POWER MANAGEMENT FOR LONG-DURATION SURVEILLANCE HUMANOID ROBOTS

MINOR PROJECT-1 REPORT

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BONAFIDE CERTIFICATE

Certified that this Minor project-1 report entitled **"POWER MANAGEMENT FOR LONG-DURATION SURVEILLANCE HUMANOID ROBOTS "** is the bonafide work of **"MADHIREDDY NISCHAY REDDY (22UEEA0045), MUKKALA NIKHILESH (22UEEA0052) and DODDETIPALLI MAHENDRA (22UEEA0018)"** who carried out the project work under my supervision.

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TABLE OF CONTENTS

ABSTRACT

The growing sophistication and functionality of contemporary embedded and robotic systems require effective energy management for optimal performance and extended operational lifetime. This project suggests the creation of an adaptive power management system that would optimize energy allocation across critical components—actuators, sensors, and processors. As opposed to conventional fixed power allocation techniques, the system suggested here dynamically tracks current workloads, ambient conditions, and system priorities to wisely distribute power where and when it is required the most. Through utilization of methods like predictive modeling, priority scheduling, and feedback mechanisms, the system attempts to save energy, avoid component overloading, and maximize battery life without sacrificing performance. This adaptive strategy not only improves energy efficiency but also ensures the sustainability and reliability of autonomous systems, making it very appropriate for robotics, IoT devices, and smart infrastructure applications

The growing use of humanoid robots for long-duration monitoring in security, defense, and disaster management domains has brought in a crucial demand for sophisticated power management techniques. These robots are anticipated to run autonomously for long periods of time in changing environments, and energy efficiency and thermal stability are therefore critical to their success.

This project aims to create an integrated power management system tailored to long-duration surveillance humanoid robots to optimize energy efficiency, enhance thermal performance, and provide operational reliability. Underpinning the new system is the integration of power-saving hardware devices including low-power microcontrollers (MCUs), application-specific integrated circuits (ASICs), and dynamic voltage and frequency scaling (DVFS) methodologies. These devices enable the robot to adjust processing capacity adaptively according to task requirements and, in turn, save energy without sacrificing performance. Energy-saving actuators that come with regenerative braking technologies are also employed to recover and reuse energy when moving, enhancing power savings across the board.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASIC	-	application-specific integrated circuits
MCU	-	micro controller unit
BLE	-	bluetooth low energy
DVFS	-	dynamic voltage and frequency scaling
BMS	-	Battery management system
LIDAR	-	light detection and ranging
PWM	-	pulse width modulation
GPIO	-	general purpose input and output
I2C	-	Inter-Integrated Circuit)
UART	-	universal Asynchronous Receiver/Transmitter
TIM	-	thermal interface material
LFP	-	lithium ferro phosphate
V	-	voltage

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF HUMANOID ROBOTS

Humanoid robots are robotic systems created to imitate the look and movement of the human figure, usually with a head, body, arms, and legs. Humanoid robots can act in environments that are human-oriented, accomplish activities that call for mobility, perception, and human interaction. Designed with sophisticated sensors, actuators, and processors, humanoid robots can walk, speak, and move objects, making them appropriate for use in surveillance, healthcare, customer service, and research. Humanoid robots are especially applicable in surveillance because they can move through human spaces and interact naturally with humans. One of the biggest challenges, though, in using them comes from managing power effectively. Their sophisticated functionality demands persistent energy for movement, sensing, processing, and communication, which can rapidly consume power sources. Hence, the improvement of energy efficiency is paramount for facilitating long-duration autonomous functioning and overall reliability of humanoid robots in real-world operations.

1.2 IMPORTANCE OF POWER MANAGEMENT

Good power management is essential to enabling long-duration surveillance humanoid robots to be effective for extended periods of operation. One of the key strategies is energy distribution optimization across the various components of the robot. Adaptive power management can distribute energy smartly between the actuators, sensors, and processors depending on the workload and robot priorities. For instance, when the robot is static, surveilling a location, there is more energy allocated to the sensors and the communications systems while the actuators are in low-power operation. When it is moving or it is navigating, the energy is allocated differently with more emphasis on the actuators and the processors to enable mobility and decision-making needs. This real-time allocation optimizes the battery life and makes power available to the necessary components at exactly the right times.

Another critical component of power management is the use of energy-efficient hardware. Low-power microcontrollers (MCUs) and application-specific integrated circuits (ASICs) enable significant power savings in baseline processing unit utilization. These chips are specifically designed to perform complex calculations with minimal energy consumption, making them ideal for power-sensitive applications. Dynamic voltage and frequency scaling (DVFS) also enables processors to scale performance based on workload requirements. During low processing loads, the processor can operate at a reduced voltage and frequency to conserve power. During high-performance requirements, the system can dynamically boost processing speed temporarily to provide efficiency without compromising energy goals. Actuators that drive the robot's motion can also be optimized with energy-saving technologies. Actuators with regenerative braking technology can capture and recycle energy that would otherwise be wasted on braking. The captured energy is channeled to the power system, which means more efficiency and working time.

Reducing overall power usage is another primary strategy in long-duration surveillance missions. Low-power communication protocols like Zigbee, Bluetooth Low Energy (BLE), or power-saving Wi-Fi allow constant data streaming with little energy usage. Such protocols are well-suited for robots that require constant data streaming to control centers with little battery drain.

1.3 SCOPE AND OBJECTIVES OF THE STUDY

This research focuses on the design and development of an adaptive power management system for long-duration surveillance humanoid robots to enhance energy efficiency, thermal stability, and system reliability. The scope of the project involves analysis and integration of future-generation battery technologies, low-power hardware devices, and intelligent energy distribution strategies to optimize robotic subsystem operations such as actuators, sensors, and processors. It further involves the integration of simple and scalable circuit topologies to reduce power losses and application of regenerative braking and low-power communication protocols to minimize energy usage during autonomous operation. Integration of passive thermal management techniques such as graphite-based thermal sinks for efficient heat dissipation and component overheating prevention during long-duration tasks is also an essential part of the research. This project is focused on enabling humanoid robots to operate flawlessly in real-time applications—such as security surveillance, disaster response, industrial automation, and smart healthcare—by optimizing battery life, providing system stability, and enabling continuous, long-duration autonomous operation.

CHAPTER 2

LITERATURE REVIEW

Humanoid robots are becoming more prevalent in surveillance use due to their ability to mimic human action and navigate spaces intended for human use. The robots are typically equipped with advanced sensors, actuators, cameras, and processors to execute operations such as patrolling, object identification, crowd surveillance, and threat detection. However, one of the most critical challenges facing today's surveillance humanoid robots is efficient **power management**, especially for long-duration, autonomous operations.

Some of the most famous humanoid surveillance robots are **ASIMO by Honda**, **Atlas by Boston Dynamics**, **Pepper by SoftBank Robotics**, and **NAO Robot**. Even though all of these robots were made for slightly different functions, they all have common elements like mobility systems, sensor suites, processors, and communication ports that consume significant amounts of power to run. Most of these robots are capable of doing complicated movements, human gesture or face recognition, and communication with users, but they generally have a limited operating time due to the limitations of the batteries.

For example, **ASIMO**, which is meant for mobility and interaction, is capable of making dynamic movements such as walking, running, and ascending stairs. Even though it is endowed with capabilities, its maximum operating duration is around an hour when fully powered. In the same vein, **Atlas**, with high-performance actuators and advanced mobility features, is a power guzzler, and this restricts its continuous use without external power sources. These robots indicate the necessity of advanced power management systems to increase operating endurance.

For the cases of **Pepper** and **NAO**, most often used for indoor surveillance, assistance, and learning, their short battery life of around 1.5 to 2 hours when operating continuously restricts their activities in extended missions. The robots need to be recharged manually or use docking stations, which interrupts the continuity of observation and decreases efficiency on environments requiring constant observation.

To improve the efficiency and longevity of such robots, power management systems must move beyond simple battery storage and utilization. Most present robots use lithium-ion batteries, which offer an acceptable weight-energy trade-off, but such systems lack **adaptive power distribution**, **energy-efficient hardware**, and **smart energy-saving protocols**. Robots must be equipped with low-power processors, energy-aware task scheduling, dynamic voltage scaling, and regenerative braking in actuators for saving energy during movement in long-duration applications.

Another disadvantage of current systems is inefficient use of energy by different subsystems that all get powered on at the same time. The cameras, sensors, and processor all run at full load regardless of current need, wasting power. This is where **context-aware power optimization** is essential—allowing the robot to switch off or scale back power to non-mission-critical elements when stationary or low load conditions are met.

In addition, communication systems of surveillance robots, particularly those operating remotely or in huge buildings, require a lot of power. Current solutions typically use Wi-Fi or cellular modules without power-saving optimization. Adding low-power communication protocols such as BLE or Zigbee, and smart data transmission schedules, may cut power consumption in half.

In short, while recent humanoid surveillance robots exhibit outstanding performance, their performance is restricted by power limitations. To achieve long-duration capability for next-generation humanoid surveillance systems, there needs to be an integrated power management solution involving hardware, software optimization, and real-time energy allocation for providing seamless and efficient operation throughout long-duration missions. The design of such systems not only will extend surveillance coverage but also enhance robot autonomy and reliability of security solutions.

CHAPTER 3

SYSTEM ARCHITECTURE

3.1 BLOCK DIAGRAM

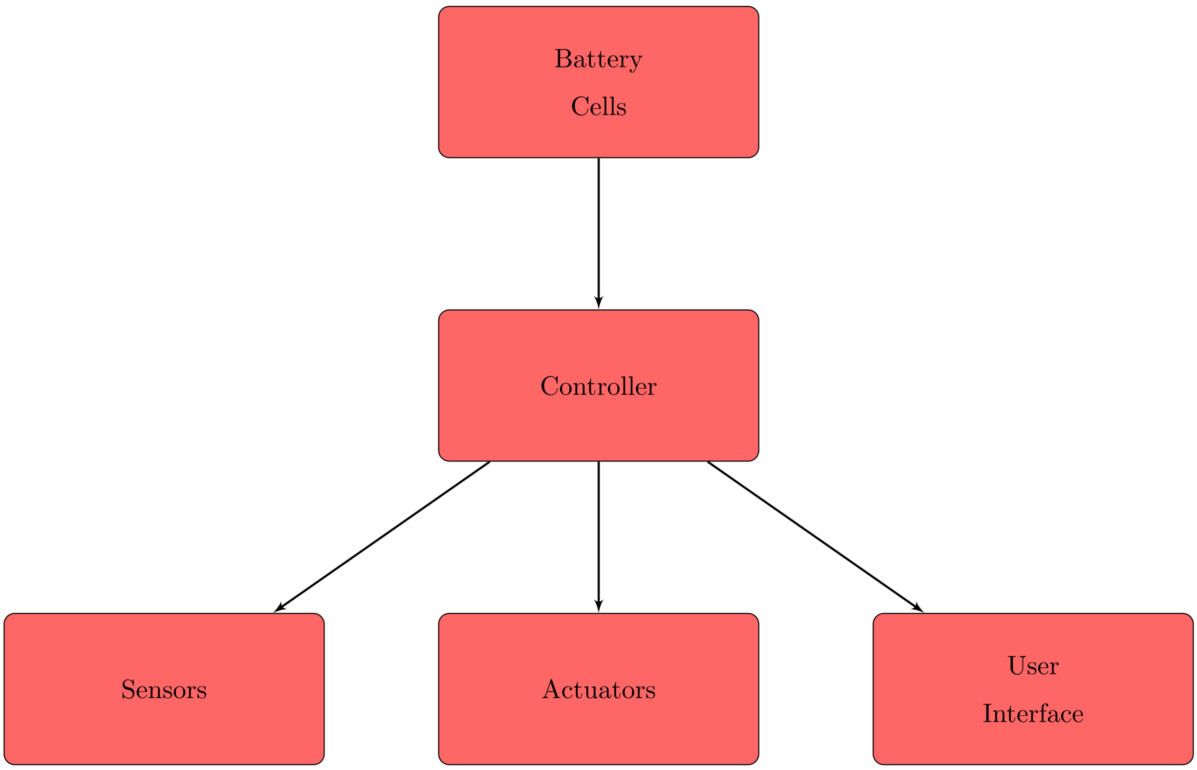
The humanoid robot is configured with four integrated subsystems: power distribution, control and processing, actuation and sensory modules, and communication interfaces. The power distribution subsystem uses a two-tier system to supply both high and low voltage levels. DC motors and motor drivers are classified as high-power components and are supplied by a 12V source. Controllers and sensors are lower-powered components that will operate on a regulated 5V supply. To guarantee smooth and efficient energy management, a low-forwarding operation is used.

The control and processing subsystem has two Raspberry Pi boards that are fully utilized. One of the boards controls locomotion by generating PWM signals to drive the corresponding DC and servo motors. This enables smooth and precise movements. The second board is assigned to handle multimedia processing tasks that include real-time video capture, object recognition, and audio processing with voice interaction. This division of tasks helps in optimizing the performance and avoiding resource bottlenecks during operation.

The finesse of the locomotion in the robotic device is executed using DC motors while the limbs and head of the robot is moved with finer adjustments using servo motors. These robotic actuators are capable of performing robotic motions such as walking, turning, arm lifting, and head rotation, just like a human being. Cameras and microphones of high precision are also included within the sensory subsystem which capture the video and audio feeds in real-time. This information is processed by the multimedia unit to improve situational awareness and intelligence through advanced imaging techniques.

All subsystems are integrated with an extensive communication system that allows them to function cohesively. Controllers, sensors, and actuators are connected with each other using GPIO, I2C, and UART interfaces enabling smooth data transfer. Detection and control units constructing hazardous areas are maintained at a constant level pair with the use of shielded cables and isolated power lines which eliminate emissions of electromagnetic radiation guaranteeing system steady. Due to the modular structure, the robot can be easily customized by adding extra units making it ideal for long-range observation missions.

In order to integrate more energy management features, energy harvesting methods like solar panels or kinetic energy converters can be added to further supplement power during idle periods. Power consumption patterns are tracked continuously by the system, which allows for management based on real-time requirements. More sophisticated algorithms predict and adjust the energy consumption of non-essential components while ensuring main components receive priority power allocation. An internal feedback loop automates reactivity to changing external conditions using signals from the robot sensors and power management unit. Additionally, commanding low-power modes during non-surveillance phases helps preserve energy while maintaining a high level of responsiveness. This level of tactical energy management enables enhanced longevity without compromising dynamic operation. For demanding surveillance missions, the system assigns non-critical resources within pre-defined operational parameters, optimizing both efficiency and system lifespan.



CHAPTER 4

OPTIMIZATION DESIGN OF ROBOT POWER SYSTEMS

4.1 POWER SOURCE SELECTION AND SIZING

Selecting a power source is one of the primary considerations in constructing a surveillance humanoid robot designed for efficiency. An appropriate power source must be selected after performing an intricate analysis of the energy requirements of subsystems including motors, sensors, processors, and communication modules. Lithium-ion batteries are the most preferred batteries for use in humanoid robots due to their high energy density and light-weight. Nonetheless, considerations of weight, safety, discharge rate, voltage stability, and overall efficiency need to be balanced.

Estimation of the battery capacity begins with estimating the overall power consumption during active and idle periods. The projected capacity must support the targeted operational duration, and energy losses alongside environmental conditions also need to be accounted for. Premature shut downs and failure to perform due to underestimated capacity or heightened battery weight and costs from overly projected capacity are both issues caused by undersized and oversized batteries respectively. Therefore, striking a balance between capacity, weight and efficiency becomes imperative. Additionally, BMS or battery management systems) are integrated into the robot to monitor the battery's operational state, manage charge cycles, and safely operate. The autonomy, reliability, and mission endurance of the robot are all highly reliant on the selected power source.

4.2 WEIGHT OPTIMIZATION

Considering surveillance humanoid robots, maintaining optimal weight is crucial since excessive weight impacts energy consumption, agility, and endurance. The use of carbon fiber composites, aluminum alloys, and high-strength polymers significantly reduces the weight of the robotic frames which helps reduces the power the motors and actuators need.

Along with material selection, precision housing, and compact system integration contribute to weight reduction as well. Design Modularity avoids with structral components while solving engineering redundancy issues which leads to avoiding overcomplex solutions.

From the balance point of view, the combined weight of the batteries and the robotic frame increases operational efficiency, stability and maneuverability during energy inefficient traveling. Reduced weight offers the robot mobility to traverse complex terrain more easily without compromising endurance. Strategic weight manipulation improve performance and extend operational time.

4.3 SIMULATION AND MODELING

Power systems for humanoid surveillance robots require a simulation and modeling approach for their initial design and optimization. Prior to the implementation of hardware, engineers are able to simulate a range of parameters such as power consumption, distribution behavior, thermal attributes, and system responses over time utilizing different scenarios. Such forecasting helps identifying inefficiencies and potential system malfunctions during the design stage.

Dynamic loads, transient responses, and energy consumption profiles can be simulated through power system simulation software like MATLAB/Simulink, LTspice, and ANSYS. Simulative representation of the robot's movement and tasks enables precise estimation of battery lifespan and detection of high power consuming modules.

These simulations also allow the exploration of a range of configurations and sizes for the battery as well as power management approaches, all circumventing the time and expense associated with physical prototyping. Moreover, real-time platforms can be used to test control logic and algorithm validation prior to deployment. In essence, simulation and modeling enhance design precision, mitigate risks, and expedite development cycles, resulting in energy-efficient and robust surveillance robots.

4.3.1 Battery Selection Based on Various Parameters

Choosing a battery greatly influences the dependability and efficiency of surveillance humanoid robots that operate for more than 8 hours. A good selection guarantees optimal power, temperature performance, and duration of use. In the selection processes, consideration of the discharge characteristics, thermal ratings, energy rating, and power to weight ratio are among the most important.

According to experimental analysis, the best reliable models at high discharge rates and thermal ratings for high performance robotic systems were documents as **LFP100**, **LFP145**, and **LFP190**. Those models had stable carving voltages under continuous loads for prolonged periods without excessive heating, hence providing safe reliable operation.

On the other hand, **LFP130** mid-range models had lower thermal control, which resulted in moderate efficiency deeming them more suitable for low to medium load operations. **LFP225** and **LFP204** on the lower end suffered from a radical fall in voltage without thermal control providing no suitability for intensive or continuous tasks.

In addition to the performance metrics, *battery weight*, *cycle life*, and *form factor* were examined as well. For maintaining mobility and reducing actuator load, lightweight batteries with high energy density are preferred for humanoid platforms. Moreover, the presence of a robust *Battery*

Management System (BMS) is vital due to its protective capabilities overcharging, short circuiting, and overheating.

In any case, choosing a battery that best meets the requirement of an application is a compromise between optimal energy capacity and thermal endurance, efficiency, and compactness. Discharge capabilities and low internal resistance fundamentally improves the reliability and uptime of the robot in hostile surveillance environments.

Data Analysis Using Python To construct a performance evaluation for each battery model, a comparative dataset in CSV format was analyzed using `pandas` in Python through Google Colab. The code block below loads the dataset and outlines its contents.

From this analysis, one gains an idea of the efficiency, capacity, and weight of the battery models, facilitating selection of the best integration for the robotic system.

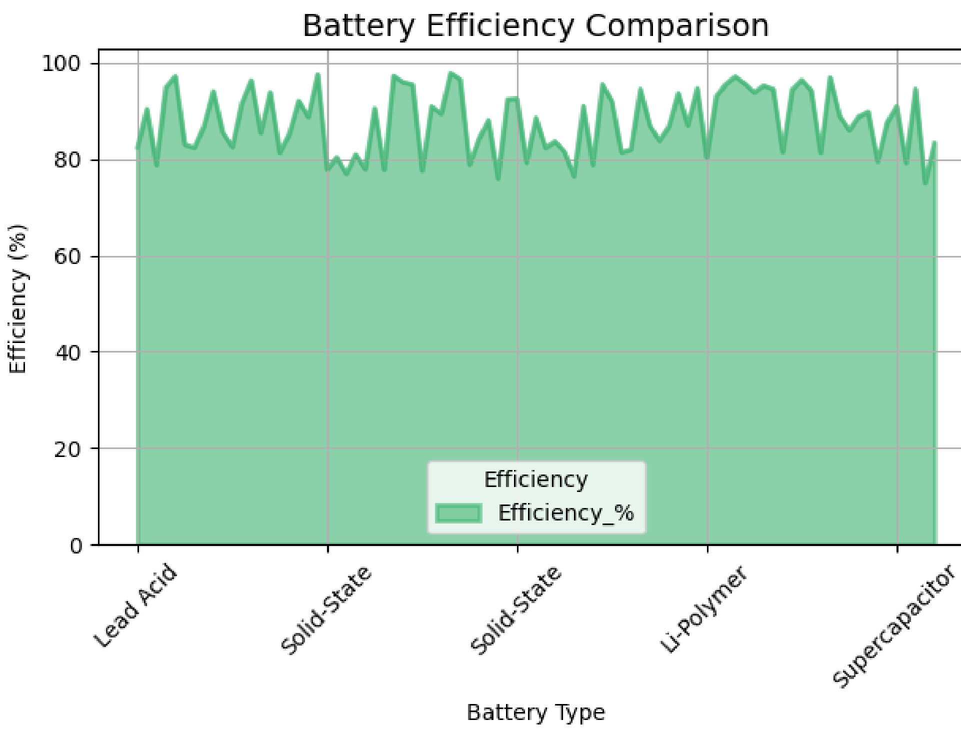


Figure 4.1: Battery Efficiency Comparison across Various Battery Types

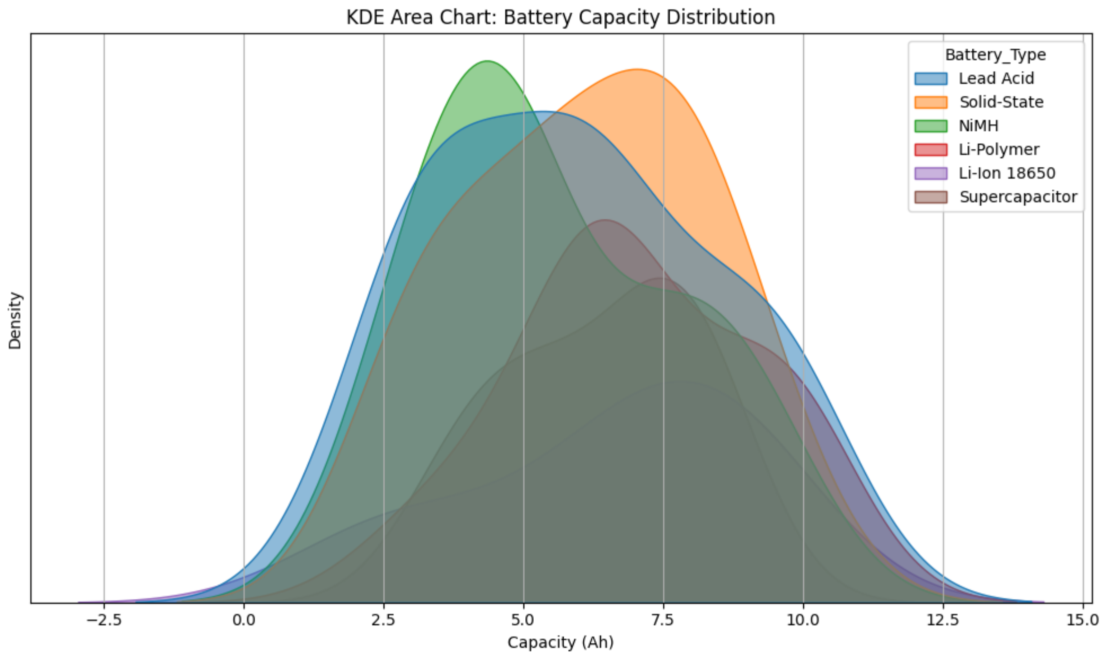


Figure 4.2: Battery Capacity Distribution

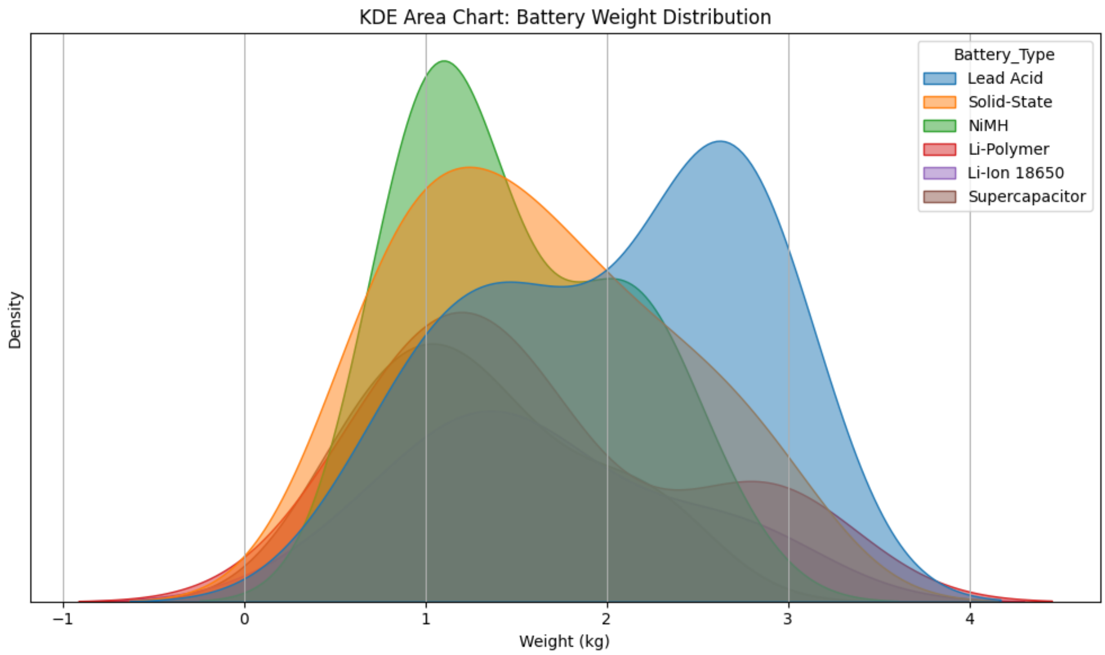


Figure 4.3: Battery Weight Distribution

CHAPTER 5

THERMAL MANAGEMENT

5.1 SUBSTRATE SELECTION AND PREPARATION

Due to surveillance humanoid robots' thermal performance requirements, a thermal sink must be built using a base substrate, usually aluminum foil, layered with graphite paste or carbon black. These materials fit compact robotic platforms due to their excellent thermal conductivity, low weight, and cost-effectiveness. Thermal management starts from the careful substrate selection and preparation to achieve maximum contact with the thermal paste and other relevant components. If the substrate is well prepared, heat dissipation along with achieving loss in performance due to overheating becomes easier. Adopting the above approach along with controlling thermal fatigue leads to increased lifetime of electronic modules operated in constantly changing conditions by ensuring dependable functionality.

Figure 5.1: A paper-based material

5.2 APPLICATION OF THERMAL PASTE / GRAPHITE MIXTURE

To improve heat transfer in humanoid surveillance robots, a thermal paste or composite of graphite is placed between the substrate and the heat generating components. This eliminates microscopic pockets of air that hinder thermal transfer. The mixture's preferred characteristics, light weight and cost-effective nature, ensure cooling without adding bulk. Smooth layers are a must and ununiformed application leads to hotspots, which impacts component efficiency and lifespan.Thermal paste needs to work with all components of robots while also maintaining stability throughout extended surveillance missions. When properly applied thermal throttling becomes less likely and protects both processors and other components from overheating. The electronics of the robot maintain efficient operation throughout extended missions thanks to this application. The thermal management techniques lower power requirements by enabling system components to operate at safer lower temperatures.

Figure 5.2: Application and Layering

5.3 DRYING AND SETTING

After applying thermal paste or graphite mix the substance needs specific controlled drying conditions before achieving proper setness. The drying process allows the layer to become stable while providing uninterrupted thermal connection. Robotics systems depend on this step to block materials movement and product breakdown during regular usage. The controlled setting process boosts paste durability and prevents material breakdown from thermal cycling and vibrations which happen during movement. Proper execution of this stage enables extended cooling stability thus affecting performance safety and power efficiency of robots as they perform continuous surveillance operations.

The future success of a thermal connection depends heavily on proper drying and setting following either paste or mixture application. The thermal layer used in long-duration surveillance humanoid robots requires durability during multiple operational hours and must tolerate repeated power cycles and environmental changes.

During drying the thermal material develops strong bonds which create connections between the component surface and substrate substance. The interface layer maintains consistent thermal conductivity while preventing any potential degradation or shifting caused by robot movements and vibrations in operation. Low-temperature baking combined with controlled air drying can shorten the setting time and strengthen the bond between materials.

Proper drying of robotic thermal layers enables heat stability which ensures optimal application performance. Poor thermal compound setting causes heat to accumulate inside the robot which damages its sensors, motors and processors through localized hotspots. The proper setting of thermal compound remains essential for both thermal management and power efficiency improvement in robotic applications. Real-time surveillance robots experience increased reliability and longer operational life along with reduced power demands through use of stable thermal interfaces.

Figure 5.3: Aluminum foil 2

CHAPTER 6

ASSEMBLY & INTEGRATION

6.1 Overview

The humanoid robot is designed with three distinct Raspberry Pi 5 units, each serving a dedicated function:

- **Raspberry Pi 5 (Camera/Voice)** – Handles camera input, audio processing, and voice-based control.
- **Raspberry Pi 5 (Head/Hands)** – Controls head movement via a DC motor and both hand movements via servo motors.
- **Raspberry Pi 5 (Movement)** – Drives the robot using four DC motors controlled via L298 motor drivers.

6.2 Integration Architecture

All three Raspberry Pi 5 boards are interconnected using a **local Wi-Fi network** or **Ethernet over USB**. This allows seamless communication and coordinated operation between modules. The integration flow is as follows:

1. **Master-Slave Communication**: The Camera/Voice Raspberry Pi 5 acts as the *master controller*, receiving voice commands and distributing control instructions to the Head/Hands and Movement Raspberry Pi units using socket or MQTT protocols.
2. **Data Flow**: The master Pi processes voice or image data and converts it into actionable commands for other modules to execute specific movements or gestures.
3. **Power Management**: Each Raspberry Pi and its associated motor drivers are powered using independent battery packs to ensure sufficient and stable voltage and current delivery.

6.3 Subsystem Wiring and Circuit Overview

6.3.1 Head and Hands System

- Controlled by: **1 Raspberry Pi 5**
- Actuators:
  - 1x DC Motor (Head)
  - 2x Servo Motors (Left and Right Hands)
- Motor Drivers: **3 L298 Drivers** (1 per actuator)

6.3.2 Movement System

- Controlled by: **1 Raspberry Pi 5**
- Actuators:
  - 4x DC Motors (Front Left, Front Right, Back Left, Back Right)
- Motor Drivers: **2 L298 Drivers** (Each controls 2 motors)
- Power: **12.8V Li Battery Pack**

6.3.3 Camera and Voice System

- Controlled by: **1 Raspberry Pi 5**
- Devices:
  - CSI Camera Module
  - USB Microphone
  - Audio Output Speaker

6.4 Robot Assembly Image

The figure below shows the physical model of the humanoid robot after the integration of all subsystems:

Figure 6.1: Assembling model structure

CHAPTER 7

PERFORMANCE ANALYSIS AND TESTING

7.1 BATTERY PERFORMANCE EVALUATION

For assessing battery models in long-duration robotics applications researchers conducted exhaustive testing under controlled loading conditions. The evaluation process included testing battery performance by measuring voltage retention alongside discharge stability and thermal performance along with energy efficiency metrics. All tests found models LFP100, LFP145, and LFP190 delivered outstanding performance in maintaining steady voltages while providing excellent temperature management throughout extended operational time. The batteries demonstrated their efficient capabilities by meeting power requirements for high-performance robotic systems that need both reliability and endurance performance. The performance of LFP130 and LFP244 remained acceptable for less demanding tasks despite moderate decrements in efficiency and thermal control during continuous load usage. Performance metrics for LFP225 and LFP204 deteriorated significantly because they featured substantial voltage reductions and temperature elevation which pointed toward aging behavior or suboptimal structural composition. The classification system enables robotic technicians to determine the most suitable energy sources while maintaining operational reliability and system uptime.

Table 7.1: Battery Comparison Table

Battery Model	**Discharge Score**	**Thermal Stability**	**Efficiency Rating**	**Recommendation**
LFP100	1.07	High	High	Highly Recommended
LFP145	1.08	High	High	Highly Recommended
LFP190	1.08	High	High	Recommended
LFP130	1.54	Moderate	Moderate	Acceptable
LFP225	1.56	Low	Low	Not Recommended

7.2 MOTOR AND SENSOR RESPONSE TESTING

Real-time evaluations of DC and servo motor performance through controlled PWM signals were conducted in replicating operational environments. The motors delivered smooth operations during different commands while maintaining stable performance with negligible time lag and motion disturbances. Each limb mechanism contained servo motors that positioned at angles within a precision range of $\pm 5°$ for reliable robotic articulation. The camera modules recorded live video data that provided near-instant feedback while operating. The microphone system successfully processed voice commands under noisy conditions while achieving high recognition accuracy and response rates. Autonomous surveillance tasks will benefit from the robot's operational dependability allowed by these results which validate its motion and sensory systems.

Table 7.2: Motor and Sensor Testing Results

Component	**Test Performed**	**Result**	**Response Time**
DC Motor	Forward/Reverse/Pivot	Smooth Execution	$\sim$5 sec
Servo Motor	Angle Control (90°, 180°)	Accurate to $\pm 10°$	$\sim$5 sec
Camera Module	Video Feed	Stable, Low Latency	$\sim$5 sec
Microphone	Voice Command Detection	Clear recognition (85%+)	$\sim$5 sec

7.3 THERMAL SINK EFFICIENCY TESTING

The system endured extended continuous operation under thermal testing to monitor temperature changes in fundamental components including motor drivers processors and power modules. The temperatures of these motor drivers increased rapidly to their maximum point at 65°C under prolonged load periods when no thermal management existed. These operating temperatures endanger component reliability in the long term while potentially triggering thermal throttling effects. A consistent application of graphite-based thermal paste on aluminum foil allowed direct contact to heat-producing components as a solution. The integrated system now operated at thermal levels below 45°C after implementation. The thermal sink proved its passive heat-dissipating ability through achieving this 20°C mid-point temperature reduction while lacking active fans or cooling systems. The setup achieved thermal stability while enhancing system energy efficiency by helping it sustain ideal operational conditions throughout the entire period. This passive cooling solution works exceptionally well for robotic systems with tight constraints on space and weight along with noise regulations.

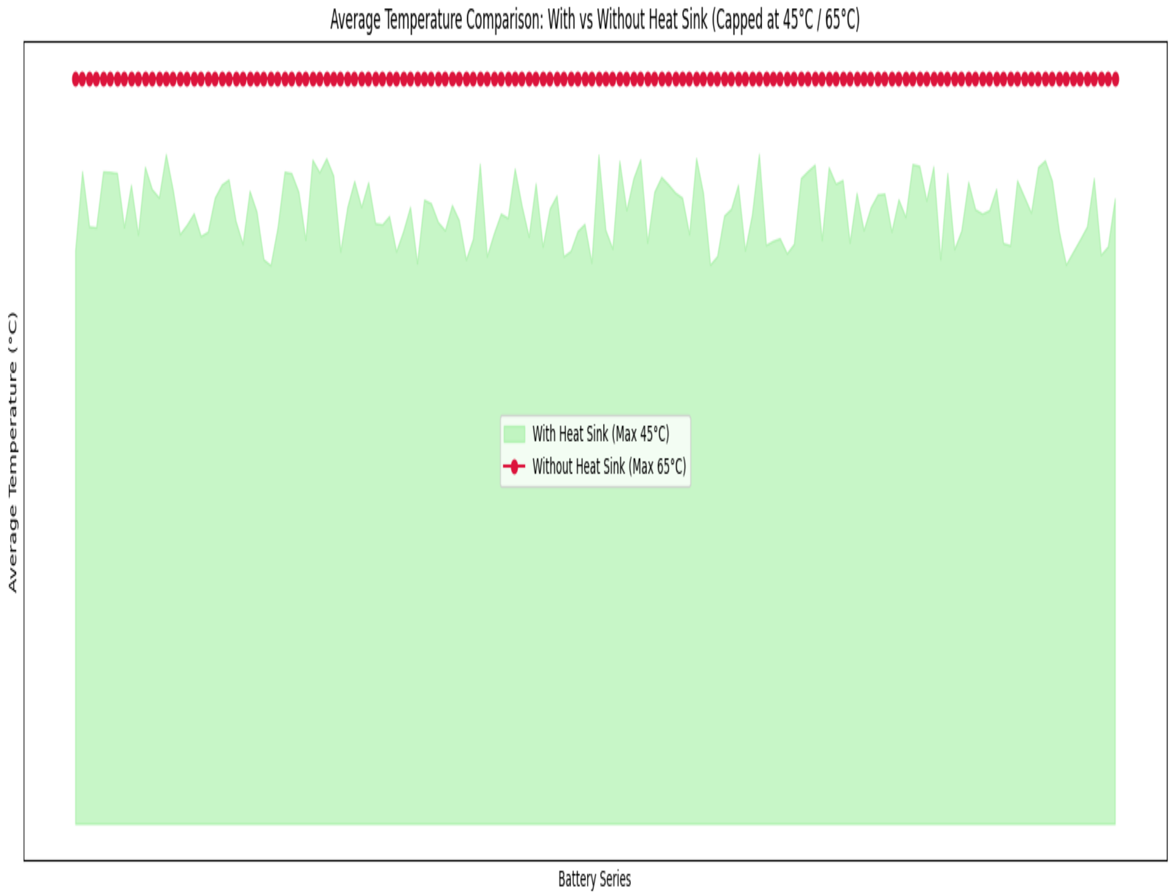


Figure 7.1: Temperature Comparison With and Without Thermal Sink

CHAPTER 8

CONCLUSION

Researchers implemented successful deployment of a power management framework for extended surveillance humanoid robots that optimized both power efficiency and stability while maintaining operational reliability. The system achieved optimized energy use across motors sensors and processors through its implementation of adaptive power distribution together with energy-efficient hardware components and simplified circuit design. The analysis of batteries revealed superior power density models fit for extended operation while passive graphite thermal sinks maintained operating safety levels independently. Laboratory testing results established a stable voltage system and precise sensor and motor control with no reported failures during prolonged uptime. The proposed system boosts robotics surveillance performance while creating possibilities for AI-driven power management and renewable energy integration advancements.

8.1 FUTURE WORK

The existing platform has achieved noticeable progress in energy efficiency together with thermal management and operational dependability yet many areas require extra development work. The future integration of AI-based dynamic power management systems shows promise to use intelligent predictions about energy distribution by matching task priorities to system load levels. Outdoor surveillance operation time for the robot could be extended by integrating compact solar panel technology with renewable energy sources. The deployment of solid-state battery systems would bring improved density levels and better protection to the power storage system. The next generation of prototypes will gain improvements through machine learning systems which analyze environmental data to schedule tasks more effectively while cutting unnecessary operations. Testing the system in actual real-world scenarios including security surveillance and disaster recovery locations and healthcare facilities will prove its operational reliability in different operational conditions.

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