constrained environment than table tennis. The puck travels in a straight line or a single bounce rather than a 3D arc, but the reaction time required is correspondingly shorter and the tolerance for actuator error is tighter, since a missed intercept results in an immediate goal for the opponent. Building

¹

<https://www.thestandard.com.hk/world/article/330130/AI-table-tennis-robot-can-beat-elite-players-Sony-says>

an air hockey robotic opponent is thus a compact, low-cost problem that is analogous to many of the larger scale perception-action problems that are being studied on a larger and more expensive scale, while still being achievable in the scope, budget, and time constraints of a senior design project. This class of problems has direct application to problems like collision avoidance and human-robot interaction in shared physical spaces, where systems need to safely and consistently react to human driven motion.

Our goal is to build a robotic air hockey opponent that autonomously tracks and intercepts an incoming puck to defend against and return shots, using vision-based perception and a stepper-driven actuation system, on a compact tabletop air hockey table.

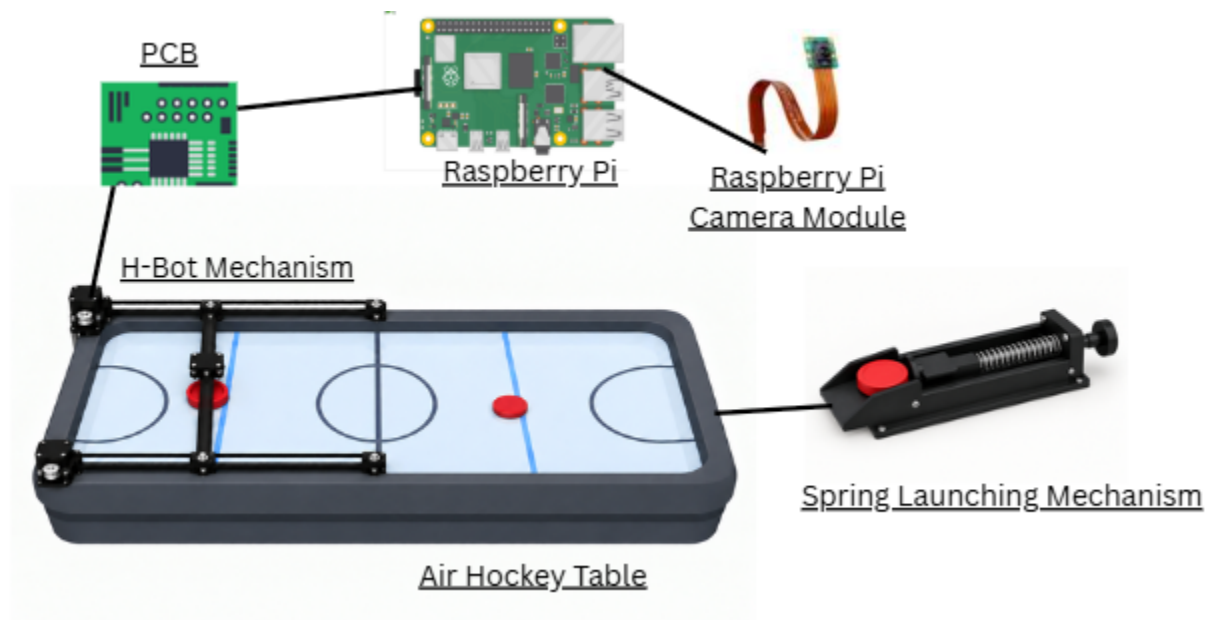
1.2 Solution

Our solution uses an overhead camera to track the puck's position in real time, a Raspberry Pi to process this video and compute an intercept target, and a paddle mounted on an H-bot belted mechanism to physically reach that target. The system is organized into three subsystems: perception, actuation, and sensing.

The actuation subsystem moves the paddle to this intercept point. Two NEMA 17 stepper motors, driven by TMC5160A motor drivers on a custom PCB and controlled over SPI by the Raspberry Pi, drive a belt in an H-bot configuration. This gives the paddle two degrees of freedom while keeping both motors stationary, allowing for fast acceleration with a mechanically simple design.

The sensing subsystem adds a pair of IR break-beam sensors at fixed, known positions on the table, independent of the camera. These sensors provide ground-truth measurements of when the puck crosses a given point, which are used to validate and correct the vision system's position and velocity estimates, and to help isolate failures to either the perception or actuation subsystem during testing.

1.3 Visual Aid

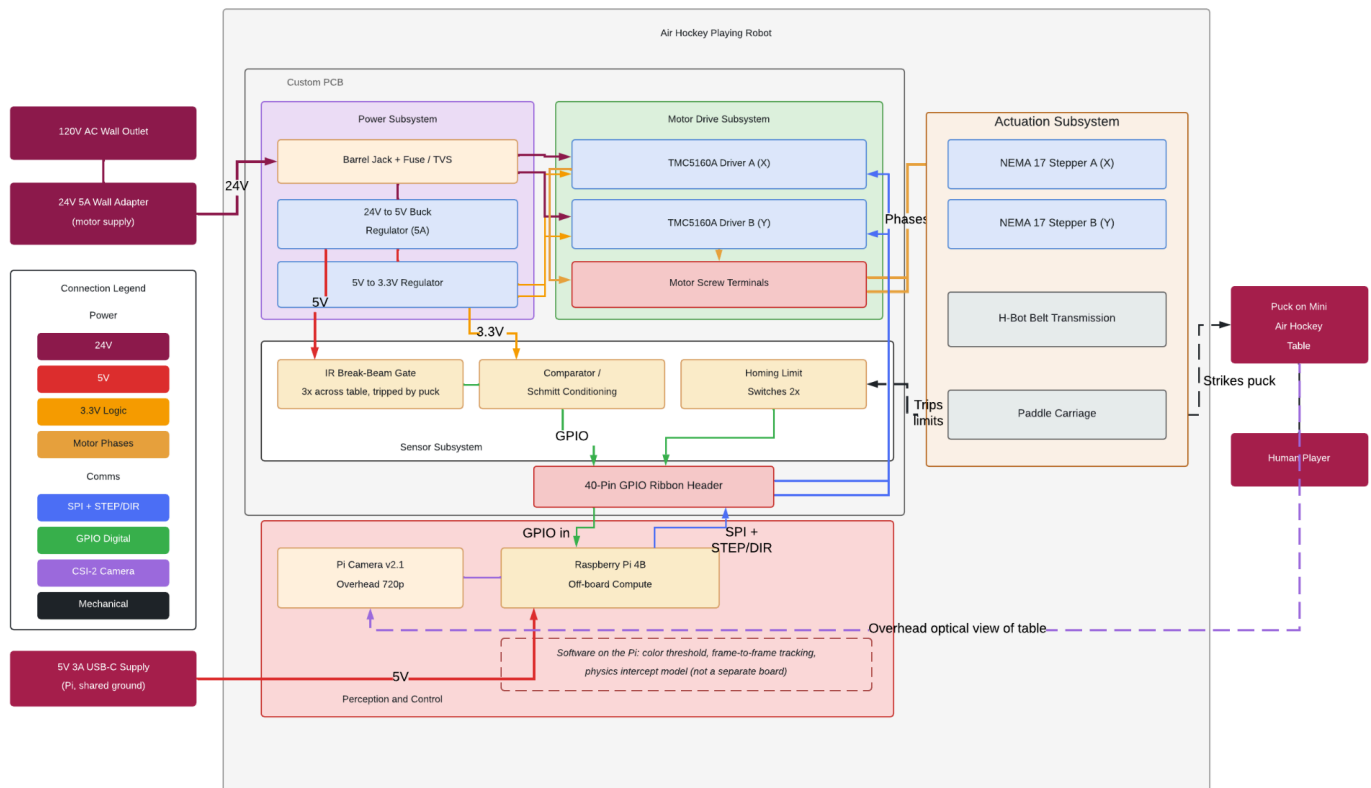


1.4 High-Level Requirements

The system must detect the puck's position and velocity and command the paddle to its predicted intercept point within 30 ms of the puck entering the camera's field of view, to leave sufficient time for the paddle to physically reach the target before the puck crosses the goal line.

The system must make paddle contact with at least 75% of incoming straight shots traveling at speeds up to 4 m/s, and must make paddle contact with at least 50% of incoming single-bounce shots traveling at speeds up to 4 m/s.

2.1 Block Diagram



2.2 Subsystem Overview

2.2.1 Power Subsystem

The power subsystem distributes and regulates power for the robot's motors, drivers, and sensors. A 24 V / 5 A DC supply serves as the primary input, with 24 V supplied directly to the two TMC5160A motor drivers. A buck converter steps this voltage down to 5 V at up to 5 A for low-voltage components, while a 3.3 V rail supplies the required logic and sensors. The Raspberry Pi 4B is powered independently from the PCB. Input protection is included to protect the PCB from overcurrent and voltage transients.

2.2.2 Motor Drive Subsystem

The motor drive subsystem interfaces the Raspberry Pi with the two NEMA 17 stepper motors used by the H-Bot mechanism. Two TMC5160A motor drivers receive 24 V power from the power subsystem and control the phase currents supplied to each motor. The Raspberry Pi configures the drivers over SPI and provides STEP/DIR signals to command motor movement. Together, the drivers provide the current and control necessary to achieve the speed and torque required for puck interception.

2.2.3 Sensor Subsystem

The sensor subsystem provides additional puck detection and homing information to the Raspberry Pi. Two IR break-beam sensors are positioned around the table to detect puck crossings, with their outputs conditioned into reliable 3.3 V digital GPIO signals. Two limit switches are also included to establish the H-Bot's reference position during homing and calibration. These sensors provide independent physical measurements that complement the camera-based perception system.

2.2.4 Perception and Control Subsystem

The perception and control subsystem uses a Raspberry Pi 4B and overhead camera to detect the puck, estimate its trajectory, and determine the required paddle response. The camera captures the playing surface at 720p and 120 FPS through the Raspberry Pi's CSI-2 interface, while software uses color thresholding to identify and track the puck across successive frames. From these observations, the Raspberry Pi estimates puck position, velocity, and direction and uses a physics model to predict an intercept location. The resulting movement command is then sent to the motor drivers through SPI and STEP/DIR signals within the timing constraints required for interception.

2.2.5 Actuation Subsystem

The actuation subsystem physically positions the paddle using a two-degree-of-freedom H-Bot gantry driven by two NEMA 17 stepper motors. The H-Bot belt arrangement combines the rotation of the two motors to produce X- and Y-axis translation of a lightweight paddle carriage over the robot's side of the table. The mechanism is designed to reach all required intercept positions while achieving the speeds necessary to respond to pucks traveling at up to 4 m/s.

2.3 Subsystem Requirements

2.3.1 Subsystem 1 Requirements:

- The power subsystem must accept a 24 V DC input from the 24 V / 5 A motor supply.
- The power subsystem must provide 24 V power to both TMC5160A motor drivers.

- The 24 V-to-5 V buck regulator must provide 5 V at up to 5 A.
- The power subsystem must provide 3.3 V logic power to the required components.
- The power subsystem must provide the required power continuously while the mechanism is operating.
- The input protection circuit must protect the PCB from input overcurrent and voltage transients.

2.3.2 Subsystem 2 Requirements:

- The motor drive subsystem must control two NEMA 17 stepper motors.
- Each TMC5160A must receive 24 V motor power from the power subsystem.
- The motor drivers must receive SPI and STEP/DIR control signals from the Raspberry Pi.
- The motor drive subsystem must provide the appropriate phase outputs to each NEMA 17 motor.
- The motor drive subsystem must provide sufficient current to operate each motor under the maximum expected load.

2.3.3 Subsystem 3 Requirements:

- The sensor subsystem must contain three IR break-beam sensors for puck detection.
- The sensor subsystem must condition the break-beam signals into reliable digital signals.
- The sensor subsystem must provide the conditioned sensor signals to the Raspberry Pi through GPIO.

- The sensor subsystem must contain two homing limit switches.
- The homing switches must provide position-limit information to the Raspberry Pi through GPIO.
- The sensor subsystem must operate from the specified 3.3 V logic supply.

2.3.4 Subsystem 4 Requirements:

- The camera must provide 720p image data to the Raspberry Pi 4B.
- The camera must be mounted above the table such that the playing surface is within its optical field of view.
- The Raspberry Pi 4B must receive image data from the camera through the CSI-2 interface.
- The software must identify the puck using color thresholding.
- The software must track the puck across successive frames.
- The system must calculate the puck's direction and velocity from its tracked positions.
- The system must calculate an intercept location using the puck's position, velocity, and the physics model.
- The Raspberry Pi must communicate the required paddle movement to the motor-drive subsystem using SPI and STEP/DIR.
- The perception and control subsystem must process the puck's movement quickly enough to determine an intercept before the puck reaches the paddle.

2.3.5 Subsystem 5 Requirements:

- The actuation subsystem must provide two degrees of freedom for paddle movement.
- The actuation subsystem must use two NEMA 17 stepper motors.
- The H-Bot belt transmission must translate motor rotation into movement of the paddle carriage.
- The paddle carriage must be capable of reaching the required intercept locations on the playing surface.
- The paddle must be capable of moving at a sufficient speed to intercept pucks traveling at the maximum specified 4 m/s.
- The paddle must remain within the travel limits established by the homing switches.
- The actuation subsystem must respond to movement commands from the motor-drive subsystem.

2.4 Tolerance Analysis

A preliminary timing analysis was performed to determine whether the system can intercept a puck under expected operating conditions. Assuming a 1 m table and a puck speed of 4 m/s², with the player contacting the puck 25 cm from their goal and the robot intercepting 10 cm from its goal, the puck travels approximately 65 cm, providing ~163 ms for the system to react.

At 120 FPS, two frames required for velocity estimation take approximately 16 ms; allowing for overhead, 18 ms is allocated to image capture. An additional 10 ms is allocated for color-threshold detection and trajectory estimation, leaving ~135 ms for paddle movement. If the

² Journal of Robotics and Mechatronics, Vol. 34, No. 5, Fig. 17. <https://www.fujipress.jp/jrm/rb/robot003400050956>

intercept is selected to limit paddle travel to 10 cm, the required average paddle velocity is approximately 0.74 m/s, which is feasible with the selected NEMA 17 stepper motors³.

Parameter	Estimate
Total reaction time	~163 ms
Image capture	18 ms
CV + trajectory calculation	10 ms
Available movement time	~135 ms
Maximum paddle travel	10 cm
Required average paddle speed	~0.74 m/s

3.1 Ethics, safety and societal impact

3.1.1 Human Safety Issues:

Due to our project consisting of pucks and paddles moving at high velocities, human safety must be taken into consideration. We must prepare for the possibility of the puck being sent back at high velocity to an individual. The IEEE Code of Ethics 7.8.II.9⁴ urges engineers to avoid injuring others. To ensure we do this, we will test the paddle so that it is not accelerated at speeds that could cause injury to an individual if a puck were to hit them. It will also be tested to ensure that, when returning the puck, the puck does not fly off the board when hitting a wall.

³<https://www.omc-stepperonline.com/nema-17-bipolar-59ncm-84oz-in-2a-42x48mm-4-wires-w-1m-cable-connector-17hs19-2004s1>

⁴ IEEE, "IEEE Code of Ethics," *IEEE*, Jun. 2020. [Online]. Available: [IEEE Code of Ethics](#)

Ensuring that neither of these scenarios becomes a reality will greatly improve human safety for observers and players.

Another safety concern is our H-bot mechanism. This mechanism can injure individuals, as it accelerates the paddle in a few different ways. It could hit an individual. When moving the paddle to defend the puck, the mechanism could accelerate into the hand of an individual. This poses a risk of injury. To combat this, the range of motion of the machine will be limited, and players will be required to stay on the side of the table that does not consist of the mechanism. This mechanism could also injure someone by moving when someone is adjusting the motor or one of the rails. To avoid this issue, as stated above, players and observers will not be allowed near the side of the table that contains this mechanism, and engineers will not be near it when it is active.

The final safety concern is the launcher. This device is intended to launch a puck at varying velocities. If a puck were to be launched at an individual, this could cause harm. To avoid this scenario, anyone using the launcher will be trained on how to use it and will be required to check the environment to ensure there is no one in the direction of the launcher when it is loaded (even if it is not currently being launched). To ensure total safety, the launcher will only be loaded right before it is used. Pucks will not be sitting in the launcher for extended periods of time.

3.1.2 Human Privacy:

Because our system contains a camera, human privacy becomes a concern. Although the camera is pointed at the air hockey table, it is continuously recording video at 120 fps. This can

cause individuals to be accidentally captured on camera. The IEEE Code of Ethics 7.8.I.1 discusses protecting the privacy of others. To ensure that we do this, two things will be done. Firstly, all individuals who participate will be made aware of the camera. Both the intended purpose, recording the table, and the unintentional side effect, that they could end up on camera, will be stated. Also, all footage will be deleted once it is no longer needed for processing intercept points. This ensures that there is no saved footage of any individuals.

3.1.3 Laboratory Safety Compliance:

Due to the fact that this project will be developed in laboratories at the University of Illinois Urbana-Champaign, we will adhere to all campus safety and laboratory regulations. This includes following all safety protocols when handling our PCB, Raspberry Pi products, launcher, air hockey table, H-bot mechanism, and any other supplies that end up being used.

3.1.4 Societal Impacts:

This project has a couple of positive societal impacts. The first of which is entertainment. Because the game traditionally requires two players, when an individual cannot find someone to play with, they become unable to play. This project solves this issue because it allows air hockey to be played alone. It takes a fun game and makes it more accessible to users, as there are now fewer requirements to play. Another positive impact is that this concept is applicable in other spaces. The concept of tracking movement to predict future movement and respond accordingly has many uses. When applied to vehicles, we could track pedestrians and other vehicles ahead of

time to avoid collisions. When applied to sports, we can predict ball paths and intercept those paths, allowing for training automation in sports like soccer and lacrosse (where there could be a robotic goalie blocking shots). These concepts have many applications that can improve safety and efficiency in society.