ECE 445

SENIOR DESIGN LABORATORY

PROPOSAL

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# Tennis Ball Picking-up Machine

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# Contents

# 1 Introduction

## 1.1 Background

In tennis training and competitions, players and coaches frequently face the time-consuming task – collecting tennis balls which are scattered around the court. Traditional manual ball collection is not only physically exhausting but also detracts from players' and coaches' valuable training time, especially in high-intensity practice sessions or large-scale events.

Existing manual retrieval methods, such as ball tubes and rolling collectors, require continuous human effort and are impractical for training sessions with a small number of personnel.

Although there are some automated ball collectors, they often suffer from **limited intelligence**, **inefficient energy usage**, or **enormously cost**.

## 1.2 Objective

Efficient ball retrieval is a critical yet underdeveloped aspect of tennis training. Current solutions either rely human effort or cost enormous money.

Our project introduces a novel solution by integrating **computer vision-based detection, autonomous navigation, and an optimized ball collection mechanism**.

This system will identify tennis balls, plan an optimized retrieval path, and collect them efficiently using a mechanical pickup mechanism. By significantly reducing labor costs and improving training efficiency, this innovation aims to enhance the training experience and contribute to the intelligent evolution of sports technology.

## 1.3 Visual Aid

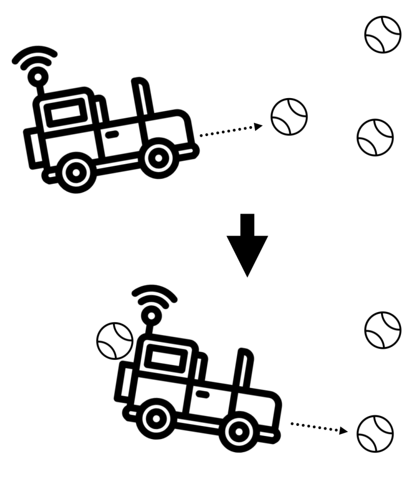

Figure 1: Tennis Ball Recognition and Picking-up Process

## 1.4 High-Level Requirements

- The **image recognition system** should detect and locate **at least 90%** scattered tennis balls under varying lighting conditions.

- The **electronic control system** should enable the cart to reach and collect a detected tennis ball **within 10 seconds** from a distance of 5 meters while avoiding obstacles.

- The **motion system** should enable the cart to turn by a minimum angle (with **within 3°** **error**) that positions the target ball at the center of the path.

- The **collection system** must achieve a **95% success rate** in collecting detected tennis balls and locking them in the storage compartment.

# 2 Design

- Physical Diagram

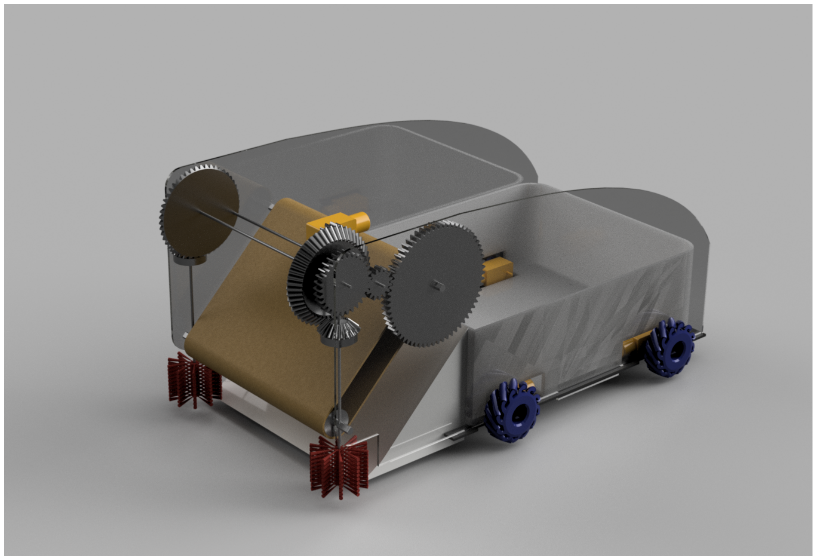

Figure 2: Physical Design Diagram

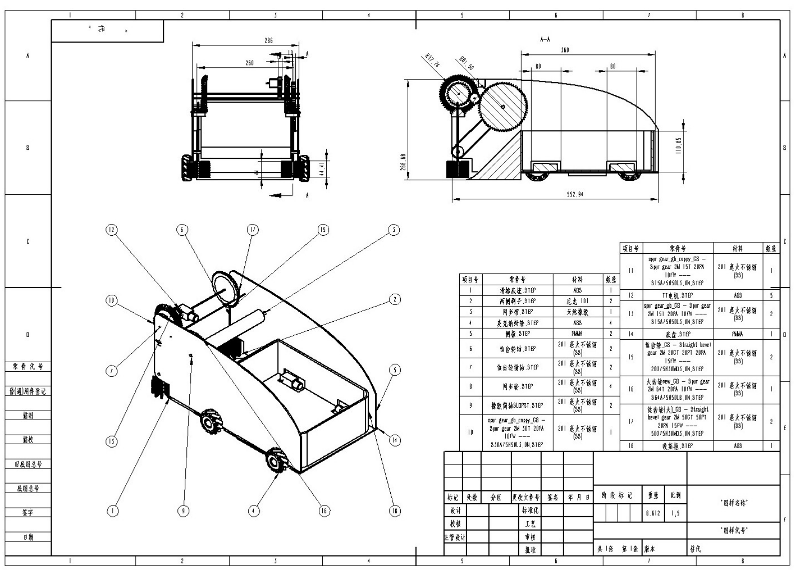

Figure 3: Engineering Drawing With Size And Section

- Block Diagram

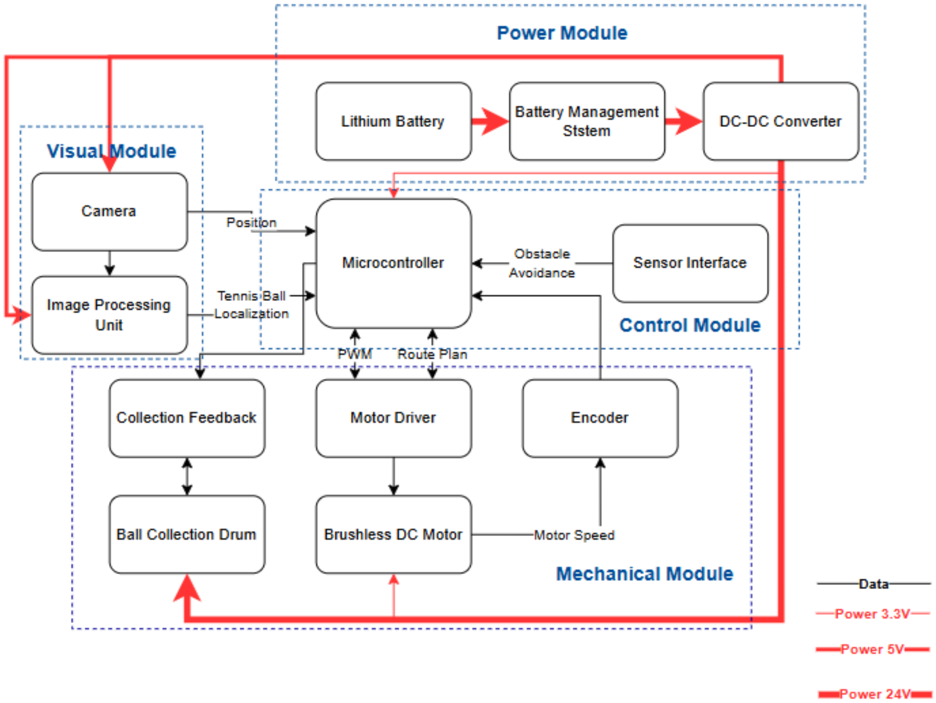


Figure 4: System Block Diagram

## 2.1 Visual System

### 2.1.1 Sensor Selection

- **RGB Camera**: We choose an RGB camera as our sensor, capturing the environment in front of the cart, allowing effective detection of yellow tennis balls against the court background. It can recognize tennis balls on court through the yellow color and circle shape, calculating the angle from the nearest tennis ball with center.
- **Camera Placement**: The camera is placed at the **front of the robot with a slight downward angle**, ensuring effectiveness to capture all tennis balls in camera's sight.

### 2.1.2 Processing Platform

- **Hardware**: Raspberry Pi 4 Model B (8GB RAM)
- **Software**: OpenCV for image processing, Python for implementation

### 2.1.3 Image Processing Workflow

1. **Color Segmentation (HSV Filtering)**: The captured image by RGB camera will be converted to HSV color space, and a yellow color threshold can be applied to recog-

nize tennis balls.[1]

2. **Morphological Processing**: We apply noise reduction using Gaussian blur and morphological operations (opening and closing) to refine the detection.
3. **Shape Detection**:
   - **Hough Circle Transform**: Detects circular objects in the processed image.
   - **Contour Detection**: Identifies the largest yellow region with a circular shape.
4. **Target Selection**: The circular object with the largest area will be chosen as the next-pickup target, since it is the nearest tennis ball from the cart.
5. **Angle Calculation**: The target tennis ball's position relative to the image center is used to compute its angular deviation.

#### 2.1.4 Output and Communication

**Communication Protocol**: The vision module communicates with the motor control module via **UART serial communication**.

**Data Format**: JSON format is used for structured communication:

```
{"direction": "left", "angle": 15.3}
```

- **"direction"**: "left" or "right" based on whether the tennis ball is to the left or right of the center of the cart.
- **"angle"**: The deviation angle in degrees.

**Handling No Detection Cases**:

- Case 1: Send `"direction": "none", "angle": 0` when the tennis ball is at the center of current scene, means that the cart can go straight to pick it.
- Case 2: Send `"direction": "none", "angle": none` when there is no tennis ball in the scene.

#### 2.1.5 Communication and Control Strategy

The communication between the vision module and the motor control module follows as:

1. The vision module detects the nearest tennis ball and provides its relative position to the cart's center. The position is encoded as JSON data with format

   ```
   {"direction": "left", "angle": 15.3}
   ```

2. The motor control module rotates the cart based on the provided direction and angle.

3. Once the cart has rotated for given angle, it stops and waits for a confirmation signal from the vision module to make sure the cart has right direction.
4. The vision module checks whether the tennis ball is now centered:
    - If the ball is centered, it sends `"direction": "none", "angle": 0` to indicate that the cart can move forward.
    - If not, it continues sending updates and wait for rotation until the ball is centered.
5. After moving forward and detecting that the ball is no longer in the vision, the tennis ball is successfully picked up, and the vision module start to detect the next nearest tennis ball, and then sends the next tennis ball's position, repeat progress listed above.
6. If no new tennis ball is detected, it sends `"direction": "none", "angle": "none"` to control module, indicating that the cart should rotate 45 degrees clockwise to check whether there are tennis balls in the sight, and wait for a new signal.
7. If after a full rotation, no ball is detected, the picking up task is done and the process terminates.

## 2.2 Electronic Control System

The electronic control module mainly includes the vision system, control module, mechanical system, and power module. The electronic control module is the core part of the tennis ball pick-up machine and is responsible for coordinating tennis ball recognition, motion control, and power management. Its main functions include processing the tennis ball distribution and position distance recognized by the vision system, conducting route planning, and controlling the movement of the car to achieve real-time obstacle avoidance, Meanwhile, the electronic control module also manages the power supply to ensure DC-DC voltage conversion from 12V/5V/3.3V through a 24V main battery.

### 2.2.1 Microcontroller

- The control module is mainly based on the STM32H743ZI as the microcontroller, with a main frequency of approximately 400MHz. The microcontroller receives data from the visual system, processes the position information of the tennis ball, and performs route planning. In addition, the processor interacts with the sensor interface to detect the external environment in real time and make obstacle avoidance adjustments[2]. By obtaining the pick path and environmental information, the microcontroller can calculate motion control instructions promptly, send PWM signals to the Motor Driver, adjust wheel movement to quickly reach the position of the tennis ball to be picked up, and adjust the motor speed and lifting system for picking based on the number of tennis balls returned by the picking box.

- Requirement 1: This microcontroller must support two SPI and I2C communication interfaces and 12-bit ADC signal acquisition.
- Requirement 2: The operating voltage should be at 3.3V/5V, with 1MB RAM and 2MB Flash storage.

#### 2.2.2 Image Processing Unit

- The visual module consists of a camera and an image processing Unit, which is equipped with a high-performance GPU and a 6-core ARM architecture processor to process computer vision tasks in real time. In this module, the camera collects image data to identify the position of the tennis ball and performs route planning and environmental modeling. The visual system sends the tennis ball-coordinated information to the control module through the UART or CAN bus. The control module can calculate the distance and offset angle on time and control the motor to drive the wheels to pick up the tennis ball at the position.
- Requirement 1: Supports CSI interface and possesses Tensor and other acceleration reasoning tasks.
- Requirement 2: The working voltage is 5V and the power consumption is less than 10W.

#### 2.2.3 Motor Driver

- The Motor Driver mechanical module is mainly composed of a Mecanum wheel moving system and drum-type picking mechanism, achieving efficient picking and transportation of tennis balls. The STM32H743ZI controller calculates the speed and angle of the wheel and quickly adjusts the direction of picking. The picking structure is driven to rotate by a DC motor to adapt to the picking of tennis balls in different scenarios, and the lifting height can be freely adjusted by the number of balls inside the frame.
- Requirement 1: Support PWM signal control; motor drive supports PWM signal adjustment speed.
- Requirement 2: The total power is around 300W (including rotation loss and control loss)

#### 2.2.4 Power Module

- The Power Module uses a 24V main battery as its power source and provides voltage suitable for different modules through a DC-DC buck circuit[3]. The image processing unit is powered by a 5V step-down output, the STM32H743ZI and control circuit are powered by 3.3V/5V, and the motor drive part is directly powered by a 24V battery to ensure stable power output. The power module adopts a battery management system to detect the power output and power consumption status of each module, ensuring normal operation.

- Requirement 1: Support 24V to 5V/3.3V DC-DC conversion to adapt to the power requirements of different modules.
- Requirement 2: Support power management system to ensure stable power supply.

## 2.3 Vehicle Motion System

To control the vehicle's motion, four Mecanum wheels are powered by four individual TT motors. By controlling the motors separately, the trolley can rotate and move in any direction in the plane. As discussed in [4], Mecanum wheels can be controlled using Arduino.

### 2.3.1 Mecanum Wheels

- As the key to motion, we decided to use Mecanum wheels instead of common wheels because such wheels can simplify vehicle motion. Traditional wheels are separated into drive wheels and steering wheels, so the path of the car is always a curve. By applying Mecanum wheels, we divided the motion of the vehicle into an in-place rotation and straightforward moving.
- Requirements 1: Two kinds of Mecanum wheels are needed so that directions can be controlled separately. [5]
- Requirements 2: The wheels need enough strength to support the weight of the vehicle with a maximum load of tennis balls.

### 2.3.2 TT motors

- TT motors are widely used in miniature robots. Four motors are needed to control all wheels. They receive special signals from the Arduino micro-controller, such as PWM.
- Requirements: Motors must have a cable that is compatible with the micro-controller. Motors should own suitable rotation speed with enough torque.

## 2.4 Tennis Ball Collection System

There are many different kinds of designs to collect the tennis ball. For instance, the Eagnas Roller Ball Collector [6] and a fan-type structure designed by Çabuk et al. [7] After evaluating many different designs, we find that most of them can not deal with balls in the corner. Our Roller and brush system solves the problem that it can collect all of the tennis balls, no matter if they are at the wall or in the corner.

### 2.4.1 Motor

- To drive the collecting synchronous pulley, another kind of motor is used at the first gear, considering to have larger torque with faster rotation speed.

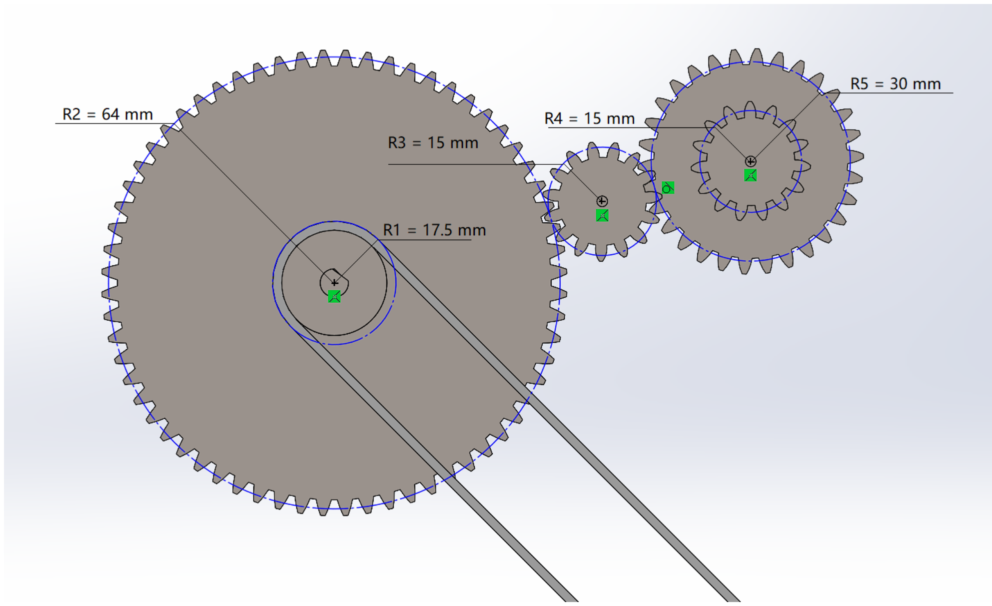


Figure 5: Size of Gear Set

- Requirements 1: The rotation speed of the motor should be fast enough. According to Figure 5, the angular velocity of the motor $\omega_2$ has the relationship:

$$\frac{R_3\omega_2}{R2}R_1 = 2\pi R_t R_M \omega_1 \tag{1}$$

  where:

  - $R_1$ is the radius of the inner final gear.
  - $R_2$ is the radius of the outer final gear.
  - $R_3$ is the radius of the initial gear.
  - $R_M$ is the radius of the Mecanum wheel.
  - $\omega_1$ is the angular velocity of the wheel motor.
  - $R_t$ is the radius of tennis balls.

  The rotation speed of the motor should be at least 7.3 times faster than the wheel motor to deal with tennis balls with maximum density.

- Requirements 2: When lifting the tennis ball, the fraction between the rubber synchronous belt and the balls should defy gravity with the relationship of

$$f = nmg\cos\theta \tag{2}$$

  where:

  - $n$ is the maximum number of tennis balls on the belt.

- $m$ is the mass of a single tennis ball.
- $g$ is the gravity.
- $\theta$ is the angle between the belt and the ground, which is 45°.

According to the principles of gear set:

$$\tau = fR_1 \tag{3}$$

To deal with tennis balls with maximum density, the torque of the motor needed is 0.778 N*m.

#### 2.4.2 Gear Set and Synchronous Pulley

- As discussed in the last section, the gear ratio of the gear set should be suitable so that the speed and torque of the motor are enough for extreme situations. The number of teeth and diameter of the gears are calculated carefully to fulfill the distance of the motor and synchronous wheel.
- Requirements: To reduce the torque needed, the initial gear is designed to have 30 teeth. It is the smallest gear in the system, with a radius of 15 mm. The module of the gear is 2, which is thought to be large enough for stable working.

#### 2.4.3 Collecting Brushes and Bevel Gear

- The rotation axis of the brushes and the motor are perpendicular to each other. After previous calculations, the torque of a single motor is large enough for the entire collecting system to work well. To simplify the structure, we use a pair of bevel gears to rotate the torque of the motor.
- Requirements: There are little requests for the rotation speed of the brushes, but the gear ratio should be suitable to ensure that there is enough space to place the cinema in the front of the vehicle.

### 2.5 Tolerance Analysis

- Changes in lighting conditions can significantly affect the accuracy of image processing. In outdoor tennis courts, it can fluctuate with weather or time, such as direct sunlight, shadow interference, or insufficient nightlight. The path planning and picking behavior of the entire vehicle will be affected if the change in lighting condition leads to a high misjudgment rate of the tennis ball detection algorithm, thereby reducing the overall performance.
- To evaluate and reduce the risks caused by lighting changes, we plan to validate the feasibility of the visual system through mathematical modeling and simulation analysis. Specifically, we will use an image noise model to simulate the impact of different lighting conditions on detection accuracy by detecting performance under different brightness, contrast, and occlusion conditions using color recognition

algorithms. Our experimental results indicate significant changes in detection accuracy and confidence under different environmental conditions. For example, by introducing a certain degree of Gaussian noise to simulate random noise in an image, the model can not accurately identify the target. Therefore, under the influence of Gaussian noise, the confidence level decreased by approximately **"0.06"**; Under strong lighting conditions, the confidence level increased by about **"0.27"**, which is due to **"the enhancement brought by the strong light"**, making the edges of the tennis ball and other targets more prominent. In addition, under low light and motion blur conditions, the decrease is relatively small, at 0.06 and 0.02, respectively. These changes indicate that variations in lighting and noise have a certain impact on the accuracy of object detection, and the system can improve its accuracy by adjusting the image to be recognized.

- Overall, the stability and power consumption control of the visual system are key challenges to the success of the project. Through mathematical modeling, simulation analysis, and experimental verification, we will evaluate the impact of different lighting conditions on system performance and take corresponding optimization measures to ensure that the vision system can work stably in complex environments.

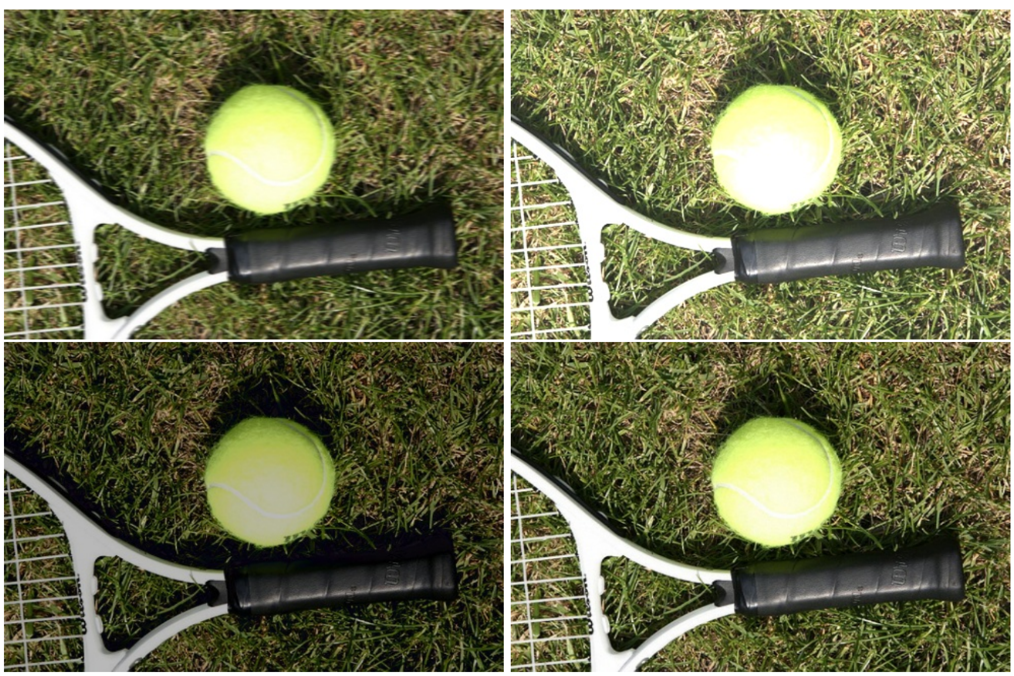

Figure 6: Tennis Ball Under Different Lighting Conditions

# 3 Ethics and Safety

## 3.1 Ethical Considerations

Our **automated tennis ball-picking cart** aligns with the **IEEE Code of Ethics** prioritizing **safety, responsible design and fair treatment of people**.

### 3.1.1 Public Safety and Welfare

- According to **the IEEE Code of Ethics I.1**, we will **prioritize the safety, health and welfare of the public** [8]. Our device will operate autonomously on the court, requiring robust **collision detection** and **obstacle avoidance** modules to prevent accidental injuries to players, coaches, or bystanders.
- We will ensure that our **path planning and object detection algorithms** minimize the risk of the cart colliding with people or equipment.

### 3.1.2 Transparency and Honesty in Technical Work

- As per **IEEE Code of Ethics I.5**, we commit to providing **accurate performance estimates** of our system's capabilities, including detection accuracy, movement speed, and pickup efficiency [8].
- We will **acknowledge and address system limitations** and incorporate **user feedback** to improve our design.

### 3.1.3 Environmental Responsibility

- In accordance with **IEEE Code of Ethics I.1**, we will strive to comply with **ethical design and sustainable development practices**, ensuring that the cart's **battery and electronic components comply with RoHS (Restriction of Hazardous Substances) regulations** [8].

## 3.2 Safety Considerations

### 3.2.1 Mechanical Safety

- The cart includes **moving mechanical parts** such as **motorized collection rollers and wheels**, which pose potential safety risks.
- To mitigate these risks:
  - The **picking mechanism** will be designed with protective casing to prevent unintended contact with users.
  - The **navigation system** will ensure that the cart does not operate at dangerous speeds that could cause injury.

#### 3.2.2 Electrical and Battery

- Our device will use a **rechargeable battery**, which poses risks such as **overheating, short circuits, and fire hazards**.
- To comply with **UL 1642 (Standard for Lithium Batteries)** and **IEC 62133 (Safety Requirements for Rechargeable Cells and Batteries)**, we will:
  - Integrate **battery management circuitry** to prevent overcharging and deep discharge.
  - Use manufacturer-recommended **temperature protection** and **current regulation mechanisms**.
  - Include **clear safety warnings** about proper handling and charging.

#### 3.2.3 Autonomous Navigation

- The cart will rely on **computer vision and sensor-based path planning**, which must ensure **reliable real-time object detection** to avoid unintended collisions.
- To enhance safety:
  - The system will include **emergency stop functionality** to halt operation if unexpected obstacles are detected.
  - We will implement **human-interference module** for operator or supervisor to hand over the operation in case of emergency.
- As per **IEEE Code of Ethics I.1**, we will promptly disclose any **potential risks that could endanger users or the environment** [8].

#### 3.2.4 Campus and Facility Safety Regulations

- If the device is tested on **university premises**, we will obtain **approval from campus safety officials** to ensure compliance with any local policies regarding autonomous robotics testing.
- We will conduct **controlled testing in designated areas** to minimize risks to people and equipment.

By adhering to these **ethical guidelines and safety measures**, we will develop an **autonomous tennis ball-picking cart that is safe, reliable, and ethically responsible**, contributing to the intelligent automation of sports training.

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