Search and Rescue Hexapod

A Project Report
Presented to
The Faculty of the Computer Engineering Department

San Jose State University
In Partial Fulfillment
Of the Requirements for the Degree
Bachelor of Science in Computer Engineering

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02/2019

APPROVED FOR THE COLLEGE OF ENGINEERING

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Abstract

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From 2006 to 2015, the number of disasters each year has ranged from as low as 530 to as high as 731, according to 2016 World Disaster Report of International Federation of Red Cross and Red Crescent Societies. Over 100 million people were affected and thousands were killed by disasters every year. Disasters often left a trail of destruction on its path. Around the world, governments and aid organizations work round-the-clock to keep the death rates as low as possible. Robots are often used to help in searching and rescuing survivors.

On disaster sites, rescuers usually had to work against the clock searching for survivors. Most of the time, rescue workers could not travel through small gaps, underground tunnels, or fit into air pockets beneath fallen buildings. Also, traditional ways of removing debris using excavators and shovels are inefficient and dangerous. The weight of equipment and rescuers might shift the rubble's structure posing serious threat to survivors and workers.

The Search and Rescue Hexapod can navigate easily through disaster sites searching for victims. Human rescuers can operate the hexapod from a safe distance via radio frequency. It can be sent to areas that are too dangerous for rescuers. The hexapod is equipped with camera and transmission system to provide the operator with live feed video. With this, rescuers can monitor the environment around the hexapod, while looking for survivors. The 3D printed body parts reduced the weight significantly, which eliminated the risk of shifting the rubble's structure. Most importantly, the hexapod is replaceable. Its broken parts can be reprinted and replace.

Acknowledgments

We would like to express sincere gratitude to Professor Frank Lin for being our advisor in the project. Our team have gotten great assistance and valuable suggestions from throughout the developing process. Lastly, we would like to thank the College of Engineering and Professor Fatoohi Rod for the great opportunity to experience the process of creating an engineering product.

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Chapter 1 Introduction

1.1 Project Goals and Objectives

Search and rescue (SAR) operations often pose great threats to the victim and rescuer lives. With advanced technologies, robots are being used in SAR operations to cut costs and improve efficiency. Our project goal is to build a remote-controlled six-legged robot (hexapod) to support the SAR team on land. The objectives of the project include:

- A six-legged robot that is controllable via radio frequency.
- Equipped with camera and transmission system that provide the operator with live feeds.
- Six degrees of freedom to have swift and steady locomotion.
- 3D printed body parts that reduce the costs and weights.
- Printable and replaceable body parts.

In a SAR operation, time and safety are of the essence. The hexapod can not only reduce the time for searching and locating the victims, but also keep the rescuers out of harm’s way.

1.2 Problem and Motivation

Every year, millions of people are affected by disasters around the world. Robots are often use in SAR operation for searching and rescuing victims. When lives are at stake, timing is everything. SAR robots help rescuers in locating survivors quickly, while minimizing the risks they have to take.

Although the idea of SAR robots emerged during the early 1980s, developments in this field did not begin until the 1990s. At first, machines were used to penetrate rubbles and locate the victims beneath them. As technology continues to advance, there are many situations and tasks that could be done by SAR robots. One significant advantage of robot is the ability to fit into places humans cannot. They can travel through small gaps or fit into air pockets beneath fallen buildings. While rubbles and fallen buildings often have unstable structure, the weight of rescuers and equipment can cause a collapse. Such deadly risk can be eliminated with light weight robots. As a result, we are motivated to build the Search and Rescue Hexapod. The six-legged robot comes with printable body parts which reduce its weight significantly. Wireless control allows rescuers to operate the robot from a safe distance. It is equipped with a camera that allow the robot to broadcast its video to the operator. Once deployed, the robot can navigate through rubbles, while providing rescuers with a livestream of the surrounding. Searching and locating survivors can be much faster, and safer for both the survivors and rescuers.

1.3 Project Application and Impact

Every year, disasters such as earthquakes, hurricanes, floods, or wildfires destroy thousands of houses, and take away hundreds of thousands of lives. Around the world, robotic technology has been used by governments more frequently in providing lifesaving solutions when disasters strike. In fact, robots have been used to assist with disasters in 17 countries. The use of robots in search and rescue operation was first documented in September 11, 2001. While searching in rubble, these robots were able to "reach places that people and dogs could not, and penetrating two to three time farther than cameras on poles". When it comes to aid in disaster relief, robots provided more efficient ways than traditional human aid.

The Search and Rescue Hexapod will have a great impact on how survivors are rescued during and after disasters. In every SAR operation, time is of the essence. The SAR hexapod can reduce the amount of time and effort it takes to locate survivors. It requires less than 10 minutes to ready and deploy the hexapod. Mobility and lightweight makes it a better tool to search for survivors in a rubble. The mortality rate of disasters can be improved if survivors are found and rescued quicker. The hexapod is most effective in a Chemical, Biological, Radiological, Nuclear or Explosive Event. It can replace human to search for victims or explore the disaster site. The exposure of rescuers to unnecessary risks and dangers are reduced significantly. Since the hexapod body is 3D printed, repairing and replacing broken parts are much easier.

1.4 Project Results and Deliverables

The final product of our project is a fully functional hexapod that is controllable via radio frequency. As the name suggested, our robot is designed with six legs, allowing swift and steady movements. Each leg is divided into three segments, i.e., coxa, femur, and tibia, connected by three servo motors. Together, these servo motors dictate the joints' motions to move the leg. Thus, a total of eighteen servo motors are used for the hexapod movements. An FPV camera – capable of broadcasting video via 5.8GHz radio frequency – is mounted on top of the hexapod. Two servo motors control the pant and tilt of the camera, providing the operator with a wider view of the surrounding. Our hexapod is powered by a 3-cells 5000mAh Li-Po Battery, allowing the robot to operate for approximately 25 minutes. A remote controller and an FPV monitor are included in the final product. The hexapod will also come with a user manual of details about the functionalities of the robots, and how to operate it safely. 3D schematics of the body parts are also provided for reprinting and replacement. Upon completing the project, a formally written report will be delivered. The report will contain the architecture design, steps and progresses in making the hexapod, as well as, the functional requirements.

1.5 Project Report Structure

The remain of the report will be divided into seven sections, includes:

- **Background and Related Work:** this section covers all about the background and technologies of our Hexapod project. It also has the summary of state of the art and also some information in the literature search part.
- **Project Requirements:** this section covers all the requirement for our project includes domain and business requirements, system functional requirements, non-functional requirements, context and interface requirements, technology and resource requirements.
- **System Design:** this section covers all the designs of this project includes architecture design, interface and component design, structure and logic design. we also discuss about design constraints, problems, trade-offs, and solutions.
- **System Implementation:** this section covers the detailed methodology of how the hexapod was implemented, both hardware and software.
- **Tools and Standard:** this section cover all the tools and standards that are required for our project.
- **Testing and Experiment:** this section covers the scope and the approach for testing and experiment. We also cover all the results and analysis of the testing and experiments.
- **Conclusion and Future Work:** this section discusses the conclusion and future work that could enhance the overall quality of the project.

Chapter 2 Background and Related Work

2.1 Background and Used Technologies

The name of the Hexapod come from ancient Greek where ‘hex’ means ‘six’ and ‘pod’ refers to ‘foot’. In entomology, the term ‘Hexapod’ refers to the class Insecta or Hexapoda which are any member of the largest class of the phylum Arthropoda [5]. This idea project is categorized as a service robot. It is insect-inspired of a flexible-walking style of a spider, which can walk freely and steadily on any rocky and uneven terrain. The concept of the hexapod is based on the symmetric and stable walking style of a six-legged robot design which is able to explore any terrain. We try to improve it further to serve human’s purposes, i.e., traveling and carrying goods to complex locations. Currently, there are three main types of walking gait that it usually moves: alternating three legs on the ground, quadruped or crawl which only advances one leg at a time. There are two approaches to architecture design of its control which are centralized and decentralized. Centralized approach specifies transitions of all legs, while the decentralized architecture connects six legs in parallel and interact between neighboring legs [6].

2.2 Literature Search

In the last couple decade, hexapod walking robot has gotten a considerable attention in the last couple decade. Due to the high demand for search and rescue operations required after natural disasters or even destruction of building and other type of construction. Not only that, other form of hexapod was used in space to discover new planet such as the Mars.

In January 31, 2018, a robot named Opportunity has completed its 14th year of its mission of exploring the surface of the Mars [1]. Because of its potential, many researchers were involved in this field in the past couple years. They confirm that legged walking robots are ideal for space missions. One example is that NASA has developed the ATHLETE robots which promised to continuously operate in space up to 10 years by using mixed design between legged and wheeled architecture.

The hexapod robots are defined as a programmable robot with six legs attached to its body. The legs are controlled in different degree so that it can move within encountered environments. Depend on demand, hexapod robots can be designed to become suitable for terrestrial and space applications [2]. Added features can be variable geometry, good stability, omnidirectional motion, adaptation to different terrains and fault tolerant locomotion [2]. One of the most motivating factors to continue its development is climbing over obstacles. Indeed, robots with wheels restrict themselves from working in environments where obstacles are bigger than its half diameter of its wheels. Even the wheeled chassis is fast but not compatible for rough terrains [3].

On the other hand, legged walking robots can achieve overcome sizable obstacles compared to its leg size [2]. This is also the main reason bringing legged robots to the mainstream operations such as exploration of seabed, new planets, and nuclear power stations, and search and rescue. Beyond those mainstream operations, legged robots can also be used in a variety of tasks such as forest harvesting, transporting cargo, being as service robots or even entertaining machines [2]. There are many areas that engineers need to improve before the hexapod walking robots can be used widely. Some of the disadvantages are high cost, high complexity, relatively slow in speed and lack of energy efficiency factor [2].

2.3 State-of-the-art Summary

Currently, the State-of-the-Art of designing and manufacturing robotic design to serve areas what inaccessible by human being are NASA's ATHLETE robot and Boston Dynamics' LS3. ATHLETE project is aiming to develop a multi-purpose system of "docking and mating" with existing special purpose devices currently in space, including refueling stations, maintaining sockets, object collecting station. Since the fact that this is a hybrid robot between legged and wheeled robots, it has to rely on new level of complexity algorithms to be able to either walk or roll on wheel whenever possible. To be able to operate more freely among large obstacles, the legs are designed to have 6 degrees of freedom. Also, its strong supporting architecture can carry a payload up to 990 lbs.

Due to its special design, docking in allowed between many ATHLETEs which makes the process of transporting to space easier. It holds the record of climbing up to 35-degree slope on solid surface and 25-degree slope on soft surface. NASA plan to implement a launchable grappling hook to allow it to haul itself up even in vertical slope. The new voice and gesture commands will be implemented to allow suited astronauts to control it wirelessly. More and more modern and newly invented technologies are employed to robotic devices.

In this project's case, the 6-legged hexapod and addition modules would cost a fraction compared to the ATHLETE. Currently, there are many ideas that are trying to bring robots to space to perform discovery missions and such. Our project is not trying to solve the problem in space but on earth. With a small-scale design, no wheels, the search and rescue hexapod are more suitable to operate in small space and fragile destructive surrounding. This project, however, might be comparable to the ATHLETE robot as it adopts somewhat of the same technology and physical design. Therefore, there are many benefits when trying to make this project a State-of-the-Art.

Chapter 3 Project Requirements

3.1 Domain and Business Requirements

The domain and business requirements for the hexapod include:

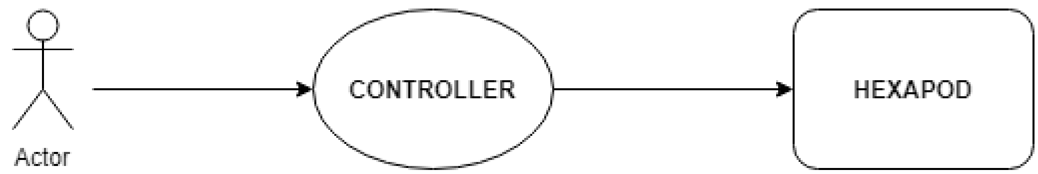

Figure 1: The interaction between the user, the controller, and the Hexapod

Here's the list of features that user can use the controller to interact with the Hexapod Project:

- Right joystick allows users to move the hexapod forward, backward, left, or right. By changing movement mode, users can shift the body forward, backward, left, or right while standing still, using the same joystick.
- Pressing right joystick allows users to turn the LED lights on/off.
- Left joystick allows users to rotate the hexapod left or right, shift the body up and down. By changing movement mode, users can pitch forward or backward, roll right or left while standing still, using the same joystick.
- Pressing left joystick allows users to change the movement modes of the hexapod.
- Two potentiometers allow users to control the pan and tilt of the camera turret.
- Three push buttons allow users to adjust the height or speed of the hexapod. First button is used to change between adjusting the height or speed. Second and third buttons are used to decrease or increase the value respectively.

3.2 System (or Component) Functional Requirements

The functional requirements for the hexapod include:

- Controllable via radio frequency: the hexapod shall be control by a remote controller over 2.4GHz radio frequency.
- Six degrees of freedom: the hexapod shall perform the following movements:
  - Move forward or backward
  - Move left or right
  - Shift up or down
  - Swivels left or right
  - Pitch forward or backward
  - Roll right or left
- 3D printed body parts: all parts of the hexapod shall be 3D printed with Polylactic Acid (PLA) to reduce the overall weight.

- Camera and transmission system: camera on the hexapod shall broadcast live video over 5.8GHz radio frequency.
    - The camera provides operator with live video of the hexapod's surrounding.
    - Camera is equipped with two servo motors that allow pan-tilt and wider view.

3.3 Non-functional Requirements

The non-functional requirements of the hexapod include:

- Hexapod must be optimized in power efficiency.
- Hexapod must not cause any damage to the surrounding.
- The network transmission between Hexapod and the controller must be secured so that it's not easy to hack into the network.
- Hexapod must be optimized in the overall size, the smaller the better.
- The hexapod movements should be swift and smooth
- 3D printed body parts should be easy to replace

3.4 Context and Interface Requirements

For our project, we use Eclipse, Pololu Maestro Servo Controller and Arduino IDE for developing, and testing. All firmware functions for the hexapod is written in C/C++ running on Raspbian Stretch OS. The remote controller's firmware is implemented using Arduino IDE. The compiled hexapod's firmware is automatically run on Raspberry Pi start up by a written bash script.

When it comes to the remote, we use the Arduino Nano as the main microcontroller to process inputs from the joysticks, buttons and potentiometer. Also, two nRF24 modules are used to transmit and receive radio frequency between the remote controller and the hexapod.

3.5 Technology and Resource Requirements

In order to successfully build this project, all hardware requirements and software requirements must be satisfied. For hardware requirements, all the components that were used for this project must be able to help the Hexapod in movement and optimizing in size and power consumption. For software requirements, the environment that we used to implement the source code for this project must be able to write and compile into the Hexapod and the remote controller. Also, it must be easy to fix and debug the code in case if we have any problems in software requirement for this project.

Table 1: Requirements for Hardware Components

Parts		Quantity	Description
On Hexapod	Raspberry Pi 3 B+	1	microcomputer for Hexapod’s body.
	Pololu Maestro Servo Controller	1	24-channels servo controller.
	5000 mAh Li-Po Battery.	1	use to power the Hexapod.
	Eachine TX03 AIO FPV camera	1	use for transmission system.
	Eachine FPV monitor	1	use for transmission system on the remote controller.
	nRF240L1P Transceiver	1	use to receive signals from the remote controller.
	LewanSoul LDX-218 Metal Gear Servo Motors	18	use for leg movement of Hexapod.
	MG90s Metal Gear Micro Servos	2	use for camera’s pan-tilt.
	Buck Converters	2	use for regulating voltages on the Hexapod.
	Logic-Level Converter	1	use for converting logic-level between the Raspberry Pi and Maestro Servo Controller.
	Latching Push Button	1	use for turning on/off the Hexapod.
On Remote Controller	Arduino Nano V3	1	microcontroller for remote controller.
	Nextion 3.2” LCD Display	1	use for displaying information on remote controller.
	Joysticks	2	use for controlling the Hexapod movements.
	Potentiometer	2	use for controlling the Hexapod movements.
	Push Button	3	use for controlling the Hexapod movements.
	Latching Push Button	1	use for turning on/off the remote controller.
	nRF240L1P Transceiver	1	use to transmit signals to the Hexapod.

	Buck Converters	1	use for regulating voltages on the remote controller.
	AA Battery Pack	1	use to power the remote controller.

Table 2: Software Requirements

Environment	**Description**
Eclipse	main development environment to program the Hexapod.
Arduino IDE	main development environment to program the remote controller
Pololu Maestro Servo Controller	main software to test and calibrate servo motors

Chapter 4 System Design

4.1 Architecture Design

As the name suggested, our robot is designed with six legs which will provide stable and swift movements. Each leg is divided into two segments, i.e., tibia and femur which leads to the leg segment design shown in Figure 2 The hexapod is designed and built with roughly 14 inches in diameter and weighs around 7 lbs. Its body is 3D printed with Black PLA (Polylactic Acid). Each leg is equipped with three LewanSoul LDX-218 Metal Gear servo motors. The system has an onboard Raspberry Pi 3 Model B+ microcomputer which consists of a Broadcom ARMv8 Cortex-A53 that has clock speed of 1.4Ghz. It also has a Pololu Maestro 24-Channel Servo Controller and a nRF24L01P transceiver for motor control and receiving signals. The overall microarchitecture of the system is demonstrated in Figure 5.

In regarding to live feeds, we used the Eachine TX03 AIO FPV Camera to stream video to a monitor at the operator’s end. The turret is built using two MG90S Metal Gear micro servo motors to pan and tilt the camera. This provide the operator a better and wider view of the surrounding area. The camera submodule along with transmitting setup is shown in Figure 3.

The hexapod is remote controlled by a custom-built controller. The controller is designed built using an Arduino Nano V3.0. The device consists of joysticks, push buttons and potentiometers for inputting signals. These signals are processed by the Arduino into packages and sent to the Hexapod via a nRF24L01P transceiver.

In this project, we use radio frequency as the main protocol for communication. Comparing with other protocols, radio frequency has the advantage of availability on the field over Wi-Fi, and the advantage of range over Bluetooth. This is more efficient to use in remote area or disaster sites. Two nRF24L01P Transceiver modules are used for signal communication between the remote controller and the hexapod. From real-life testing, the transceivers provide stable signal with maximum range of 1 kilometer in open field. The range is significantly reduced to around 400 meters when tested indoor. Figure 4 contains the controller unit in modular level.

From our research on real spider locomotion, we will implement and mimic its movement so our hexapod ability to walk smoothly. Figure 1 shows the overall architecture design of the hexapod, as well as the gait of forward movement. Each leg is clearly labeled to show its position for each step of the hexapod.

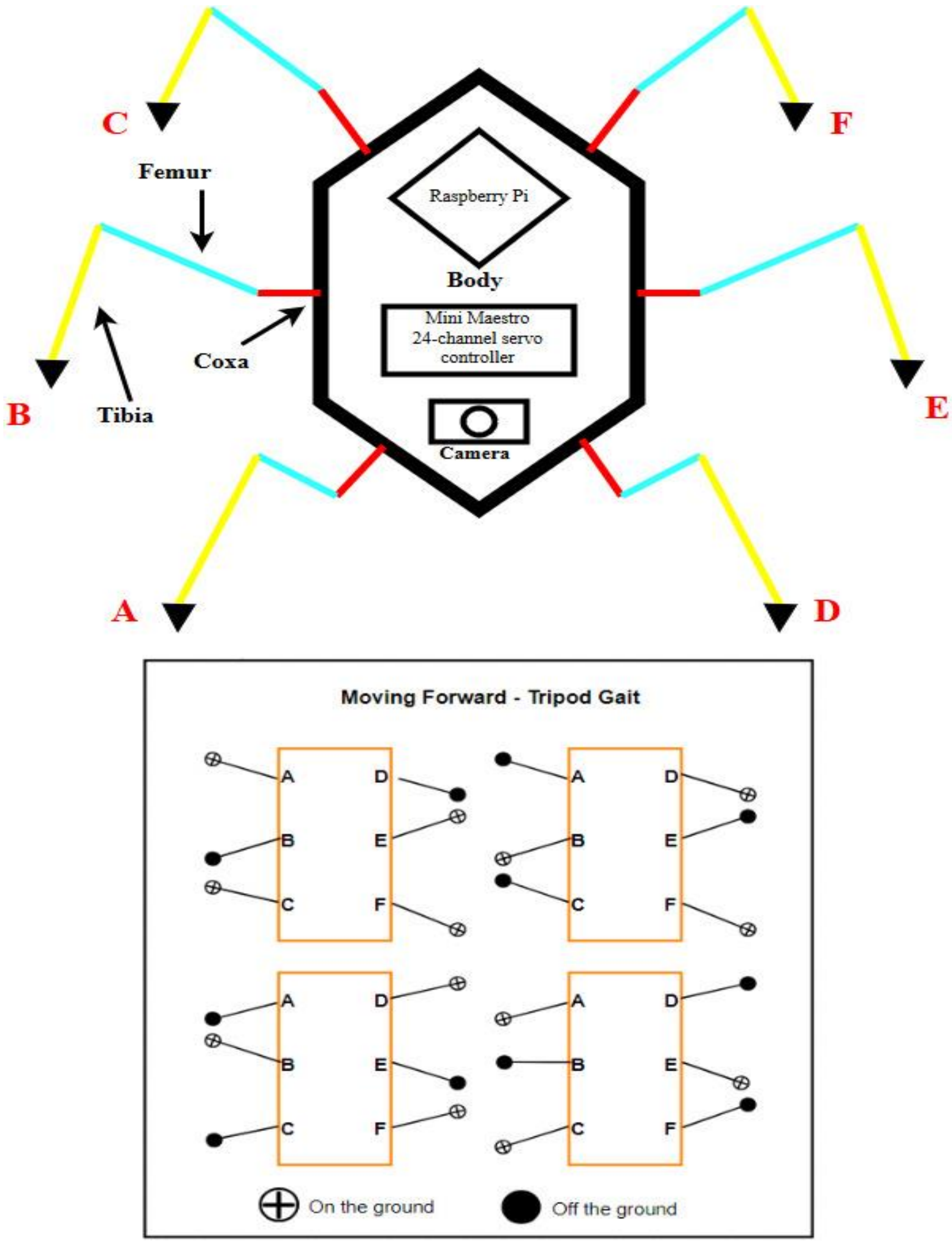

Figure 2: Hexapod overall design with diagram of leg movements

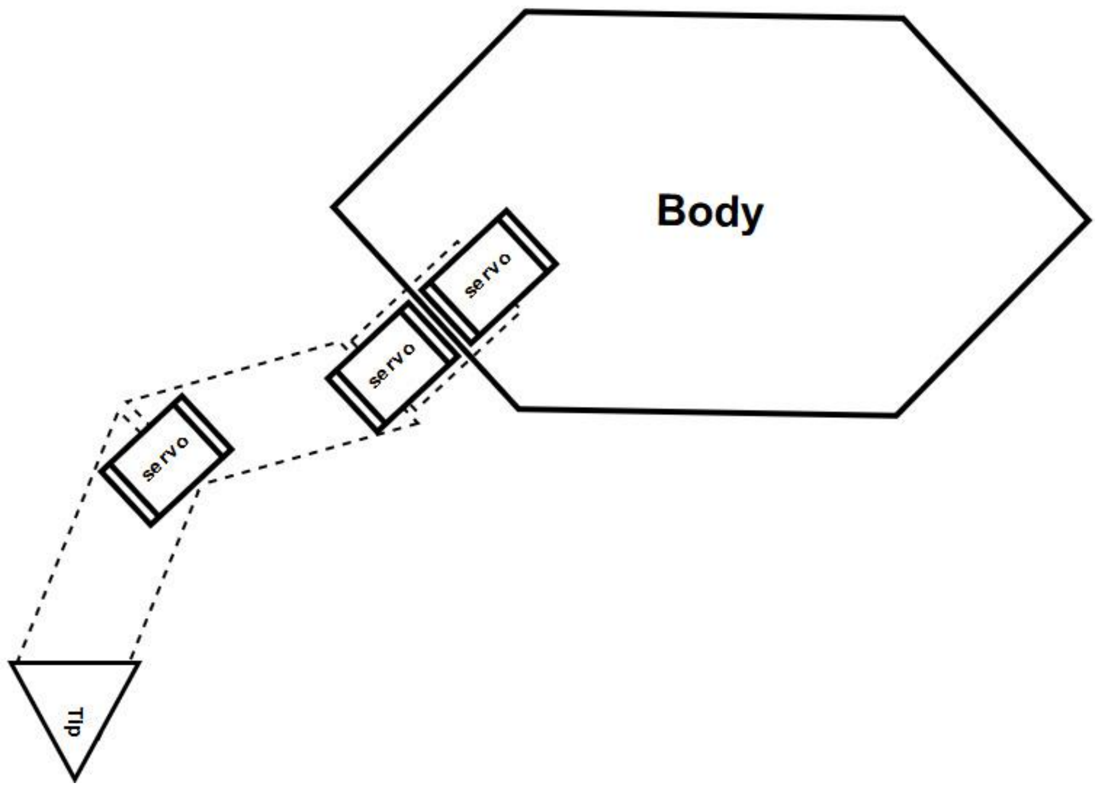

Figure 3: Leg architecture design

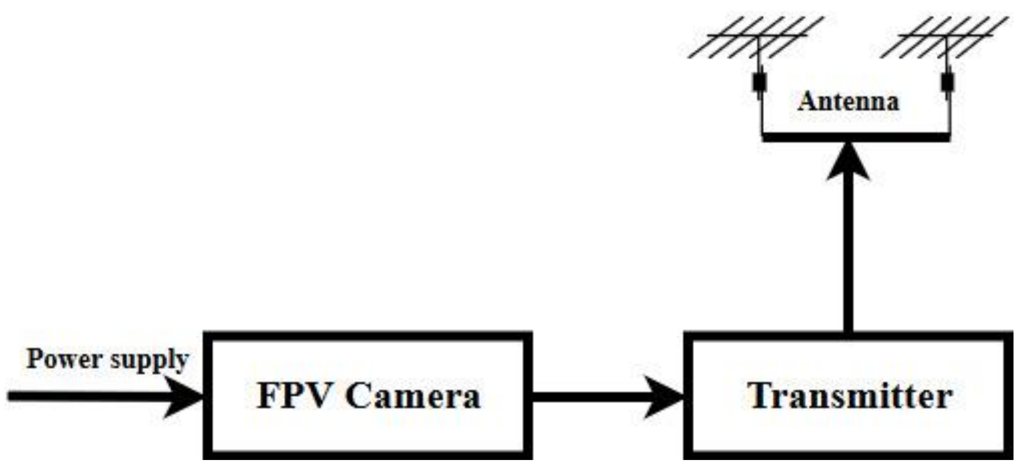

Figure 4a: External camera unit architecture (Power Supply = 5V DC)

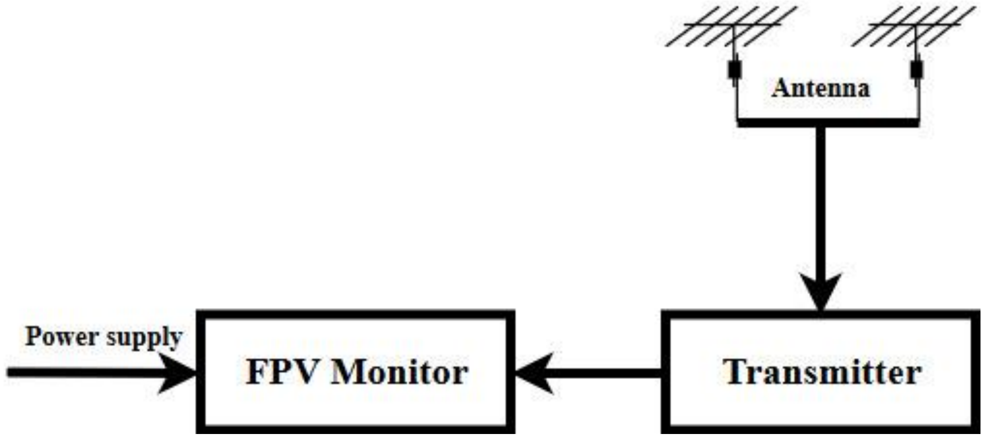

Figure 4b: External controlling unit architecture (Power Supply = 5V DC)

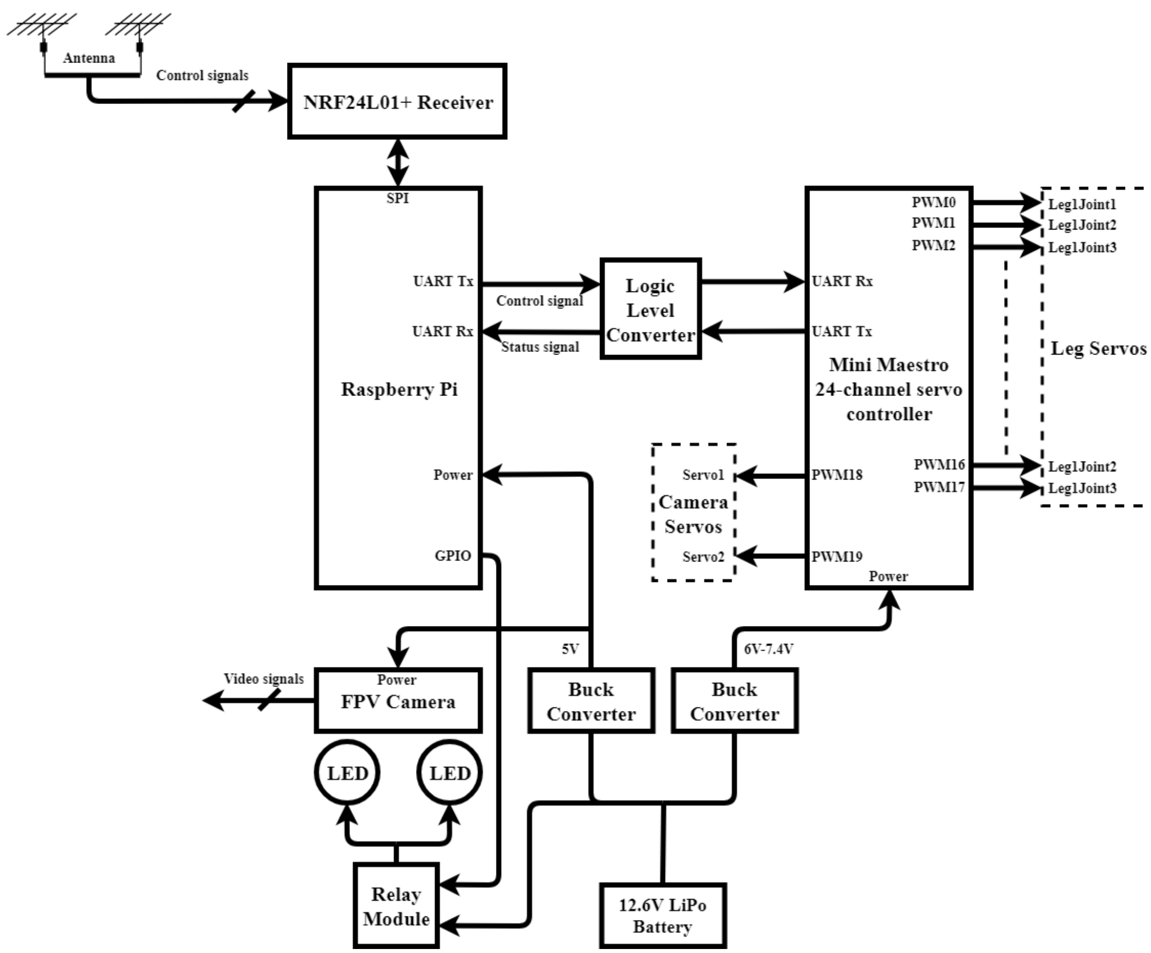

Figure 5: Hardware architecture of the Hexapod

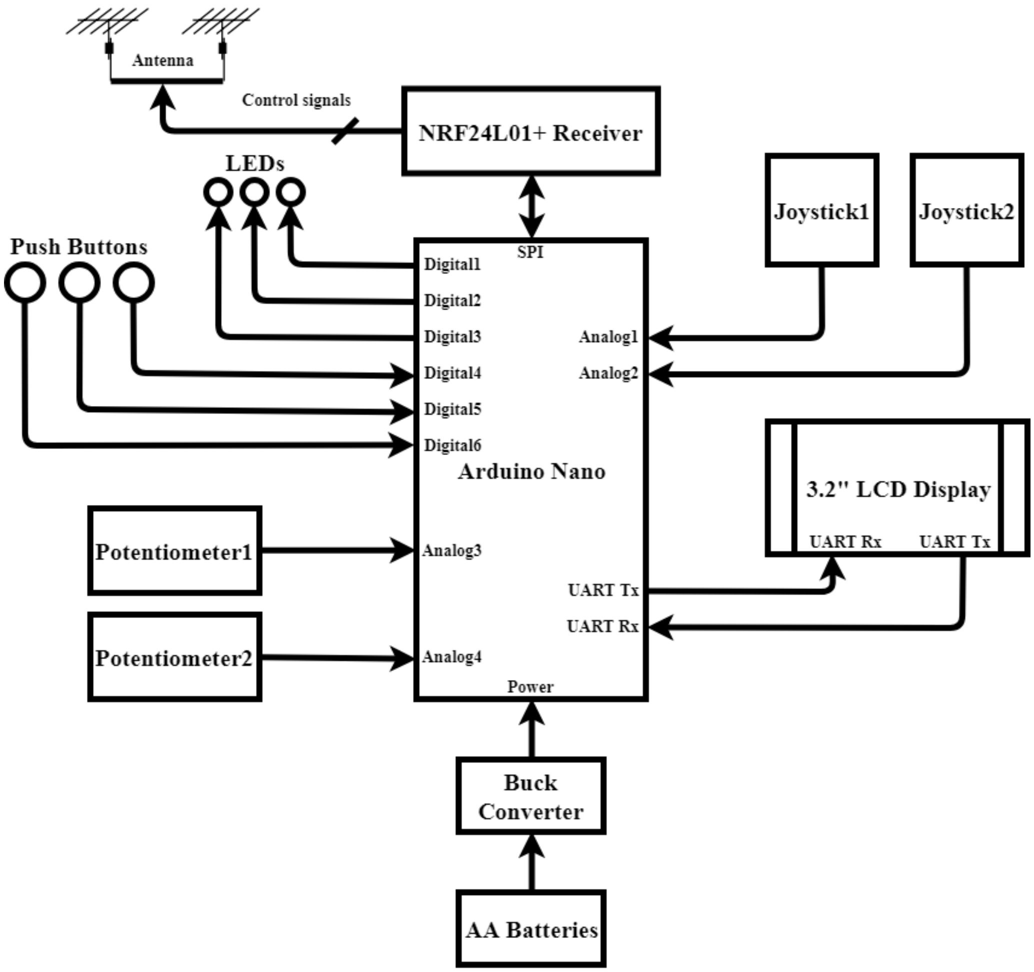

Figure 6: Hardware architecture of the Controller

4.2 Interface and Component Design

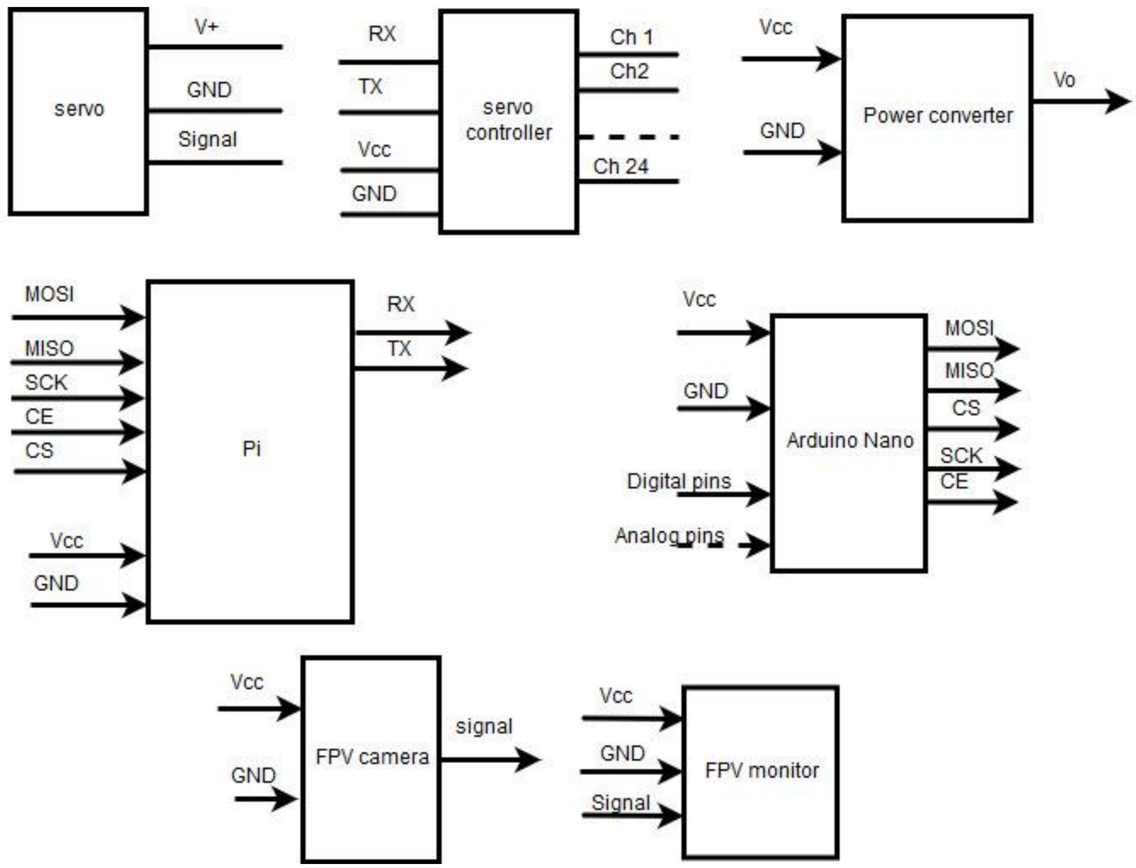

Figure 7: Hexapod components

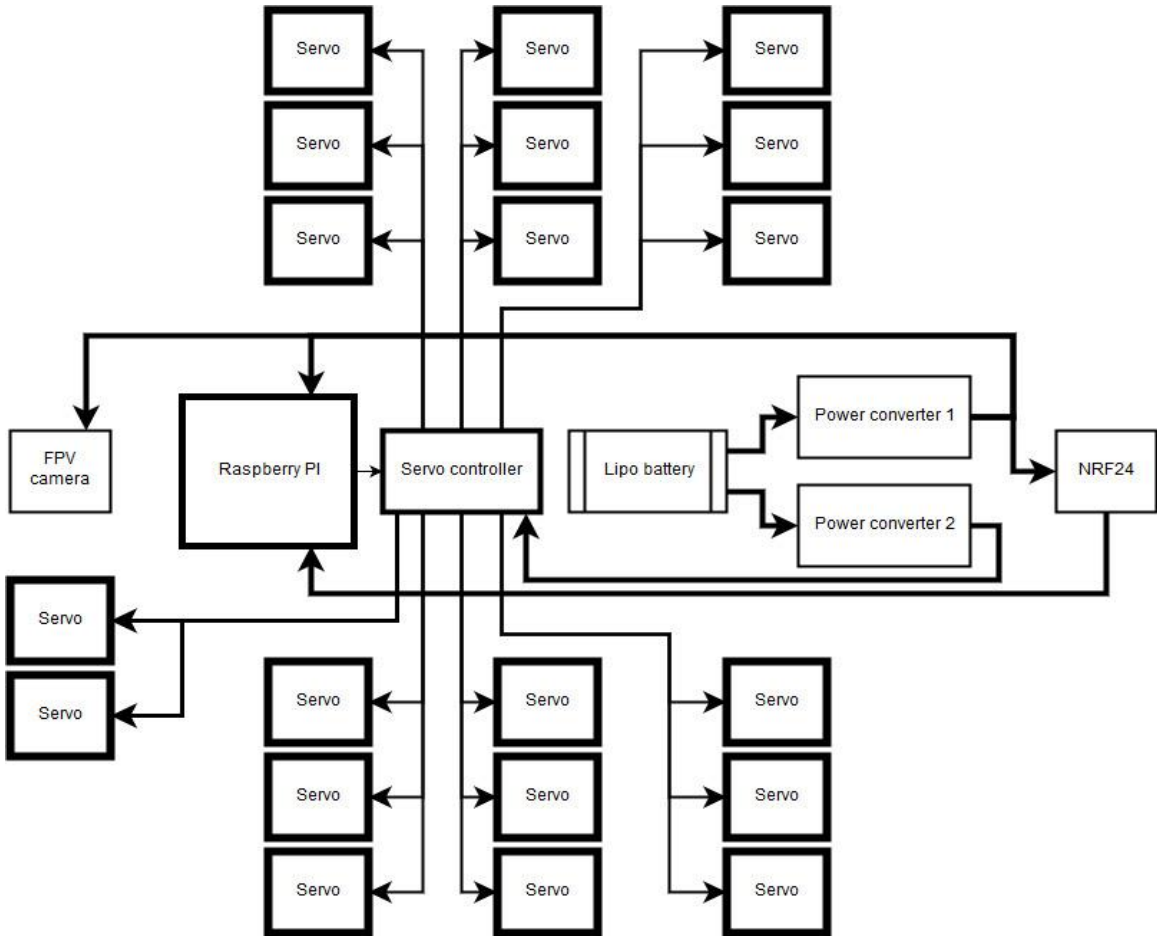

Figure 8: Hexapod component design

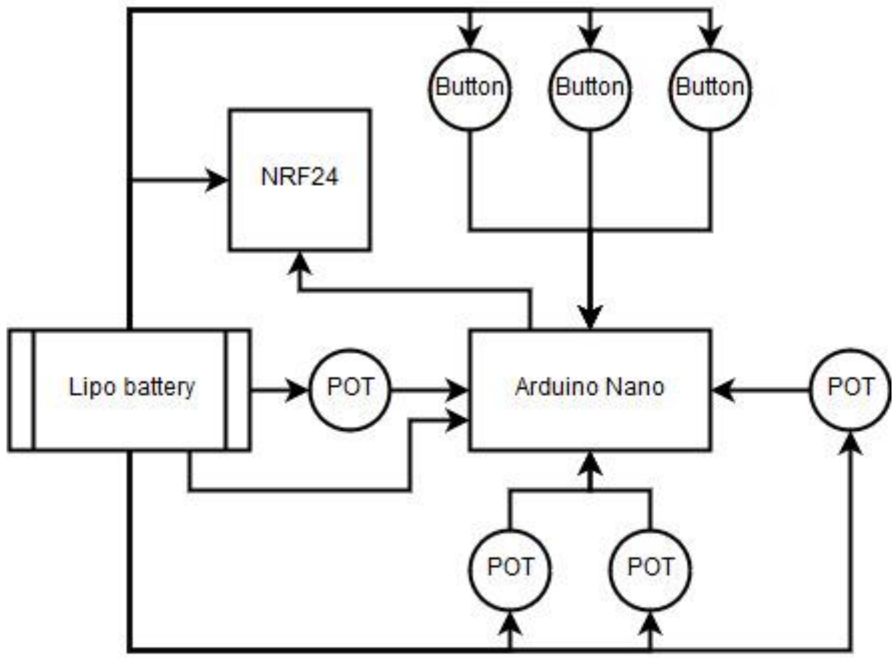

Figure 9: Controller component design

The SAR hexapod has two main component interfaces with Raspberry Pi 3 B+ single board computer shown in Figure 7 and 8. The two power converter modules are to convert the power coming from Li-Po battery to appropriate voltage so it can be used to power the Raspberry Pi, servo controller, nRF240L1P, FPV camera and lighting system. Each of the converter manages one voltage level, either 5V or 7.4V. The servo controller is to communicate with the Pi through UART interface and use its onboard controller to manage all 20 servos' movement accordingly. The nRF240L1P module is used as radio frequency receiver to retrieve signal from the remote controller and sent the received signals to the PI to process. The FPV camera module is an independent system. It transmits video footage to the FPV monitor using its own wireless protocol.

The remote control is designed based on the Arduino Nano microcontroller shown in Figure 9. There are four potentiometers connected to analog pins and three buttons connected to digital pins. All signal from joysticks, potentiometers and buttons will be processed by the Arduino Nano before sending them out using nRF240L1P through SPI interface.

4.3 Structure and Logic Design

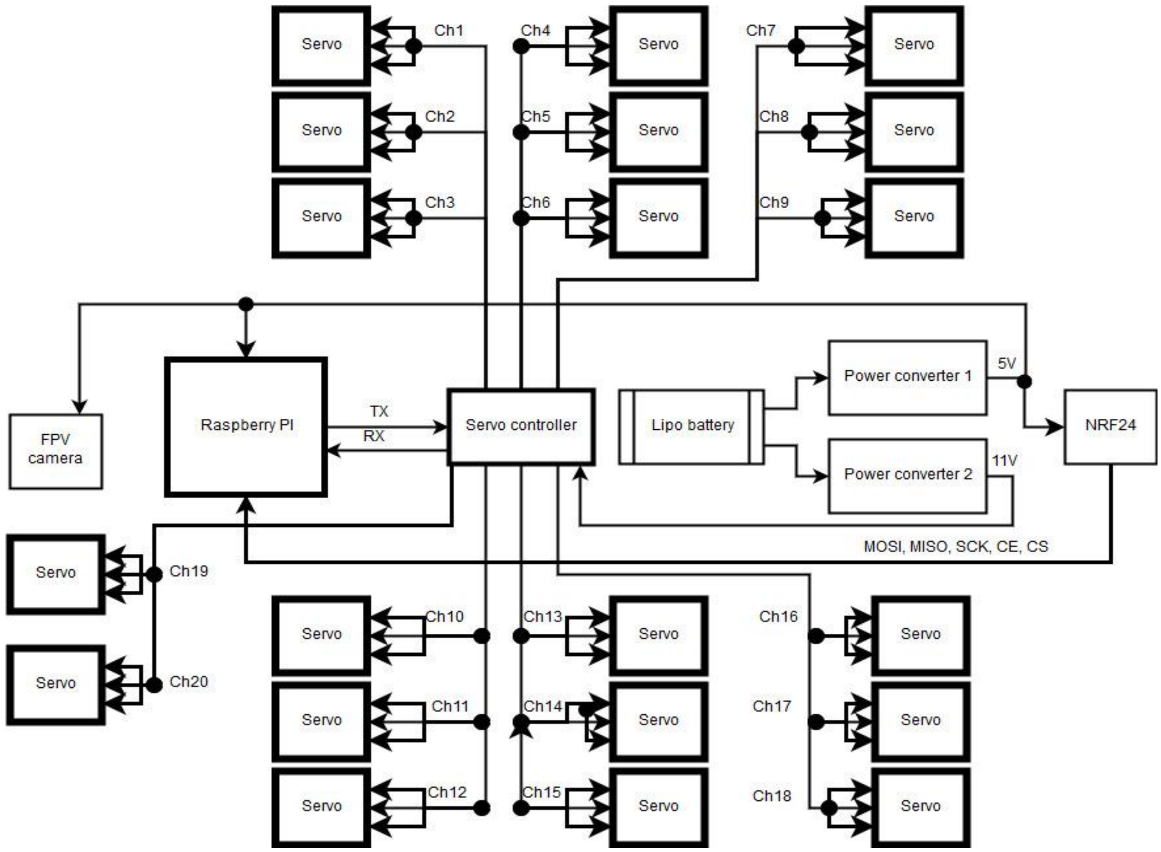

Figure 10: Hexapod Schematic Layout

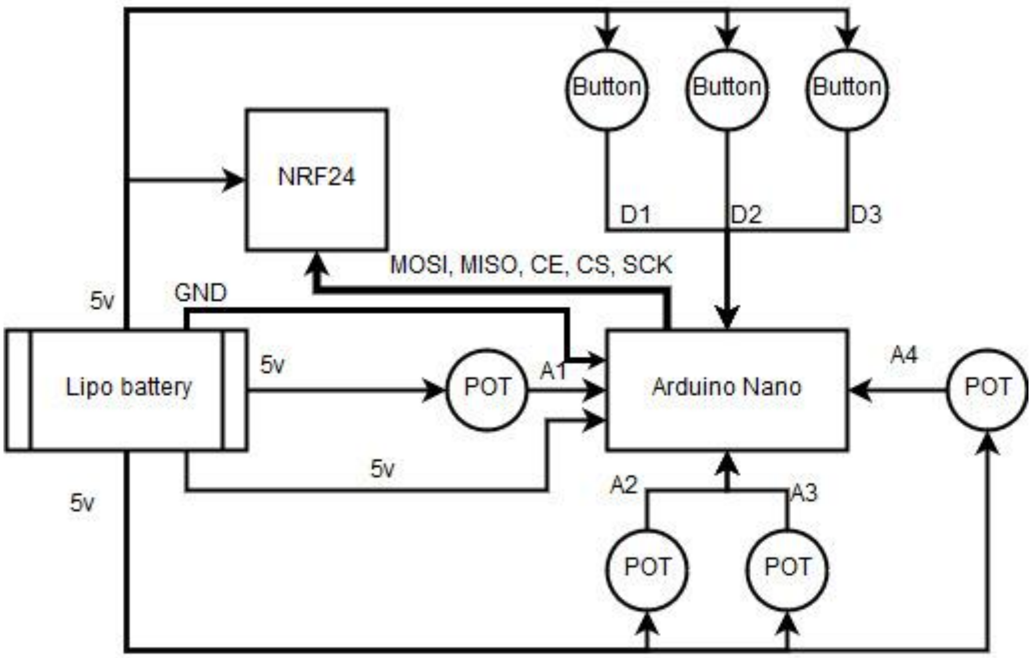

Figure 11: Controller Schematic Layout

Figure 12a: Side view of Hexapod prototype

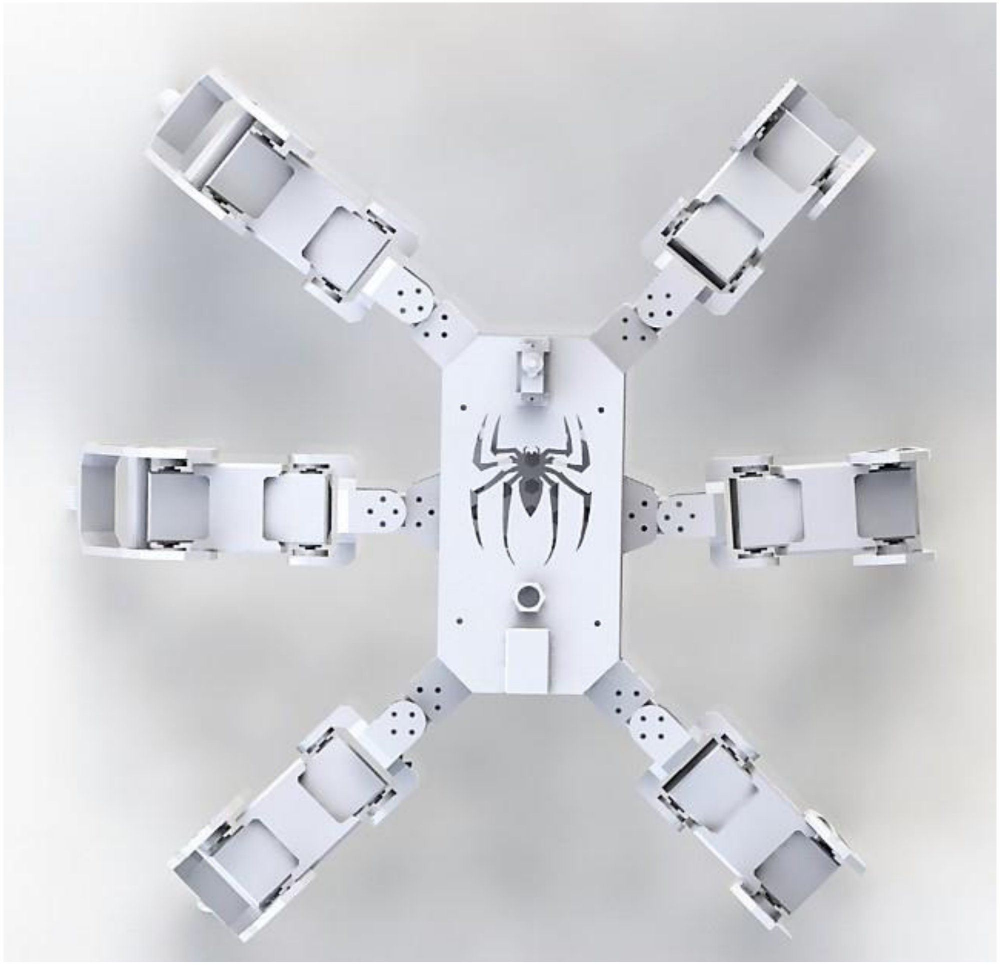

Figure 12b: Top view of Hexapod prototype

Figure 12c: Image of final product in real life

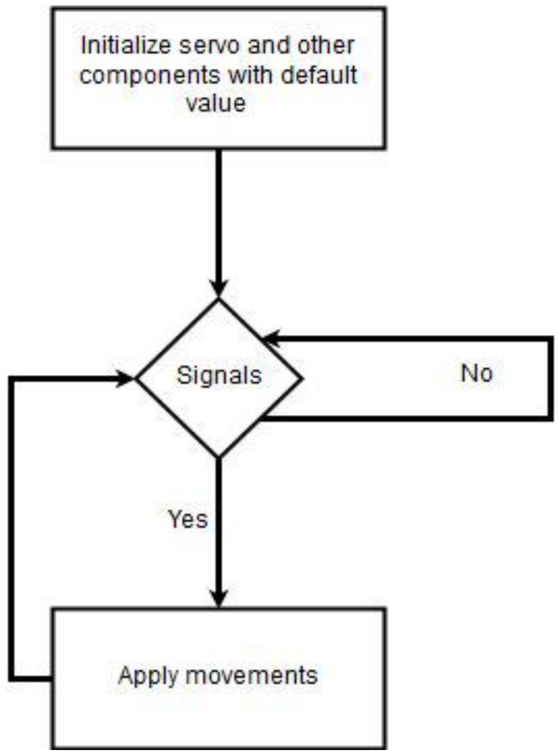

Figure 13: Flowchart for software design

In Figure 10 and 11, they show connectivity interface between components in hexapod robot and the remote controller. There are 20 servos associated with leg movement and camera angle adjustment. Each of the servo is managed by the Maestro servo controller (24 channels) after receiving signal from the Pi through UART protocol. There are 3 connections acquired by servo which are power line, ground, and PWM signal directly from the servo controller. Incoming signals through nRF24L01P module will be passed to the Pi to process with calculations and algorithms. The processed signals will be sent to the servo controller afterward.

On the remote controller, signals from buttons and potentiometers are connected to the Arduino's digital and analog pins. The microcontroller will rearrange these signals into packages and send them out using SPI interface through nRF24L01P transmitter.

The software to control the robot is follow the flowchart shown in Figure 13. All components will be initialized and set to idle position. They wait for signals from the controller UART to take action. If there is no command signal, the hexapod will stop after complete previous actions.

Figure 12 shows the prototype designed in SolidWorks software which is used to design all parts for 3D printing.

4.4 Design Constraints, Problems, Trade-offs, and Solutions

4.4.1 Design Constraints and Challenges

In the process of building the hexapod, there are some constraints and challenges that need to be address. The biggest constraint of the project is resources and budgets. Since the hexapod is only a prototype, the servo motors may lack precision comparing to industrial grade motors or robotic actuator. Also, due to the goal of having a lightweight hexapod, the body parts are 3D printed using Polylactic Acid (PLA) plastic. Therefore, the hexapod body parts have limited strength and durability.

As mentioned in the architecture design, we are using the nRF24L01P Transceiver for communication between the remote controller and the hexapod. The real-life test shows that the maximum range of the module is only around 100 meters for indoor uses. Our goal is to keep a safe distance between the hexapod and the operator. Thus, the limited range present another challenge to our design.

4.4.2 Design Solutions and Trade-offs

With the constraints and challenges in previous section, there are some solutions and trade-offs that we need to take under consideration. In order to maintain a low cost, the servo motors are not state of the art. Despite the lack of precision, the motors used in our project are of decent quality that can still get the job done. Yet, the hexapod is completely scalable by upgrading the servo motors.

As for the body parts, we would like to have a lightweight and replaceable hexapod. Therefore, PLA plastic for 3D printed parts is the best option. The strength and durability of the hexapod is limited, but it is a trade-off that we are willing to accept. Nonetheless, it is not impossible to improve the durability of the robot. Aluminum can be used instead of PLA plastic for body parts, but this will increase the overall cost and weight of the hexapod significantly.

Chapter 5 System Implementation

5.1 Implementation Overview

The scope of this project is to build a hexapod that is controllable with the remote controller. We have to design and print out the body parts of the robots, attached them with the servos and microcontroller, testing the body part and servo motors. The firmware is written in C/C++ running on Raspbian Stretch OS. The controller's firmware is implemented using Arduino IDE.

5.2 Implementation of Developed Solutions

Two main functions that are essential for this project is to establish a secure and stable connection between the controller and the hexapod to send the signal, and the second essential function is to implement the four degree of freedom movement, which the hexapod could move forward, backward, left, right, or rotating all depend on the input signal from the controller. Therefore, we used the microchip nRF24L01P, that is connected to the SPI port of the hexapod's microcontroller, and picked a unique frequency at 2.4 GHz as the solution to establish the wireless connection between the controller and the hexapod. With this solution, the connection would be secured and we could also increase stability and the range how far that we could control the hexapod wirelessly.

For the six degree of freedom, we used the Inverse Kinematics and Forward Kinematics algorithms as solution to determine the movement of our hexapod. By using this algorithm, we could calculate all the required angles for each leg of the hexapod given its end effector.

5.3 Implementation Problems, Challenges, and Lesson Learned

How well our hexapod could move is all depending on how familiar and understanding we are with the Inverse Kinematics and Forward Kinematics algorithms. Although we managed to implement the movement of six legs, there is a small problem in the hexapod's walking. When moving forward and backward, we noticed that the hexapod's movement is not straight. Forward movement is slightly tilted to the right. We tried to make changes to the firmware, however, the problem is not solved. A possible cause of the problem is due to the designed structure of the hexapod's body.

The lesson we learned after facing this problem is that the body structure needs better design.

Chapter 6 Tools and Standards

6.1 Tools Used

6.1.1 Hardware

We decided to use Raspberry Pi 3 Model B+ microcomputer which consists of a Broadcom ARMv8 Cortex-A53 that has clock speed of 1.4Ghz as the main board for the hexapod. The system also has a Pololu Maestro 24-Channel Servo Controller and a nRF24L01P transceiver for motor control and receiving signals. The Pololu Maestro 24-Channel Servo Controller includes the setting of target servo angle, speed, and acceleration.

In regarding to live feeds, we used the Eachine TX03 AIO FPV Camera to stream video to a monitor at the operator's end. The camera is capable of transmitting live feed through 2.4GHz radio frequency. The turret is built using two MG90S Metal Gear micro servo motors to pan and tilt the camera.

Our controller is designed built using an Arduino Nano V3.0. The device consists of joysticks, push buttons and potentiometers for inputting signals. These signals are processed by the Arduino into packages and sent to the Hexapod via a nRF24L01P transceiver. Th nRF24L01 Transceiver modules are used for signal communication between the remote controller and the hexapod. It has advantage of availability on the field over Wi-Fi, and the advantage of range over Bluetooth, maximum range of 1 kilometer in open field

6.1.2 Software

Eclipse, Pololu Maestro Servo Controller and Arduino IDE are used for developing, and testing the source codes. All firmware functions for the hexapod is written in C/C++ running on Raspbian Stretch OS.

The remote controller's firmware is implemented using Arduino IDE. The compiled hexapod's firmware is automatically run on Raspberry Pi start up by a written bash script.

The Pololu Maestro Servo Controller is a software that we used to test the servo motors. The software is also used to limit the range of the motors.

6.2 Standards

6.2.1 Hardware standard

- The Hexapod can be manually controlled via wireless controller. The controller will use the radio frequency to enhance the range of receiving signal between the Hexapod and the controller.
- The Hexapod must be able to move forward/backward/right/left, rotate right/left, shift forward/backward/right/left/up/down, pitch forward/backward, roll right/left, however the user wants to control it.
- Hexapod must not cause any damage to the surrounding when walking.
- Hexapod must be wireless and portable.
- 3D printed body parts should be easy to replace when damaged.

- The Hexapod is also required to have the camera and transmission system to transfer all the visual data to the user via the remote controller.
- The camera provides operator with live feed video.
- Camera is equipped with 2 servo motors that allow pan and tilt.

6.2.2 Software standard

- Hexapod must be optimized in power efficiency.
- The network transmission between hexapod and the controller must be secured so that it's not easy to hack into the network.
- The hexapod movements should be swift and stable.
- We use Eclipse, Pololu Maestro Servo Controller and Arduino IDE for developing, and testing.

Chapter 7 Testing and Experiment

7.1 Testing and Experiment Scope

For the testing part, we decided to split these testing portions into the total of 4 scope. The first scope was to test the connection signal between the controller to the Hexapod. The next scope would be the unit testing which we would test all the functionalities of each component that we used for our Hexapod. The third scope then would be testing its integration level which we would focus on testing its main functionality, which was the Hexapod's movement and its terrain adaptation ability. Then the last scope we would focus on testing the stability of the overall project, including all hardware and software components.

Table 3: Test Case Table for Each Scope

Scope #	Title	Reason	Expected Outcome
1	Connection	To test the connection between the controller and the Hexapod.	Hexapod could transmit/receive signal to/from the controller.
2	Unit testing	To test all the functionalities of all the components	All the function work as expected.
3	Stability	Focus testing on the stability of the overall project.	The whole system has no errors and work as expected.

7.2 Testing and Experiment Approach

7.2.1 Connection

To test the RF connectivity between the controller and the RF receiving module attached on the hexapod, we write a script to test both distance and reliability in term of data loss. There is various situation being tested such as open field, inside complex building at the same level, inside complex building at different levels. With those situations tested, we can determine how far the signal can travel in different situations that can happen when the hexapod is in action. This is eliminating the total loss since we are able to keep it in the controllable range. However, the data needs to be verified on the receiving end to ensure the data correctness within acceptable losing rate. Since we want the longest distance and the most reliable transmission, the transmitting data rate 250kbps is used to test instead of 1Mbps and 2Mbps. While the controller keeps sending same data continuously at certain rate in different cases, the receiver generates beeping sound if they are still connected, checks the correctness of incoming data, and also calculating the data loss rate with respect to the time setup of the transmitter.

7.2.2 Unit Testing

Every unit involved in this project were being tested to confirm its functionality and reliability. Part list is shown in Table 1. With the use of this project, we used code to test The Raspberry Pi and Arduino Nano microcontroller ‘s GPIO, UART and SPI communication protocols and verified the correctness via Saleae Logic analyzer. To test the Mini Maestro servo controller, we connect the servo to each channel and check if it moves with respect to control signal from the board. This process is duplicated for all 20 servos. The FPV camera and monitor are testes with multiple different channel to look for the most reliable channel in the testing area. Lastly, the battery and the two-power regulator are measured with multimeter to ensure the output voltage and current to meet the requirement of the system and components.

7.2.3 Stability Testing

To verify the firmware needs to collaborate well with built hardware, we have tested all designed functions which were programed in the controller and examine the hexapod’s according action. There are buttons, joysticks, potentiometers, battery pack and LCD display which need to be tested. While buttons are pushed or joysticks and potentiometers are moved, there must be corresponding messages displayed on the LCD and movements on the hexapod which also includes camera servos and LED light. There is a buzzer is connected to the controller. It will make unique beeping sequences when an action is taken successfully. The battery life is also tested by measuring the duration while it is in action from 100% to out of power stage.

7.3 Testing and Experiment Results and Analysis

7.3.1 Testing results

Analyzing connectivity between the hexapod and the controller is important and critical for its operational purpose. Various situations are tested to figure out its maximum controllable distance and successful data transfer rate at different distance. The result is recorded in Table 4, Figure 14-17.

Table 4: Connection testing result with data rate 250Kbps

#	Test case	Max distance(m)
1	Open field	120
2	Same Level Complex Building	43
3	Different Level Complex Building (consecutive floor)	29
4	Different Level Complex Building (1 floor separation)	21

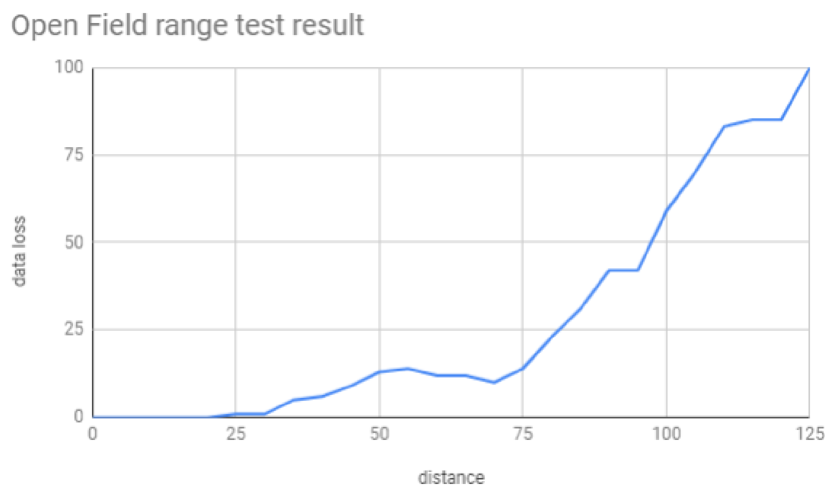

Figure 14: Test case "Open Field"

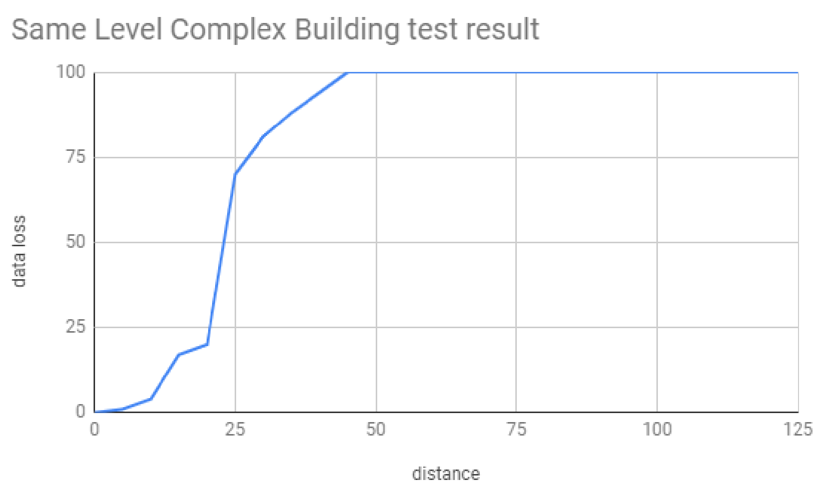

Figure 15: Test case "Same Level Complex Building"

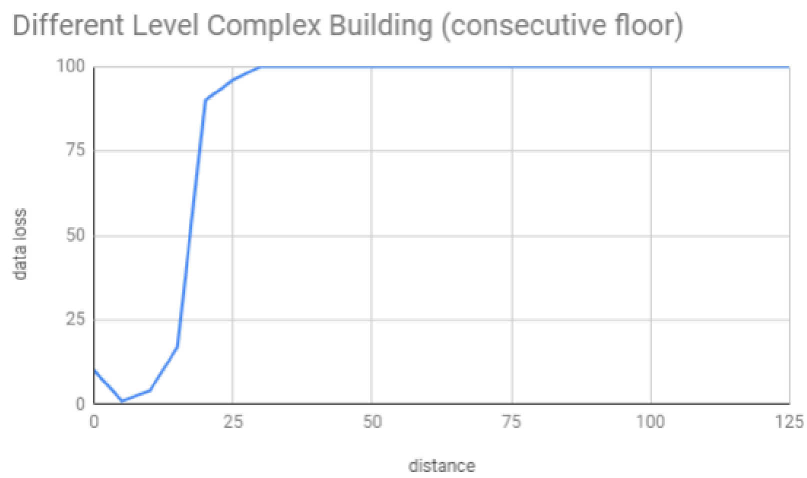

Figure 16: Test case "Different Level Complex Building (consecutive floor)"

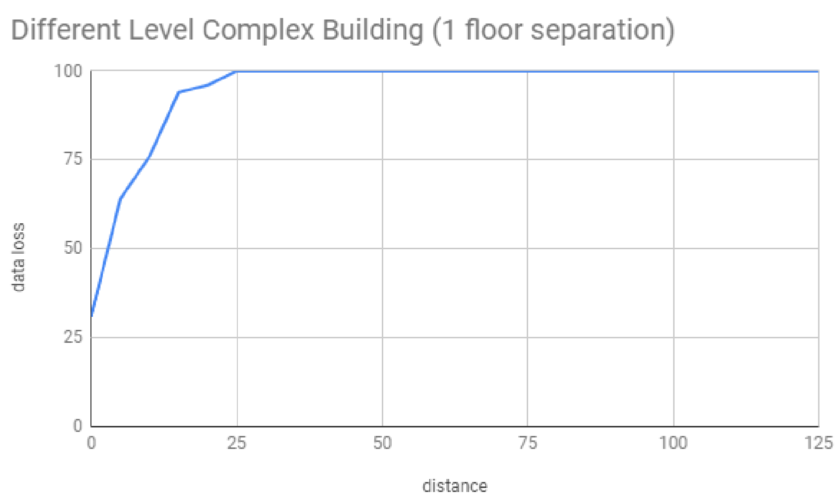

Figure 17: Test case "Different Level Complex Building (1 floor separation)"

Unit testing result is recorded in Table 5. It includes all components used in this project. Each component is tested carefully to ensure its functionality and durability.

Table 5: Unit Testing Results

Parts	**Testing result**
Raspberry PI 3	GPIO, SPI, and UART protocols are all working correctly
Arduino Nano	GPIO, SPI, and UART protocols are all working correctly
Mini Maestro	All 24 channels work correctly and able to control servos with accurate rotating angles
5000mAh Lithium Battery	Output consistent 7V signal through various loads
Power regulator	Power regulator was able to output stable voltage (5v and 3.3v)
FPV camera and FPV monitor	Transmitting video flawlessly in available 2.4Ghz channels
Precision Robotic Servo and Micro Servos	All servos rotate to target angles with reasonable accuracy

Stability test result is recorded. While all of the controlling buttons and joysticks' positions are tested, the LCD and the hexapod are observed to verify their behavior. Tested functions include moving forward, moving backward, moving left, moving right, rotating left, rotating right, height adjustment, speed adjustment, mode switching, turning on LED, camera movement (up, down, left, right). We also observed the information displayed on the LCD to ensure it displays correct information. All test is successful as expected. The battery life is also measured. With this current used 5000mAh Li-Po Battery, the battery is actually able to last from 5-10 minutes depending on the intensity of movements and also the use of utility such as LED light, connectivity and environmental temperature.

Operating time is crucial in every Search and Rescue operations. We tested the battery by letting the Hexapod run on a fully charged one until the cut-off voltage is reached. Its voltage is recorded every 5 minutes (Figure 18). The results allow us to have a rough estimation of the Hexapod's operating time, which is around 25 minutes.

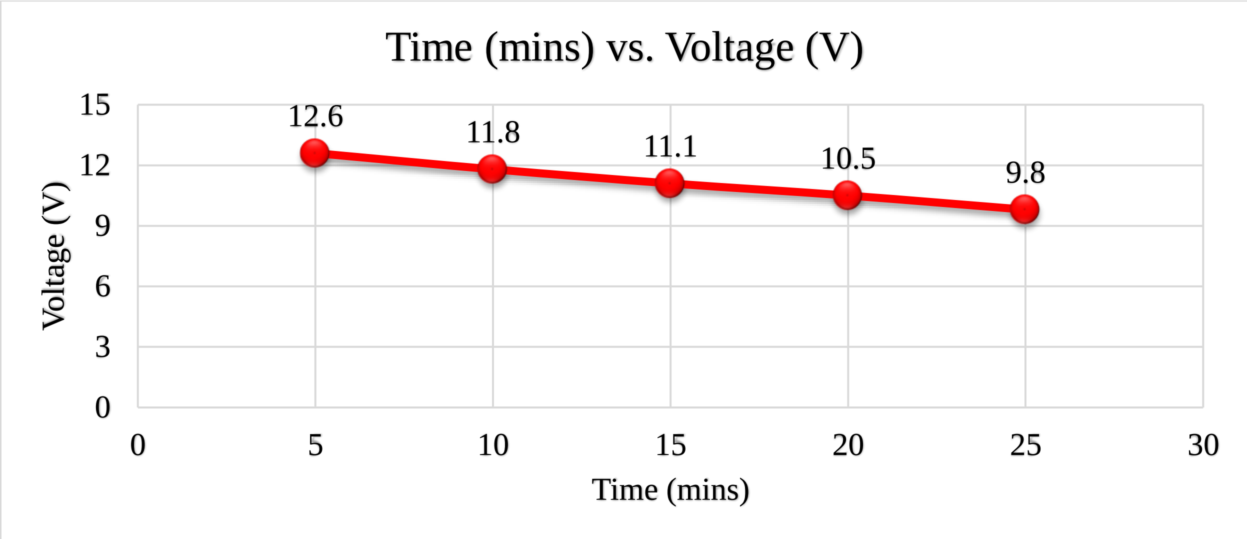

Figure 18: Graph of battery voltage over time

While operating the Hexapod, the temperature of important components is also measured (Figure 19). Since the body are 3D printed, this helps in designing the robot to ensure its parts do not heat up and melt.

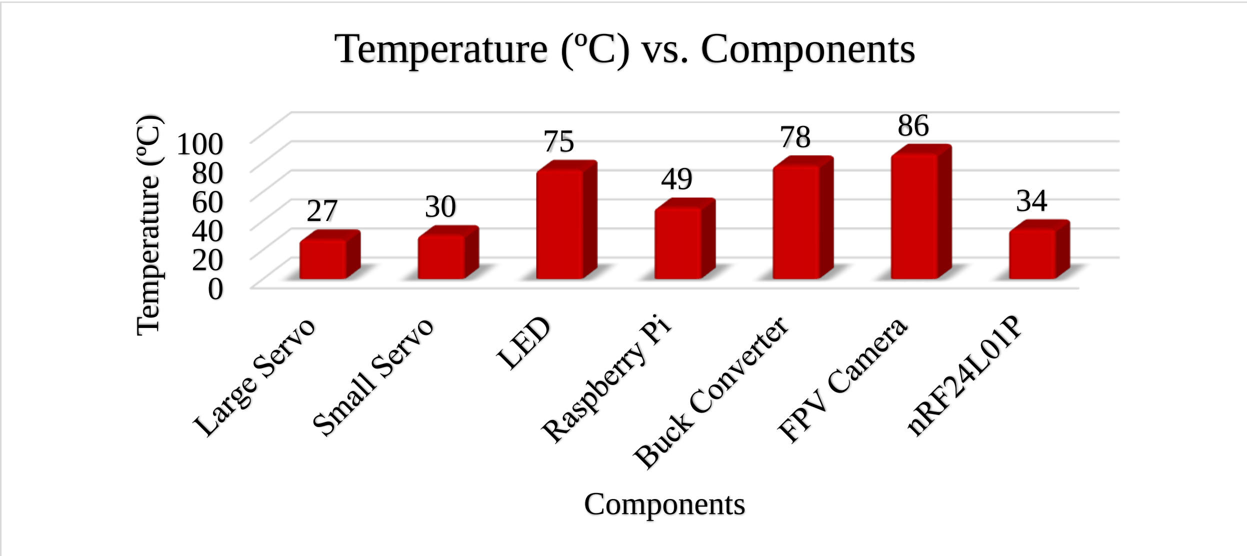

Figure 19: Graph of components temperature over time

Chapter 8 Conclusion and Future Work

8.1 Conclusion

Each year, there's been more than thousand incidents that people have been reported missing due to natural disaster, or rescuers arrived at the scene way too late. Most of the cases were because the victims were stuck in an area that is really hard to access because of collapsing of the building or trees. In order for the rescuers to find the victim's location and save them would be consuming a lot of times, and that is the reason why some operations didn't go as planned. Thus, in order to save time in looking for the victim's location, we decided to build the hexapod. Overall, our robot is able to walk with six degrees of freedom with an adjustable speed. Since we used radio frequency as main connection between the controller and robot, we also managed to control it in an acceptable range for this prototype. Frequency of 2.4GHz is not ideal for penetrating thick walls or grounds. Due to this, data lost rate between the controller and the hexapod, at max range (Table 4) is significantly increased to 80%-90%.

8.2 Future Work

We would like to implement the terrain adaption feature in the future. This will allow the hexapod to navigate through rough and uneven terrain easily. With this current prototype, the hexapod can only handle flat or near flat surface. Also, autonomous ability is another feature we would like to consider in future version of our hexapod. With this ability, we only need to set up the route and the robot will find its way to get to the destination without human control. It can be a huge help in certain situation that lacks of signal radio frequency strength. Lastly, we plan to increase the transmitting signal using other radio frequency module.

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Appendices

Appendix A – Algorithms

Forward Kinematics: the method for determining the orientation and position of the end effector (x, y, z) coordinates relative to the center of mass, given the joint angles and link lengths of the robot leg.
Inverse Kinematics: the opposite of Forward Kinematics. It is useful when you have a desired end effector position (x, y, z), but need to know the joint angles required to achieve it.

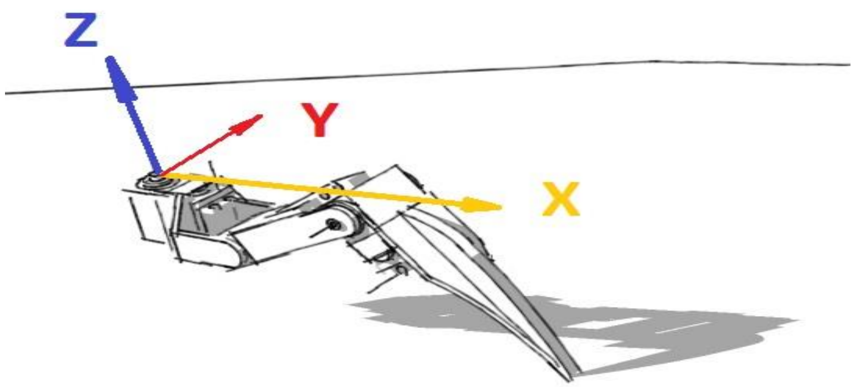

Figure 20: 3D coordinates of a single leg

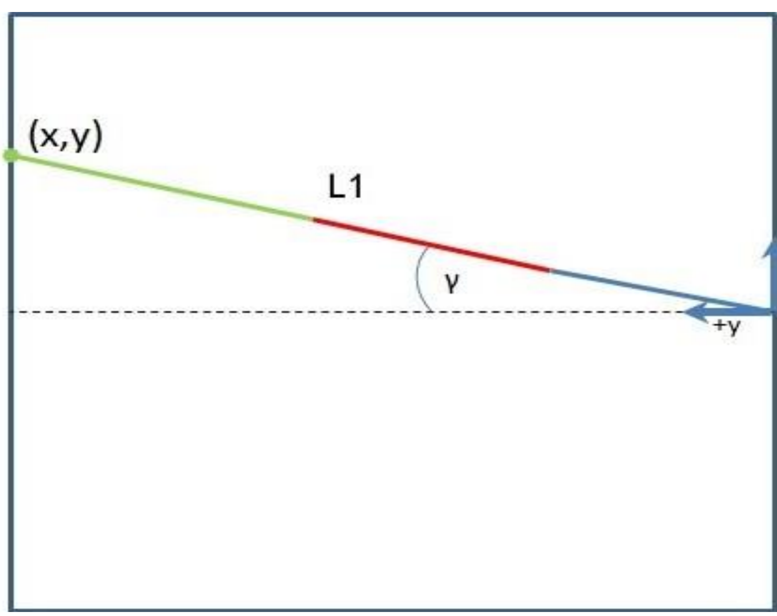

Figure 21: Single leg (in x and y coordinates view) with leg angle γ. Blue = Coxa, red = Femur, green = Tibia

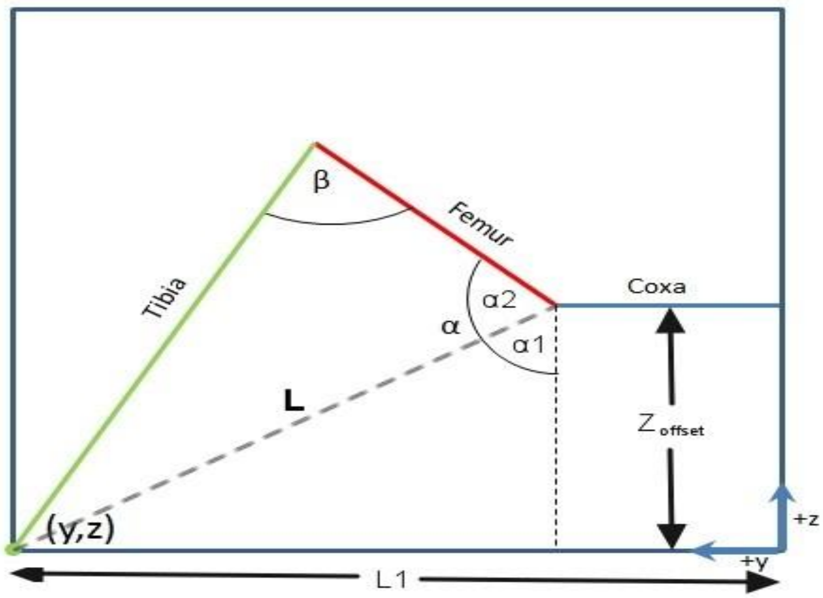

Figure 22: Single leg (in y and z coordinates view) with leg angle α and β. Blue = Coxa, red = Femur, green = Tibia

In order to calculate the joint angles, given the desired end effector coordinates, the following equations are used:

$$\gamma = \tan^{-1}\left(\frac{x}{y}\right)$$

$$L = \sqrt[2]{z_{offset}^2 + (L1 - Coxa)^2}$$

$$\alpha_1 = \cos^{-1}\left(\frac{z_{offset}}{L}\right)$$

$$\alpha_2 = \cos^{-1}\left(\frac{Tibia^2 - Femur^2 - L^2}{-2(Femur)(L)}\right)$$

$$\beta = \cos^{-1}\left(\frac{L^2 - Tibia^2 - Femur^2}{-2(Tibia)(Femur)}\right)$$