ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Tennis Ball Picking-up Machine

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April 14, 2025

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1 Introduction

1.1 Problem and Solution Overview

In tennis training scenarios, a large number of balls are often left scattered on the court, requiring repeated manual collection. This task is not only physically tedious and time-consuming, but it also interrupts the efficiency of practice sessions. While commercial ball-picking machines exist, they are typically expensive, heavy, and often rely on complex mechanical designs or GPS-based navigation, making them impractical for lightweight, cost-sensitive applications in educational and research contexts.

Our project proposes a compact, low-cost, and fully autonomous tennis ball pickup system that integrates a computer vision module, a motion control system, and a mechanical pickup structure. Unlike deep learning-based methods such as YOLOv8 that require large annotated datasets and high computational power[1], we adopt a lightweight classical computer vision approach using HSV color segmentation and circular shape detection to identify tennis balls in real time. This enables real-time image processing even on low-power devices like the Raspberry Pi 4. The visual system outputs the relative direction and angle of the nearest tennis ball and communicates with the motion controller via UART serial communication using structured JSON messages.

Beyond vision module, traditional ball-picking robots often suffer from poor adaptability and limited control accuracy, especially when navigating or responding to dynamic changes in the court environment. Our system addresses this through a custom-designed electronic control unit that interprets directional and angular data from the vision module and commands the robot's motors accordingly. This communication is implemented using structured JSON data over UART, ensuring modularity and reliability.

Also, traditional mechanical pickup mechanisms are frequently unable to retrieve balls located at the corners of the court or near the edges[2], leading to inefficiencies or the need for manual intervention. To overcome this limitation, our design includes rotating brushes mounted on both sides of the robot. These brushes gently sweep balls from the corners into the central pickup path, significantly improving the robot's collection coverage and robustness. This three-part integration—vision, control, and mechanical design—offers a novel and accessible solution for autonomous tennis ball retrieval, with broad applications in education, research, and low-cost sports robotics.

1.2 Visual Aid

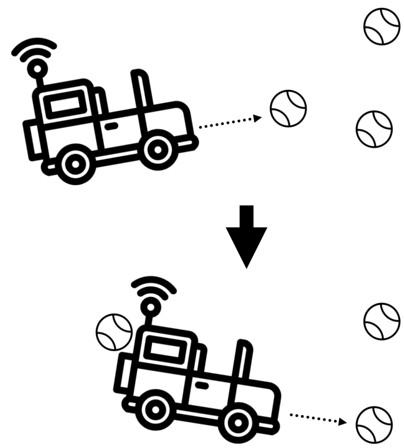

Figure 1: Tennis Ball Recognition and Picking-up Process

1.3 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

2.1 Block Diagram

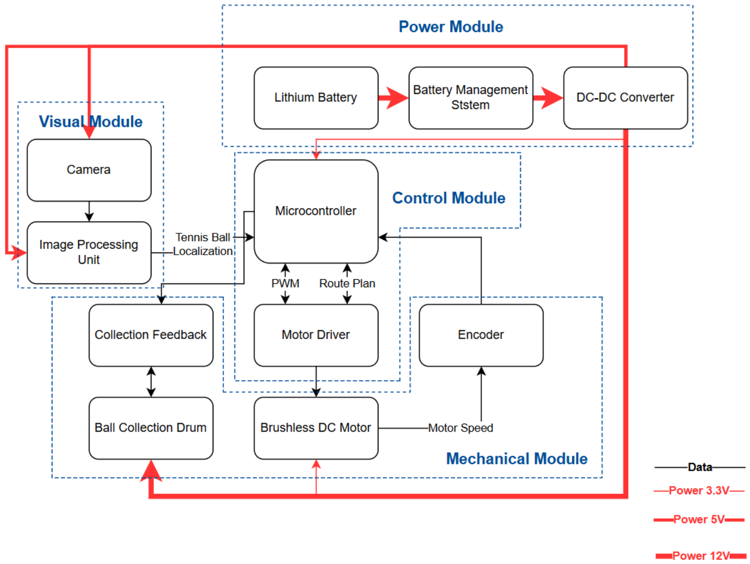

Figure 2: System Block Diagram

2.2 Physical Diagram

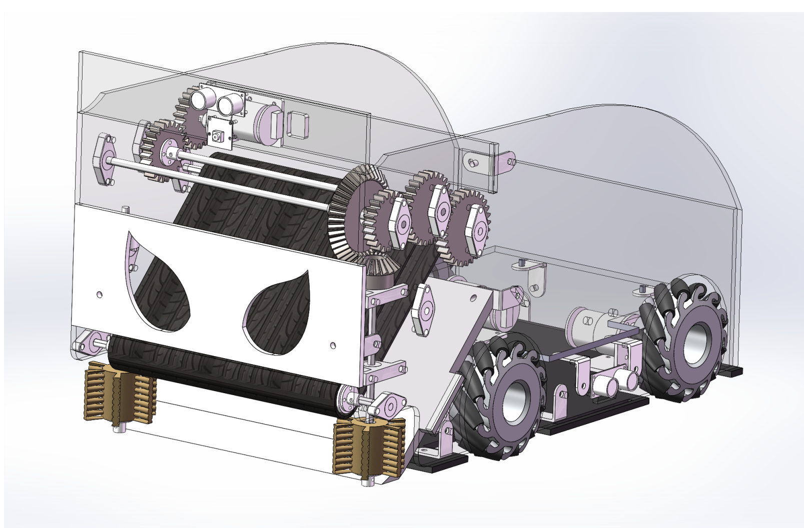

Figure 3: Design Modeling Diagram

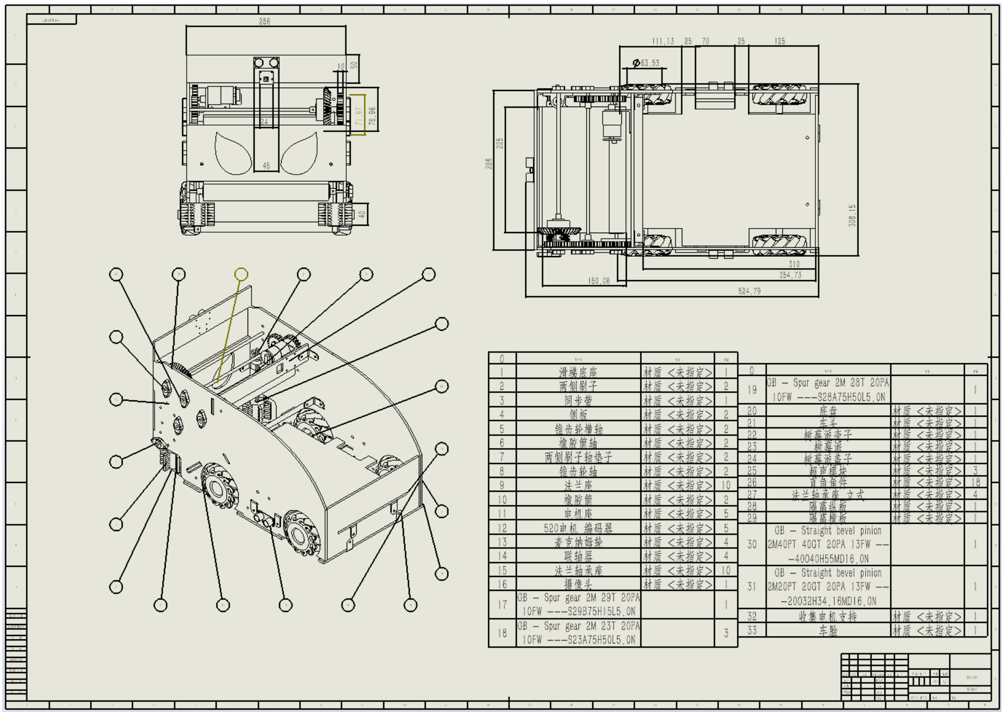

Figure 4: Engineering Drawing With Size And Section

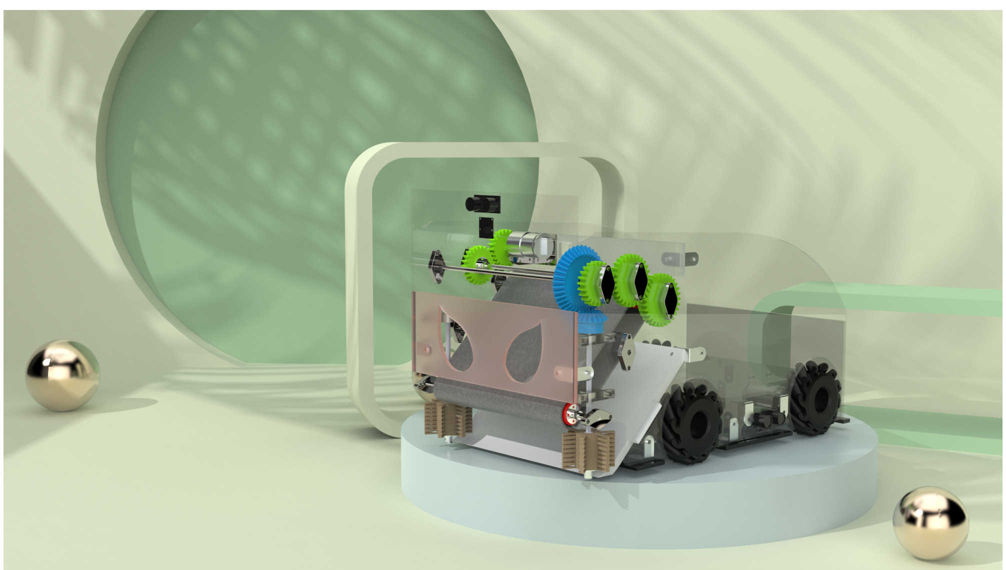

Figure 5: Product Rendering Graph

2.3 Schematic Diagram

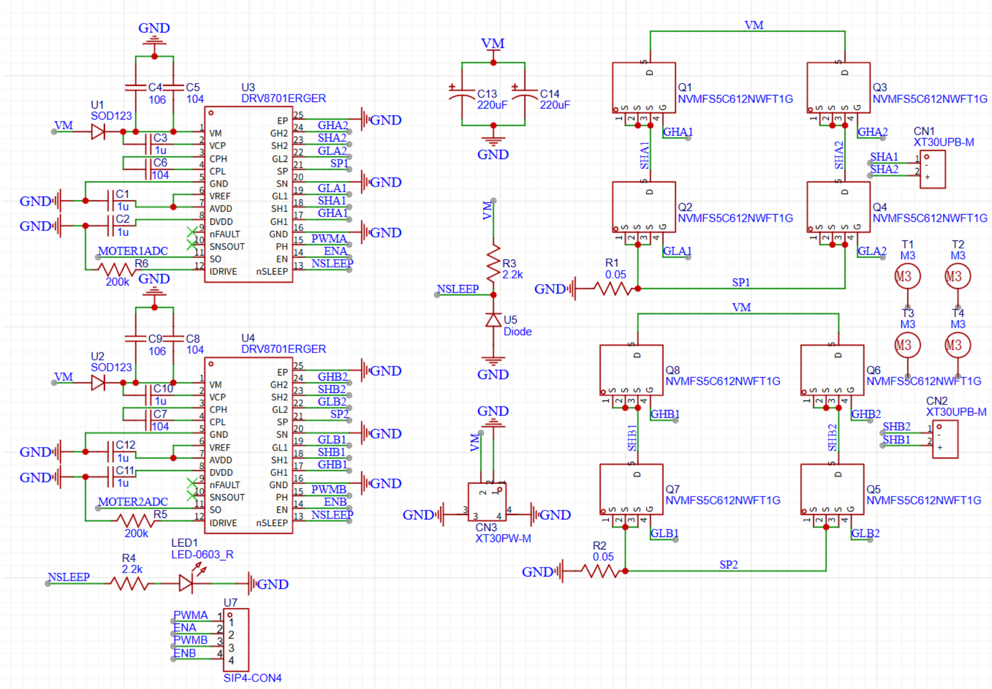

Figure 6: Motor Driver Schematics

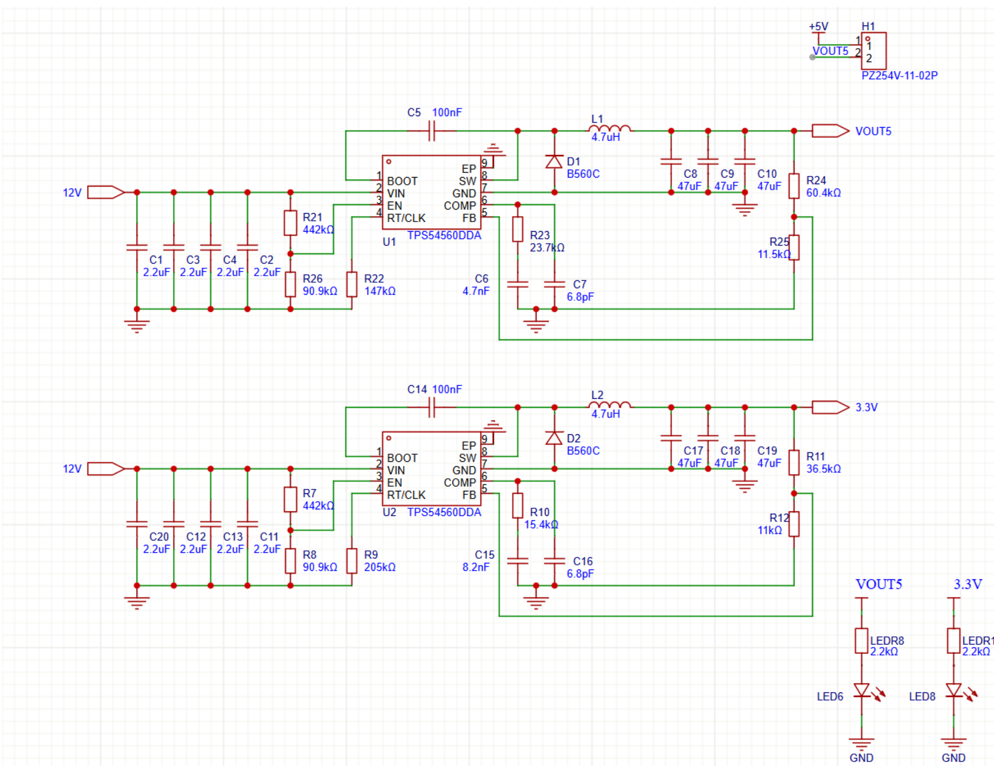

Figure 7: DC-DC Voltage Reduction Schematics

2.4 PCB Layout

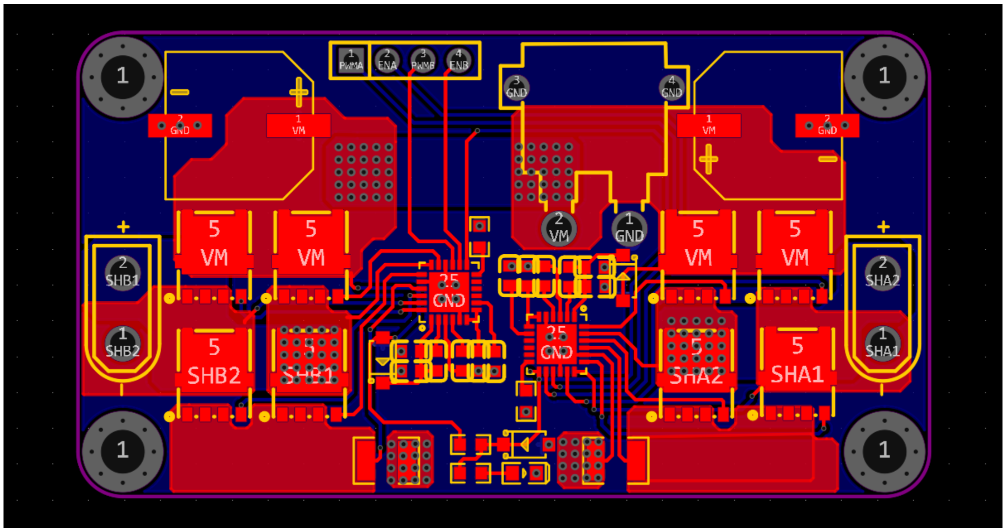

Figure 8: Motor Driver PCB Drawing

2.5 Visual System

2.5.1 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.

2.5.2 Processing Platform

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

2.5.3 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 recognize tennis balls.[3]
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.

2.5.4 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.

2.5.5 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.

2.6 Electronic Control System

The control module mainly includes the TI TMS320F280039C microcontroller and motor drive unit. This module can achieve closed-loop DC motor speed control through PWM signals and SPI interfaces, which also perform real-time management path planning simultaneously. The microcontroller TM280039C receives tennis ball position information from the image processing module and drives the motor to control the direction of the car's movement.

2.6.1 Microcontroller

The TM280039C microcontroller is responsible for the core control tasks of the system, including generating PWM signals for motor drives and executing path-planning algorithms. The microcontroller interacts with external image processing units through UART and SPI interfaces to obtain motion trajectory data. The controller uses TI's cost-effective real-time control chip, with a built-in 120 MHz main frequency and high-precision PWM module (20 ns duration), which can accurately control the motor speed (error $\leq \pm 0.5\%$) while ensuring low latency in data processing. The controller is connected to the TI LaunchPad development board through the JTAG interface for firmware burning and debugging. The advantage of this microcontroller lies in its real-time response capability and compatibility with multi-protocol communication, making it suitable for core control scenarios in high-dynamic electromechanical systems.

Table 1: R&V Table For Microcontroller

Requirement	**Verification Method**
Supports SPI full duplex communication with a speed of $\geq$ 10Mbps	A. Connect the microcontroller to the communication object and logic analyzer through SPI interface; B. Configure SPI clock frequency to 10MHz (main mode) and send 1MB data blocks; C. The receiving end sends back data and records the transmission time; D. Verify the consistency between received and sent data, with a total time of $\leq$ 800ms (rate $\geq$ 10Mbps).
Supports UART communication with a speed of $\geq$ 19.2kbps	A. Connect the microcontroller UART interface to the USB-UART Port and serial debugging assistant; B. Set the baud rate to 19.2kbps and send 128 bytes of random data; C. Return data to the terminal to verify data consistency.

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Requirement	Verification Method
PWM output precision $\leq 0.5\%$	A. Set the PWM frequency to 20kHz, with a duty cycle of 50 %, and connect it to an oscilloscope; B. Measure the PWM pulse width and calculate the deviation between the actual duty cycle and the theoretical value; C. Repeat testing with 10% and 90% duty cycles, and verify that the error is $\leq 0.5\%$.

2.6.2 Motor Driver

The motor drive module adopts the DRV8701 driver chip design, and two DRV8701ERGER chips are used in the circuit to drive one motor. DRV8701 has current detection and overcurrent protection functions and can efficiently drive external N-channel MOSFETs.

The external power MOSFET model is NVMFS5C612NWFT1G, with a total of 8, forming two sets of full bridge circuits to drive two motors respectively. The DRV8701 driver chip controls MOSFETs through independent high and low gate drive signals (such as GHA1, GLA1, GHB2, GLB2, etc.) to achieve motor forward and reverse rotation and PWM speed control.

Control signals such as PWMA/B and ENA/B are connected to the main control MCU through pin interfaces, and the main control can achieve motor start-stop and speed regulation through these pins. The power input terminal (VM) is equipped with large capacity capacitors (C13, C14) for filtering, suppressing power ripple, and ensuring stable operation of the drive circuit. Each node is also equipped with decoupling capacitors (such as C3, C4, C6, C7, etc.) to further enhance the system's anti-interference capability. The overall design balances efficient driving capability and circuit stability, making it suitable for control applications of high-current DC motors.

Table 2: R&V Table For Motor Driver

Requirement	Verification Method
Can drive two DC motors, each supporting a maximum current output of 2A	A. Connect the microcontroller to the communication object and logic analyzer through SPI interface; B. Configure SPI clock frequency to 10MHz (main mode) and send 1MB data blocks; C. The receiving end sends back data and records the transmission time; D. Verify the consistency between received and sent data, with a total time of $\leq$ 800ms (rate $\geq$ 10Mbps).
Supports PWM control for speed regulation, with a frequency range of 1kHz to 50kHz	A. Connect the motor drive board to the DC power supply (VM=12V); B. Connect two motors to the CN1 and CN2 interfaces; C. Use a signal source to provide PWM and EN signals respectively; D. Connect the ammeter and measure the current value of the motor load during operation, ensuring that each output current is not greater than 2A.

2.7 Power Module

The power module can provide multi-level stable voltage output for the system. The module consists of a lithium-ion battery pack, a battery management system, and a DC-DC conversion circuit, supporting 12V/5V/3.3V voltage conversion to meet the full load power supply requirements of the electromechanical system. The main power input of the lithium-ion battery pack is 12V, with a capacity of 2.1Ah, and supports a continuous discharge current of 2A. The DC-DC conversion circuit supports multi-level output to meet high conversion efficiency.

2.7.1 Lithium Battery

As the core energy unit of the system, the lithium-ion battery pack adopts a high-energy density cell design, which can provide stable and durable power output. In the absence of an external power supply, the battery needs to maintain continuous operation of the system for 4 hours. At the same time, lithium-ion batteries work in conjunction with DC-DC conversion circuits to prioritize the instantaneous current demand of high-power loads (such as motors) while maintaining the voltage stability of logic circuits.

Table 3: R&V Table For Battery

Requirement	Verification Method
The battery pack outputs a stable 12V voltage and supports a continuous discharge current of 2A	A. Use electronic loads to test the battery output voltage under different output currents (0.5A/1A/2A); B. Verify that the voltage is maintained at around 12V.
Supports long battery life and meets the requirement of 4-hour continuous operation	A. Connect the system (motor logic circuit) representing the actual load in a fully charged state; B. Run continuously for 5 hours, record voltage changes and remaining capacity; C. Verify whether it can support continuous operation for 4 hours under typical application loads.
Strong adaptability to dynamic loads	A. Simultaneously connect high loads (such as motors) and low-power modules (such as MCUs, cameras); B. Start the motor and observe whether there is interference or power failure in the logic power supply (3.3V/5V); C. Observe voltage stability through an oscilloscope.

2.7.2 DC-DC Voltage Reduction

The DC-DC buck module adopts the TPS54560DDA buck regulator design, which stabilizes the 12V voltage to 5V and 3.3V respectively, providing an independent power supply for various circuit units such as vision modules and microcontrollers in the system. Two TPS54560DDA chips (U1 and U2) are used in the circuit, responsible for voltage outputs of 5V and 3.3V, respectively.

Each power module adopts multi-stage ceramic capacitors (such as C1-C24, C20-C12) for input filtering, suppressing high-frequency interference, and is equipped with Schottky rectifier diodes (D1, D2) to protect the output terminal and prevent voltage backflow. The combination of inductors (L1, L2) and multiple high-capacity capacitors (such as C8-C10, C17-C19) forms an LC filtering network, effectively reducing ripple output and improving dynamic response performance. Set the output voltage value through feedback resistors (R23/R25 and R11/R12) and optimize the loop stability by combining compensation networks (such as C6/C7/R23). The frequency setting resistors (R22, R9) are used to set the operating frequency of the chip, balancing efficiency and volume.

Table 4: R&V Table For DC-DC Voltage Reduction

Requirement	**Verification Method**
Stable conversion of 12V input to 5V and 3.3V outputs	A. After powering on, measure whether the voltage of VOUT5 and VOUT3.3 is within the range of 5V ± 5% and 3.3V ± 5% respectively; B. Use an oscilloscope to observe the output voltage waveform and confirm that there is no serious overshoot or voltage drop phenomenon.
The output voltage remains stable during dynamic load changes	A. Simultaneously connect the high-power motor (12V) and the logic module (3.3V/5V); B. Start the motor and monitor the logic voltage output; C. Collect the voltage waveform during operation with an oscilloscope to verify the DC-DC response capability and stability.

2.8 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.

2.8.1 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.

2.8.2 JGB37-520 motors

- JGB37-520 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. The motor comes with an encoder, which can output to check the instantaneous speed and steering, which is conducive to regulation and control. At the same time, purchase the acrylic plate base with the motor base, which is designed and installed by the hole size on the motor base.
- Requirements: Motors must have a cable that is compatible with the micro-controller. Motors should own suitable rotation speed with enough torque.

Table 5: R&V Table for Mobility System

Requirement	Verification Method
Mecanum Wheel Selection	
Wheel diameter shall be 97 mm $\pm$ 2 mm	A. Measure wheel diameter at three different positions; B. Use Mitutoyo 500-196 digital caliper for precision; C. Verify that all measured values fall within the specified tolerance.
Each wheel shall support a load of $\geq$ 5 kg at 0.5 m/s	A. Place a 5.1 kg mass on the wheel attached to a static test rig; B. Observe any visible deformation or instability; C. Confirm that performance remains within acceptable bounds.

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Requirement	Verification Method
Roller angle shall be 45° $\pm$ 0.5°	A. Use Wixey WR300 digital protractor to measure roller angle; B. Measure at multiple rollers to ensure uniformity; C. Confirm all values fall within specified tolerance.
JGB37-520 Encoder Motor	
Rated speed shall be 200 RPM $\pm$ 10 at 12 V	A. Connect motor to a variable DC power supply and set to 12 V; B. Use DT-2234C tachometer to measure RPM; C. Repeat measurements and verify that all results fall within tolerance.
Stall torque shall be $\geq$ 0.25 Nm	A. Secure the motor shaft and apply force using a CDI 2503MFRMH torque wrench; B. Gradually increase torque until stall condition is observed; C. Record torque value and confirm it meets the requirement.
Motor shall meet IP54 waterproof rating	A. Perform spray test by directing water at 1 L/min for 5 minutes; B. Ensure no ingress of water into motor housing; C. Inspect and verify no functionality loss post-test.

2.9 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.

2.9.1 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.
- Requirements 1: The rotation speed of the motor should be fast enough. According to Figure **??**, the angular velocity of the motor ω_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.
  - ω_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.
  - θ 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.

2.9.2 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.

2.9.3 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.

Table 6: R&V Table for Ball Collection Mechanism

Requirement	Verification Method
Wall/Corner Collection	
The mechanism shall collect balls located within 2 cm of a wall	A. Mark a test court with 2 cm grid lines adjacent to the wall; B. Place balls at 2 cm distance and activate the mechanism; C. Observe and record whether the ball is successfully collected.
The 90° corner retrieval success rate shall be ≥95%	A. Perform 20 trials of ball placement in 90° corners; B. Record retrieval outcomes using a high-speed camera; C. Calculate success rate and confirm it meets the requirement.
Brush Mechanism	

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Requirement	Verification Method
Brush rotational speed shall be 60 RPM ± 5	A. Activate the brush mechanism; B. Use a DT-2236 laser tachometer to measure RPM; C. Repeat measurements and confirm values fall within the specified range.
Brush contact force shall be 2 N ± 0.2 N	A. Use SH-50 force gauge to measure the contact force between brush and surface; B. Conduct measurements at multiple positions; C. Ensure all measured values lie within the tolerance range.

2.10 Tolerance Analysis

We confirm that the motor and gear transmission structure of the tennis pickup system is one of the keys to the project's success and also the most challenging part. This structure directly determines whether the robot can effectively collect tennis balls from the ground and from corners. If the motor's output torque or speed is insufficient, it will result in ball omission or jamming, severely impacting system performance. Therefore, we conduct a mathematical analysis to verify that the design still meets the project requirements under real-world deviations.

2.10.1 Motor Torque Requirement Analysis

According to mechanical design principles, the pickup system motor must overcome the friction between the rubber timing belt and the tennis balls, lifting the balls along the inclined belt. The torque is calculated as follows:

$$\tau = fR_1 = nmg\cos\theta \cdot R_1$$

where:

- $n = 3$: Maximum of 3 balls simultaneously on the belt
- $m = 0.058\,\mathrm{kg}$: Mass of a single tennis ball
- $g = 9.8\,\mathrm{m/s^2}$: Gravitational acceleration
- $\theta = 45^\circ$: Inclination angle of the belt relative to the ground
- $R_1 = 0.015\,\mathrm{m}$: Radius of the inner gear

Substituting values:

$$f = 3 \cdot 0.058 \cdot 9.8 \cdot \cos(45^\circ) \approx 1.2\,\mathrm{N}$$
$$\tau = 1.2 \cdot 0.015 = 0.018\,\mathrm{N} \cdot \mathrm{m}$$

Considering transmission losses and peak load conditions, we introduce a safety margin of 20 times, resulting in a target torque:

$$\tau_{\text{target}} = 0.018 \cdot 20 = 0.36\,\mathrm{N} \cdot \mathrm{m}$$

The selected motor outputs $0.45\,\mathrm{N} \cdot \mathrm{m}$ under rated conditions, providing a 25% redundancy margin.

Considering practical error sources:

- Motor performance fluctuations: May vary by $\pm 10\%$ due to voltage or temperature
- Gear backlash and transmission efficiency: Estimated efficiency around 90%
- Timing belt slippage: Estimated maximum transmission loss of 5%

The worst-case effective output torque is:

$$\tau_{\text{eff}} = 0.45 \cdot 0.9 \cdot 0.95 = 0.384\,\mathrm{N} \cdot \mathrm{m} > 0.36\,\mathrm{N} \cdot \mathrm{m}$$

Thus, even under adverse conditions, the torque requirement is still satisfied.

2.10.2 Speed Requirement and Gear Tolerance Analysis

The system requires the pickup motor to operate at three times the angular velocity of the wheel motor:

$$\omega_2 = 3 \cdot \omega_1$$

If the wheel motor runs at $100\,\mathrm{RPM}$, then:

$$\omega_2 = 300\,\mathrm{RPM}$$

The selected motor has a no-load speed of $350\,\mathrm{RPM}$, and the gear reduction ratio is $1 : 1.1$, resulting in:

$$\omega_{\text{belt}} = \frac{350}{1.1} \approx 318\,\mathrm{RPM} > 300\,\mathrm{RPM}$$

This meets the speed requirement with sufficient margin.

2.10.3 Conclusion

The above analysis confirms the practical feasibility of the pickup motor and gear mechanism, even when tolerances and deviations are considered. The system provides adequate torque and speed redundancy, ensuring reliable operation under conditions such as high ball density, slippage, and energy degradation, fully satisfying the project's pickup task requirements.

3 Cost and Schedule

3.1 Cost Analysis

Here is a comprehensive rundown of the project's costs, which factors in the labor expenses as well as material costs. The total budget has two main categories: (1) Team members' hourly wages/problems, and (2) The parts and services needed for hardware and software deployment.

3.1.1 Labor Costs

Labor costs have been estimated based on how much expected annual income a recent ECE graduate of the University of Illinois can earn per hour. The formula applied is:

$$\textbf{Hourly Rate (\$)} \times 2.5 \text{ (overhead)} \times \textbf{Hours Worked} = \textbf{Total Labor Cost}$$

Table 7: Labor Cost Breakdown

Team Member	**Hourly Rate ($)**	**Hours**	**Overhead Factor**	**Total ($)**
Member A	35	50	2.5	125
Member B	35	45	2.5	112.5
Member C	35	41	2.5	102.5
Member D	35	47	2.5	117.5
			Grand Total	**457.5**

3.1.2 Parts and Services

The ensuing table indicates all of the components, as well as the involvement of outside services, which are essential to the deployment of the project:

Table 8: Material and Service Costs

Description	Source	Qty.	Unit Cost ($)	Total ($)
Raspberry Pi 4	Online Shopping	1	63.84	63.84
Slide Base	3D printing	1	11.4	11.4
Brushes	Online Shopping	10	0.43	4.3
Slide Base	3D printing	1	11.4	11.4
Velcro Belt	Online Shopping	1	3.29	3.29
Side Broad	Laser Cutting	2	2.29	2.29
6mm D Axis	Online Shopping	8	0.57	5.71
Brush Gasket	3D printing	2	Free	Free
Flange Coupling	Online Shopping	11	0.37	4.09
Plastic Cylinder	3D printing	2	Free	Free
Motor	Online Shopping	5	4.24	21.21
Mecanum Wheel	Online Shopping	4	2.39	9.54
Diamond Bearing	Online Shopping	10	0.64	6.43
Vertical Bearing	Online Shopping	6	0.64	3.86
Spur Gears	3D printing	4	Free	Free
Bevel Gears	3D printing	2	Free	Free
Trolley Chassis	Laser Cutting	1	4.29	4.29
Head Board	Laser Cutting	1	1.57	1.57
Straight Corner Piece	Online Shopping	16	0.04	0.6
Isolation Vertical Plate	Laser Cutting	1	4.57	4.57
Isolation Horizontal Plate	Laser Cutting	1	4.57	4.57
Electron Component	Online Shopping	1	16.05	16.05
Double End Cabling	Online Shopping	10	0.1	1
Battery	Online Shopping	1	2.74	2.74
			Subtotal	**182.75**

Grand Total

$$\textbf{Total Labor} + \textbf{Total Parts/Services} = \$457.5 + \$182.75 = \boxed{\$640.25}$$

3.2 Schedule

This section outlines the project timeline with weekly milestones and task allocation among team members. The schedule covers all phases from design to final testing.

Table 9: Project Schedule with Task Allocation

Task	Week	Member A	Member B	Member C	Member D
Architecture Selection	1	Y	Y	Y	Y
Collector Structure Design	2-3	Y			
Whole Structure Design	3-5	Y	Y	Y	Y
Parts Procurement	6	Y	Y	Y	Y
Mechanical Assembly	6-7	Y	Y		
Software Development	6-7			Y	Y
System Integration	8	Y	Y	Y	Y
Testing & Debugging	9	Y	Y	Y	Y
Final Documentation	10	Y	Y	Y	Y

4 Ethics and Safety

4.1 Ethical Considerations

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

4.1.1 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.

4.1.2 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.

4.1.3 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].

4.2 Safety Considerations

4.2.1 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.

4.2.2 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.

4.2.3 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].

4.2.4 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.

References

[1] S. Gu, X. Chen, W. Zeng, and X. Wang, "A deep learning tennis ball collection robot and the implementation on nvidia jetson tx1 board," in *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 2018, pp. 170–175. DOI: 10.1109/AIM.2018.8452263.

[2] M. Xiao, Q. Wen, L. Ji, and W. Wang, "Tennis ball picking robot based on bluetooth control," in *Proceedings of the 2021 2nd International Conference on Control, Robotics and Intelligent System*, ser. CCRIS '21, Qingdao, China: Association for Computing Machinery, 2021, pp. 12–16, ISBN: 9781450390453. DOI: 10.1145/3483845.3483848. [Online]. Available: https://doi.org/10.1145/3483845.3483848.

[3] H.-C. Kang, H.-N. Han, H.-C. Bae, M.-G. Kim, J.-Y. Son, and Y.-K. Kim, "Hsv color-space-based automated object localization for robot grasping without prior knowledge," *Applied Sciences*, vol. 11, no. 16, p. 7593, 2021. DOI: 10.3390/app11167593. [Online]. Available: https://doi.org/10.3390/app11167593.

[4] M. Yashar and Y. Hashim, "Design and implementation of arduino controlled mecanum wheel robot car," in *2024 21st International Multi-Conference on Systems, Signals Devices (SSD)*, 2024, pp. 474–479. DOI: 10.1109/SSD61670.2024.10548130.

[5] K.-L. Han, O.-K. Choi, J. Kim, H. Kim, and J. S. Lee, "Design and control of mobile robot with mecanum wheel," in *2009 ICCAS-SICE*, IEEE, 2009, pp. 2932–2937.

[6] N. Chawla, W. Alwuqayan, A. Faizan, and S. Tosunoglu, "Robotic tennis ball collector," in *Conference on Recent Advances in Robotics, Florida International University*, 2012, pp. 1–6.

[7] V. U. Çabuk, A. Kubilay Şavkan, R. Kahraman, F. Karaduman, O. Kırıl, and V. Sezer, "Design and control of a tennis ball collector robot," in *2018 6th International Conference on Control Engineering Information Technology (CEIT)*, 2018, pp. 1–6. DOI: 10.1109/CEIT.2018.8751917.

[8] IEEE. ""IEEE Code of Ethics"." (2016), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 02/08/2020).