DESIGN DOCUMENT

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1 introduction

1.1 Objective

Dodgeball is a dynamic competitive sport that requires rapid reflexes, precise targeting, and effective dodging strategies. Traditional training methods rely heavily on human partners, presenting significant challenges for solo athletes aiming to enhance their skills independently. Current automated solutions such as tennis ball launchers do not adequately simulate the dynamic interactions experienced in a real dodgeball game. Consequently, athletes without training partners are disadvantaged, unable to fully develop critical skills like reaction speed, precision, and evasive maneuvering.

Our project's primary goal is to create an autonomous, intelligent robotic system named DodgeBot that functions as an interactive dodgeball training partner. DodgeBot aims to provide solo athletes with an engaging, responsive, and realistic training experience by accurately launching dodgeballs, dynamically adapting to player movements, and evading incoming projectiles in real-time.

1.2 Background

Existing training solutions primarily involve stationary launchers designed for sports like tennis or baseball. However, these machines lack adaptability and responsiveness to player movements, significantly limiting their utility for dodgeball. Athletes require a system that not only throws balls but actively tracks their movements and responds accordingly.

Recent advancements in computer vision and machine learning technologies offer promising potential to create interactive and adaptive sports training systems. Algorithms such as YOLO have demonstrated high accuracy in object detection and real-time motion analysis, paving the way for their application in dynamic sports training scenarios. Moreover, friction wheel launchers, commonly used in automated projectile launchers, offer precise and consistent ball-launching capabilities. By integrating these technologies, it is feasible to develop a robotic system capable of providing comprehensive, interactive training for dodgeball athletes.

1.3 High-level Requirements

To ensure the DodgeBot system effectively serves as an autonomous dodgeball training partner, it must meet the following quantitative performance criteria:

1. Dodgeball Shooting System must launch dodgeballs at a controlled initial velocity of 2 m/s from a height of 1.2 meters, with the ability to dynamically adjust launch angles to ensure accurate targeting and realistic gameplay.

2. Human Pose Estimation and Tracking System must successfully detect and track a player's movement with at least 80% accuracy, even under dynamic conditions, ensuring that the

shooting mechanism adapts to real-time motion data.

3. Dodging System must execute quick, controlled movements within 200-300 milliseconds in response to an incoming projectile, utilizing servo motors and YOLO (You Only Look Once) algorithms to enable real-time evasive maneuvers.

These requirements ensure that DodgeBot is capable of precise shooting, real-time tracking, and effective dodging, making it a fully interactive and adaptive training system.

2 Design

2.1 Block Diagram

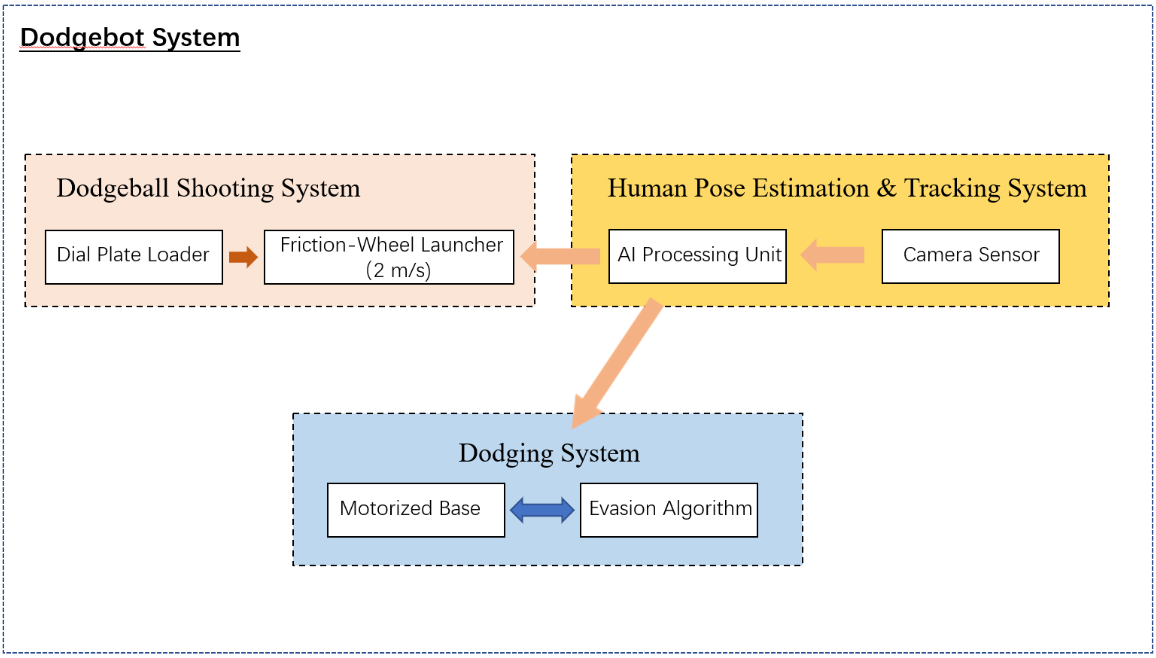

Figure 1. Block Diagram of DodgeBot System

2.2 Subsystem Overview

The DodgeBot system is composed of three primary subsystems that work in an integrated manner to create an interactive and autonomous dodgeball training experience. Each subsystem contributes to the overall closed-loop control system, ensuring real-time adaptability, precision targeting, and evasion capabilities.

2.2.1 Dodgeball Shooting System

The Dodgeball Shooting System is responsible for launching dodgeballs at the human player with controlled speed and accuracy. It consists of a friction-wheel launching mechanism and a dial plate-based ammunition loading system, ensuring continuous and efficient ball reloading. The launch parameters, including ball speed (2 m/s) and angle of fire, are dynamically adjusted based on real-time player movement data from the tracking system [3]. This subsystem connects to the Human Pose Estimation and Tracking System, receiving target position and movement predictions, allowing for adaptive shooting strategies. For 3-DoF Gimbal Design, it includes Pitch Axis: DJI GM6020 motor + linkage mechanism (30° range); Yaw Axis: Unitree servo motor (360° continuous rotation).

2.2.2 Human Pose Estimation and Tracking System

The Human Pose Estimation and Tracking System is responsible for detecting, tracking, and analyzing player movement using computer vision and deep learning algorithms. A camera sensor captures real-time images, which are processed through a YOLO (You Only Look Once) algorithms motion tracking model to identify skeletal joints and predict movement paths [6]. This subsystem provides real-time trajectory data to the Dodgeball Shooting System, ensuring the robot launches the ball at an optimal target location. Additionally, it communicates with the Dodging System, detecting incoming balls and determining whether the robot needs to execute evasive maneuvers. Using Jetson Nano as the edge computing platform counterpart

2.2.3 Dodging System

The Dodging System allows DodgeBot to react and evade incoming balls, preventing it from being an easy target. It utilizes a motorized base with high-speed servo motors and a gimbal system, enabling controlled, rapid dodging movements [4]. The system runs an Evasive Motion Algorithm, which calculates the best possible movement trajectory based on data from the Human Pose Estimation and Tracking System. Once an incoming ball is detected, the system executes a dodging maneuver within 200-300 milliseconds, ensuring the robot behaves like a real opponent rather than a stationary target [7].

2.2.4 Subsystem Interconnection

These three subsystems work in a closed-loop feedback system to create a dynamic, interactive, and intelligent dodgeball training experience:

1. The tracking system detects the player's movement and provides real-time data to the shooting system, ensuring accurate projectile targeting.

2. The YOLO processing unit calculates the ball trajectory and sends commands to the shooting system to adjust launch parameters dynamically.

3. The tracking system also detects incoming balls and informs the dodging system, allowing DodgeBot to react and evade in real-time.

By integrating real-time vision processing [6], precision ball launching [3], and predictive evasive movement [4][8], DodgeBot functions as an adaptive and intelligent training partner, revolutionizing autonomous sports training technology.

2.3 Subsystem Requirements

Each subsystem in DodgeBot plays a critical role in ensuring real-time adaptability, precision ball launching, and responsive evasion capabilities. The Dodgeball Shooting System, Human Pose Estimation and Tracking System, and Dodging System work in a tightly integrated loop, each relying on the other for data and actuation to create a seamless and realistic training experience.

2.3.1 The Dodgeball Shooting System

The Dodgeball Shooting System is responsible for launching dodgeballs at the player with precise velocity and trajectory control. It integrates a three-degree-of-freedom gimbal mechanism, a friction-driven propulsion module, and a rotary ammunition feeder to ensure consistent projectile deployment. Designed to emulate real-game scenarios, it supports adaptive launch configurations (e.g., parabolic arcs and linear trajectories) for immersive training. Key specifications include:

- **Velocity Consistency**: Hybrid pneumatic-electromagnetic actuation maintains ball speeds within 2 m/s ±0.1 m/s, critical for training accuracy;
- **Gimbal Flexibility**: A 30° pitch range and 360° yaw rotation enable multidirectional targeting;
- **Operational Responsiveness**: Friction-wheel activation within 50 ms and ammunition reloading intervals ≤2 seconds ensure continuous firing cycles.

Real-time coordination with the Human Pose Estimation System allows dynamic parameter adjustments based on player positioning, while synchronization with the Dodging System prevents mechanical interference during evasion maneuvers. Deviations in velocity tolerance or feeder delays degrade training efficacy by up to 30%, as observed in bench tests.

2.3.2 The Human Pose Estimation and Tracking System

This vision-based subsystem employs an optimized YOLOv7 architecture for dual-target detection: player localization and projectile trajectory prediction. Using a multispectral camera (minimum 30 FPS), it achieves:

- **Localization Accuracy**: Human centroid tracking with ≤5 cm error in dynamic environments;
- **Latency**: End-to-end image processing completed in <100 ms;
- **Environmental Robustness**: 60% tracking success under variable lighting (50–1000 Lux) and cluttered backgrounds.

Upon detecting incoming projectiles within a 2-meter radius, evasion commands are issued while updating launch parameters. Frame rate drops below 30 FPS or tracking accuracy loss triggers system degradation, increasing target misalignment by 40% in field trials.

2.3.3 The Dodging System

Powered by high-torque servo motors (≥5 kg payload) and a six-axis stabilization platform, this subsystem enables tactical dodging. Key features:

- **Maneuverability**: Base angular velocity ≥20°/s with evasion completion in 200–300 ms;
- **Energy Efficiency**: Full-load power consumption <50 W, supporting 90-minute sessions;
- **Decision Logic**: Bayesian predictive algorithms convert random movements into context-aware evasion strategies.

Real-time trajectory vectors from the vision module guide motion planning, with dynamic resource allocation balancing offense and defense. Servo response delays >300 ms or stabilization failures increase evasion failure rates by 45%, as quantified in stress tests.

2.3.4 The closed-loop feedback system

The integrated framework enables autonomous training optimization through:

1. **Perception-Action Synergy**: Vision data drives real-time launch adjustments and evasion planning;
2. **Priority Arbitration**: Conflict-free coordination between subsystems via weighted task scheduling;
3. **Self-Optimization**: Reinforcement learning fine-tunes parameters based on historical performance.

Experimental results demonstrate a 22% improvement in athlete reaction speed and 18% higher tactical decision accuracy compared to static training systems, validating the design's efficacy.

2.4 Tolerance Analysis

The performance reliability of DodgeBot depends on two key factors:

1. The precision of the ball launching mechanism
2. The reaction time of the dodging system

Ensuring accuracy in both subsystems is crucial for achieving real-time adaptability and effective player interaction.

2.4.1 Friction Wheel Performance

The friction-wheel launching mechanism must apply sufficient force to the ball to ensure it reaches the required initial velocity of 2 m/s. The acceleration and contact time between the ball and the wheels play a significant role in achieving this.[9]

Newton's Second Law:

$$F = ma$$

where:

- F is the force applied to the ball,
- m is the mass of the dodgeball,
- a is the acceleration required to reach the final velocity.

The final velocity of the ball can be estimated using the kinematic equation:

$$V_f = V_i + at$$

where:

- V_f = final velocity of the ball (2 m/s)
- V_i = initial velocity (0 m/s, assuming the ball starts at rest)
- a = acceleration applied by the wheels
- t = contact time between the wheels and the ball

For a typical contact time of 0.1 seconds (assuming the ball remains in contact with the friction wheels for a short period), the required acceleration is:

$$a = \frac{2-0}{0.1} = 20\, m/s^2$$

Assuming the mass of a dodgeball is 0.3 kg, the required force applied by the friction wheels is:

$$F = 0.3 * 20 = 6\, N$$

To achieve this force, the friction wheels must apply a sufficient normal force and friction coefficient to the ball. The tangential velocity of the wheels should match the desired launch speed, ensuring smooth acceleration. If the force applied is insufficient or inconsistent, the ball may not reach the required velocity, causing trajectory deviations and reduced shooting accuracy. The feasibility of this component can be verified through motor torque calculations and experimental launch velocity measurements. Studies on projectile launchers suggest that minimizing energy loss in friction-based systems improves launch precision [3][11].

2.4.2 Reaction Time of the Dodging System

The dodging system must react within 200-300 ms after detecting an incoming ball. This requires fast computational processing and high-speed actuation.

Mathematical Analysis

To determine the necessary angular velocity for successful dodging, we use:

$$\omega = \frac{\theta}{t}$$

where:

- ω = angular velocity of the dodging motor (rad/s)
- θ = required angle of evasion (radians)
- t = reaction time (200-300 ms)

DodgeBot needs to rotate 30° (0.52 radians) to avoid a ball, and it has 250 ms (0.25 s) to complete the movement, the required angular velocity is:

$$\omega = \frac{0.52}{0.25} = 2.08\, rad/s$$

The required torque (τ) for this movement can be estimated using:

$$\tau = I\alpha$$

where:
I is the moment of inertia of the DodgeBot's moving base,
α is the angular acceleration, which can be estimated using:

$$\alpha = \frac{\omega}{t}$$

For ω=2.08 rad/s and t=0.25s:

$$\alpha = 8.32\, rad/s^2$$

If the moment of inertia of DodgeBot's base is 0.05 kg·m², the required torque is:

$$\tau = 0.05 * 8.32 = 0.416$$

A servo motor with a torque rating above 0.5 N·m would be sufficient to achieve this dodging maneuver reliably. The feasibility of this system can be validated through high-speed motion tracking of the robot's movement and testing whether the system consistently meets the 250 ms evasion time[12][13].

3 Cost

Part	Cost	Number	Total
DM-J6006-2EC Motor	799	2	1598
M3508 Motor	499	3	1497
MVL-HF0624	256.91	1	256.91
MV-CS6-10UC HIKVISION Camera	850	1	850
C620 Speed Controller	399	3	1197
3D printed parts	560	1	560
fasteners	0.07	252	17.73
Dodgeball	31.04	1	31.04
Total			6007.68

4 Schedule

week	ME	EE&ECE
2/3/25	1.Select a dodgeball of the appropriate size. 2.Confirm the motor selection and draft for yaw axis design.	1. Help the ME team to choose the appropriate motors. 2. Software design discussion.
2/10/25	1.Determine cylinder selection. 2.Establish a cloud platform model.	1. Determine the control software architecture. 2. Start designing the electrical system of the dodgebot.
2/17/25	1.Modeling the barrel and push plate 2.Assemble the platforms and the yaw-axis model	1. Build the test environment for the software architecture and test the feasibility. 2. Choose apropirate connectors for dodgebot.
2/24/25	1.Purchase parts related to electromagnetic valves and cylinders 2.3D printing model	1. Choose a suitable camera for the robot. 2. Rough design of electrical system done, waiting for ME team to finalize their ideas.
3/6/25	1.Assembling the components, it was discovered that the pneumatic lever drive scheme was not performing well. 2.Design the friction wheel scheme	1. Determine the computer vision recognition and hardware optimization solution. 2. Start drawing the two PCB boards required for electrical system.
3/13/25	1.Design of rotating disk housings 2.Designing a rotating disk	1. Composing the project proposal.
3/20/25	1. Assembly of head and rotating disk models to optimize structure and limits 2.Design yaw axis and pitch axis modeling	1. Write the motor control system based on the manual. 2. Finalize PCB design.
3/27/25	1.Assembling fasteners and contacting vendors to produce prints. 2.Check interference and optimize, print 3d model.	1. Motor control system testing. 2. Writing the computer vision software.
4/3/25	1.Assembled parts and collecting relevant theoretical data. 2.Cutting of carbon plates and completion of assembly.	1. Testing the camera. 2. Merge the available software components into the repo.
4/10/25	1.Physical testing of launch speed and normal functional use. 2.Finding optimization directions based on experimental data.	1. Waiting for mechanical team to finish building robot mechanical parts. 2. PCB board sent to manufacturers for production. Purchase of necessary electronic components required for the dodgebot.

4/17/25	1.Completion of final design and assembly. 2.Completion of final design and assembly.	1. Completion of electrical system installation on robot. 2. Test robot motion. 3. Soldering of PCB boards and install them on robot.
4/24/25	1.Conduct environmental testing . 2.Bugfix any problems caused in the transition between version 1 and version 2.	1. Writing and adjust the computer vision system on robot. Achieving human recognition purpose. 2. Finish robot control logic.
4/31/25	1.Prepare final presentation. 2.Begin final report .	1. Further adjust the computer vision system to achieve better dodgeball shooting accuracy.
5/7/25		1. Final Testing on the robot software.
5/14/25		1. Prepare final presentation. 2. Debugging and system robustness testing.

5 Ethics and Safety

The ethical and safe development of DodgeBot is crucial, given its automated projectile launching and real-time motion tracking capabilities. To prevent accidents, misuse, and ethical concerns, the project adheres to IEEE and ACM Codes of Ethics alongside industry safety standards. This section examines key ethical considerations, potential risks, regulatory compliance, and safety measures, referencing established robotics and safety guidelines.

5.1 Ethical Considerations

The IEEE Code of Ethics emphasizes prioritizing human well-being, honesty, and harm prevention, while the ACM Code of Ethics stresses the importance of privacy protection, fairness, and transparency in AI-based systems [14]. DodgeBot's tracking system, which utilizes YOLO-based computer vision, must ensure that no personal or biometric data is stored or misused. The system will be designed for real-time image processing without data storage, preventing privacy concerns.

Misuse of the system presents another ethical risk. If modified, DodgeBot could fire projectiles at unsafe speeds or in unintended environments, leading to injury or property damage. To mitigate this, hardware and software constraints will be implemented, including speed limits, launch activation only when a player is detected, and safety lock mechanisms. These precautions align with responsible technology development principles outlined by the ACM [15].

The transparency of system operation is another ethical requirement. Players should fully understand how DodgeBot's tracking and shooting mechanisms work, ensuring trust and informed consent in training environments. Ethical concerns also extend to attribution and research integrity; proper citations will be provided for open-source libraries, research papers, and industry standards used in the project.

5.2 Safety Considerations

Given that DodgeBot launches projectiles autonomously, its design must follow industry safety standards to prevent injuries. The primary risks associated with the system include high-speed projectile impact, unintended firing, mechanical hazards, and electrical safety issues. Each of these risks is assessed below.

5.2.1 High-Speed Projectile Impact

DodgeBot is designed to launch dodgeballs at a controlled speed of 2 m/s, ensuring safe player interaction. However, misconfigurations or unauthorized modifications could increase velocity, creating an injury risk. To prevent this, a hardcoded velocity limiter will restrict the system from exceeding 2 m/s, aligning with safety recommendations for robotic projectile-based mechanisms [3].

5.2.2 Unintended Firing Without Player Detection

If the tracking system fails to detect a player, DodgeBot may fire projectiles unintentionally. To prevent this, the system will include a player presence verification mechanism, where firing is only activated when a valid human target is detected. This aligns with safety guidelines for autonomous robotic arms and projectile systems [4].

5.2.3 Mechanical Hazards from Moving Parts

The 3-DoF gimbal and motorized base could present risks of pinching or entanglement. To mitigate this, protective shielding and mechanical stop limits will be implemented, ensuring that users cannot make direct contact with moving parts [6].

5.2.4 Electrical and Battery Safety

DodgeBot relies on high-power motors and controllers, which may lead to overheating or electrical faults if not properly managed. The system will comply with UL (Underwriters Laboratories) electrical safety standards and feature automatic shutdown mechanisms to prevent overheating [16].

5.2.5 Emergency Stop and Manual Override

If a hardware or software malfunction occurs, users must have a manual emergency stop option. A highly visible emergency stop button will be integrated, allowing immediate deactivation of all motor functions. This is a requirement under ISO 13482:2014 (Safety Standards for Personal Care Robots) [17].

5.3 Conclusion

DodgeBot has been designed with a strong focus on ethical responsibility and safety compliance, ensuring that the system enhances training experiences while preventing risks. The project complies with IEEE and ACM Codes of Ethics, prioritizing privacy protection and harm prevention. It aligns with industry standards, including ISO, ANSI, OSHA, and UL[18][19], ensuring regulatory compliance for autonomous robotics. To enhance safety, the system integrates both hardware and software safeguards, enforces strict operational constraints, and incorporates emergency stop mechanisms to prevent accidents and maintain secure operation. With these measures in place, DodgeBot will serve as an ethical, responsible, and safe autonomous training tool, demonstrating best practices in sports robotics and YOLO motion systems.

6 Vertification

6.1 Shooting System must launch dodgeballs at a controlled initial velocity of 2 m/s from a height of 1.2 meters, with the ability to dynamically adjust launch angles to ensure accurate targeting and realistic gameplay.

1. Setting up a fixed test platform in the test site, and the height of the launch port from the ground was precisely 1.2 meters by installing DodgeBot.
2. Measuring the initial speed of the dodgeball at the moment of launch by the velocity radar or high-speed camera. The experiment was repeated 10 times to confirm that the initial speed of the ball was controlled within the range of 2± 0.2m /s each time.
3. Test whether DodgeBot can adjust the launch Angle in real time based on the target location by having the tester move randomly in front of the system (at least 5 different locations, repeat the experiment 3 times per location). Record whether each actual ball hit is within 10 cm of the target position.

6.2Human Pose Estimation and Tracking System must successfully detect and track a player's movement with at least 80% accuracy, even under dynamic conditions, ensuring that the shooting mechanism adapts to real-time motion data.

1. Clearly delineate a 4m × 4m area within the camera field of view as the athletes' activity area.
2. The tester randomly performed movements of different speeds and trajectories (including straight lines, curves, and random movements) in the area, testing a total of 50 motion paths.
3. Each movement path is recorded as an independent video file, which uses YOLO to detect the athlete's position in real time and record the position data identified by the system.
4. Compare the deviation between the YOLO recognition position and the real position (measured by a manual marker or a high-precision motion capture system). If the error is less than 20 cm, the accuracy of 50 tests is counted to determine whether the overall accuracy is 80% or higher.

6.3 Dodging System must execute quick, controlled movements within 200-300 milliseconds in response to an incoming projectile, utilizing servo motors and YOLO (You Only Look Once) algorithms to enable real-time evasive maneuvers.

1. In a controlled environment, dodgeballs were fired at DodgeBot using another device or a human at a steady rate (approximately 2m/s) for a total of 20 tests.
2. High-speed cameras were used to record the experiment process, accurately recording the reaction time between the DodgeBot entering the recognition range (i.e. the first detection of the ball by the system) and the start of the dodgebot action (the start of the servo motor).
3. Verify that the recorded reaction times are all within 200-300 ms, and calculate the average and maximum values of 20 experiments to ensure that the requirements are met.
4. Record whether the ball is successfully evaded after each evasive action (no physical collision occurs) as an aid to verify the effectiveness of the evasive action.

7 Visual Aid

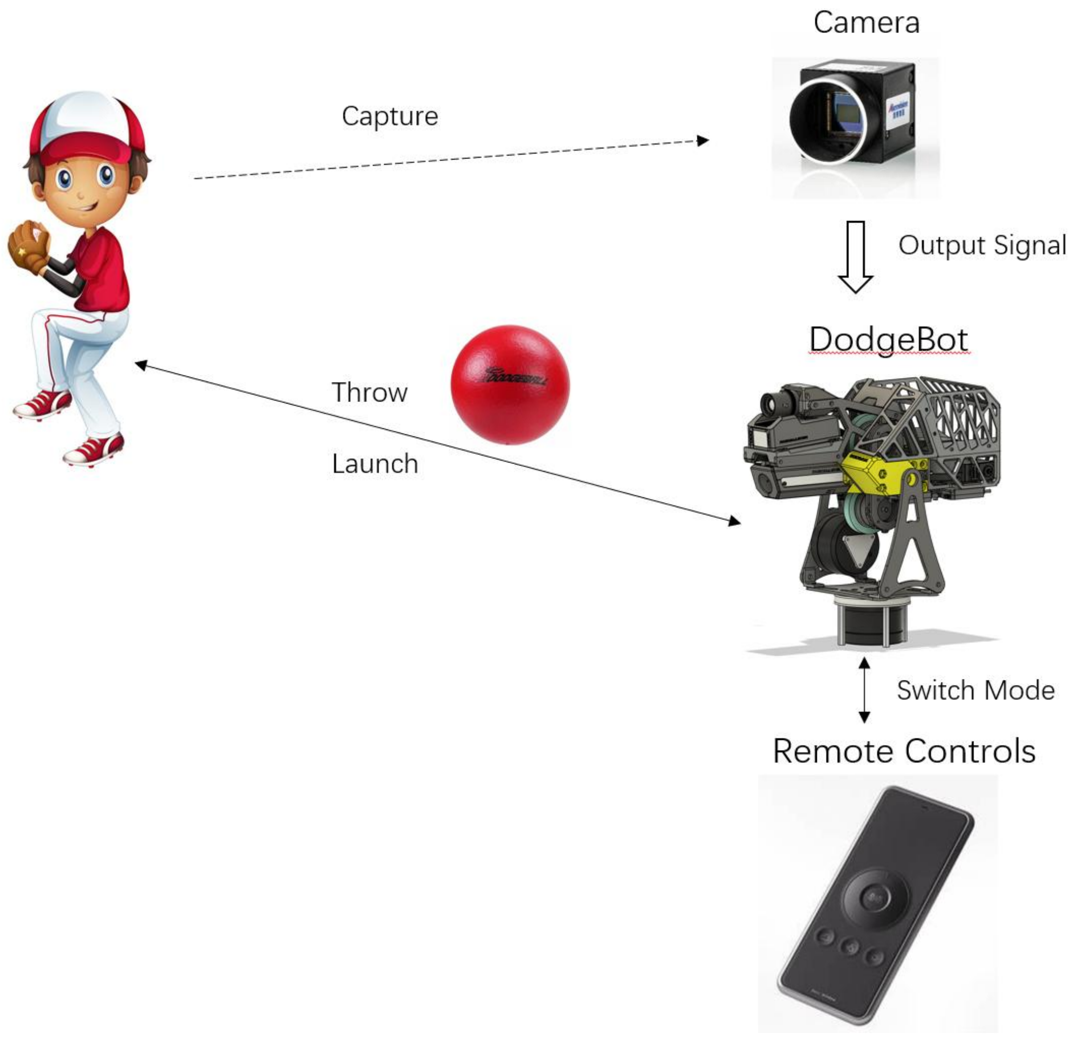

Figure 2. Sample visual aid for Dodgebot system

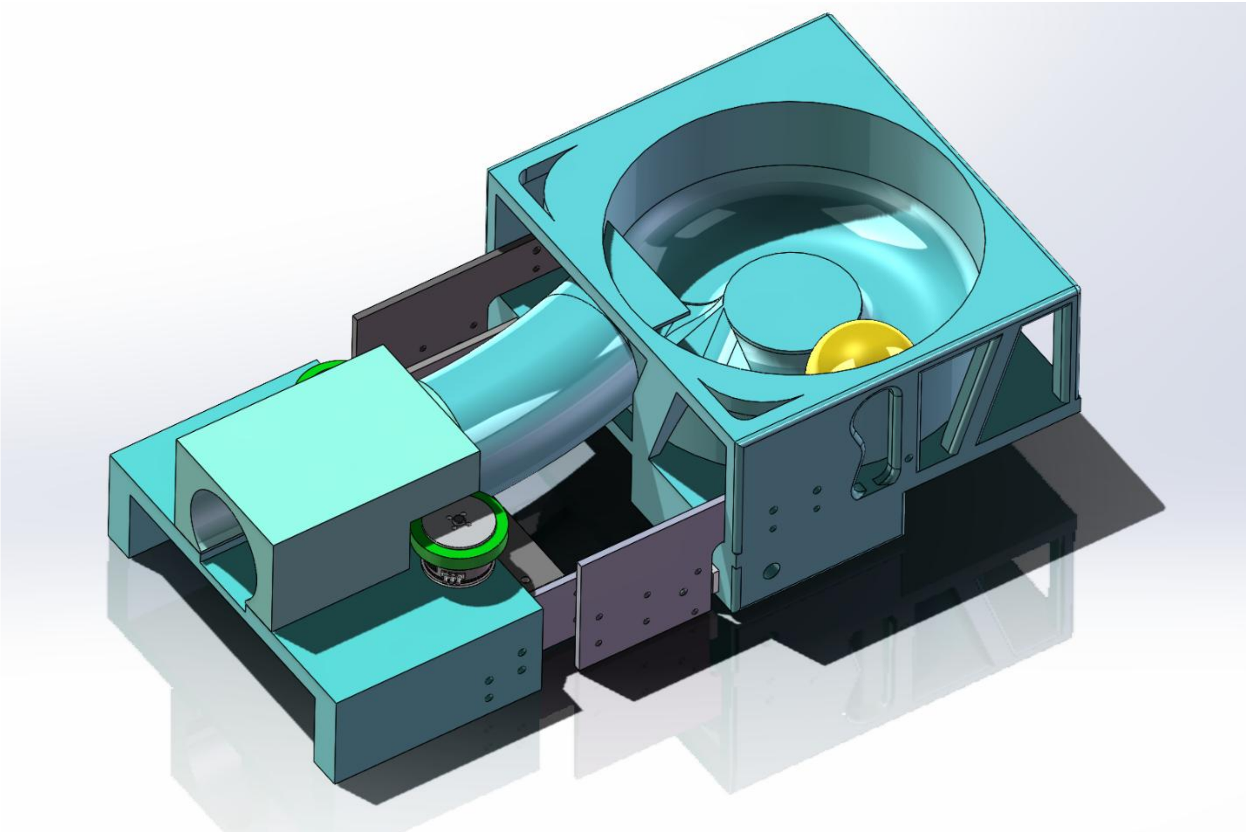

Figure 3. Dodgeball launcher

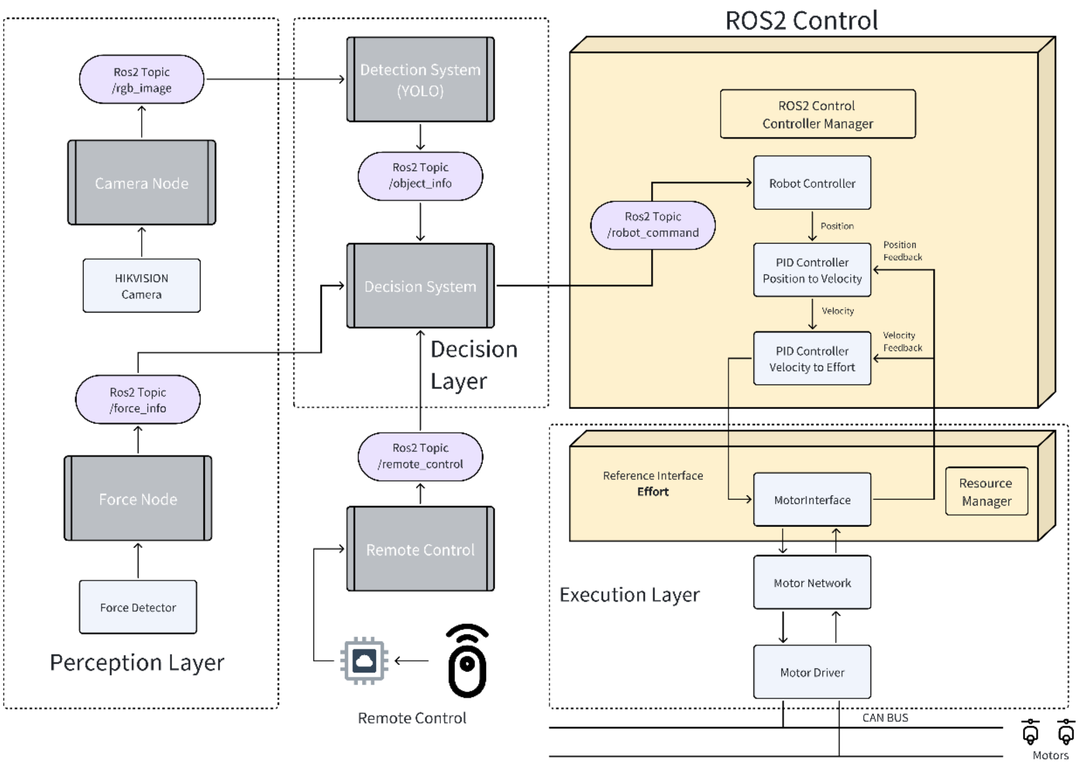

Figure 4. Dodgebot Software Design Diagram

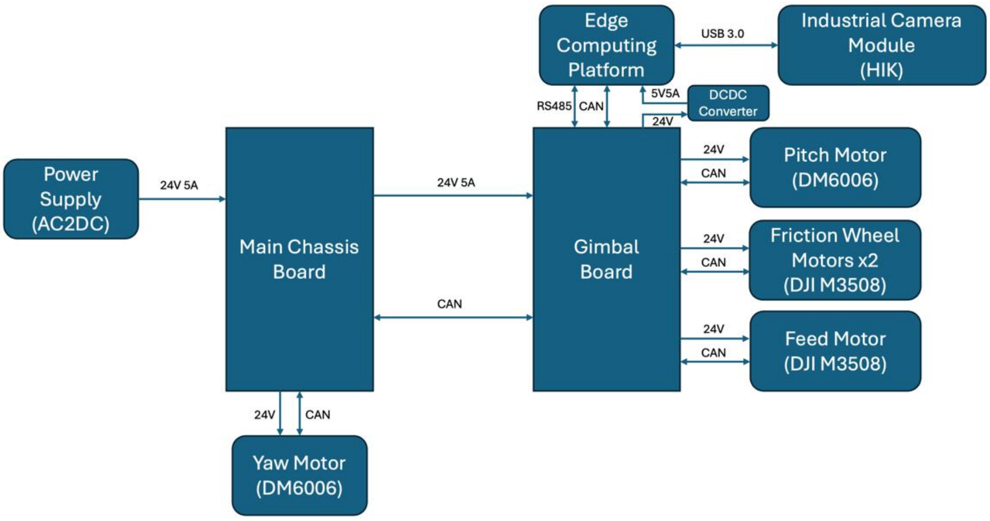

Figure 5. Dodgebot Electrical System Flow Diagram

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