

ECE 445

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Tennis Ball Collector

Team 13

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1. Introduction

1.1 Problem

Tennis practices often involve repeatedly stopping play to collect balls scattered around the court. During drills, a coach or player may use dozens of tennis balls before having to walk around the court and manually retrieve them. This reduces the amount of time available for actual practice and can be particularly inconvenient when a coach is running a practice alone or managing multiple players. Manual ball hoppers can make carrying balls easier, but they still require a person to move around the court and collect each ball.

Autonomous ball-collection systems offer another approach by allowing a robot to locate and retrieve balls without continuous human control. However, such systems introduce several engineering challenges. The robot must reliably identify tennis balls, navigate through a defined area, avoid obstacles, remain within the court boundaries, collect balls mechanically, and operate for a useful amount of time from a portable battery. These functions must work together reliably enough that operating the robot requires less effort than collecting the balls manually.

Our project addresses this problem by developing a compact autonomous tennis-ball collector intended initially for controlled indoor practice environments. The system is designed to reduce repetitive ball-collection work and allow players and coaches to spend more of their practice time on tennis activities. From an economic perspective, the design emphasizes a relatively small robotic platform built from commonly available electronic and mechanical components rather than a large specialized system. The project may therefore demonstrate how autonomous collection functionality can be implemented using comparatively accessible hardware.

Safety and welfare are also relevant because the robot contains moving motors, a rotating intake mechanism, a lithium-polymer battery, and autonomous navigation. A navigation failure could result in a collision with a person or surrounding equipment, while electrical or battery failures could create overheating or fire hazards. For these reasons, obstacle detection, boundary detection, motor control, battery protection, and the ability to stop the robot remotely are incorporated into the design rather than treated as optional features. This approach is consistent with ECE 445's expectation that projects consider societal impact, potential negative consequences, applicable standards, and safe and ethical operation.

1.2 Solution

Our solution is a battery-powered autonomous robot that searches a defined area for tennis balls, approaches detected balls, collects them through a motorized intake, and stores

them in an onboard hopper. The prototype will be evaluated in a 6 m × 6 m indoor test area bounded by white tape and containing standard yellow tennis balls under normal room lighting.

The robot is divided into three primary subsystems: Vision and Navigation, Power, Drive, and Communication, and Intake and Storage. A Pixy2 camera provides information used to detect tennis balls, while an STM32F405 microcontroller serves as the primary controller. An MPU-6050 IMU, wheel encoders, boundary sensors, and distance sensors provide additional information about the robot's movement and surroundings. The robot will normally follow a systematic back-and-forth search pattern. When the camera detects a ball, the controller will interrupt this pattern, approach and align the robot with the ball, collect it, and then resume searching.

Two independently controlled rear motors provide differential steering. At the front of the robot, a motorized horizontal drum containing two curved blades will direct balls onto a shallow fixed ramp and into a rear-sloping hopper. The current design targets a drum speed of approximately 10 rpm and a hopper capacity of 10 tennis balls. A ball-passage sensor will provide information for counting collected balls, while an additional full-hopper sensing method will prevent the robot from continuing to collect balls after reaching capacity. An ESP8266 Wi-Fi module will provide an external webpage through which the user can issue start and stop commands and view basic robot status information.

1.3 Visual Aid

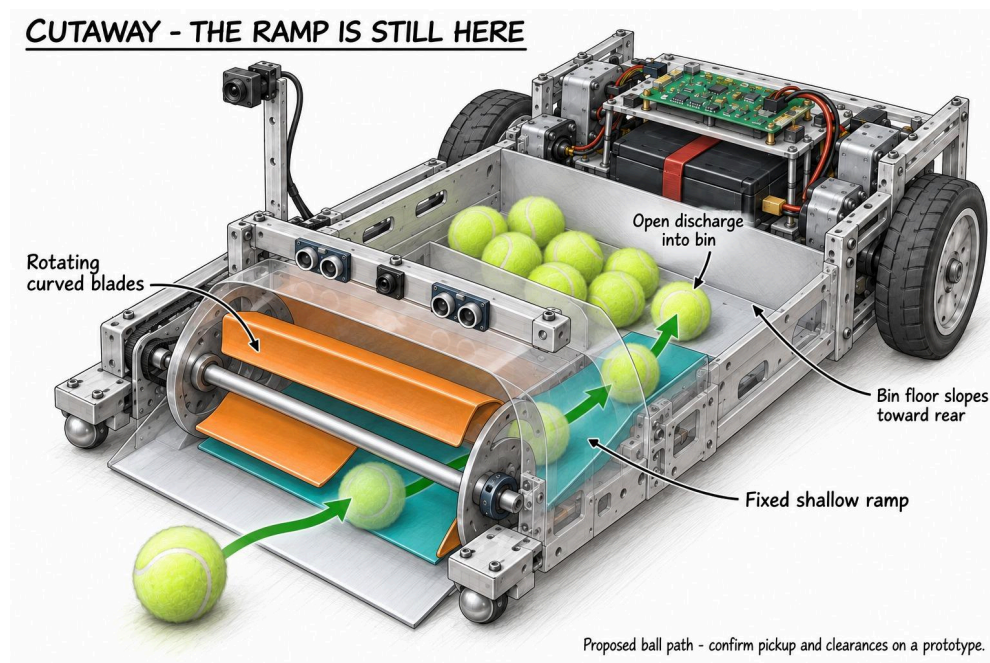


Figure 1: Conceptual operation of the autonomous tennis ball collector.

1.4 High-Level Requirements

These are the High-level requirements that our project will accomplish:

- **Autonomous Collection:** Starting with an empty hopper, the robot shall autonomously collect and retain at least 8 of 10 stationary tennis balls within 10 minutes of receiving the web start command, without human assistance, in at least 2 of 3 test layouts.
- **Obstacle Avoidance:** When approaching a stationary 30 cm × 30 cm × 30 cm obstacle at 0.20 m/s, the robot shall stop or steer around the obstacle without any part of the robot making contact in 5 of 5 trials.
- **Battery Operation:** On one fully charged battery, the robot shall operate for at least 15 minutes without recharging or experiencing an uncommanded controller reset while driving, operating the intake, and maintaining its Wi-Fi connection.

2. Design

2.1 Block Diagram

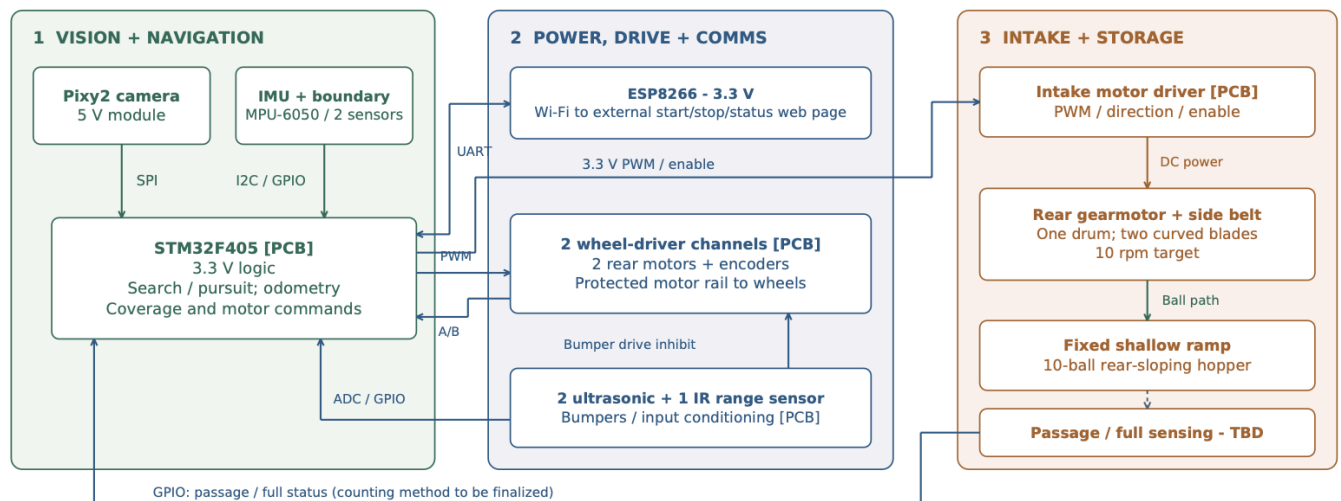


Figure 2: Block diagram of the tennis ball collector.

2.2 Subsystem Overview

2.2.1 Vision and Navigation

The Vision and Navigation subsystem is responsible for locating tennis balls, estimating the robot's movement, identifying boundaries, and generating motion commands. A Pixy2 camera communicates with the STM32F405 through SPI and provides visual information used for ball detection. An MPU-6050 IMU and boundary sensors communicate with the controller through I²C and GPIO interfaces. Wheel encoders provide additional motion feedback from the drive system. Together, these inputs allow the controller to perform search, pursuit, odometry, and coverage functions.

During normal operation, the robot will follow a systematic back-and-forth search pattern. Once a tennis ball is detected, the controller will temporarily interrupt the search trajectory and use the ball position to steer toward it. After collection, the robot will return to its search behavior. Boundary sensors provide a redundant method of preventing the robot from leaving the designated operating region if visual boundary detection is unreliable.

2.2.2 Power, Drive, and Communication

The Power, Drive, and Communication subsystem supplies electrical power, produces robot motion, detects obstacles, and provides the wireless user interface. The proposed power source is a 3S LiPo battery with an 11.1 V nominal voltage and a target capacity of 2200 mAh. Battery power passes through protection and monitoring circuitry before being distributed to the motor drivers and voltage regulators. The PCB produces a regulated 5 V rail for the camera and range sensors and a 3.3 V rail for the STM32, ESP8266, and digital logic.

Two motor-driver channels independently control the rear drive motors, enabling differential steering. Wheel encoders return motion information to the controller. Two ultrasonic sensors, one IR range sensor, and physical bumpers provide obstacle information and a secondary means of inhibiting the drive system. An ESP8266 communicates with the STM32 and provides Wi-Fi connectivity to an external webpage for start/stop control and system status.

2.2.3 Intake and Storage

The Intake and Storage subsystem physically transfers tennis balls from the ground into the robot and retains them. The current mechanical design consists of a slow front gearmotor connected that rotates two curved blades. The motor rotates at a target speed of approximately 10 rpm. As the robot approaches a ball, the rotating blades lift and direct the ball over a shallow fixed ramp into a rear-sloping hopper designed to hold approximately 10 tennis balls.

A sensor located along the ball path will detect balls entering the hopper so that the controller can maintain a collection count. A second sensing function will indicate when the hopper is full.

2.3 Subsystem Requirements

2.3.1 Vision and Navigation Requirements

This subsystem directly supports the autonomous collection high-level requirement by allowing the robot to locate a ball and position it correctly in front of the intake.

The subsystem shall satisfy the following requirements:

- For a stationary tennis ball initially 1.0 m in front of the robot and within $\pm 20^\circ$ of the camera centerline, the subsystem shall guide the robot until the ball is 20 ± 5 cm ahead of the intake lip and within ± 5 cm of the intake centerline in at least 9 of 10 approaches.
- The Pixy2 camera shall communicate ball-location information to the STM32F405 through the SPI interface.
- The MPU-6050 shall provide inertial information to the STM32 through I²C, while boundary sensors shall provide digital or conditioned GPIO inputs.
- Wheel-encoder signals shall provide the controller with A/B encoder information for estimating wheel displacement and supporting odometry.
- The navigation software shall transition between search and ball-pursuit behavior without requiring human control after the start command.
- Boundary detection shall prevent both drive wheels from crossing the outside edge of the designated white-tape boundary during an autonomous collection test. This matches the defined success condition for the current test procedure.

Verification of the primary navigation requirement will use marked ball positions and overhead video. The robot will be stopped immediately before pickup so that the final ball position relative to the intake can be measured independently of the collection mechanism.

2.3.2 Power, Drive, and Communication Requirements

This subsystem supports all three high-level requirements because the robot cannot navigate, collect balls, or avoid obstacles without stable electrical power and controllable locomotion.

The subsystem shall satisfy the following requirements:

- For an input voltage between 10.5 V and 12.6 V, the custom PCB shall simultaneously provide a regulated $5.0 \text{ V} \pm 0.25 \text{ V}$ rail at 1.0 A and a $3.3 \text{ V} \pm 0.165 \text{ V}$ rail at 0.50 A continuously for at least 15 minutes.

- The protected battery rail shall provide power to both wheel-driver channels and the intake motor driver without causing an uncommanded STM32 reset during simultaneous drive, intake, and Wi-Fi operation.
 - MCU-side digital interfaces shall operate at 3.3 V logic levels. Any sensor or encoder signal exceeding the allowable MCU input level shall be conditioned before reaching the STM32.
 - The two wheel-driver channels shall accept independent PWM control from the STM32 so that the robot can move forward and perform differential turns.
 - The obstacle-detection system shall allow the robot to stop or steer around a $30 \times 30 \times 30$ cm stationary obstacle while traveling at 0.20 m/s without physical contact in 5 of 5 trials.
 - The ESP8266 shall maintain its Wi-Fi connection throughout a 15-minute operating test while allowing the user to issue start and stop commands and receive robot status information.
 - Battery voltage/current monitoring shall be communicated to the STM32 through the proposed INA219 I²C interface.
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2.3.3 Intake and Storage Requirements

The Intake and Storage subsystem directly supports the autonomous collection requirement by converting successful navigation into physical ball retrieval.

The subsystem shall satisfy the following requirements:

- At a robot approach speed of 0.03 m/s, the two-blade intake drum and fixed ramp shall transfer a stationary tennis ball whose center is within ± 5 cm of the intake centerline completely into the hopper in at least 8 of 10 trials.
 - After entering the hopper, the ball shall remain inside for at least 5 seconds during each successful collection trial.
 - The intake drum shall rotate at a target speed of approximately 10 rpm during collection.
 - The hopper shall physically accommodate 10 standard tennis balls without preventing the intake mechanism from operating.
 - The passage sensor shall provide a detectable signal to the STM32 when a ball enters the hopper so that the software can update its ball count.
 - The full-hopper sensing system shall provide a digital status signal that allows the STM32 to stop further collection once the hopper reaches its designed capacity.
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2.4 Tolerance Analysis

One of the largest risks to the project is whether the intake drum can reliably capture a tennis ball while the robot is moving. If the drum rotates too slowly relative to the robot's forward motion, the robot may push the ball instead of lifting it onto the ramp. If it rotates unnecessarily fast, the mechanism could increase power consumption and make ball behavior less predictable.

The proposed intake speed is 10 rpm, while the subsystem test specifies a robot approach speed of 0.03 m/s.

The drum's angular velocity is

$$\omega = (10 \text{ rev/min}) * (2\pi \text{ rad/ 1 rev}) * (1 \text{ min/ 60 s}) = 1.047 \text{ rad/s.}$$

If the effective radius from the center of the drum to the tip of a curved blade is r , the blade-tip tangential velocity is

$$v_{\text{tip}} = \omega r.$$

For example, for an effective radius of 5 cm,

$$v_{\text{tip}} = (1.047)(0.05) = 0.0524 \text{ m/s.}$$

The robot's approach velocity is

$$v_{\text{robot}} = 0.03 \text{ m/s.}$$

Therefore,

$$v_{\text{tip}}/v_{\text{robot}} = 0.0524/0.03 \approx 1.75.$$

Under this assumed 5 cm effective blade radius, the blade tip moves approximately 1.75 times faster than the robot approaches the ball, indicating that the rotating blade has sufficient relative motion to move around and lift the ball rather than simply advancing into it.

We can also determine the minimum effective radius needed for the blade-tip velocity to equal the robot velocity:

$$r_{\text{min}} = v_{\text{robot}}/\omega = 0.03/1.047 \approx 0.0287 \text{ m} = 2.87 \text{ cm.}$$

Thus, at 10 rpm, an effective blade radius greater than approximately 2.9 cm produces a tangential speed greater than the specified 0.03 m/s robot approach speed.

This calculation does not prove that the ball will be captured, because actual performance also depends on blade geometry, friction, ball deformation, ramp angle, motor torque, and contact location. Instead, it establishes that the proposed rotational speed is kinematically reasonable and provides a quantitative starting point for mechanical testing. The final design will validate the analysis experimentally using the required 9-of-10 collection test.

3. Ethics, Safety, and Societal Impact

3.1 Ethical Considerations

The autonomous nature of the tennis-ball collector creates an obligation to consider the safety of users and nearby people throughout the design process. The IEEE Code of Ethics emphasizes prioritizing public safety, health, and welfare and communicating factors that could endanger people or the environment. It also emphasizes making realistic technical claims based on available evidence. These principles are directly relevant because the robot moves without continuous human control and contains rotating mechanisms and an energy-dense battery. [1]

To address these responsibilities, the robot will use multiple mechanisms for detecting unsafe situations rather than relying only on the camera. Ultrasonic and infrared sensors will detect obstacles, boundary sensors will prevent the robot from leaving the designated operating area, physical bumpers will provide an additional safety input, and the wireless interface will allow the operator to stop the robot. The system will be tested at controlled speeds before autonomous testing around people. Performance claims in the final report will be based on measured test results rather than expected or simulated performance.

The camera creates a smaller but still relevant privacy concern. The camera is required for ball and boundary detection, not for identifying people. Therefore, image information should be processed only to the extent required for navigation, and the system should not intentionally record, store, or transmit identifiable images of players or bystanders. The wireless interface should transmit only necessary robot information such as operating state, battery status, and ball count.

3.2 Electrical and Battery Safety

The proposed robot uses a 3S LiPo battery, with an 11.1 V nominal voltage and approximately 12.6 V when fully charged. Lithium-based batteries require careful handling because short circuits, overcharging, physical damage, or excessive current can result in overheating and fire.

The battery system will therefore include protection circuitry and current/voltage monitoring. Power wiring and PCB traces will be sized for their expected currents, exposed conductive connections will be insulated, and the battery will be mechanically secured to prevent movement or puncture. Charging will only be performed with equipment intended for the selected battery chemistry and cell configuration. The battery will be inspected before use and will not be used if it shows swelling, physical damage, or abnormal heating.

Battery-related standards such as IEC 62133 and UL 2054 provide useful safety context for rechargeable battery systems; previous ECE 445 design documentation likewise identifies these standards as relevant references for LiPo handling and storage. [2][3]

3.3 Mechanical and Autonomous Operation Safety

The intake mechanism contains a rotating drum, motor, and curved blades. These components create possible pinch and entanglement hazards. The rotating components will therefore be enclosed wherever practical, and the intake will only operate when the system is enabled. The robot should also include an easily accessible means of removing motor power during testing.

Autonomous movement creates an additional collision hazard. The design addresses this through two ultrasonic sensors, an IR range sensor, physical bumpers, and boundary detection. Before full autonomous operation, motor control and obstacle detection will be tested at low speed in a controlled area. The obstacle-avoidance requirement provides a quantitative safety test: at 0.20 m/s, the robot must avoid contact with a 30 cm cube in five consecutive trials.

3.4 Wireless Communication and Fail-Safe Behavior

The ESP8266 provides Wi-Fi communication between the robot and the user's external device. Because the wireless link provides start/stop control, the robot must not depend exclusively on a continuously functioning wireless connection for safe operation. Loss of communication should not cause uncontrolled motion. The STM32 will therefore retain local authority over obstacle detection and motor shutdown even if the ESP8266 connection is lost.

The final implementation should define a fail-safe state in which invalid control information, a controller fault, or an emergency stop causes the drive and intake motors to be disabled. This follows the general engineering principle of placing public safety ahead of continued operation and is consistent with the IEEE ethical responsibilities relevant to the project.

3.5 Societal, Economic, Environmental, and Global Impact

The primary societal benefit of the project is convenience and time savings. Automating repetitive ball collection could allow players and coaches to spend a larger portion of a practice session performing drills rather than retrieving balls. The concept could be useful for individual players, coaches working alone, training facilities, and other environments in which many balls must repeatedly be collected.

Economically, the project explores whether this functionality can be implemented using a relatively compact robot and commonly available embedded hardware. The goal is not to claim that the prototype will immediately compete commercially with existing products, but to demonstrate the feasibility of a smaller autonomous system.

Environmental considerations arise primarily from the rechargeable battery, PCB, motors, and electronic components. Rechargeable operation reduces the need for disposable batteries, but lithium batteries and electronic assemblies eventually become electronic waste and should be recycled through appropriate channels rather than discarded with normal waste. Energy consumption can also be reduced through efficient motor control and by disabling motors when the robot is idle.

Globally, tennis is played in many different environments, so a future version of the system could potentially be adapted to different court surfaces, lighting conditions, court markings, and operating environments. The current prototype, however, is intentionally limited to a controlled 6 m × 6 m indoor test environment with normal room lighting and standard yellow tennis balls. We should therefore avoid claiming reliable operation on full outdoor tennis courts until those environments have actually been tested.

References

- [1] IEEE, “IEEE Code of Ethics,” Institute of Electrical and Electronics Engineers.
- [2] UL Solutions, *UL 2054: Household and Commercial Batteries*.
- [3] IEC, *IEC 62133: Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes—Safety Requirements for Portable Sealed Secondary Cells and Batteries*.