DEPARTMENT: Software Engineering

COURSE: SEN 4821 - Robotics Project

LEVEL: 400 Level

SEN 481 ROBOTICS PROJECT DOCUMENTATION

AUTONOMOUS WASTE COLLECTION ANT ROBOT

A Smart Hexapod Walking Robot with AI Vision

PROJECT TYPE:

Hexapod Walking Robot with AI Vision

APPLICATION:

Autonomous Waste Identification, Collection & Disposal

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PROJECT TEAM MEMBERS

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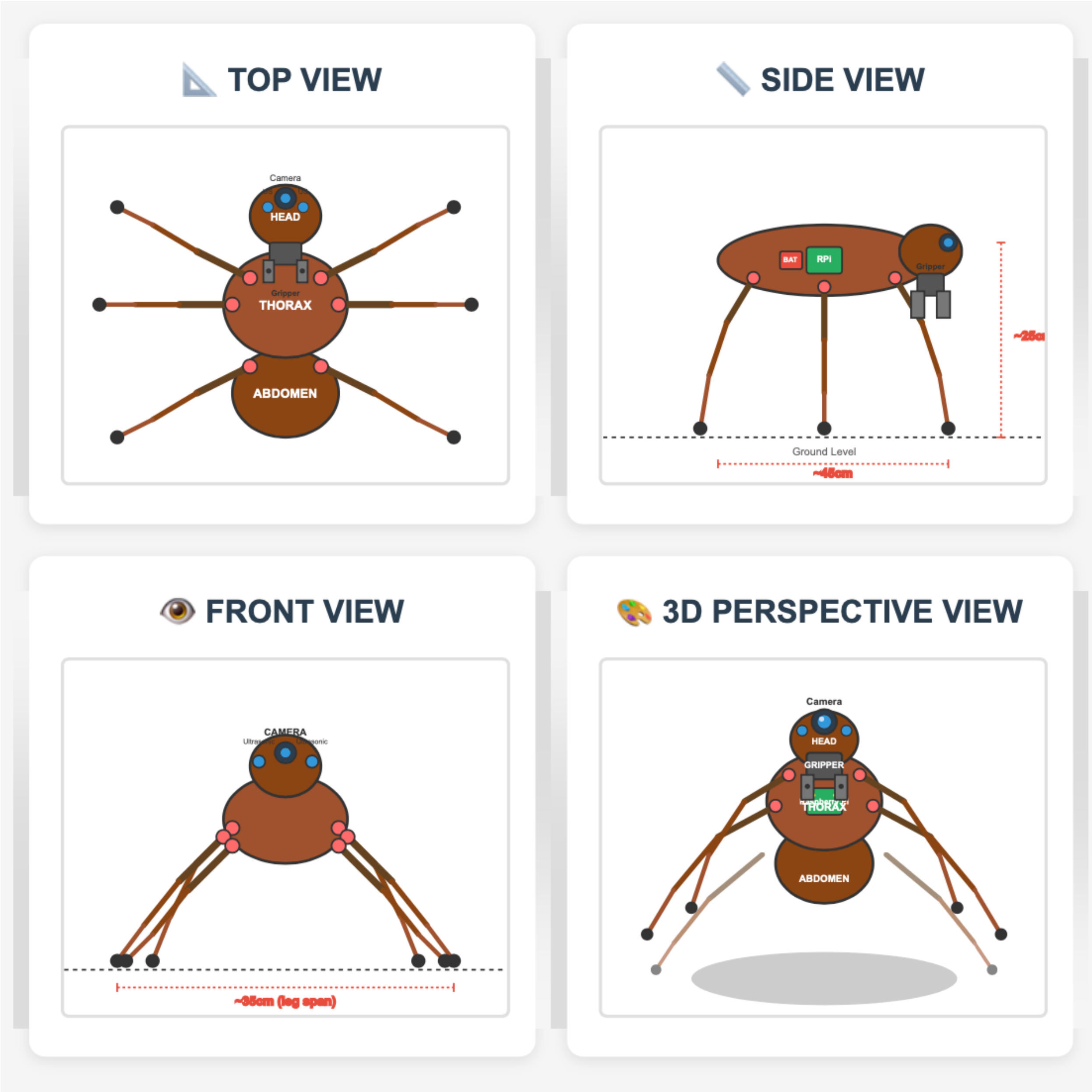
Robot Visual Design



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1. PROJECT OVERVIEW

1.1 Project Description

This project involves designing and building a hexapod (6-legged) ant-inspired robot capable of:

- **Autonomous navigation** using leg-based locomotion (no wheels)
- **Waste detection** using computer vision and AI
- **Object manipulation** through a gripper mechanism
- **Waste classification** (recyclable vs. non-recyclable)
- **Autonomous disposal** at designated collection points

1.2 Biomimetic Inspiration

The design mimics ant morphology and behavior:

- **Six-leg configuration** for stable terrain traversal
- **Segmented body** (head, thorax, abdomen)
- **Mandible-inspired gripper** for object manipulation
- **Antenna sensors** for obstacle detection

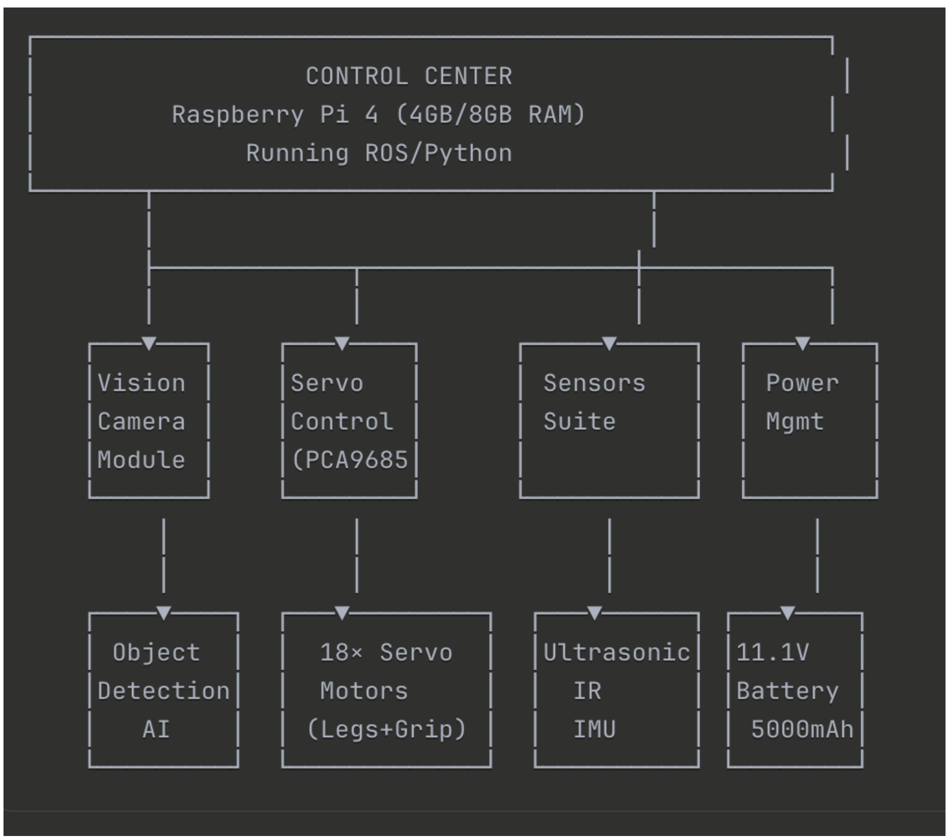
1.3 Key Specifications

- **Payload Capacity:** 0.5 - 1.0 kg
- **Walking Speed:** 0.1 - 0.3 m/s
- **Operating Time:** 45-60 minutes per charge

- **Detection Range:** 0.5 - 3 meters
- **Classification Accuracy:** >85% (target)
- **Dimensions:** 45cm (L) × 35cm (W) × 25cm (H)
- **Weight:** 2.5 - 3.5 kg
- **Degrees of Freedom:** 18 DOF (3 per leg × 6 legs)

2. SYSTEM ARCHITECTURE

2.1 System Block Diagram



2.2 Subsystem Overview

2.2.1 Locomotion System

- 18 servo motors (3 per leg × 6 legs)
- Tripod gait controller for stable walking
- Inverse kinematics for smooth leg movements

2.2.2 Vision & AI System

- Camera module for image acquisition
- CNN-based waste classification using YOLOv5
- Real-time object detection and distance estimation

2.2.3 Manipulation System

- 2-DOF gripper mechanism (base rotation + jaw open/close)
- Adjustable gripping force
- Object size adaptation (50mm - 150mm opening range)

2.2.4 Sensor Suite

- Obstacle detection using ultrasonic sensors
- Ground proximity sensors (IR)
- Body orientation tracking (IMU)

3. HARDWARE COMPONENTS SPECIFICATION

3.1 MAIN PROCESSING UNIT

Raspberry Pi 4 Model B

- **Model:** 4GB or 8GB RAM variant
- **Processor:** Broadcom BCM2711, Quad-core Cortex-A72 @ 1.5GHz
- **Storage:** 64GB MicroSD Card (Class 10, UHS-I)
- **Operating System:** Raspberry Pi OS (64-bit)
- **Purpose:** Main controller, AI inference, sensor fusion
- **Quantity:** 1
- **Datasheet:** raspberrypi.com/documentation

Alternative: NVIDIA Jetson Nano 4GB (better GPU for AI processing)

3.2 SERVO MOTORS (LOCOMOTION)

MG996R Metal Gear Servo

- **Torque:** 11 kg·cm @ 4.8V, 13 kg·cm @ 6V
- **Speed:** 0.17 sec/60° @ 4.8V
- **Operating Voltage:** 4.8V - 7.2V

- **Weight:** 55g
- **Gear Type:** Metal gears (high durability)
- **Control:** PWM (50Hz, 1000-2000μs pulse width)
- **Rotation:** 180° (120° usable range)
- **Current Draw:** 500mA typical, 2.5A stall
- **Quantity:** 18 (3 per leg × 6 legs)
- **Purpose:**
    - Coxa joint (hip): Body-leg connection, lateral movement
    - Femur joint (knee): Up-down leg motion
    - Tibia joint (ankle): Foot positioning

3.3 SERVO MOTORS (GRIPPER & CAMERA)

MG90S Micro Servo

- **Torque:** 2.2 kg·cm @ 4.8V
- **Speed:** 0.10 sec/60° @ 4.8V
- **Weight:** 13.4g
- **Quantity:** 2-4 units
- **Purpose:**
    - Gripper base rotation (1 unit)
    - Gripper open/close mechanism (1 unit)
    - Camera pan/tilt servos (2 units)

3.4 SERVO CONTROLLER

PCA9685 16-Channel 12-bit PWM Servo Driver

- **Channels:** 16 per board (expandable to 62 via I2C addressing)
- **Resolution:** 12-bit (4096 steps)
- **Communication:** I2C (address: 0x40-0x7F)
- **Supply Voltage:** 2.3V-5.5V (logic), 5V-10V (servo power)
- **PWM Frequency:** 40Hz - 1000Hz (typically 50Hz)
- **Current Capability:** 25mA per channel
- **Quantity:** 2 boards
  - Board 1 (0x40): Leg servos
  - Board 2 (0x41): Gripper and camera servos
- **Datasheet:** NXP PCA9685

Connections:

- V+ (Servo Power): 6V regulated supply
- VCC (Logic): 5V from Raspberry Pi
- GND: Common ground
- SDA/SCL: I2C communication (GPIO2/GPIO3)

3.5 CAMERA MODULE

Raspberry Pi Camera Module V2

- **Sensor:** Sony IMX219 8-megapixel
- **Resolution:** 3280 × 2464 pixels (still), 1920×1080@30fps (video)
- **Field of View:** 62.2° horizontal × 48.8° vertical
- **Connection:** CSI 15-pin ribbon cable
- **Focus:** Fixed (optimized for 50cm - infinity)
- **Quantity:** 1
- **Mount:** Pan-tilt mechanism using 2 servos
- **Datasheet:** Raspberry Pi Camera Docs

3.6 ULTRASONIC SENSORS

HC-SR04 Ultrasonic Distance Sensor

- **Range:** 2cm - 400cm
- **Accuracy:** ±3mm
- **Operating Voltage:** 5V DC
- **Current Draw:** 15mA
- **Frequency:** 40kHz ultrasonic
- **Trigger Input:** 10µs TTL pulse
- **Echo Output:** 5V pulse (requires voltage divider for Pi)
- **Quantity:** 3-4 sensors

    - Front: 2 sensors (left/right obstacle detection)
    - Sides: 2 sensors (lateral awareness)
- **Purpose:** Obstacle detection, cliff detection

Important: Echo pin outputs 5V - must use voltage divider (1kΩ + 2kΩ resistors) to protect Raspberry Pi 3.3V GPIO pins.

3.7 INFRARED SENSORS

IR Proximity Sensor (E18-D80NK)

- **Detection Range:** 3cm - 80cm (adjustable via potentiometer)
- **Operating Voltage:** 5V DC
- **Output:** Digital (high/low)
- **Current Draw:** <25mA
- **Quantity:** 2-4 units
- **Purpose:** Ground detection (prevent falls), close-range obstacles
- **Mounting:** Downward-facing at leg/body junction

3.8 INERTIAL MEASUREMENT UNIT (IMU)

MPU6050 6-Axis Gyroscope & Accelerometer

- **DOF:** 6 (3-axis gyro + 3-axis accelerometer)

- **Communication:** I2C (address: 0x68 or 0x69)
- **Gyroscope Range:** ±250, ±500, ±1000, ±2000 °/s
- **Accelerometer Range:** ±2g, ±4g, ±8g, ±16g
- **Operating Voltage:** 3.3V - 5V
- **Quantity:** 1
- **Purpose:** Body orientation, tilt detection, balance control
- **Datasheet:** InvenSense MPU6050

3.9 POWER SYSTEM

LiPo Battery 3S

- **Type:** Lithium Polymer (LiPo)
- **Configuration:** 3S1P (3 cells in series)
- **Voltage:** 11.1V nominal (12.6V full, 9.0V cutoff)
- **Capacity:** 5000mAh - 6000mAh
- **Discharge Rate:** 30C continuous
- **Connector:** XT60 or Deans T-plug
- **Weight:** ~400-500g
- **Quantity:** 1
- **Runtime:** 45-60 minutes estimated

Safety Equipment Required:

- LiPo fireproof storage bag

- Battery voltage alarm (<3.3V per cell)
- Balance charger (IMAX B6 or equivalent)

Voltage Regulators

5V Buck Converter (for Raspberry Pi)

- **Model:** LM2596 DC-DC Buck Converter
- **Input:** 11.1V LiPo
- **Output:** 5V @ 3A (adjust to 5.1V under load)
- **Efficiency:** ~85-90%
- **Quantity:** 1

6V Buck Converter (for Servos)

- **Model:** D24V50F6 or equivalent
- **Input:** 11.1V LiPo
- **Output:** 6V @ 5A continuous (10A peak recommended)
- **Quantity:** 1
- **Purpose:** High-current servo power rail

3.3V Regulator (for Sensors)

- **Model:** AMS1117-3.3 or LD1117V33
- **Input:** 5V
- **Output:** 3.3V @ 1A
- **Quantity:** 1

Power Protection

- **XT60 Connectors:** 60A continuous rating
- **10A Blade Fuse:** Main battery protection
- **5A Fuse:** Servo rail protection
- **2A Fuse:** Logic rail protection
- **Emergency Stop Switch:** Manual cutoff
- **4700µF Capacitor:** Servo power rail filtering (reduces voltage spikes)

3.10 MECHANICAL COMPONENTS

Structural Materials

Robot Chassis & Frame

- **Material Options:**
  - 3mm-5mm acrylic sheets (laser-cut, budget-friendly)
  - Aluminum plates (stronger, more expensive)
  - 3D printed PLA/PETG (custom shapes)
  - Carbon fiber sheets (lightweight, expensive)
- **Base Plate:** 250mm × 200mm
- **Body Segments:** Custom cut to design
- **Quantity:** 5-8 plates

Leg Segments

- **Material:** Aluminum rods (6mm diameter) or 3D printed
- **Dimensions per leg:**
  - Coxa (hip segment): 60mm
  - Femur (thigh segment): 80mm
  - Tibia (shin segment): 100mm
- **Quantity:** 6 complete leg sets (18 segments total)

Foot Pads

- **Material:** Rubber or silicone
- **Diameter:** 15-20mm
- **Purpose:** Traction and shock absorption
- **Quantity:** 6

Fasteners & Hardware

- **M3×6mm screws:** 50 pieces (servo mounting)
- **M3×10mm screws:** 30 pieces (brackets to body)
- **M3×16mm screws:** 20 pieces (through-body connections)
- **M3 nuts:** 80 pieces
- **M3 lock washers:** 40 pieces
- **M2.5×6mm screws:** 10 pieces (Raspberry Pi mounting)
- **M3 standoffs:** 20-30 pieces (15mm, 20mm lengths)

Servo Brackets

- **Type:** Aluminum L-brackets or 3D printed

- **Quantity:** 18-24 pieces
- **Purpose:** Mount servos at correct angles for leg joints

3.11 GRIPPER MECHANISM

Design Specifications

- **Type:** Parallel jaw gripper
- **Material:** 3D printed PLA/ABS or aluminum
- **Opening Width:** 50mm (closed) - 150mm (open)
- **Gripping Force:** 1-3 kg
- **Actuation:** MG90S servo with mechanical linkage
- **Force Sensor (optional):** FSR 0.2kg-20kg (2 units, one per jaw)

3.12 ADDITIONAL ELECTRONICS

- **5V Cooling Fan:** 40mm×40mm×10mm (Raspberry Pi cooling)
- **LED Indicators:** 5mm LEDs - Red, Green, Blue (3-5 units)
- **220Ω Resistors:** Current limiting for LEDs
- **Emergency Stop Button:** Red mushroom-style, Normally Closed
- **Active Buzzer:** 5V piezo (audio feedback)
- **Wires:** 22-26 AWG stranded (signal), 16 AWG (power)
- **Cable Ties:** Various sizes for wire management

- **Heat Shrink Tubing:** Wire protection and insulation

4. ELECTRONICS & WIRING

4.1 POWER DISTRIBUTION DIAGRAM

```
LiPo Battery (11.1V 5000mAh)
         │
         ├─── [Emergency Stop Switch]
         │
         ├─── [10A Fuse]
         │
         ┴
         ┬
    ┌─────────┐
    │         │
    │  Power  │
    │  Dist.  │
    │  Board  │
    │         │
    └─────────┘
      │  │  │ │
      │  │  │ └──> 11.1V RAW (Reserve)
      │  │  │
      │  │  └─────> 6V Buck Converter (5A)
      │  │               └──> Servo Power Rail (18× servos)
      │  │
      │  └────────> 5V Buck Converter (3A)
      │                  └──┬──> Raspberry Pi 4 (via GPIO or USB-C)
      │                     ├──> PCA9685 VCC
      │                     └──> Sensors (HC-SR04, IR)
      │
      └───────────> 3.3V Regulator (1A)
                         └──> MPU6050, Logic-level sensors
```

4.2 RASPBERRY PI GPIO PIN ASSIGNMENT

GPIO Pin	Function	Connected To	Voltage	Notes
GPIO2 (SDA)	I2C Data	PCA9685, MPU6050	3.3V	Pull-up resistors
GPIO3 (SCL)	I2C Clock	PCA9685, MPU6050	3.3V	Pull-up resistors
GPIO4	Output	Buzzer	3.3V	PWM capable
GPIO17	Output	LED Green	3.3V	Status indicator
GPIO18	Output	LED Red	3.3V	Error indicator
GPIO22	Output	Ultrasonic Trig (Front)	3.3V	
GPIO23	Input	Ultrasonic Echo (Front)	3.3V	Via voltage divider
GPIO24	Output	Ultrasonic Trig (Side L)	3.3V	
GPIO25	Input	Ultrasonic Echo (Side L)	3.3V	Via voltage divider
GPIO5	Output	Ultrasonic Trig (Side R)	3.3V	
GPIO6	Input	Ultrasonic Echo (Side R)	3.3V	Via voltage divider
GPIO12	Input	IR Sensor 1	3.3V	Ground detection
GPIO13	Input	IR Sensor 2	3.3V	Ground detection
GPIO16	Input	Emergency Stop	3.3V	Internal pull-up
5V Power	Output	Sensor VCC	5V	Max 1A shared
3.3V Power	Output	Sensor VCC	3.3V	Max 50mA
GND	Ground	Common ground	0V	Multiple connections

I2C Addresses:

- PCA9685 Board 1 (Legs): 0x40

- PCA9685 Board 2 (Gripper): 0x41
- MPU6050 IMU: 0x68

4.3 PCA9685 SERVO CHANNEL ASSIGNMENT

Board 1 - Legs (Address 0x40)

Channel	Leg	Joint	Servo
0	Right Front	Coxa	MG996R
1	Right Front	Femur	MG996R
2	Right Front	Tibia	MG996R
3	Right Middle	Coxa	MG996R
4	Right Middle	Femur	MG996R
5	Right Middle	Tibia	MG996R
6	Right Rear	Coxa	MG996R
7	Right Rear	Femur	MG996R
8	Right Rear	Tibia	MG996R
9	Left Front	Coxa	MG996R
10	Left Front	Femur	MG996R
11	Left Front	Tibia	MG996R
12	Left Middle	Coxa	MG996R
13	Left Middle	Femur	MG996R
14	Left Middle	Tibia	MG996R
15	Left Rear	Coxa	MG996R

Board 2 - Gripper & Extras (Address 0x41)

Channel	Function	Servo
0	Left Rear Femur	MG996R
1	Left Rear Tibia	MG996R
2	Gripper Base Rotation	MG90S
3	Gripper Jaw Open/Close	MG90S
4	Camera Pan	SG90
5	Camera Tilt	SG90
6-15	Reserved	-

4.4 WIRING SPECIFICATIONS

Wire Gauge Selection

Purpose	AWG	Current	Color
Battery to Main	14	15A	Red/Black
Power Distribution	16	10A	Red/Black
Servo Power Rails	18	5A	Red/Black
Logic Power	22	1A	Red/Black
GPIO Signals	24	0.5A	Various
Sensor Lines	26	0.1A	Various
I2C Communication	26	-	Yellow/Orange

Wire Color Standards

- **Red:** Positive voltage (V+)
- **Black:** Ground (GND)
- **Yellow/Orange:** I2C communication
- **Green:** GPIO outputs
- **Blue:** GPIO inputs

4.5 VOLTAGE DIVIDER CIRCUIT (HC-SR04 Echo Pin)

Circuit Design:

```
Echo Pin (5V) ──┬──[ 1kΩ ]──┬── Raspberry Pi GPIO (3.3V)
                │            │
               GND     [ 2kΩ ]
                            │
                           GND

Calculation: Vout = Vin × R2/(R1+R2) = 5V × 2kΩ/3kΩ = 3.33V
```

Calculation: Vout = 5V × 2kΩ/(1kΩ+2kΩ) = 3.33V (safe for Pi)

Required Components:

- 1kΩ resistor (3 units, one per ultrasonic sensor)
- 2kΩ resistor (3 units, one per ultrasonic sensor)

4.6 CRITICAL WIRING NOTES

1. **Common Ground:** ALL components must share common ground
2. **Servo Power Capacitor:** 4700µF across 6V rail (reduces spikes)

3. **I2C Pull-ups:** 4.7kΩ resistors on SDA/SCL (if not on boards)
4. **Fuse Protection:** Install fuses before voltage regulators
5. **Star Grounding:** Single ground point to reduce noise

5. MECHANICAL DESIGN

5.1 LEG KINEMATICS

Leg Configuration

Coxa (60mm)

Body ●————●———— Femur (80mm)

|

●——— Tibia (100mm)

|

● Foot

```
        Coxa (60mm)
Body ●───────● Femur (80mm)
             │
             ● Tibia (100mm)
             │
             ● Foot
```

Joint Specifications:

- **Coxa Joint:** Horizontal rotation, ±45° range

- **Femur Joint:** Vertical rotation, 0-120° range
- **Tibia Joint:** Vertical rotation, 0-150° range

Total DOF: 3 per leg × 6 legs = 18 DOF

Leg Positioning on Body

- **Front legs (RF, LF):** ±30° from center axis
- **Middle legs (RM, LM):** ±90° from center axis
- **Rear legs (RR, LR):** ±150° from center axis

5.2 BODY STRUCTURE

Overall Dimensions

- **Length:** 450mm (including head)
- **Width:** 350mm (maximum leg span)
- **Height:** 250mm (standing position)
- **Ground Clearance:** 80mm minimum

Body Segments

1. **Head:** 80mm × 80mm × 60mm
   - Houses camera with pan-tilt mount
   - Front ultrasonic sensors
2. **Thorax:** 200mm × 150mm × 80mm
   - All 6 legs attach here
   - Raspberry Pi mounting

- PCA9685 boards mounting

3. **Abdomen:** 150mm × 120mm × 100mm
   - Battery compartment
   - Gripper mechanism base
   - Power distribution board

5.3 GRIPPER DESIGN

Specifications

- **Type:** 2-finger parallel jaw
- **Opening Range:** 50mm (closed) to 150mm (open)
- **Gripping Force:** 1-3 kg adjustable
- **Weight Capacity:** 0.5 kg typical waste items
- **Actuation:** Single MG90S servo with linkage
- **Linkage Ratio:** 1:2 (servo angle to jaw separation)

5.4 3D PRINTED COMPONENTS

Component	Quantity	Material	Infill	Est. Print Time
Body segments	3	PLA/PETG	30%	8 hours
Servo brackets	24	PLA	50%	12 hours
Leg segments	18	PETG	40%	10 hours
Foot pad holders	6	TPU	100%	2 hours
Gripper jaws	2	ABS	50%	3 hours
Camera mount	1	PLA	30%	2 hours

Sensor housings	6	PLA	20%	3 hours
Battery tray	1	PETG	30%	4 hours

Total Print Time: 40-50 hours

6. AI/ML VISION SYSTEM

6.1 OBJECT DETECTION MODEL

YOLOv5 (You Only Look Once v5)

- **Framework:** PyTorch
- **Model Variant:** YOLOv5s (small) or YOLOv5n (nano)
- **Input Resolution:** 320×320 or 416×416 pixels
- **Inference Speed:** 30-60 FPS on Raspberry Pi 4
- **Model Size:** 7-14 MB after quantization

Waste Categories to Detect:

1. Plastic bottle
2. Aluminum can
3. Paper/cardboard
4. Glass bottle
5. Organic waste
6. General trash

Alternative Models:

- MobileNet SSD (TensorFlow Lite)
- EfficientDet-Lite

6.2 DATASET PREPARATION

Data Collection Requirements

- **Total Images:** 1000-2000 minimum
- **Per Class:** 150-300 images
- **Sources:**
  - Custom photography (recommended)
  - Public datasets: TACO, TrashNet
  - Data augmentation for variety

Annotation

- **Tool:** LabelImg or Roboflow
- **Format:** YOLO format (class x_center y_center width height)
- **Data Split:**
  - Training: 70% (700-1400 images)
  - Validation: 20% (200-400 images)
  - Testing: 10% (100-200 images)

6.3 MODEL TRAINING

Training Environment Options

1. Google Colab (free GPU access)
2. Local machine with NVIDIA GPU
3. Cloud platforms (Azure ML, AWS SageMaker)

Training Parameters

- **Epochs:** 100-200
- **Batch Size:** 16 (adjust for GPU memory)
- **Learning Rate:** 0.01 initial
- **Image Size:** 416×416 pixels
- **Augmentation:** Flip, rotate, scale, color jitter

Training Duration:

- 2-6 hours on GPU (NVIDIA GTX 1660 or better)
- 24-48 hours on CPU (not recommended)

6.4 MODEL OPTIMIZATION

Optimization Steps

1. **Export to ONNX format** for compatibility
2. **INT8 Quantization:** Reduces model size by 75%
3. **Model Pruning:** Remove redundant weights (optional)

Expected Performance:

- Model Size: 7-14 MB (quantized)

- Inference Time: 50-150ms per frame
- Accuracy: 85-92% mAP (mean Average Precision)

6.5 DISTANCE ESTIMATION

Monocular Camera Method

Uses known object size and focal length calculation:

Formula: Distance (m) = (Actual Height × Focal Length) / Bbox Height (pixels)

Calibration Process:

1. Place known objects (e.g., plastic bottle 0.20m tall) at measured distances
2. Record bounding box heights at 0.5m, 1.0m, 2.0m
3. Calculate focal length constant
4. Test accuracy across operating range

Example Calculation:

- Bottle height: 0.20m
- Bbox height at 1m: 150 pixels
- Focal length = (150 × 1.0) / 0.20 = 750 pixels

7. ASSEMBLY INSTRUCTIONS

7.1 PHASE 1: COMPONENT PREPARATION (Week 1-2)

Step 1: Inventory Check

- Verify all components against Bill of Materials
- Test battery voltage (should be 11.1V ± 0.3V)
- Check servo horns and mounting screws
- Inspect 3D printed parts for defects

Step 2: Servo Testing & Calibration

1. Connect each servo individually to PCA9685
2. Power with 6V supply
3. Test sweep from 0-180°
4. Mark 90° center position on servo horn with marker
5. Record any faulty servos for replacement

Step 3: Raspberry Pi Setup

1. Flash Raspberry Pi OS (64-bit) to SD card
2. Enable SSH and set hostname
3. Boot and update system
4. Install required Python libraries
5. Enable I2C and Camera interfaces via raspi-config

7.2 PHASE 2: MECHANICAL ASSEMBLY (Week 3-5)

Step 1: Body Construction

1. Cut acrylic/aluminum plates (laser cutter or jigsaw)

2. Drill mounting holes:
   - Servo brackets: 3mm diameter
   - Standoffs: 2.5mm diameter
3. Sand all edges smooth (220 grit sandpaper)
4. Test-fit components before final assembly

Step 2: Leg Assembly (Per Leg - 20-30 minutes each)

1. Attach servo bracket to coxa servo
2. Mount coxa servo to body at correct angle
3. Secure with M3×10mm screws (apply Loctite threadlocker)
4. Connect coxa link (60mm) to servo horn
5. Mount femur servo to coxa link
6. Connect femur link (80mm)
7. Attach tibia servo to femur link
8. Connect tibia link (100mm) with foot pad
9. Install rubber foot pad
10. Route and secure wiring along leg

Repeat for all 6 legs

Step 3: Gripper Assembly

1. Assemble 3D printed gripper linkage
2. Mount base rotation servo (MG90S)
3. Attach jaw open/close servo

4. Test opening range: 50mm to 150mm
5. Optional: Install force sensors on jaws

Step 4: Camera Mount

1. Assemble pan-tilt mechanism with 2× SG90 servos
2. Attach camera module to mount
3. Secure to head section
4. Route camera ribbon cable carefully

7.3 PHASE 3: ELECTRONICS INTEGRATION (Week 6-7)

Step 1: Power Distribution Assembly

1. Solder components on perfboard:
    - XT60 female connector
    - Emergency stop switch terminals
    - 10A fuse holder
    - Screw terminals for regulators
2. Install buck converters (adjust voltages)
3. Add 4700µF capacitor across 6V servo rail
4. Install LED indicators

Step 2: Component Mounting

1. Mount Raspberry Pi on thorax using M2.5 standoffs
2. Secure PCA9685 boards near servo clusters

3. Install power distribution board centrally
4. Place battery in abdomen (Velcro straps)
5. Mount sensors: ultrasonic (front/sides), IR (downward), IMU (center)
6. Install emergency stop button (accessible location)

Step 3: Wiring

1. Connect battery to power board via XT60
2. Wire emergencies stop in series with battery positive
3. Connect voltage regulators to distribution board
4. Wire all servos to PCA9685 channels (see Section 4.3)
5. Connect sensors to GPIO pins (see Section 4.2)
6. Build voltage dividers for ultrasonic echo pins
7. Connect I2C devices (PCA9685, MPU6050)
8. Verify common ground connections

Step 4: Cable Management

1. Route power cables along body underside
2. Use cable ties every 5cm
3. Keep signal wires away from high-current wires
4. Leave slack at all joint locations
5. Hot glue cables at fixed attachment points
6. Label all connections

8. TESTING & CALIBRATION

8.1 UNIT TESTING CHECKLIST

Test ID	Component	Test Procedure	Pass Criteria
T-001	Power System	Measure voltage rails	11.1V, 6V, 5V, 3.3V (±5%)
T-002	Servos	Sweep all servos 0-180°	Smooth motion, no noise
T-003	Ultrasonic	Test at known distances	±3cm accuracy
T-004	Camera	Capture test image	Clear, focused image
T-005	Object Detection	Test on waste samples	>80% confidence
T-006	Locomotion	Walk 1 meter forward	Stable gait, straight
T-007	Gripper	Pick up bottle	Successful grip
T-008	Obstacle Avoid	Place object in path	Robot stops/avoids
T-009	Battery Life	Full operation	>45 minutes
T-010	Emergency Stop	Press during motion	All motors halt

8.2 CALIBRATION PROCEDURES

Servo Calibration

1. Position each servo to physical 90° angle
2. Record PWM value at this position
3. Calculate offset for each servo
4. Save calibration data to configuration file

Camera Calibration

1. Print checkerboard pattern (9×6, 25mm squares)
2. Capture 20+ images from different angles
3. Calculate camera intrinsic matrix
4. Calculate lens distortion coefficients
5. Save calibration parameters

Distance Estimation Calibration

1. Place known objects at measured distances
2. Record bounding box dimensions
3. Calculate focal length constant
4. Verify accuracy across 0.5m - 3m range

8.3 INTEGRATION TESTING

Scenario 1: Single Object Collection

1. Place plastic bottle 1 meter from robot
2. Start autonomous operation
3. Observe complete cycle: Detect → Approach → Grip → Dispose
4. Measure completion time (target: 60-90 seconds)

Scenario 2: Multiple Objects

1. Place 3 different waste items in view
2. Verify robot prioritizes closest object

3. Collect all items sequentially
4. Measure overall success rate (target: >80%)

Scenario 3: Obstacle Course

1. Create path with obstacles between robot and waste
2. Verify ultrasonic sensors detect obstacles
3. Observe path replanning behavior
4. Successful navigation to target

8.4 PERFORMANCE METRICS

Metric	Target	Measurement Method
Detection Accuracy	>85%	Test on 50 objects
Approach Precision	±10cm	Measure final position
Grip Success Rate	>90%	20 attempts
Walking Speed	0.15 m/s	Time over 1 meter
Battery Life	45-60 min	Continuous operation
Obstacle Detection	10-200cm	Sensor range test

9. BUDGET & COST ANALYSIS

9.1 DETAILED COST BREAKDOWN (USD)

Category	Component	Qty	Unit Price	Total

Processing	Raspberry Pi 4 (4GB)	1	$55	$55
	MicroSD Card 64GB	1	$12	$12
Servos	MG996R (legs)	18	$8	$144
	MG90S (gripper)	4	$5	$20
Controllers	PCA9685 Driver	2	$12	$24
Vision	Pi Camera V2	1	$25	$25
Sensors	HC-SR04 Ultrasonic	3	$3	$9
	IR Proximity	2	$4	$8
	MPU6050 IMU	1	$6	$6
Power	LiPo 3S 5000mAh	1	$40	$40
	Buck Converters	2	$7	$14
	LiPo Charger	1	$25	$25
	XT60, Fuses, etc	-	$10	$10
Mechanical	Acrylic/Al Plates	1 set	$30	$30
	3D Printing (1kg)	1	$20	$20
	Brackets, Hardware	1 set	$30	$30
Electronics	Wires, Resistors, etc	1 set	$30	$30
Misc	Adhesives, Ties, LEDs	1 set	$15	$15
Tools	Soldering Kit (opt)	1	$30	$30
	Multimeter (opt)	1	$20	$20
	TOTAL			**$567**

9.2 COST OPTIMIZATION

Potential Savings:

- Use lab equipment (tools, multimeter): Save $50
- 3D print servo brackets instead of metal: Save $15
- Buy servo bulk packs (10-20% discount): Save $25-30
- Use recycled materials for chassis: Save $20

Optimized Budget: $450-500

10. EXPECTED OUTCOMES

10.1 TECHNICAL ACHIEVEMENTS

Hardware Deliverables

1. **Functional Hexapod Robot**
    - 18-DOF locomotion system
    - Stable tripod gait walking
    - 0.5-1.0 kg payload capacity
    - 45-60 minute battery life
2. **AI Vision System**
    - Real-time object detection (30-60 FPS)
    - 6 waste categories classified

- 85% classification accuracy

- Distance estimation ±10cm

3. **Autonomous Operation**

   - Obstacle detection and avoidance
   - Self-navigation to targets
   - Adaptive gripping mechanism
   - Error recovery capabilities

10.2 DEMONSTRATION SCENARIOS

Live Demo (5-7 minutes)

- Place 5 different waste items on floor
- Robot autonomously detects, approaches, grips, and disposes
- Success rate target: 4/5 objects (80%)
- Showcase obstacle avoidance
- Display waste classification on screen

10.3 PROJECT DELIVERABLES

Documentation:

1. Technical report (this document)
2. Circuit diagrams (Fritzing/KiCad)

3. 3D CAD models (STL files)
4. Source code repository (GitHub)
5. User operation manual
6. Video demonstration (5-10 minutes)

Presentation Materials:

1. PowerPoint slides (15-20 slides)
2. Live demonstration
3. Project poster (A1 size)

10.4 LEARNING OUTCOMES

Technical Skills:

- Embedded systems programming
- Computer vision and AI/ML
- Robotics kinematics
- Power electronics design
- Mechanical design and fabrication
- System integration

Soft Skills:

- Project management
- Technical documentation
- Teamwork and collaboration

- Problem-solving
- Presentation skills

11. SAFETY CONSIDERATIONS

11.1 ELECTRICAL SAFETY

LiPo Battery Safety Rules

⚠️ **CRITICAL:**

1. Never discharge below 3.0V per cell (9.0V total)
2. Never charge unattended
3. Always use balance charger
4. Store in LiPo safety bag
5. Never puncture or damage battery
6. If battery swells/smokes: place in metal container outside

Working with Electronics

- Disconnect power before wiring
- Use insulated tools
- Verify polarity before connections
- Install fuses for overcurrent protection
- Wear anti-static wrist strap

11.2 MECHANICAL SAFETY

During Assembly & Testing

- Servos generate significant torque under load
- Keep fingers away from moving parts
- Use emergency stop during all tests
- File down sharp edges on cut materials
- Wear safety glasses when cutting/drilling

Testing Procedures

1. Test servos individually before assembly
2. Test walking with robot elevated initially
3. Clear testing area of obstacles and people
4. Have emergency stop accessible
5. Monitor for overheating components

11.3 OPERATIONAL SAFETY

Pre-Operation Checklist:

- Battery voltage >11.0V
- Emergency stop tested and functional
- All connections secure
- Testing area clear
- Fire extinguisher accessible

12. REFERENCES & DATASHEETS

12.1 COMPONENT DATASHEETS

Microcontrollers:

1. Raspberry Pi 4 Documentation: raspberrypi.com/documentation
2. Raspberry Pi Camera V2: raspberrypi.com/documentation/accessories/camera.html

Motor Controllers: 3. PCA9685 Datasheet: www.nxp.com/docs/en/data-sheet/PCA9685.pdf 4. MG996R Servo: towerpro.com.tw/product/mg996r

Sensors: 5. HC-SR04 Ultrasonic: cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf 6. MPU6050 IMU: invensense.tdk.com/wp-content/uploads/2015/02/MPU-6000-Datasheet1.pdf

Power: 7. LM2596 Buck Converter: www.ti.com/lit/ds/symlink/lm2596.pdf 8. LiPo Battery Safety: batteryuniversity.com/article/bu-409

12.2 ACADEMIC REFERENCES

Hexapod Robotics: 9. Tedeschi, F., & Carbone, G. (2014). "Design of Hexapod Walking Robots" 10. Erden, M. S. (2008). "Free gait generation with reinforcement learning"

Computer Vision: 11. Redmon, J., & Farhadi, A. (2018). "YOLOv3: An Incremental Improvement" 12. Jocher, G. (2021). "YOLOv5: State-of-the-Art Object Detection"

Waste Detection: 13. Aral, R. A. (2018). "Classification of TrashNet Dataset" 14. Hong, J. (2020). "TrashCan: Semantically-Segmented Dataset"

12.3 SOFTWARE & TOOLS

Development: 15. PyTorch: pytorch.org/docs 16. OpenCV: docs.opencv.org 17. ROS: wiki.ros.org

Design Tools: 18. Fusion 360: autodesk.com/products/fusion-360 19. Fritzing: fritzing.org 20. Roboflow: roboflow.com

APPENDICES

APPENDIX A: QUICK REFERENCE TABLES

Power Requirements Summary

Component	Voltage	Current	Power
Raspberry Pi 4	5V	3A	15W
18× MG996R Servos	6V	9A peak	54W
Camera Module	5V	250mA	1.25W
Sensors (all)	3.3-5V	200mA	1W
Total Peak	-	-	**~70W**

I2C Device Addresses

Device	Address	Configurable
PCA9685 Board 1	0x40	Yes (A0-A5)
PCA9685 Board 2	0x41	Yes (A0-A5)
MPU6050 IMU	0x68	Yes (AD0 pin)

APPENDIX B: TROUBLESHOOTING GUIDE

Problem	Cause	Solution
Servos jitter	Low current supply	Add capacitor, upgrade converter
No camera feed	Ribbon cable loose	Reseat cable, check enable
I2C not detected	Wiring error	Check connections, verify address
Robot tips	CoG too high	Lower battery position
Gripper fails	Binding linkage	Lubricate, check angles
Slow detection	Large model	Reduce input size, use YOLOv5n

APPENDIX C: PROJECT TIMELINE

Week	Phase	Tasks
1-2	Preparation	Component procurement, 3D printing
3-5	Mechanical	Body and leg assembly
6-7	Electronics	Wiring and integration
8-9	Software	AI training, programming
10-11	Testing	Integration and debugging

12-13	Final	Documentation, video, presentation
14	Defense	Project demonstration and exhibition

CONCLUSION

This documentation provides comprehensive specifications for building an ant-inspired hexapod robot with autonomous waste collection capabilities. The project demonstrates integration of mechanical design, electronics, computer vision, and artificial intelligence.

Key Features:

- 18-DOF walking locomotion
- AI-powered waste detection (>85% accuracy)
- Autonomous navigation and manipulation
- Complete technical specifications and datasheets
- Detailed assembly procedures
- Budget: ~$550-600

Success Criteria: ✓ Stable hexapod walking

✓ Real-time object detection

✓ Autonomous waste collection

✓ 45+ minute operation time

✓ Complete documentation