ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Autonomous Lawn Patrol Robot for Stray Cat Deterrence

Team #13

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1 Introduction

1.1 Problem Statement

In many residential neighborhoods, especially in suburban areas in the United States, houses are often surrounded by open lawn spaces. Stray or feral cats may frequently enter these private areas, which can lead to hygiene concerns, property maintenance issues, and disturbance to residents.

Existing solutions for preventing animals from entering private yards mainly rely on manual intervention, physical barriers, or simple deterrent devices. These approaches are often inconvenient, inconsistent, or ineffective over long-term use. Therefore, there is a need for a more automated and intelligent system that can monitor outdoor spaces and safely deter unwanted animals.

With the advancement of mobile robotics and vision-based sensing technologies, an autonomous patrol robot provides a promising approach to continuously monitor the environment and respond to detected targets.

1.2 Proposed Solution and Visual Aid

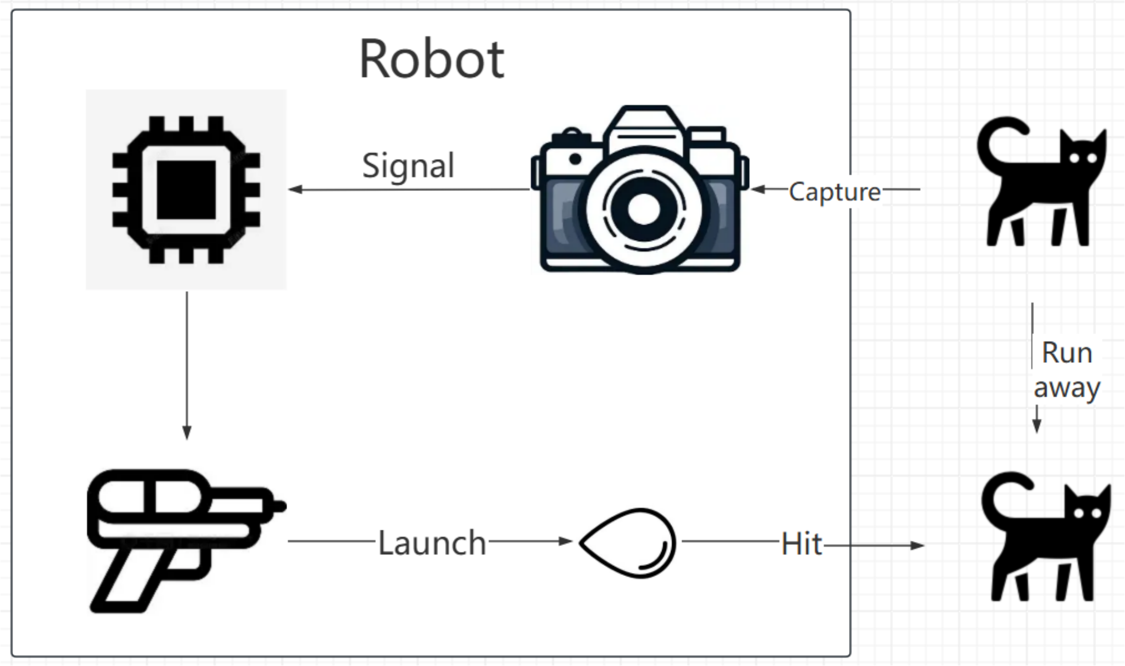


Figure 1: Visual aid of the proposed autonomous cat deterrence robot system.

The proposed solution is an autonomous mobile robot designed to patrol residential lawn areas and deter stray cats. The robot will move within a predefined region using a four-wheel differential-drive chassis. A camera mounted on a servo-driven gimbal will be used to detect and track cat targets through a vision-based recognition system.

When a target is detected and confirmed within an appropriate range and direction, a targeted water jet deterrence mechanism will be activated to safely drive the animal away. The robot's behavior will be coordinated using a finite state machine that manages transitions between patrol, target tracking, and deterrence modes.

Although the intended application scenario is outdoor lawn monitoring, prototype testing and functional validation will be conducted in controlled indoor environments such as tabletop setups due to practical constraints.

1.3 High-level Requirements

The autonomous cat deterrence robot system shall meet the following requirements:

(1) Target Detection Requirement:

- Detect a cat or cat-sized target within a distance range of **0.5–3 m** under normal outdoor daylight conditions.
- Achieve a target detection success rate of at least **90%** in repeated tests within the operating area.

(2) Autonomous Navigation Requirement:

- Autonomously patrol a predefined outdoor area of approximately **50 m**^{2}.
- Complete one patrol cycle of the predefined area within **10 minutes** under normal operating conditions.

(3) Deterrence Requirement:

- Activate the water-spray deterrence mechanism only when a valid target is within the effective operating range of **0.5–2 m**.
- Provide sufficient spray response to drive the target away from the protected area without causing physical harm.

(4) Safety and System Reliability:

- Maintain stable operation of the sensing, control, drive, and actuation modules during continuous prototype testing.
- The robot operates at a safe movement speed (maximum moving speed should be less than 0.5 m/s) and with a non-harmful spray intensity suitable for animal deterrence (water pressure should be under 100 kPa).

2 Design

2.1 Block Diagram and Physical Design

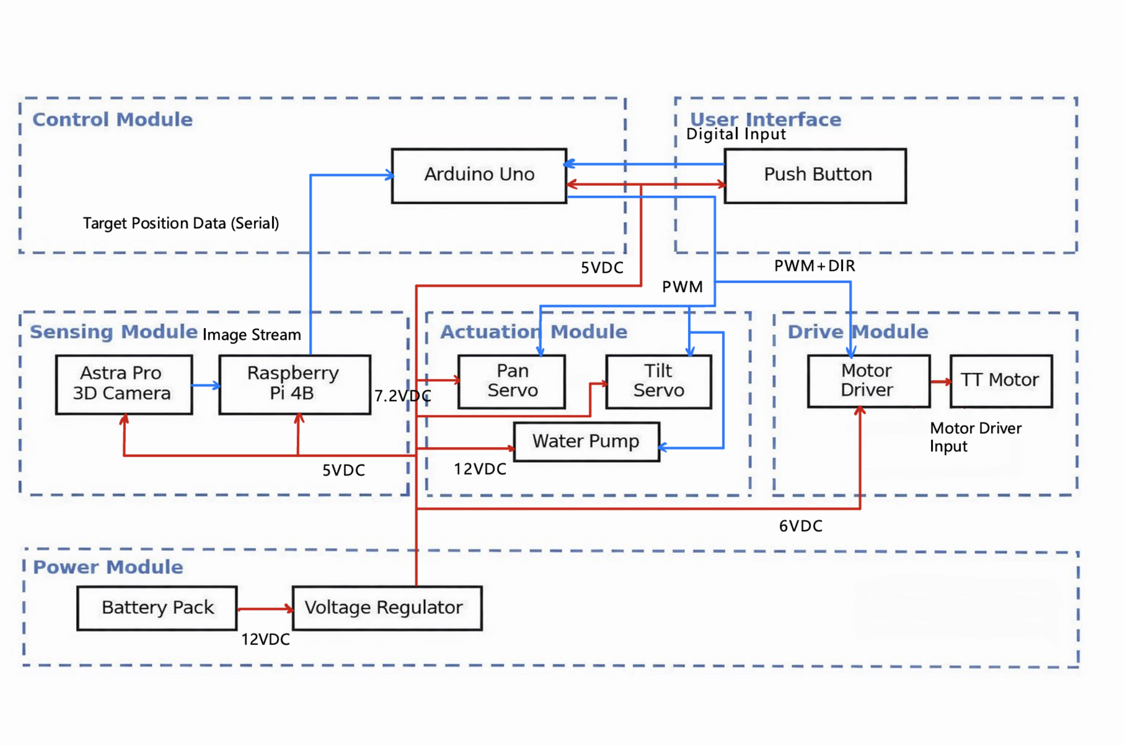


Figure 2: Block Diagram

The overall system is organized into five functional modules: sensing, control, actuation, drive, and power, together with a simple user interface. The sensing module consists of the Astra Pro 3D Camera and the Raspberry Pi 4B. The camera captures image and depth information, while the Raspberry Pi performs target perception and generates target position data. This processed target information is then transmitted to the Arduino Uno in the control module through serial communication.

The Arduino Uno serves as the central low-level controller of the robot. It receives target position data from the Raspberry Pi and digital input from the push button in the user interface module, and then generates the corresponding actuator commands. For the actuation module, the Arduino outputs PWM control signals to the pan servo, tilt servo, and water pump control path so that the camera–nozzle assembly can be oriented toward the target and the deterrence spray can be activated when needed. For the drive module, the Arduino outputs motor control signals to the motor driver, which in turn drives the TT motors to move the robot platform.

The power module distributes energy from the battery pack to the different subsystems through voltage regulation. Based on the current design, the regulator provides different voltage levels to match subsystem requirements, including 5 V for the sensing electronics and controller, approximately 6 V for the drive subsystem, and 12 V for the water pump. In this way, the block diagram shows both the data flow and the power flow of the system. The design separates high-level perception on the Raspberry Pi from low-level hardware control on the Arduino, which reduces control complexity and improves modular integration of the full robot system.

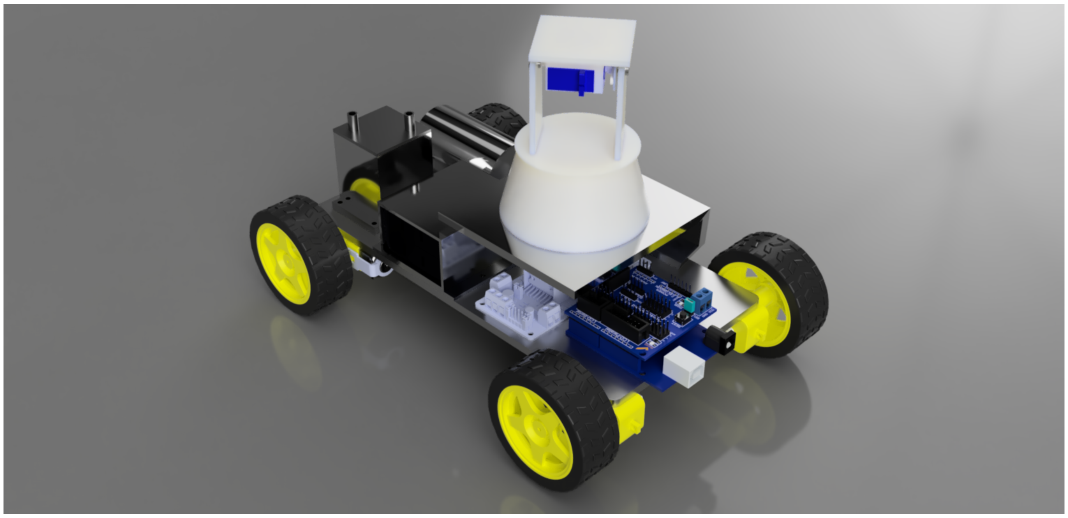


Figure 3: CAD model of the autonomous cat deterrence robot prototype.

2.2 Sensing System

2.2.1 Function and Components

The sensing system is responsible for perceiving the environment, detecting cat-like targets, and providing target position information to the control module. It consists of an Astra Pro 3D camera and a Raspberry Pi 4B single-board computer.

The Astra Pro camera captures both RGB image and depth data simultaneously. It operates at 5V DC supplied by the power module. The camera's depth measurement range is 0.6m–8m which covers the required detection range of 0.5m–3m.

The Raspberry Pi 4B receives the image and depth data from the camera via USB. It runs a YOLO-based object detection algorithm to identify cat targets. Once a target is detected and verified by focusing over 1 second, the Raspberry Pi computes the target's position relative to the control system through serial communication.

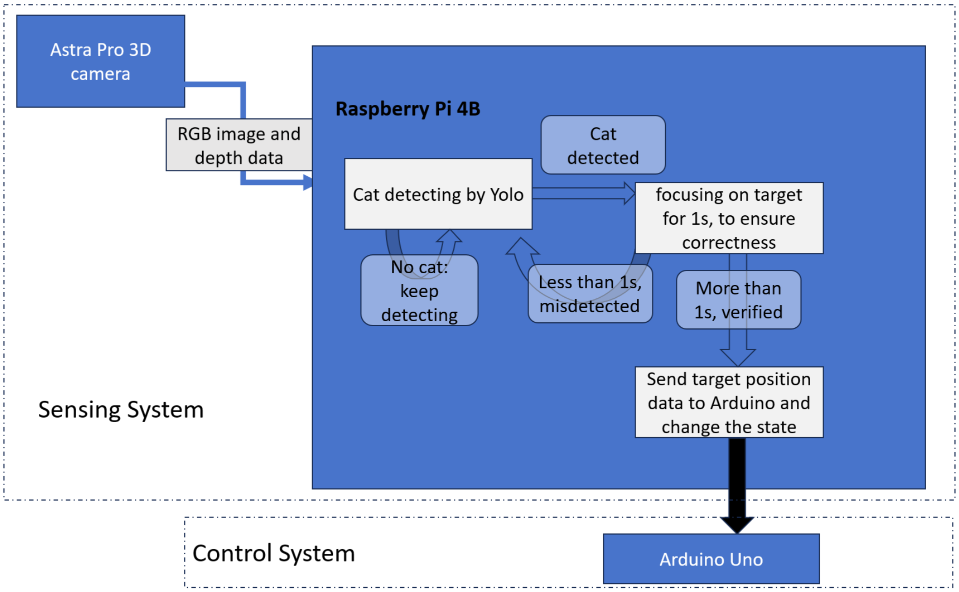


Figure 4: The block diagram of the sensing system.

2.2.2 Interactions with Other Subsystems

- **To Control System**: The Raspberry Pi sends target position data (e.g., detection flag, pan angle, tilt angle, distance) to the Arduino Uno via UART. This data serves as the input for the finite state machine and the gimbal aiming.
- **From the Power System**: Both the Astra Pro camera and the Raspberry Pi receive 5V DC from the power module.

2.2.3 Hardware Requirement

To catch the target continuously, the camera should provide high frame rate data immediately.

Requirement	**Verification**
1.The camera shall provide RGB and depth data at a minimum frame rate of at least 15 fps.	1.Run a capture script on the Raspberry Pi to log frame timestamps. Calculate average frame rate over 1000 frames. Frame rate shall be over 15 fps.
2.The Raspberry Pi shall complete one detection and position calculation cycle within 0.5 seconds.	2.Measure time from image capture to UART data output using logic analyzer or timestamped logging. Average latency should be under 0.5 s.

2.2.4 Target Detection

The YOLO model running on the Raspberry Pi performs real-time inference on the RGB images to detect the presence of cat-like targets. The detection output includes the bounding box coordinates and confidence score. The system considers a detection valid only when the confidence exceeds a preset threshold (e.g., 0.5).

Requirement	**Verification**
1.The vision system shall detect a cat-sized target at distances from 0.5m to 3.0m under indoor or shaded outdoor lighting conditions with a success rate of at least 90%.	1.Place a cat-sized test target (e.g., stuffed animal) at distances 0.5m, 1.0m, 2.0m, and 3.0m. Run detection for 50 trials per distance under specified lighting. Record success rate.
2.The false positive rate shall not exceed 10% when no cat is present.	2.Run the detection system for 5 minutes in an environment with no cat but with other common objects. Count the number of false detections.

2.2.5 Distance Measurement

The depth data provided by the Astra Pro camera is directly used to measure the target distance. The system reads the depth value at the center of the locked target's bounding box as the target distance. If the depth data in that region is invalid (e.g., out of range or too noisy), the system uses the nearest valid depth value or temporarily holds the last valid distance.

Requirement	**Verification**
1.The depth measurement accuracy shall be within ±10% for targets.	1.Compare depth readings from the Astra Pro with ground-truth distances measured by a tape measure at distances 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m. Compute error at each distance.
2.The distance output update rate shall be at least 10 Hz.	2.Log the timestamps of consecutive distance outputs from the Raspberry Pi. The interval between outputs shall not exceed 100 ms over 100 consecutive measurements.

2.3 Control System

The control system coordinates all subsystems and converts sensing results into real-time control actions. A distributed architecture is adopted, where the Raspberry Pi performs high-level vision processing, and the Arduino Uno handles real-time control and decision making.

The Raspberry Pi processes image data from the camera and transmits target detection information to the Arduino via serial communication. The Arduino interprets this information and determines system behavior using a finite state machine (FSM).

As shown in Fig. 5, the system integrates sensing, control, and actuation modules, while the FSM defines system behavior.

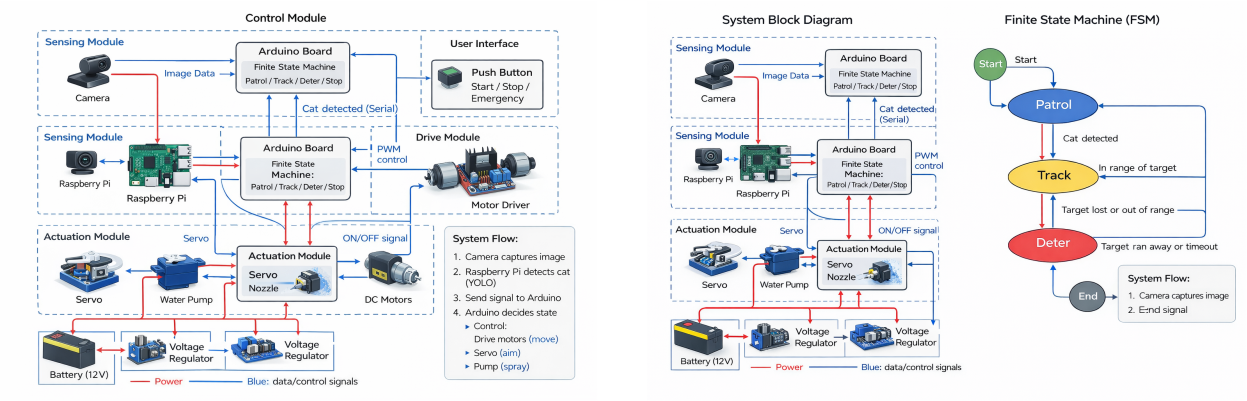


Figure 5: Control system architecture and finite state machine

2.3.1 FSM State Transition

The system behavior is governed by four states: Patrol, Track, Deter, and Stop. Correct state transitions are critical for proper system operation.

Requirement	**Verification**
The control system shall correctly transition between Patrol, Track, Deter, and Stop states based on sensing input and user commands without incorrect or skipped transitions.	**Equipment:** Raspberry Pi, Arduino Uno, serial monitor, push button. **Procedure:** Upload FSM program. Simulate target detection, target loss, and emergency stop. Observe transitions via serial monitor. Repeat for five cycles. **Verification criterion:** All transitions shall follow FSM logic with no incorrect states. **Results:** Record observed transitions in a table.

2.3.2 Control Output

The Arduino generates control signals for motors, servos, and the water pump based on FSM states.

Requirement	Verification
The control system shall generate correct PWM and digital output signals corresponding to each FSM state.	**Equipment:** Arduino Uno, motor driver, servos, water pump circuit, oscilloscope or LEDs. **Procedure:** Run system in each state. Measure output signals and observe actuator behavior. **Verification criterion:** Patrol → motors active, pump OFF; Track → motors + servo active; Deter → pump ON; Stop → all OFF. **Results:** Record signal measurements and observed outputs.

2.3.3 Control Response Time

The system must respond quickly to detection inputs.

Requirement	Verification
The control system shall respond to detection input and generate actuator commands within 0.5 s.	**Equipment:** Raspberry Pi, Arduino, high-speed camera or timestamp logging. **Procedure:** Send detection signal and measure delay to actuator response. Perform 10 trials. **Verification criterion:** Average response time $<$ 0.5 s; no trial $>$ 0.7 s. **Results:** Record response time for each trial.

2.3.4 Communication Reliability

Reliable communication between Raspberry Pi and Arduino is required.

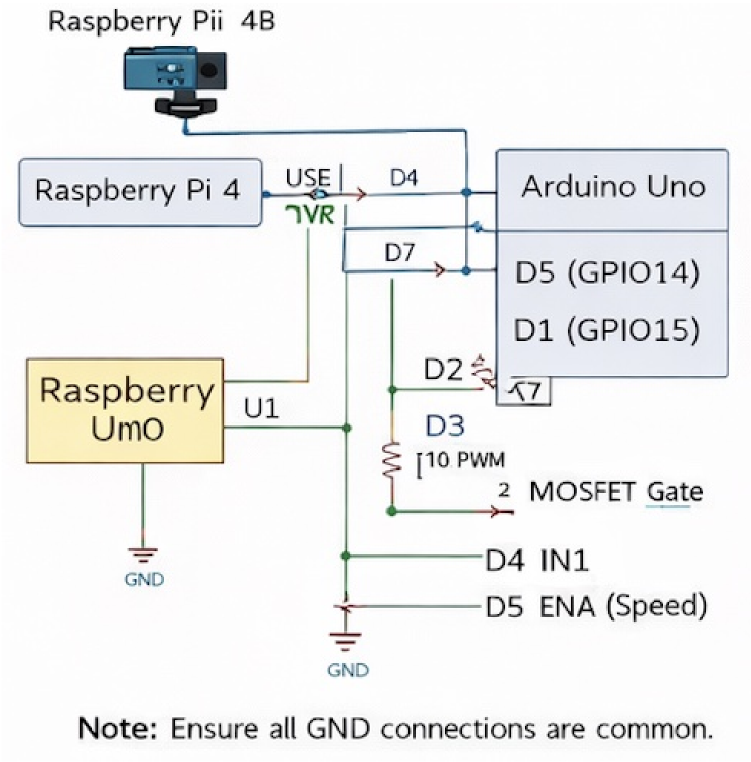
Requirement	Verification
The control system shall correctly receive serial data without loss or corruption during operation.	**Equipment:** Raspberry Pi, Arduino, serial monitor. **Procedure:** Continuously send data for 5 minutes and compare transmitted vs received signals. **Verification criterion:** No data loss or corruption shall occur. **Results:** Record transmission success rate.

2.3.5 Emergency Stop

The system must safely stop all operations when required.

Requirement	**Verification**
The control system shall immediately enter Stop state and disable all outputs when the emergency button is pressed.	**Equipment:** Arduino Uno, push button, full system setup. **Procedure:** Operate system in different states and press button. Observe system behavior. **Verification criterion:** System enters Stop within 0.2 s and disables all actuators. **Results:** Record response time and behavior.

2.4 Schematics



Note: Ensure all GND connections are common.

Figure 6: Power Supply and Voltage Regulation Circuit.

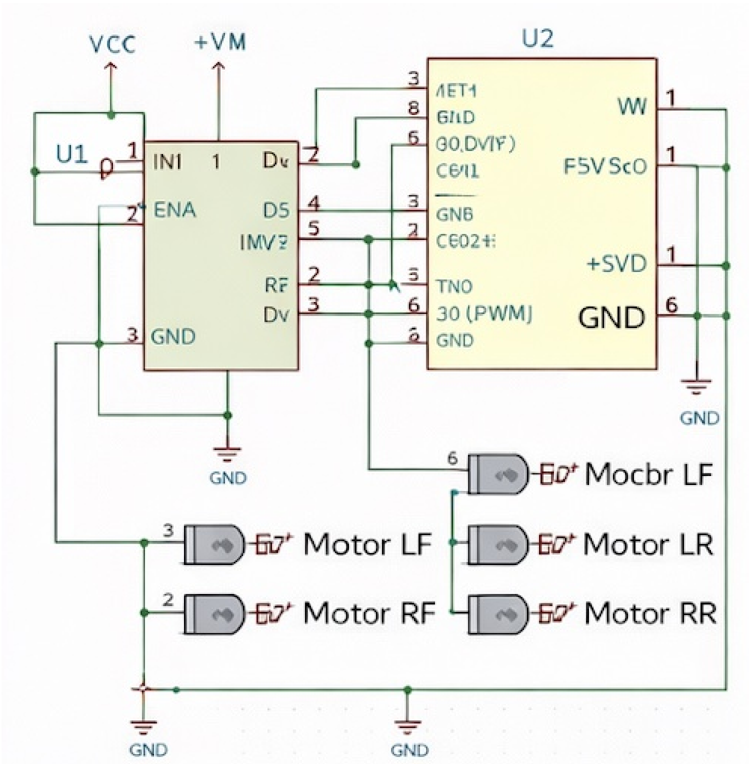


Figure 7: Arduino Actuator Control Wiring.

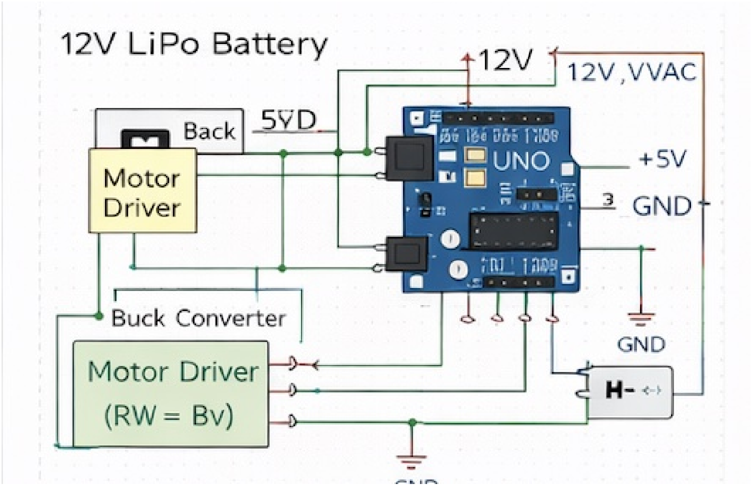


Figure 8: Astra Pro–Raspberry Pi Sensor Connection.

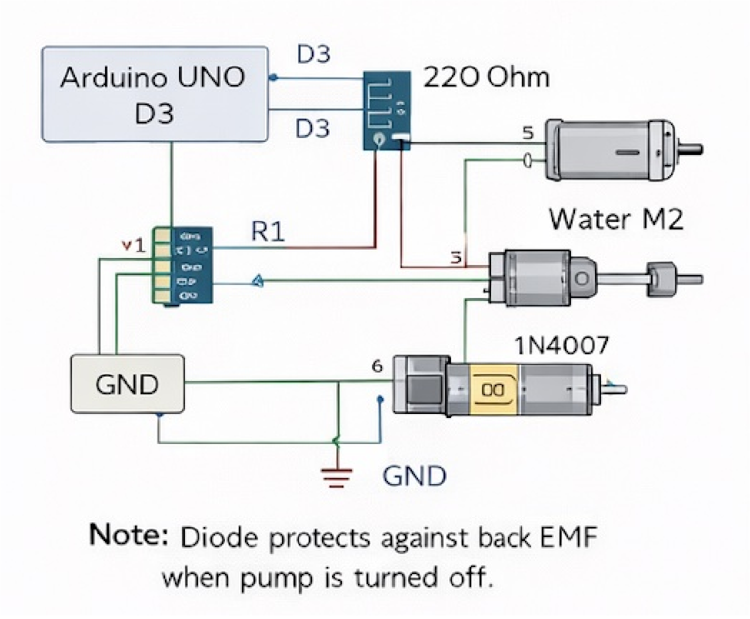


Figure 9: Complete system interconnection diagram.

2.5 Actuation System

The actuation system is responsible for converting digital control commands into physical deterrence actions. In our design, this subsystem consists of a servo-driven gimbal for directional aiming and a DC water pump for spray output. Together, these components enable the robot to orient the camera–nozzle assembly toward the target and deliver a controlled water spray response.

2.5.1 Pan Axis

The pan axis provides horizontal aiming capability for the robot. It is driven by a 360° MG996R servo and is designed to give the camera–nozzle assembly wide horizontal coverage during patrol and target tracking. Since the robot is expected to respond to targets approaching from different directions in a small outdoor operating area, sufficient pan coverage is necessary to avoid requiring excessive chassis rotation for every aiming action. In addition, the pan axis must move without cable entanglement, structural collision, or obvious blockage.

Requirement	Verification
The pan axis shall rotate the camera–nozzle assembly through at least 300° of horizontal coverage without mechanical interference or cable blockage.	**Equipment:** protractor or printed angle scale, Arduino controller, assembled gimbal. **Procedure:** Mount the gimbal on a rigid test stand and define a reference direction as 0°. Command the pan servo through its full intended range in steps of approximately 30°. Measure the nozzle direction at each step and inspect the motion for collision, cable entanglement, or mechanical blockage. **Verification criterion:** The measured total horizontal coverage shall be at least 300°, and no motion blockage or structural interference shall occur during the test. **Results:** Record the measured angle range in a table and provide photos or video of the sweep.

2.5.2 Tilt Axis

The tilt axis provides vertical adjustment of the nozzle and camera. It is driven by a second MG996R servo and is designed to operate over a range from approximately 0° to 45°. This range is sufficient for short-range target aiming in the intended prototype environment. Since the camera and nozzle are mounted together and remain fixed relative to each other, reliable tilt positioning directly affects whether the spray direction follows the sensed target location.

Requirement	Verification
The tilt axis shall adjust the nozzle elevation from 0° to at least 45°, with angle error no greater than $\pm 5^\circ$ at commanded setpoints.	**Equipment:** protractor or digital angle gauge, Arduino controller, assembled gimbal. **Procedure:** Fix the gimbal on a test stand and command the tilt servo to 0°, 15°, 30°, and 45°. Measure the actual nozzle elevation at each setpoint and repeat the measurement three times. **Verification criterion:** The mechanism shall reach at least 45°, and the measured angle at each setpoint shall remain within $\pm 5^\circ$ of the commanded angle. **Results:** Record commanded angle, measured angle, and error in a table.

2.5.3 Gimbal Position Stability

Because the actuation subsystem uses open-loop servo positioning, the mechanical stability of the gimbal is important. Excessive backlash, vibration, looseness, or mounting flexibility would reduce aiming consistency and make the spray direction less repeatable. Therefore, the gimbal must maintain acceptable positioning accuracy after repeated motion cycles rather than only in a single demonstration.

Requirement	Verification
After 20 repeated pan–tilt cycles, the final aiming direction of the camera–nozzle assembly shall remain repeatable within ±5° in both axes.	**Equipment:** protractor or angle gauge, Arduino controller, assembled gimbal. **Procedure:** Define one test cycle as pan motion across the intended operating range plus tilt motion from $0°$ to $45°$ and back. Run 20 continuous cycles. After the final cycle, command the gimbal to return to a reference pose and measure the final pan and tilt angles. Repeat the full test three times. **Verification criterion:** The final measured pose after each trial shall remain within $\pm 5°$ of the reference pose, and no visible loosening or severe oscillation shall occur. **Results:** Record final pose error for each trial and note any visible backlash or vibration.

2.5.4 Water Pump and Nozzle Output

The water pump generates the physical deterrence output of the robot. In the current design, a 12 V DC water pump delivers water from the onboard reservoir through tubing to a nozzle with a 6 mm inlet and a 1.5 mm outlet. This configuration is intended to produce a directed spray with sufficient range for short-range deterrence. At the current stage, the desired output is a mist-like spray, although the final spray pattern will depend on the actual interaction among the pump, tubing, and nozzle after assembly.

Requirement	Verification
The pump–nozzle assembly shall produce a directed spray that reaches an effective distance of at least 1.5 m under nominal operating conditions.	**Equipment:** onboard reservoir, 12 V pump, 6 mm to 1.5 mm nozzle, tape measure, floor distance markers, target board or collection surface. **Procedure:** Fill the reservoir and mount the nozzle in the intended operating configuration. Place distance markers every 0.5 m from the nozzle exit. Activate the pump for 3 s per trial and repeat five trials. Observe the farthest distance at which the spray remains visibly directed and reaches the test zone. **Verification criterion:** In at least 4 out of 5 trials, the spray shall visibly and directionally reach the 1.5 m test zone rather than only drifting or dripping short of the mark. **Results:** Record the farthest clearly reached distance in each trial and provide photos or video.

2.5.5 Water Path Integrity

In addition to range, the water path must remain mechanically and functionally reliable during operation. Leakage at tubing joints, intermittent flow, or unstable output would reduce deterrence performance and could also interfere with nearby electronics. Therefore, the assembled pump, tubing, and nozzle must maintain continuous output during a short sustained spray test.

Requirement	Verification
The pump–nozzle assembly shall produce a stable deterrence output for a continuous 30 s spray test without leakage at tubing joints or interruption of flow.	**Equipment:** fully assembled water path, reservoir, absorbent paper or dry inspection surface, stopwatch. **Procedure:** Fill the reservoir and run the pump continuously for 30 s while the robot remains stationary. Inspect all tubing connections, the pump outlet, and the nozzle mount during and after the test. **Verification criterion:** The spray shall remain continuous throughout the 30 s interval, and no visible leakage shall appear at tubing joints or connectors. **Results:** Record pass/fail observations and note any leakage location.

2.5.6 Actuation Response Time

The actuation subsystem must respond quickly enough for practical target deterrence. Once the control subsystem issues a valid command, the system should begin either gimbal motion or pump activation without excessive delay. If the response is too slow, the target may leave the effective range before the deterrence action is delivered.

Requirement	Verification
After a valid control command is issued, the actuation subsystem shall begin either gimbal motion or pump activation within 0.5 s.	**Equipment:** Arduino controller, test command program, smartphone camera or high-frame-rate video, stopwatch or video frame analysis. **Procedure:** Issue a command from the controller to either move the gimbal or activate the pump while recording the event on video. Measure the time from command issuance to the first visible actuator response. Perform at least 10 trials for servo actuation and 10 trials for pump actuation. **Verification criterion:** The average response time for each actuator type shall be less than 0.5 s, and no individual trial shall exceed 0.7 s. **Results:** Summarize the measured response times in a table.

2.6 Drive System

The drive system is responsible for providing the robot with ground mobility, including forward motion, turning, and basic patrol movement within the predefined operating area. In our design, this subsystem consists of four TT motors and commercial dual-channel DC motor driver modules. Together, these components convert controller commands into wheel motion and determine whether the robot can move stably, carry the full prototype load, and perform reliable directional changes during operation.

2.6.1 TT Motor Selection

The current chassis design uses four TT motors to drive a conventional four-wheel mobile platform. Each motor has a rated voltage of 6 V, a recommended operating range of 3–9 V, and a rated current of approximately 200 mA. These motors are selected because they are lightweight, inexpensive, and sufficiently capable for a compact student prototype. Since the robot is not intended to move at high speed, the drive subsystem prioritizes controllability, stable motion, and reliable turning performance rather than maximum velocity.

Requirement	Verification
The drive subsystem shall operate the TT motors within the intended motor supply range of 3–9 V during nominal operation.	**Equipment:** multimeter, regulated supply or onboard battery-regulator system, assembled drive subsystem. **Procedure:** Power the robot under nominal operating conditions and measure the motor supply voltage while the robot is stationary, during startup, and during forward motion under load. Repeat the measurement for representative operating cases. **Verification criterion:** The measured motor supply voltage shall remain within 3–9 V in all nominal test cases. **Results:** Record the measured voltages in a table for each operating condition.

2.6.2 Motor Driver Interface

The TT motors are actuated through commercial dual-channel DC motor driver modules provided by the supplier. These driver modules receive low-power logic commands from the control subsystem and provide the required output power to the motors. Since the robot uses four TT motors, multiple driver channels are used so that all four wheels can be driven appropriately. The motor drivers therefore form the electrical interface between the controller and the drive hardware.

Requirement	**Verification**
The motor driver modules shall provide correct forward and reverse direction control to all four TT motors without channel failure.	**Equipment:** assembled drive subsystem, Arduino controller, test command program, marked motor channels. **Procedure:** Lift the robot so that all wheels are off the ground. Command each motor channel individually in both forward and reverse directions. Observe the wheel rotation direction and confirm that each channel responds correctly to its command. **Verification criterion:** All four motors shall rotate in the intended direction for both forward and reverse commands, and no motor channel shall fail to respond. **Results:** Record pass/fail results for each motor channel in a table and provide video if needed.

2.6.3 Straight-Line Motion

Because the robot performs patrol motion in a predefined area, straight-line motion is an important drive capability. In the current prototype, the drive subsystem is operated in open loop without encoder feedback. As a result, the quality of straight-line travel depends on motor consistency, chassis symmetry, wheel alignment, and driver stability. The robot is not expected to move with perfect precision, but it should maintain approximately straight motion under nominal conditions.

Requirement	**Verification**
When commanded to move forward on a flat surface, the robot shall travel 1.0 m with lateral deviation no greater than 0.20 m under nominal full-load conditions.	**Equipment:** flat test surface, tape measure, floor markers, fully assembled robot. **Procedure:** Mark a 1.0 m straight test path on the floor. Place the fully assembled robot at the start line and command it to move forward along the path. Measure the lateral offset between the robot's final position and the intended straight-line path. Repeat the test five times. **Verification criterion:** In at least 4 out of 5 trials, the lateral deviation at the end of the 1.0 m run shall not exceed 0.20 m. **Results:** Record the lateral deviation for each trial in a table and provide photos or video if needed.

2.6.4 Turning Capability

The robot must be able to change direction in order to patrol and reorient toward relevant areas of operation. Therefore, the drive subsystem must support controlled left and right turning rather than only forward motion. Since the platform is a standard four-wheel robot using TT motors, stable turning depends on correct motor direction control, sufficient traction, and consistent driver output.

Requirement	**Verification**
The drive subsystem shall allow the robot to complete repeatable left-turn and right-turn maneuvers without wheel lock, severe instability, or loss of control.	**Equipment:** flat test surface, floor markers, fully assembled robot, controller program. **Procedure:** Command the robot to perform left-turn and right-turn maneuvers from rest under nominal full-load conditions. Repeat each maneuver at least five times. Observe whether all required wheels respond properly and whether the robot completes each turn without becoming unstable or stuck. **Verification criterion:** The robot shall successfully complete both left-turn and right-turn maneuvers in at least 4 out of 5 trials for each direction, with no wheel lock or obvious loss of control. **Results:** Record pass/fail results for each trial and provide video documentation.

2.6.5 Load-Carrying Capability

The drive subsystem must move not only the empty chassis but also the complete prototype, including the battery, control hardware, sensing module, gimbal, pump, and other onboard components. Therefore, the motors and drivers must provide sufficient traction and torque for the robot to start from rest, move forward, and turn while carrying the full system load.

Requirement	**Verification**
The drive subsystem shall move the fully assembled robot from rest and sustain forward motion for at least 1.0 m without prolonged stalling under nominal load.	**Equipment:** fully assembled robot, flat test surface, tape measure. **Procedure:** Assemble the robot with all intended onboard components installed. Starting from rest, command the robot to move forward over a 1.0 m test distance. Repeat the test five times and observe whether the motors stall, hesitate excessively, or fail to sustain motion. **Verification criterion:** In at least 4 out of 5 trials, the robot shall start successfully from rest and complete the 1.0 m motion without prolonged stalling. **Results:** Record pass/fail results for each trial and note any startup or load-related issues.

2.6.6 Drive Stability Over Repeated Trials

Since the prototype will be tested repeatedly during integration and demonstration, the drive subsystem must remain stable over repeated runs. Loose wiring, intermittent driver failure, overheating, or unstable power delivery could cause performance degradation over time even if the robot works initially. Therefore, repeated operation is necessary to evaluate basic drive reliability.

Requirement	**Verification**
The drive subsystem shall maintain stable operation over 10 repeated movement cycles without intermittent motor-driver failure or obvious degradation in mobility.	**Equipment:** fully assembled robot, flat test surface, controller program. **Procedure:** Define one movement cycle as a forward motion test followed by a turning maneuver. Run 10 consecutive cycles under nominal full-load conditions. Observe the system for intermittent driver failure, loose wiring, abnormal motor behavior, or obvious reduction in mobility. **Verification criterion:** The robot shall complete all 10 cycles without intermittent channel failure, complete loss of motion, or obvious degradation that prevents continued operation. **Results:** Record observations for each cycle and summarize whether the subsystem remained stable throughout the test.

2.7 Tolerance Analysis

A critical function of the robot is the ability to spray water far enough to deter a stray cat from entering the protected area. This tolerance analysis evaluates whether the selected pump and nozzle configuration can provide sufficient spray range. The goal is not to predict the exact spray trajectory in all real conditions, but to verify that the subsystem is feasible and that moderate variation in pump performance will not prevent basic operation.

2.7.1 Theoretical Model

The water jet is approximated as a projectile leaving the nozzle with initial velocity v_0. For the maximum theoretical range, the launch angle is assumed to be 45°, so the projectile range can be written as

$$R = \frac{v_0^2}{g}$$

where R is the range and g is the gravitational acceleration.

The exit velocity is estimated from the pump pressure using Bernoulli's principle:

$$v_{0,\text{ideal}} = \sqrt{\frac{2P}{\rho}}$$

where P is the available pressure and ρ is the density of water.

Because the real system includes tubing losses, nozzle losses, and imperfect conversion from pressure to jet velocity, a loss coefficient η is introduced:

$$v_0 = \eta v_{0,\text{ideal}}$$

This provides a first-order engineering estimate of the achievable spray distance.

2.7.2 Assumed Parameters

- Pump rated head: $H = 5\ \text{m}$
- Pump flow rate: $Q = 1.2\text{–}1.5\ \text{L/min}$
- Nozzle geometry: $6\ \text{mm}$ inlet to $1.5\ \text{mm}$ outlet
- Water density: $\rho = 1000\ \text{kg/m}^3$
- Gravitational acceleration: $g = 9.81\ \text{m/s}^2$
- Nominal loss coefficient: $\eta = 0.7$
- Degraded-case loss coefficient: $\eta = 0.6$

The pump head is converted into pressure using

$$P = \rho g H$$

Thus,

$$P = 1000 \times 9.81 \times 5 = 49050\ \text{Pa} \approx 49.1\ \text{kPa}$$

2.7.3 Nominal Calculation

The ideal exit velocity is

$$v_{0,\text{ideal}} = \sqrt{\frac{2 \times 49050}{1000}} = \sqrt{98.1} \approx 9.90\ \text{m/s}$$

Applying the nominal loss coefficient:

$$v_0 = 0.7 \times 9.90 \approx 6.93\ \text{m/s}$$

The corresponding maximum theoretical range is

$$R = \frac{6.93^2}{9.81} = \frac{48.0}{9.81} \approx 4.89 \text{ m}$$

2.7.4 Degraded-Case Analysis

To account for performance variation, a degraded case is considered. In this case, the effective pressure is reduced by 20% due to voltage drop or pump inconsistency, and the loss coefficient is reduced to $\eta = 0.6$.

The degraded pressure is

$$P = 0.8 \times 49.1 \text{ kPa} \approx 39.2 \text{ kPa}$$

The degraded ideal velocity becomes

$$v_{0,\text{ideal}} = \sqrt{\frac{2 \times 39240}{1000}} = \sqrt{78.48} \approx 8.86 \text{ m/s}$$

Applying the degraded loss coefficient:

$$v_0 = 0.6 \times 8.86 \approx 5.32 \text{ m/s}$$

The corresponding range is

$$R = \frac{5.32^2}{9.81} = \frac{28.3}{9.81} \approx 2.88 \text{ m}$$

2.7.5 Discussion

The nominal estimate shows that the spray subsystem can theoretically reach approximately 4.9 m, while the degraded case still gives approximately 2.9 m. These values are above the minimum deterrence distance required for the project, indicating that the selected pump and nozzle combination is feasible.

It should be noted that this model is simplified. Real spray distance will be reduced by air drag, jet breakup, nozzle imperfections, and the fact that the water stream is not an ideal projectile. In practice, the effective horizontal deterrence distance will be shorter than the theoretical maximum range. However, the analysis shows that even with moderate performance degradation, the system still retains sufficient margin for prototype operation.

2.7.6 Conclusion

This analysis suggests that a water pump with a $5\ \mathrm{m}$ head and a $6\ \mathrm{mm}$-to-$1.5\ \mathrm{mm}$ nozzle can provide adequate spray performance for the deterrence function. Reasonable tolerances in pump output and flow losses do not make the subsystem infeasible, although final performance should be confirmed through physical testing and nozzle adjustment.

3 Cost

Part	Cost (rmb)
TT motor	40
Motor driver board	110
Rubber wheels	26
MG996R	33.22
Water pump	35
Nozzle	1.7
Raspberry Pi 4 Model B (8GB RAM)	699
Arduino Uno	40
Astra Pro 3D camera	85
Total cost	1069.92

4 Schedule

Week	**Jiawei Kong**	**Chentao Fang**	**Ronglong Liu**	**Yanchen Liu**
4/6	Finalize chassis layout and work with Ronglong on hardware architecture.	Finalize gimbal structure and servo layout.	Work with Jiawei on power, wiring, motor drive, and hardware integration.	Set up Raspberry Pi 4B, depth camera, and Arduino communication.
4/13	Assemble chassis and begin integrated hardware setup.	Build and test gimbal prototype with MG996R.	Complete basic circuit, power, and drive tests; start vision collaboration with Yanchen.	Implement basic sensing pipeline and start vision collaboration with Ronglong.
4/20	Refine chassis and support full hardware integration.	Integrate nozzle, tubing, and aiming mechanism.	Complete electrical integration; collaborate on robot vision and path planning.	Connect sensing, control, and path planning modules with hardware.
4/27	Complete prototype assembly and mobility testing.	Tune gimbal motion and spray direction.	Debug integrated hardware and vision system for stable operation.	Finish system integration and path-planning test for mock demo.
5/4	**Mock Demo:** Present a usable prototype with basic mobility, vision, aiming, and spraying functions.			
5/11	Improve chassis reliability and assist hardware optimization.	Improve gimbal stability and aiming accuracy.	Optimize power, wiring, and integrated control performance.	Improve robot vision, path planning, and response stability.
5/18	**Final Demo:** Present the improved system with refined functionality and better integration.			

5 Ethics and Safety

5.1 Ethics

Our project is designed as a mobile deterrence robot that uses water spray to drive stray cats away from restricted areas such as lawns or house entrances. Since the system interacts with animals and may operate in semi-public spaces, ethical considerations must be addressed carefully.

First, animal welfare is a primary concern. The purpose of this project is deterrence rather than harm. Humane deterrence methods such as motion-activated sprinklers are commonly recommended for discouraging unwanted cat presence, which supports the basic idea of using water spray as a non-lethal intervention [1]. Therefore, our design goal is to produce a short and limited spray response that is sufficient to interrupt behavior, rather than to injure or excessively frighten the animal.

Second, privacy should be considered because the robot uses a camera-based sensing system. According to IEEE materials on ethical issues in intelligent systems, surveillance, privacy, safety, and fairness are all important dimensions that should be evaluated in autonomous or semi-autonomous technologies [2], [3]. In our project, the camera and depth sensor are used only for real-time perception and control. We do not intend to perform identity recognition, store personal facial data, or use collected data beyond system operation and testing. This helps reduce unnecessary privacy risks.

Third, fairness and responsible deployment must also be considered. The system should respond only to relevant targets within the intended operating area and should avoid unnecessary activation caused by unrelated people, pets, or background motion. In addition, the robot is intended only as a practical deterrence tool for property protection and should not be used in ways that intentionally provoke, harass, or mistreat animals. Overall, the project should prioritize humane operation, limited data use, and responsible real-world deployment.

5.2 Safety

Safety is critical because the robot combines moving parts, electrical power, water delivery, and autonomous motion. Mechanical hazards must be controlled first. OSHA states that machine guarding should be provided to protect users from hazards created by rotating parts, points of operation, and other dangerous moving mechanisms [4], [5]. Therefore, all exposed rotating components, transmission parts, and pinch points in the drive and gimbal mechanisms should be shielded or positioned to reduce accidental contact during operation and testing.

Electrical safety is also important because the system contains pumps, wiring, motor drivers, and control boards operating near water. CDC safety guidance for water-related powered equipment emphasizes keeping electrical connections away from water runoff and standing water [6]. In our design, the battery, control boards, and wiring connections should be placed in protected locations, and the water tank, tubing, and nozzle should be isolated from sensitive electrical components as much as possible. During testing, the system should be operated on dry ground with careful inspection of tubing leakage and cable routing.

Operational safety must also be considered. The spray pressure and flow rate should remain within a mild range appropriate for deterrence, and the robot speed should remain low enough to avoid collisions with people, pets, or surrounding objects. Emergency stop control should be available during testing, and the robot should only be operated under supervision in controlled environments. By limiting spray intensity, shielding moving parts, isolating electronics from water, and enforcing supervised operation, the system can remain within an acceptable safety margin for prototype development and demonstration.

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