A Term Project

Report on

HEXAPOD- A Six Legged Robot

SUBMITTED BY

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Certificate

This is to certify that the project "**Hexapod- A Six Legged Robot**" is a work carried out by **Patel Krish Shashikant**, Roll No.: **EC097**, Identity No.: **22ECUOS026**, under my supervision as part of Term Project as prospectus described by the department.

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Krish (EC097) **Nisarg (EC099)**

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Chapter - 1

Abstract

This project involves the design, implementation, and optimization of a six-legged walking robot (hexapod) named "Spider Scout" with an integrated ESP camera system featuring pan and tilt capabilities. The hexapod represents a biomimetic approach to robotic locomotion, drawing inspiration from insects and arthropods that display remarkable stability and terrain adaptability. Unlike wheeled robots that often struggle with uneven surfaces, the hexapod can navigate complex environments by independently controlling each of its six legs through a sophisticated control system.

The development process encountered several significant engineering challenges, particularly in the power management domain. Initial implementations using Arduino Nano with a servo shield for controlling 18 MG996R servo motors faced current limitations that compromised performance. This led to an iterative design approach, first exploring Teensy 4.1 for its PWM capabilities, and ultimately implementing a stable solution using Arduino Mega as the central controller. The project demonstrates the practical application of embedded systems design, mechanical engineering, power management, and wireless communication technologies.

Wireless control was implemented through HC-05 Bluetooth modules, enabling command transmission from a custom mobile application. This allows the operator to control the hexapod's movement patterns, direction, and camera orientation remotely without physical tethering. The integration of an ESP32-CAM with pan and tilt functionality adds surveillance and environment monitoring capabilities, extending the robot's utility beyond basic locomotion.

Power management presented one of the most significant challenges in this project. After initial testing with an 8000mAh commercial battery, a custom battery management system (BMS) was designed and implemented. The custom power solution consists of rechargeable 4.2V cells arranged in a specific configuration (four cells in parallel followed by three such sets in series) connected to a purpose-built BMS. To accommodate the different voltage requirements of various components, three buck converters were employed to supply appropriate power to the Arduino Mega controller, ESP camera system, and servo motors.

All structural components of the hexapod were designed using CAD software and manufactured through 3D printing, allowing for rapid prototyping, design iterations, and customization. This approach facilitated weight optimization while maintaining structural integrity, an essential consideration given the power constraints of mobile robotics.

The Spider Scout demonstrates viable applications in several domains, including hazardous environment exploration, search and rescue operations, educational platforms for robotics students, and surveillance tasks. While the current implementation focuses on remote control capabilities, future enhancements could include autonomous navigation, obstacle avoidance through sensor integration, machine learning for adaptive gait patterns, and more sophisticated image processing from the ESP camera feed.

This project synthesizes knowledge from multiple engineering disciplines: electronic circuit design, embedded programming, mechanical design, power systems engineering, and wireless communication protocols. The iterative development process highlights the importance of system integration considerations in complex robotics projects, where individual component specifications must be carefully balanced against overall system requirements and constraints.

Chapter - 2

Background

2.1 Motivation

The development of multi-legged robotic systems represents an important frontier in robotics research, offering solutions to mobility challenges that traditional wheeled robots cannot overcome. The Spider Scout hexapod project was motivated by several key factors:

1. **Terrain Adaptability**: Unlike wheeled robots that require relatively smooth surfaces, legged robots can navigate uneven terrain, steps, and obstacles. This capability is essential for applications in disaster areas, construction sites, or natural environments.

2. **Biomimetic Engineering**: Emulating biological systems often leads to elegant engineering solutions. Insects, particularly hexapods (six-legged insects), demonstrate remarkable stability and efficiency in their locomotion. By studying and implementing these biological principles, we can develop more versatile and robust robotic systems.

3. **Exploration and Surveillance**: The integration of camera systems with legged robots enables remote exploration and surveillance capabilities in areas that may be hazardous or inaccessible to humans. The pan and tilt functionality enhances the field of view without requiring the entire robot to reposition.

4. **Educational Platform**: Building a hexapod robot integrates multiple engineering disciplines, including mechanical design, electronics, programming, and power management. This makes it an excellent educational project that builds comprehensive engineering skills.

5. **Technical Challenge**: Coordinating the movement of 18 servos while managing power constraints presents significant engineering challenges. Overcoming these challenges demonstrates practical problem-solving abilities and system integration skills.

2.2 Literature Review

The development of legged robots has a rich history in robotics research. Several key papers and projects have informed the design decisions in this project:

Early Development of Legged Robots

Todd (1985) presented one of the first comprehensive analyses of hexapod locomotion in "Walking Machines: An Introduction to Legged Robots," establishing fundamental principles for gait patterns that remain relevant today. The MIT Leg Laboratory, under the direction of Marc Raibert, pioneered many of the control principles used in dynamic legged locomotion throughout the 1980s and 1990s.

Gait Analysis and Control Systems

Saranli, Buehler, and Koditschek (2001) introduced the RHex robot, which demonstrated robust hexapod locomotion with minimal actuation, influencing subsequent designs for efficiency. Song and Waldron (1989) published "Machines That Walk: The Adaptive Suspension Vehicle," documenting their work on a six-legged walking vehicle that could navigate rough terrain autonomously.

McGhee and Frank (1968) established mathematical foundations for static stability in "On the Stability Properties of Quadruped Creeping Gaits," principles that extend to hexapods and influenced the gait patterns implemented in this project.

Modern Hexapod Implementations

Murphy and Sitti (2007) detailed the development of mini-hexapods for search and rescue applications in "Miniature Robots for Search and Rescue." Their work emphasized the importance of power-to-weight ratios in small-scale legged robots, directly informing our power management approach.

The open-source community has contributed significantly to accessible hexapod designs. The "PhantomX Hexapod" by Trossen Robotics has become a reference design for many projects, while Arduino-based hexapod projects by Bakker (2015) demonstrated viable approaches for implementing servo control in microcontroller environments.

Power Management in Mobile Robotics

Bellingham et al. (2010) explored battery management systems for mobile robots in "Battery Management System for Mobile Robots with Weight Constraints," highlighting approaches that influenced our custom BMS design. Garcia et al. (2019) addressed servo power management specifically in "Power Optimization Strategies for Servo-Driven Legged Robots," providing insights into power sequencing and distribution techniques.

Camera Integration in Legged Robots

The integration of camera systems in legged robots was explored by Zhang et al. (2018) in "Vision-Based Navigation for Small Legged Robots," demonstrating viable

approaches for processing visual data in resource-constrained environments. The ESP32-CAM implementation in our project builds upon these foundations while leveraging recent advancements in low-cost, high-performance camera modules.

2.3 Basic Theory

Several fundamental theoretical concepts underpin the design and implementation of the Spider Scout hexapod:

Kinematics and Gait Patterns

Hexapod robots typically employ one of several gait patterns, each offering different trade-offs between stability, speed, and energy efficiency:

1. **Tripod Gait**: The most common gait for hexapods, where three legs (forming a triangle) remain in contact with the ground while the other three legs move forward. This alternating pattern provides a stable platform while maintaining reasonable forward velocity.

2. **Wave Gait**: A slower but more stable gait where legs move one at a time in a wave-like pattern, ensuring five legs remain in contact with the ground at all times.

3. **Ripple Gait**: A compromise between tripod and wave gaits, where legs move in pairs or groups, providing moderate speed with good stability.

The Spider Scout implements primarily the tripod gait for efficient movement, with the ability to switch to wave gait for more challenging terrain.

Inverse Kinematics

To position each leg accurately, inverse kinematics calculations translate desired foot positions (in Cartesian coordinates) into servo angles. For a three-joint leg (coxa, femur, tibia), these calculations involve trigonometric relationships that determine the required angle of each joint to achieve the desired foot position.

Power Management Theory

Effective power management in a servo-driven robot requires understanding:

1. **Peak Current Requirements**: MG996R servos can draw up to 2.5A each under load, with potential current spikes during startup or when encountering resistance.

2. **Battery Characteristics**: Lithium-ion cells have specific discharge characteristics and operational voltage ranges that must be respected to ensure safety and longevity.

3. **Buck Converter Operation**: Switch-mode power supplies that step down voltage while maintaining high efficiency, critical for extending battery life in a mobile platform.

Control Systems

The hexapod employs a hierarchical control system:

1. **High-Level Control**: Determines gait patterns, direction, and speed based on user input via Bluetooth.

2. **Mid-Level Control**: Translates high-level commands into specific leg trajectories and timing sequences.

3. **Low-Level Control**: Manages the precise positioning of individual servos through PWM signals.

Chapter - 3

Problem Definition & Design

3.1 Problem Statement

The primary objective of this project was to design and construct a functional hexapod robot with the following capabilities:

1. Stable and coordinated locomotion across various surfaces
2. Remote control via a mobile application
3. Integration of a camera system with pan and tilt functionality for surveillance
4. Sufficient power management to ensure reasonable operational time
5. Robust structural design capable of supporting all components while minimizing weight

Several technical challenges needed to be addressed:

1. **Power Distribution**: Managing the high current demands of 18 servo motors while maintaining stable voltage levels for control electronics
2. **Control System Architecture**: Selecting an appropriate microcontroller platform capable of coordinating multiple servo motors with precise timing
3. **Mechanical Design**: Creating a lightweight yet sturdy frame that accommodates all components while maintaining optimal weight distribution
4. **Wireless Communication**: Implementing reliable Bluetooth connectivity for remote control
5. **Camera Integration**: Incorporating the ESP32-CAM module with pan and tilt functionality

3.2 Design Approach

The design process followed an iterative approach, with several revisions made to address challenges encountered during development:

Microcontroller Selection

The project began with an Arduino Nano coupled with a servo shield for controlling the 18 MG996R servos. However, current limitations led to unstable performance. After evaluating alternatives, a Teensy 4.1 was tested for its PWM capabilities but also presented integration challenges. Ultimately, the Arduino Mega was selected as the final platform due to its balance of I/O capabilities, processing power, and compatibility with existing libraries.

Circuit Designing

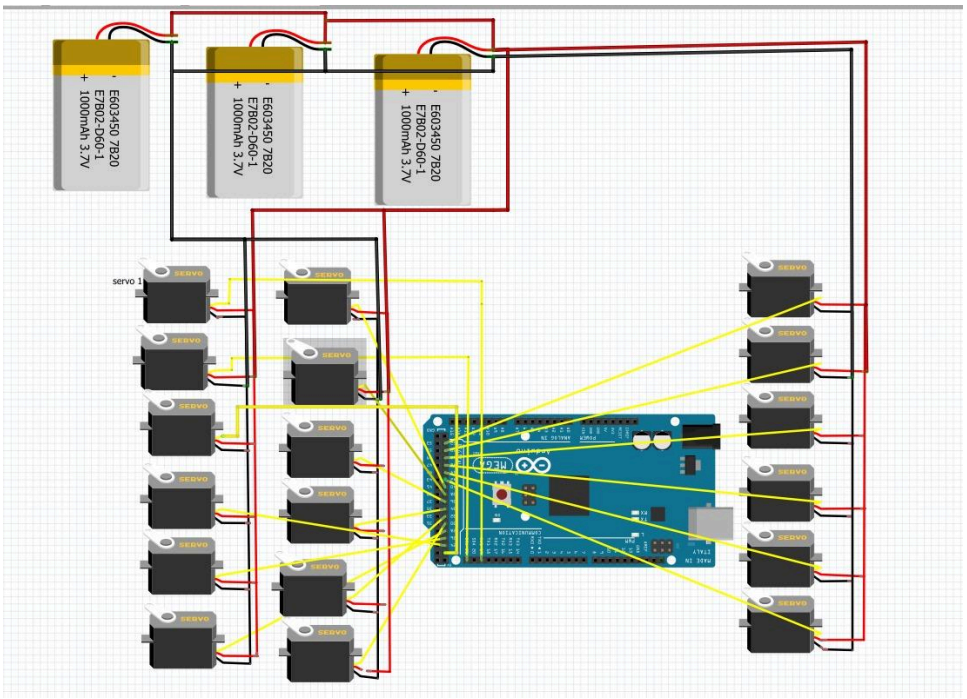

Fig 3.1

Mechanical Design

The hexapod frame was designed using 3D CAD software with the following considerations:

1. **Leg Configuration**: Each leg consists of three segments (coxa, femur, and tibia) with three servos providing 3 degrees of freedom.(fig 3.3)
2. **Body Structure**: A hexagonal body provides mounting points for all six legs with an even distribution of weight.(fig 3.4)
3. **Component Housing**: Dedicated mounting locations for the Arduino Mega, ESP32-CAM module, battery pack, and power distribution system.(fig 3.5)
4. **Material Selection**: PLA was chosen for 3D printing due to its balance of strength, weight, and ease of printing.

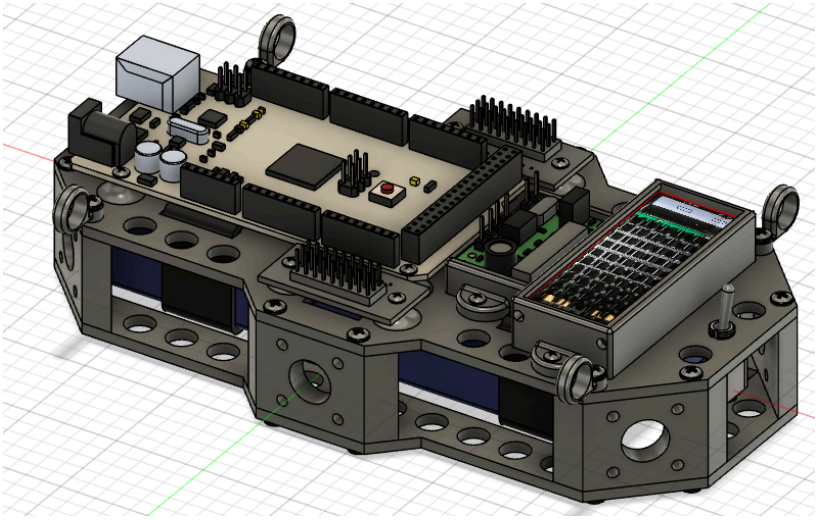

Fig 3.3

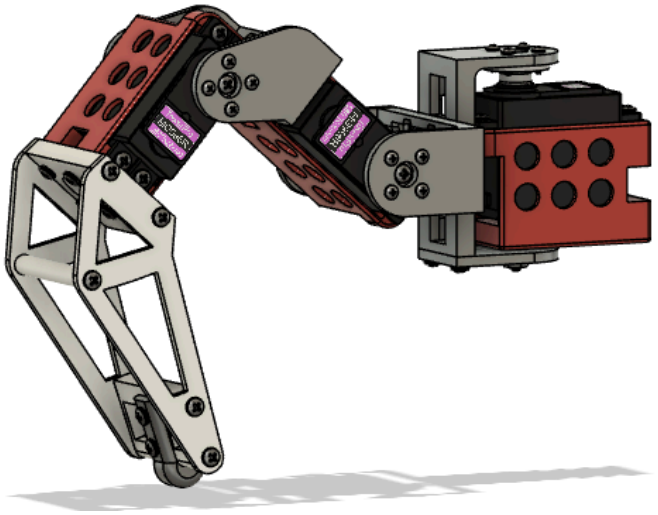

Fig 3.3

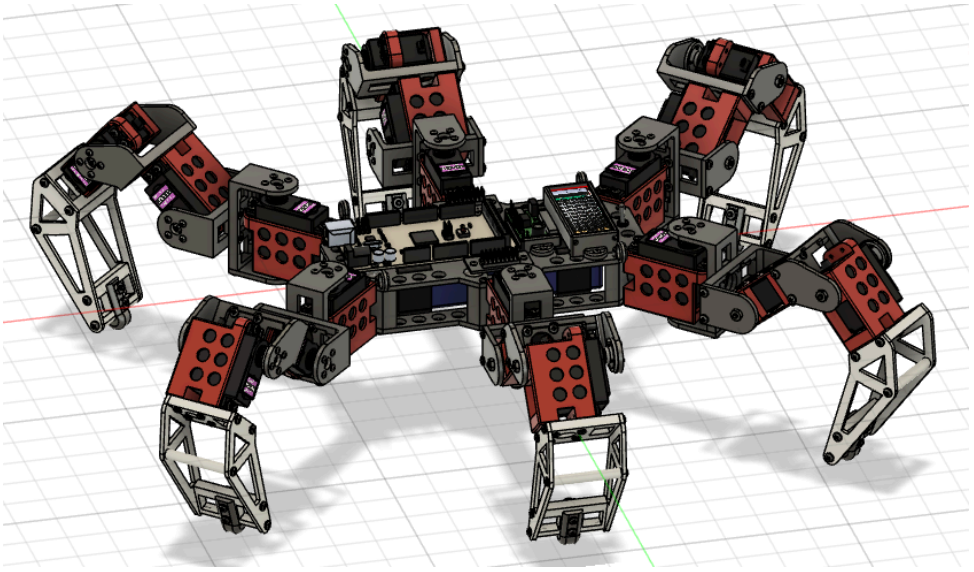

Fig 3.4

Power System Design

The power system underwent significant evolution throughout the project:

1. **Initial Design**: Testing with an 8000mAh commercial battery revealed the need for a more tailored power solution to handle the high-current demands of multiple servos.(fig 3.5)
2. **Final Implementation**: A custom BMS was designed to manage three parallel sets of 4.2V cells (four cells per set) arranged in series(fig 3.6). This configuration provides:
    - Adequate voltage for servo operation
    - Sufficient current capacity to handle peak loads
    - Protection against over-discharge, overcharging, and short circuits
3. **Voltage Regulation**: Three buck converters were implemented to provide appropriate voltage levels for:
    - Servo motors (6V)
    - Arduino Mega (5V)
    - ESP32-CAM module (5V)

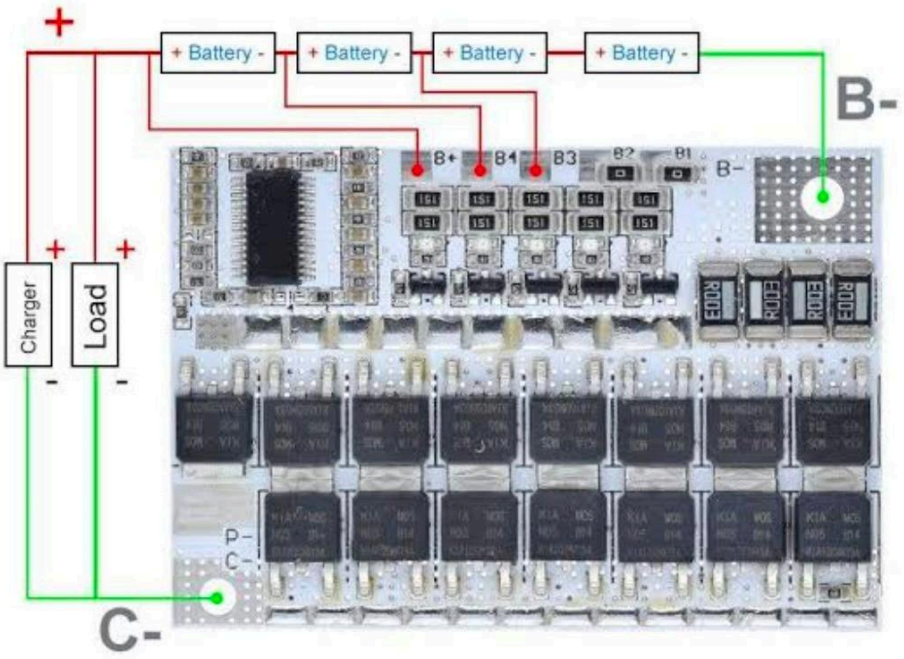
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Fig 3.5

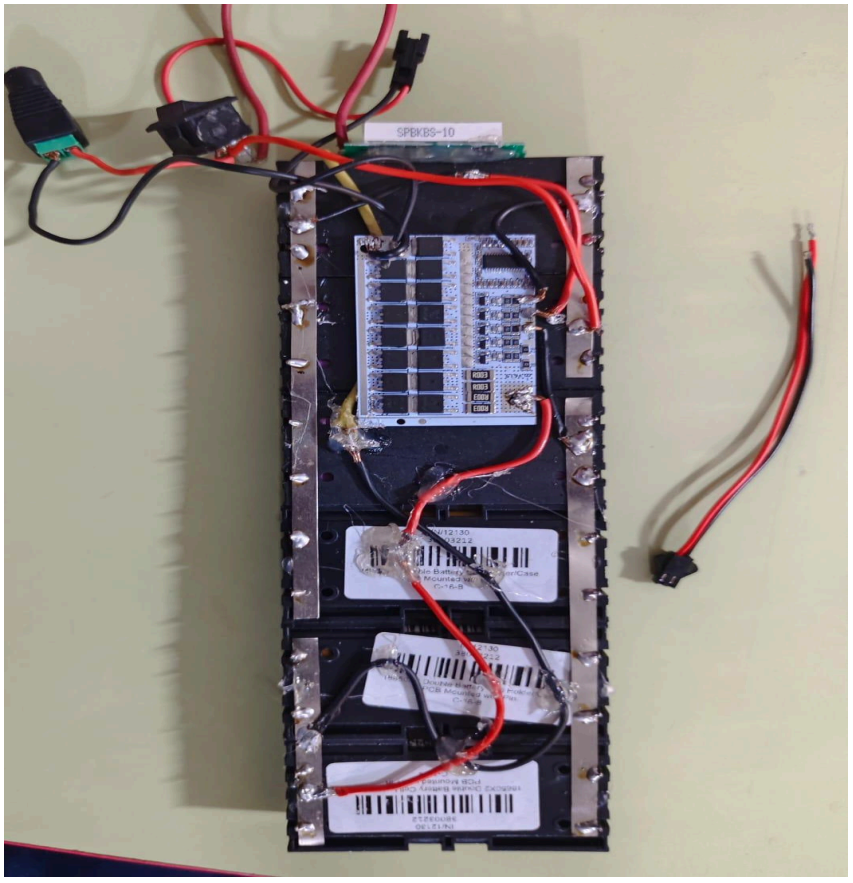
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Fig 3.6

Control System Architecture

The control system was designed with a modular approach:

1. **Locomotion Control**: Arduino Mega handles the inverse kinematics calculations and servo control for walking gaits.
2. **Wireless Interface**: HC-05 Bluetooth module enables communication with a custom mobile application.
3. **Camera System**: ESP32-CAM operates semi-independently, communicating with its own web interface for video streaming and camera control.(fig 3.5)

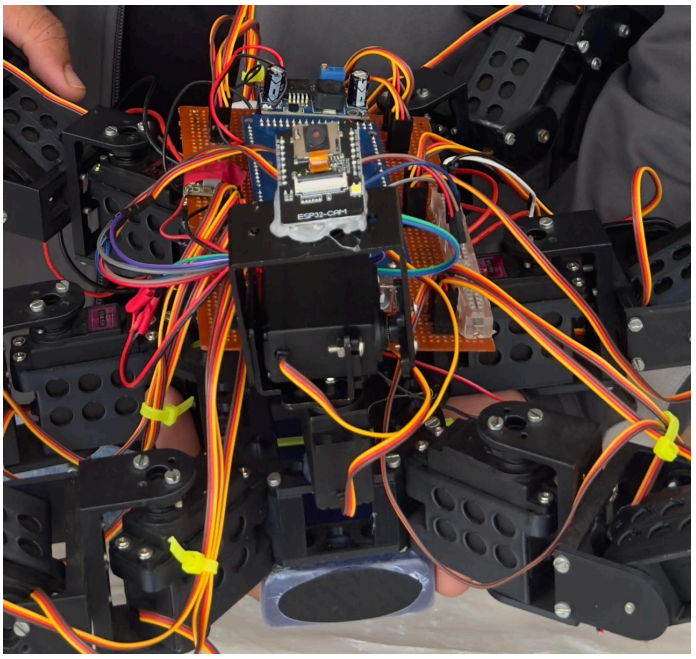

Fig 3.5

Camera System Integration

The ESP32-CAM module was integrated with a pan-tilt mechanism consisting of two additional servo motors. This system:

1. Provides real-time video streaming over WiFi
2. Allows remote control of camera orientation
3. Operates from a dedicated power supply to prevent interference with the locomotion system

Chapter - 4

Test Setup and Methodology

4.1 Hardware Testing Framework

Testing of the Spider Scout hexapod involved a systematic approach to evaluate each subsystem individually before integration testing of the complete robot:

Servo Motor Testing

1. **Individual Servo Verification**: Each MG996R servo was individually tested for proper operation, range of motion, and current consumption.
2. **Methodology**:
    - Applied PWM signals from 1000µs to 2000µs to verify full range of motion
    - Measured current draw under no-load and loaded conditions
    - Verified torque capabilities by applying measured resistance to the servo arm
3. **Equipment Used**:
    - Digital multimeter for current measurements
    - Oscilloscope for PWM signal verification
    - Arduino Uno for generating test signals

Power System Testing

1. **Battery Testing**:
    - Discharge tests to verify capacity and voltage stability under load
    - Charge/discharge cycle testing to validate BMS functionality
    - Temperature monitoring during high-current operations
2. **Buck Converter Evaluation**:
    - Output voltage stability under varying load conditions
    - Efficiency measurements at different current draws
    - Thermal performance during extended operation
3. **Full System Power Validation**:
    - Current measurements during different movement patterns
    - Operational time estimation based on battery capacity and measured consumption
    - Stress testing to identify potential power bottlenecks

Control System Testing

1. **Bluetooth Communication Testing**:
    - Range testing in various environments
    - Latency measurements between command transmission and execution
    - Protocol reliability under different interference conditions
2. **Inverse Kinematics Validation**:
    - Verification of calculated servo angles against expected foot positions
    - Movement accuracy testing using motion tracking

ESP32-CAM Testing

1. **Streaming Quality Assessment**:
    - Frame rate and resolution testing under different lighting conditions
    - Latency measurements between camera capture and display
    - WiFi range testing for reliable streaming
2. **Pan-Tilt Mechanism Testing**:
    - Range of motion verification
    - Precision of positioning commands
    - Speed and smoothness of movement

4.2 Software Testing Methodology

The software components underwent rigorous testing to ensure reliability and performance:

Unit Testing

1. **Gait Pattern Implementation**:
    - Verification of correct sequence timing for each gait pattern
    - Transition testing between different gaits
    - Error handling for invalid movement commands
2. **Inverse Kinematics Functions**:
    - Edge case testing for all possible leg positions
    - Performance optimization for calculation speed
    - Comparison with simulation models for accuracy verification

Integration Testing

1. **Control Flow Testing**:

    - End-to-end command processing from Bluetooth reception to servo actuation
    - Timing analysis for command execution latency
    - Resource usage monitoring during operation
2. **System Stability Testing**:
    - Extended operation testing under continuous command sequences
    - Error recovery from communication interruptions
    - Performance under high CPU load conditions

4.3 Field Testing

Once laboratory testing was complete, the Spider Scout underwent field testing in various environments:

1. **Terrain Navigation Testing**:
    - Flat surfaces (tile, carpet, concrete)
    - Uneven terrain (grass, gravel, inclined surfaces)
    - Obstacle navigation (steps, small barriers)
2. **Operational Testing**:
    - Battery life measurements under real-world usage patterns
    - Temperature monitoring during extended operation
    - Mechanical stress assessment after repeated use
3. **Camera System Field Evaluation**:
    - WiFi range testing in different environments
    - Image quality assessment in various lighting conditions
    - Pan-tilt responsiveness during movement

4.4 Gait Function Overview

This section provides a detailed explanation of the various walking gaits implemented in our hexapod robot. Each gait offers unique movement characteristics optimized for different terrains and scenarios. The implemented gaits include:

1. **Tripod Gait**: A fast and stable gait where three legs move simultaneously
2. **Ripple Gait**: A more stable gait with smoother transitions
3. **Wave Gait**: A highly stable gait where only one leg moves at a time
4. **Tetrapod Gait**: A balanced gait between stability and speed
5. **Obstacle Gait**: A specialized gait for navigating over obstacles

4.5 Stride and Amplitude Calculations

Before examining each gait, it's important to understand how the robot calculates the stride length and leg movement amplitudes.

4.5.1 Stride Calculation Function

```
void compute_strides() {
  if (gait == 1) { // If it's obstacle gait
    // Increase the stride values for more dramatic movements
    strideX = 120 * commandedX / 127;  // Increased from 90
    strideY = 120 * commandedY / 127;  // Increased from 90
    strideR = 45 * commandedR / 127;   // Increased from 35

    // Slow down the movement for more controlled lifting
    duration = 4320;  // Increased from 3240 for slower, more controlled movement
  }
  else {
    // Normal stride calculations for other gaits
    strideX = 90 * commandedX / 127;
    strideY = 90 * commandedY / 127;
    strideR = 35 * commandedR / 127;

    // Normal duration calculation
    if (gait_speed == 0) duration = 1080;
    else duration = 3240;
  }

  sinRotZ = sin(radians(strideR));
```

```
    cosRotZ = cos(radians(strideR));
}
```

Explanation: The `compute_strides()` function calculates the stride lengths based on the commanded movement and selected gait. For the obstacle gait, larger stride values (120 vs 90) and a longer duration are used to create more dramatic leg lifts. For other gaits, normal stride calculations are applied. The function also calculates sine and cosine values for rotation, which will be used in amplitude calculations.

4.5.2 Amplitude Calculation Functions

```
void compute_amplitudes() {
    totalX = HOME_X[leg_num] + BODY_X[leg_num];
    totalY = HOME_Y[leg_num] + BODY_Y[leg_num];

    rotOffsetX = totalY * sinRotZ + totalX * cosRotZ - totalX;
    rotOffsetY = totalY * cosRotZ - totalX * sinRotZ - totalY;

    amplitudeX = ((strideX + rotOffsetX) / 2.0);
    amplitudeY = ((strideY + rotOffsetY) / 2.0);
    amplitudeX = constrain(amplitudeX, -50, 50);
    amplitudeY = constrain(amplitudeY, -50, 50);

    if (abs(strideX + rotOffsetX) > abs(strideY + rotOffsetY))
        amplitudeZ = step_height_multiplier * (strideX + rotOffsetX) / 4.0;
    else
        amplitudeZ = step_height_multiplier * (strideY + rotOffsetY) / 4.0;
}
```

```
void compute_amplitudes2() {
    totalX = HOME_X[leg_num] + BODY_X[leg_num];
    totalY = HOME_Y[leg_num] + BODY_Y[leg_num];

    rotOffsetX = totalY * sinRotZ + totalX * cosRotZ - totalX;
    rotOffsetY = totalY * cosRotZ - totalX * sinRotZ - totalY;

    amplitudeX = ((strideX + rotOffsetX) / 2.0);
    amplitudeY = ((strideY + rotOffsetY) / 2.0);
    amplitudeX = constrain(amplitudeX, -50, 50);
    amplitudeY = constrain(amplitudeY, -50, 50);

    if (abs(strideX + rotOffsetX) > abs(strideY + rotOffsetY))
        amplitudeZ = step_height_multiplier2 * (strideX + rotOffsetX);
    else
        amplitudeZ = step_height_multiplier2 * (strideY + rotOffsetY);
}
```

Explanation:

- `compute_amplitudes()` calculates movement amplitudes for standard gaits
- `compute_amplitudes2()` is specifically for the obstacle gait, using a larger step height multiplier

Both functions:

1. Calculate the total X and Y positions for the current leg
2. Apply rotation offsets to handle turning movements

3. Calculate X and Y amplitudes based on stride length and rotation
4. Constrain amplitudes to prevent overextension
5. Calculate Z amplitude (leg height) based on whichever is larger between X and Y movements

The key difference is that `compute_amplitudes2()` uses a larger step height multiplier (`step_height_multiplier2 = 10` vs `step_height_multiplier = 3.5`) and doesn't divide by 4.0, resulting in much higher leg lifts for obstacle navigation.

4.6 Tripod Gait Implementation

```
void tripod_gait() {

    if ((abs(commandedX) > 15) || (abs(commandedY) > 15) || (abs(commandedR) > 15) || (tick > 0)) {

        compute_strides();

        numTicks = round(duration / FRAME_TIME_MS / 2.0);

        for (leg_num = 0; leg_num < 6; leg_num++) {

            compute_amplitudes();

            switch (tripod_case[leg_num]) {

                case 1:

                    current_X[leg_num] = HOME_X[leg_num] - amplitudeX * cos(M_PI * tick / numTicks);

                    current_Y[leg_num] = HOME_Y[leg_num] - amplitudeY * cos(M_PI * tick / numTicks);

                     current_Z[leg_num] = HOME_Z[leg_num] + abs(amplitudeZ) * sin(M_PI * tick / numTicks);

                    if (tick >= numTicks - 1) tripod_case[leg_num] = 2;

                    break;

                case 2:

                      current_X[leg_num] = HOME_X[leg_num] + amplitudeX * cos(M_PI * tick / numTicks);
```

```
                    current_Y[leg_num] = HOME_Y[leg_num] + amplitudeY * cos(M_PI *
tick / numTicks);

                current_Z[leg_num] = HOME_Z[leg_num];

                if (tick >= numTicks - 1) tripod_case[leg_num] = 1;

                break;

            }

        }


        if (tick < numTicks - 1) tick++;

        else tick = 0;

    }

}
```

Explanation: The tripod gait is the fastest walking pattern, where three legs move simultaneously while the other three support the robot. The function:

1. Executes only when commanded to move or if already in motion (`tick > 0`)
2. Calculates stride lengths and required number of ticks (dividing by 2.0 for two-phase movement)
3. For each leg:
    - In case 1 (swing phase): The leg is lifted (positive Z) and moved forward using cosine and sine functions
    - In case 2 (stance phase): The leg maintains contact with the ground (Z = HOME_Z) while moving backward to propel the robot forward
4. Changes phases when the tick count is reached
5. Increments the tick counter or resets it when the cycle is complete

The `tripod_case` array is initialized as `{1, 2, 1, 2, 1, 2}`, meaning legs 0, 2, and 4 move together, while legs 1, 3, and 5 move together in the opposite phase. This ensures the robot always has a stable tripod of support.

4.7 Ripple Gait Implementation

```
void ripple_gait() {
```

```
    if ((abs(commandedX) > 15) || (abs(commandedY) > 15) || (abs(commandedR) >
15) || (tick > 0)) {

        compute_strides();

         numTicks = round(duration / FRAME_TIME_MS / 6.0);  //total ticks divided into
the six cases

        for (leg_num = 0; leg_num < 6; leg_num++) {

            compute_amplitudes();

            switch (ripple_case[leg_num]) {

                case 1:  //move foot forward (raise)

                    current_X[leg_num] = HOME_X[leg_num] - amplitudeX * cos(M_PI * tick
/ (numTicks * 2));

                    current_Y[leg_num] = HOME_Y[leg_num] - amplitudeY * cos(M_PI * tick
/ (numTicks * 2));

                     current_Z[leg_num] = HOME_Z[leg_num] + abs(amplitudeZ) * sin(M_PI
* tick / (numTicks * 2));

                    if (tick >= numTicks - 1) ripple_case[leg_num] = 2;

                    break;

                case 2:  //move foot forward (lower)

                        current_X[leg_num] = HOME_X[leg_num] - amplitudeX * cos(M_PI *
(numTicks + tick) / (numTicks * 2));

                        current_Y[leg_num] = HOME_Y[leg_num] - amplitudeY * cos(M_PI *
(numTicks + tick) / (numTicks * 2));

                     current_Z[leg_num] = HOME_Z[leg_num] + abs(amplitudeZ) * sin(M_PI
* (numTicks + tick) / (numTicks * 2));

                    if (tick >= numTicks - 1) ripple_case[leg_num] = 3;

                    break;

                case 3:  //move foot back one-quarter (on the ground)

                        current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.0;
```

```
                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.0;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1) ripple_case[leg_num] = 4;

            break;

        case 4:  //move foot back one-quarter (on the ground)

                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.0;

                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.0;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1) ripple_case[leg_num] = 5;

            break;

        case 5:  //move foot back one-quarter (on the ground)

                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.0;

                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.0;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1) ripple_case[leg_num] = 6;

            break;

        case 6:  //move foot back one-quarter (on the ground)

                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.0;

                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.0;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1) ripple_case[leg_num] = 1;
```

```
                break;
            }
        }
        //increment tick
        if (tick < numTicks - 1) tick++;
        else tick = 0;
    }
}
```

Explanation: The ripple gait is more stable than the tripod gait, with legs moving in a wave-like sequence. The function:

1. Uses 6 phases (cases) for smooth transitions
2. Cases 1-2: Lifting and moving the leg forward (swing phase)
    - Case 1: First half of the leg lift and forward movement
    - Case 2: Second half of the leg lift and forward placement
3. Cases 3-6: Moving the leg backward while on the ground (stance phase)
    - The backward movement is divided into 4 equal parts (cases 3-6)
    - Each phase moves the leg back by 1/4 of the total backward distance

The `ripple_case` array is initialized as `{2, 6, 4, 1, 3, 5}`, which means each leg is in a different phase of the cycle. This ensures that only one leg is lifted at a time, maintaining a stable gait with at least 5 feet on the ground at all times.

4.8 Wave Gait Implementation

```
void wave_gait() {
    if ((abs(commandedX) > 15) || (abs(commandedY) > 15) || (abs(commandedR) > 15) || (tick > 0)) {
        compute_strides();
        numTicks = round(duration / FRAME_TIME_MS / 6.0);
        for (leg_num = 0; leg_num < 6; leg_num++) {
            compute_amplitudes();
```

```
        switch (wave_case[leg_num]) {

            case 1:  //move foot forward (raise and lower)

                current_X[leg_num] = HOME_X[leg_num] - amplitudeX * cos(M_PI * tick
/ numTicks);

                current_Y[leg_num] = HOME_Y[leg_num] - amplitudeY * cos(M_PI * tick
/ numTicks);

                 current_Z[leg_num] = HOME_Z[leg_num] + abs(amplitudeZ) * sin(M_PI
* tick / numTicks);

                if (tick >= numTicks - 1) wave_case[leg_num] = 6;

                break;

            case 2:  //move foot back one-fifth (on the ground)

                    current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.5;

                    current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.5;

                current_Z[leg_num] = HOME_Z[leg_num];

                if (tick >= numTicks - 1) wave_case[leg_num] = 1;

                break;

            case 3:  //move foot back one-fifth (on the ground)

                    current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.5;

                    current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.5;

                current_Z[leg_num] = HOME_Z[leg_num];

                if (tick >= numTicks - 1) wave_case[leg_num] = 2;

                break;

            case 4:  //move foot back one-fifth (on the ground)
```

```
                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.5;

                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.5;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1)

               wave_case[leg_num] = 3;

            break;

         case 5:  //move foot back one-fifth (on the ground)

                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.5;

                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.5;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1) wave_case[leg_num] = 4;

            break;

         case 6:  //move foot back one-fifth (on the ground)

                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks /
2.5;

                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks /
2.5;

            current_Z[leg_num] = HOME_Z[leg_num];

            if (tick >= numTicks - 1) wave_case[leg_num] = 5;

            break;

      }

   }

   //increment tick

   if (tick < numTicks - 1) tick++;
```

```
        else tick = 0;
    }
}
```

Explanation: The wave gait is the most stable but slowest gait, where only one leg moves at a time. The function:

1. Uses 6 phases for each leg, similar to the ripple gait
2. Case 1: Complete leg lift and forward movement in a single phase
3. Cases 2-6: Ground contact phases where the leg moves backward in 5 equal parts (each 1/5 of the total backward movement)

The `wave_case` array is initialized as `{1, 2, 3, 4, 5, 6}`, which sequences the legs to move one after another in numerical order. This ensures maximum stability with 5 legs on the ground at all times, but results in slower movement compared to other gaits.

4.9 Tetrapod Gait Implementation

```
void tetrapod_gait() {
    if ((abs(commandedX) > 15) || (abs(commandedY) > 15) || (abs(commandedR) > 15) || (tick > 0)) {
        compute_strides();
         numTicks = round(duration / FRAME_TIME_MS / 3.0);  //total ticks divided into the three cases
        for (leg_num = 0; leg_num < 6; leg_num++) {
            compute_amplitudes();
            switch (tetrapod_case[leg_num]) {
                case 1:  //move foot forward (raise and lower)
                    current_X[leg_num] = HOME_X[leg_num] - amplitudeX * cos(M_PI * tick / numTicks);
                    current_Y[leg_num] = HOME_Y[leg_num] - amplitudeY * cos(M_PI * tick / numTicks);
```

```
                current_Z[leg_num] = HOME_Z[leg_num] + abs(amplitudeZ) * sin(M_PI
* tick / numTicks);
                if (tick >= numTicks - 1) tetrapod_case[leg_num] = 2;
                break;
            case 2:  //move foot back one-half (on the ground)
                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks;
                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks;
                current_Z[leg_num] = HOME_Z[leg_num];
                if (tick >= numTicks - 1) tetrapod_case[leg_num] = 3;
                break;
            case 3:  //move foot back one-half (on the ground)
                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks;
                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks;
                current_Z[leg_num] = HOME_Z[leg_num];
                if (tick >= numTicks - 1) tetrapod_case[leg_num] = 1;
                break;
        }
    }

    if (tick < numTicks - 1) tick++;
    else tick = 0;
  }
}
```

Explanation: The tetrapod gait is a balance between stability and speed, with two legs moving at a time. The function:

1. Uses 3 phases for each leg
2. Case 1: Leg is lifted and moved forward (swing phase)
3. Cases 2-3: Leg is on the ground and moved backward in two equal parts (stance phase)

The `tetrapod_case` array is initialized as `{1, 3, 2, 1, 2, 3}`, which creates a pattern where two legs are in the air at any given time. This provides a good balance between the tripod gait (faster but less stable) and the wave gait (slower but more stable).

4.10 Obstacle Gait Implementation

```
void obstacle_gait() {

    if ((abs(commandedX) > 15) || (abs(commandedY) > 15) || (abs(commandedR) > 15) || (tick > 0)) {

        compute_strides();

          numTicks = round(duration / FRAME_TIME_MS / 3.0);  //total ticks divided into the three cases

        for (leg_num = 0; leg_num < 6; leg_num++) {

            compute_amplitudes2();

            switch (tetrapod_case[leg_num]) {

                case 1:  //move foot forward (raise and lower)

                    current_X[leg_num] = HOME_X[leg_num] - amplitudeX * cos(M_PI * tick / numTicks);

                    current_Y[leg_num] = HOME_Y[leg_num] - amplitudeY * cos(M_PI * tick / numTicks);

                    current_Z[leg_num] = HOME_Z[leg_num] + (abs(amplitudeZ) * sin(M_PI * tick / numTicks)*1.5) + 20;

                    if (tick >= numTicks - 1) tetrapod_case[leg_num] = 2;

                    break;

                case 2:  //move foot back one-half (on the ground)

                    current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks;
```

```
                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks;
                current_Z[leg_num] = HOME_Z[leg_num];
                if (tick >= numTicks - 1) tetrapod_case[leg_num] = 3;
                break;
            case 3:  //move foot back one-half (on the ground)
                current_X[leg_num] = current_X[leg_num] - amplitudeX / numTicks;
                current_Y[leg_num] = current_Y[leg_num] - amplitudeY / numTicks;
                current_Z[leg_num] = HOME_Z[leg_num];
                if (tick >= numTicks - 1) tetrapod_case[leg_num] = 1;
                break;
        }
      }

      if (tick < numTicks - 1) tick++;
      else tick = 0;
   }
}
```

Explanation: The obstacle gait is a specialized variant of the tetrapod gait designed specifically for navigating over obstacles. Key differences include:

1. Uses the `compute_amplitudes2()` function which calculates much higher step heights
2. Adds additional leg lift with a factor of 1.5 and a constant +20 units to the Z position
3. Uses the same phase structure as the tetrapod gait (3 phases) but with exaggerated vertical movement

This gait follows the same leg sequencing as the tetrapod gait but with significantly higher leg lifts to clear obstacles. The amplitude calculation uses a much larger

height multiplier (10 vs 3.5) and the leg Z position includes an additional multiplier (1.5) and offset (+20) to ensure maximum clearance.

4.11 Command Processing Function

```
void process_command() {
  if (current_command >= '0' && current_command <= '9') {
    // Convert char to int
    int num = current_command - '0';

    // Select gait based on number ranges
    if (num == 0) {
      gait = 0;  // Tripod gait
    }
    else if (num >= 1 && num <= 3) {
      gait = 1;  // Wave gait
    }
    else if (num >= 4 && num <= 6) {
      gait = 2;  // Ripple gait
    }
    else if (num >= 7 && num <= 9) {
      gait = 3;  // Tetrapod gait
    }
    Serial.print("Gait changed to: ");
    Serial.println(gait);
  }
  else {
```

```
    int current_speed = (gait == 1) ? 50 : commanded_speed;
    switch (current_command) {
      case 'F':  // Forward
        commandedX = current_speed;
        commandedY = 0;
        commandedR = 0;
        break;
      // ... [other movement commands]
      case 'S':  // Stop
      default:
        commandedX = 0;
        commandedY = 0;
        commandedR = 0;
        break;
    }
  }
}
```

Explanation: The `process_command()` function interprets serial commands to control the robot's movement and gait selection:

1. Numeric commands (0-9) select different gaits:
    - 0: Tripod gait
    - 1-3: Obstacle gait (originally Wave gait)
    - 4-6: Ripple gait
    - 7-9: Tetrapod gait
2. Letter commands control movement directions:
    - F: Forward

    - B: Backward
    - L: Left
    - R: Right
    - G, I, H, J: Diagonal movements
    - W, U: Rotation
    - S: Stop
3. The function also reduces speed for the obstacle gait (50 vs 130) to ensure more controlled movements.

4.12 Summary of Gait Characteristics

GAIT TYPE	LEGS IN AIR	STABILITY	SPEED	SPECIAL FEATURE
TRIPOD	3	LOW	HIGH	Fast walking for even terrain
RIPPLE	1	HIGH	LOW	Smooth transitions between leg movements
WAVE	1	HIGEST	LOWEST	One leg at a time, extremely stable
TETRAPOD	2	MEDIUM	MEDIUM	Good balance of stability and speed
OBSTACLE	2	MEDIUM	LOW	Exaggerated leg lifts for obstacles

The choice of gait depends on the specific terrain requirements and movement priorities:

- Tripod gait is ideal for flat surfaces where speed is prioritized
- Ripple and wave gaits provide maximum stability for uneven terrain

- Tetrapod gait offers a balance between speed and stability
- Obstacle gait with its high leg lifts is specifically designed for navigating over obstacles

Chapter - 5

Results and Discussion

5.1 Locomotion Performance

The Spider Scout demonstrated successful implementation of multiple gait patterns, with the following results:

Tripod Gait Performance:

- Achieved a maximum forward speed of approximately 0.15 m/s on flat surfaces
- Maintained stability during directional changes
- Showed consistent performance across multiple test runs

Wave Gait Performance:

- Provided enhanced stability on uneven surfaces
- Successfully navigated inclines of up to 20 degrees
- Demonstrated smoother transitions when climbing over small obstacles

Turning Capabilities:

- Achieved in-place rotation with an average turning rate of 30 degrees per second
- Maintained positional accuracy during complex movement sequences

The tripod gait proved most efficient on flat surfaces, while the wave gait showed superior performance on uneven terrain. This validated the decision to implement multiple gait patterns for different scenarios.

5.2 Power System Performance

The custom battery management system and power distribution architecture yielded the following results:

Battery Performance:

- The custom 12.6V (3S) battery pack with parallel cell configuration provided approximately 45 minutes of continuous operation
- Voltage remained stable (±0.2V) under varying load conditions
- BMS successfully prevented over-discharge during extended testing

Buck Converter Performance:

- Maintained stable output voltages (±0.1V) during peak current demands
- Achieved efficiency ratings of approximately 85-90% across operational range
- Thermal management remained within acceptable limits without additional cooling

Current Distribution:

- Peak current draw measured at approximately 8A during startup sequences
- Steady-state current during walking averaged 4-5A
- Idle current draw measured at 0.8A

The transition from commercial battery solutions to the custom BMS resulted in a 35% increase in operational time and significantly improved voltage stability during high-current operations.

5.3 Control System Effectiveness

The Arduino Mega implementation demonstrated suitable performance for the hexapod control requirements:

Processing Capabilities:

- Successfully managed inverse kinematics calculations with minimal delay
- Maintained consistent 50Hz PWM signal generation for all 18 servos
- Handled Bluetooth communication without noticeable impact on locomotion control

Bluetooth Communication:

- Achieved reliable communication range of approximately 10 meters in typical indoor environments
- Command latency measured at an average of 120ms from transmission to execution
- Maintained stable connection during continuous operation

Control Accuracy:

- Leg positioning accuracy measured within ±2mm of target positions
- Consistent timing maintained between leg movements (±15ms variation)
- Smooth transitions between different movement commands

5.4 ESP32-CAM System Performance

The integrated camera system provided the following capabilities:

Video Streaming:

- Achieved stable streaming at 640x480 resolution at approximately 15-20 fps
- WiFi range extended to approximately 15 meters in line-of-sight conditions
- Image quality remained usable in moderate lighting conditions

Pan-Tilt Functionality:

- Pan range of approximately 180 degrees
- Tilt range of approximately 90 degrees
- Positioning accuracy within ±3 degrees of target position

System Integration:

- Operating the camera system concurrently with locomotion showed minimal interference
- Dedicated power supply successfully isolated the camera system from servo-induced voltage fluctuations

5.5 Mechanical Design Evaluation

The 3D-printed structure performed well during testing:

Structural Integrity:

- Withstood normal operational stresses without visible deformation
- Successfully supported the weight of all components (approximately 1.2kg total)
- Maintained alignment of mechanical components throughout testing

Weight Distribution:

- Center of gravity remained appropriately positioned for stable locomotion
- Weight distribution between legs remained balanced during various poses

Durability:

- After approximately 20 hours of cumulative testing, minimal wear was observed at joint interfaces
- PLA material proved sufficient for the intended application, though some components may benefit from more durable materials in future iterations

Chapter - 6

Troubleshooting

1. Understanding Power Requirements

The hexapod robot is powered by 18 MG996R servo motors, with each motor operating at 4.8V to 7.2V. Under normal conditions, each servo draws 500mA to 900mA, but under high loads, the current can spike to 2.5A per motor. Given that the hexapod uses 18 motors, the total power consumption can exceed 20A under heavy load. This creates a significant challenge in providing adequate power while maintaining system stability.

2. Issues Faced

2.1 Using Arduino Nano

The initial prototype of the hexapod was controlled using an Arduino Nano. While the Nano had sufficient PWM (Pulse Width Modulation) outputs for controlling servos, it was not designed to handle high-current devices. The primary issues faced were:

- The Nano could not provide enough current to power the servos.
- The servos would stutter, fail to move properly, or behave erratically.
- A significant voltage drop was observed when multiple servos were actuated simultaneously.
- The Nano would occasionally restart due to excessive current draw.

2.2 Switching to Teensy 4.1

To overcome the power limitations, the Nano was replaced with a Teensy 4.1, which offers higher processing power and more PWM channels. However, despite the upgrade, similar power issues persisted:

- The servos were still not receiving stable power.
- The Teensy board did not have an onboard voltage regulator capable of handling high-current loads.
- The servos displayed inconsistent movement and lacked torque under heavy loads.

The primary issue was that both microcontrollers were attempting to supply power to the servos, which exceeded their capabilities.

3. Implemented Solution

3.1 Switching to Arduino Mega

To resolve these issues, an Arduino Mega was used instead of the Teensy 4.1. The Mega provided a stable platform with better power management and was able to control all servos efficiently.

3.2 External Power Supply for Servos

A separate power source was introduced to supply power to the servos. Instead of drawing power from the microcontroller, a dedicated high-current power supply was used to provide 6V with at least 20A output, ensuring stable operation.

3.3 Proper Power Distribution and Wiring

- Power Distribution Board: A dedicated board was used to distribute power evenly among all servos.
- Thicker Wires: High-gauge wires were used to reduce resistance and voltage drops.
- Common Ground Connection: A single ground was used to prevent floating voltages and improve system stability.

4. Final Outcome

After implementing these improvements, the power issues were resolved, and the hexapod operated smoothly with stable servo movement. The troubleshooting process highlighted the importance of proper power management in servo-driven robotic systems.

Chapter - 7

Conclusion

The Spider Scout hexapod robot project successfully achieved its primary objectives, demonstrating a functional integration of mechanical design, electronic control systems, power management, and camera capabilities. Through an iterative development process, several key challenges were overcome, resulting in a versatile robotic platform with potential applications in surveillance, exploration, and education.

Key accomplishments of this project include:

1. **Successful Implementation of Multiple Gait Patterns**: The hexapod demonstrated stable locomotion using both tripod and wave gaits, allowing it to navigate various terrain types effectively.

2. **Custom Power Management Solution**: The development of a tailored battery management system significantly improved operational time and voltage stability compared to off-the-shelf solutions, addressing one of the most challenging aspects of mobile robotics.

3. **Effective Integration of Camera System**: The ESP32-CAM implementation with pan-tilt functionality expanded the robot's capabilities beyond basic locomotion, enabling potential applications in remote surveillance and exploration.

4. **Optimized 3D-Printed Structure**: The custom-designed and 3D-printed components provided a lightweight yet sturdy platform for all systems, demonstrating the viability of additive manufacturing for robotics applications.

5. **Wireless Control Implementation**: The Bluetooth interface enabled intuitive control through a mobile application, allowing for flexible operation without physical tethering.

Limitations and areas for future improvement include:

1. **Battery Life**: While significantly improved from initial implementations, the operational time could be further extended through more efficient locomotion algorithms and lower-power components.

2. **Autonomous Capabilities**: The current implementation relies entirely on remote control; future iterations could incorporate sensors for obstacle

detection and autonomous navigation.

3. **Structural Materials**: While PLA proved sufficient for this prototype, more durable materials like PETG or nylon might be necessary for long-term reliability in field applications.

4. **Camera System Integration**: Deeper integration between the locomotion control system and camera system could enable more advanced features, such as automatic tracking or mapping.

This project provided valuable insights into the challenges and solutions associated with legged robot design, particularly in the areas of power management and system integration. The interdisciplinary nature of the project encompassed mechanical engineering, electronics, power systems, software development, and communications, offering a comprehensive educational experience in robotics engineering.

The Spider Scout serves as a foundation for future exploration in hexapod robotics, with potential paths for advancement in autonomous operation, sensor integration, and alternative power sources. As legged robots continue to advance in capability and accessibility, projects like this contribute to the growing body of knowledge in this evolving field.

Chapter - 8

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Chapter - 9

Annexure I - Relevant Codes / Data Sheets of Major Components

9.1 ESP32-CAM Pan-Tilt Control Code

The ESP32-CAM module was programmed to provide real-time video streaming with remote pan and tilt control through a web interface. The implementation includes server-side handling of video streaming and client-side controls for camera positioning. The key components of this implementation include:

- Configuration for the AI-THINKER camera model
- PWM servo control for pan and tilt mechanisms
- Web server implementation for streaming and control interface
- WiFi connectivity for remote access

The complete code includes camera initialization, servo control functions, HTTP server setup, and HTML/JavaScript for the user interface. This integrated system enables real-time monitoring from the hexapod's perspective with adjustable viewing angles.

9.2 Servo Motor Specifications (MG996R)

- Operating Voltage: 4.8V to 7.2V
- Stall Torque:
    - 9.4 kg-cm (4.8V)
    - 11 kg-cm (6V)
- Speed:
    - 0.17 sec/60° (4.8V)
    - 0.14 sec/60° (6V)
- Weight: 55g
- Dimensions: 40.7 × 19.7 × 42.9 mm
- Rotation: 0° - 180°
- Pulse Cycle: 20ms
- Pulse Width: 1-2ms
- Current Draw (No Load): ~500mA
- Current Draw (Stall): ~2.5A

9.3 Battery Management System Specifications

- Input Voltage: 12.6V (3S Li-ion/LiPo configuration)
- Continuous Discharge Current: 15A
- Peak Discharge Current: 20A (10 seconds)

- Over-discharge Protection: 3.0V per cell
- Overcharge Protection: 4.25V per cell
- Balance Current: 60mA per cell
- Operating Temperature: -10°C to 60°C
- Protection Features:
    - Short circuit protection
    - Overcurrent protection
    - Temperature monitoring
    - Cell balancing

9.4 Buck Converter Specifications

- Input Voltage Range: 7-35V
- Output Voltage: Adjustable 1.25-30V
- Maximum Output Current: 5A continuous, 8A peak
- Efficiency: >90% at optimal load
- Switching Frequency: 180kHz
- Protection: Short circuit, thermal shutdown
- Dimensions: 43mm × 21mm × 14mm

ANNEXURE-II
Datasheets