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DEVELOPMENT OF MULTI-LEGGED ROBOT CONTROLLER WITH REMOTELY CONTROL SYSTEM

AHMAD AQIL SAFWAN BIN AHMAD ZABIDI

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Bachelor of Electrical Engineering Technology (Power & Machine) with Honours

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ABSTRAK

Robot yang mempunyai banyak kaki, adalah robot yang mendapat ilham dari alam semulajadi seperti haiwan serangga atau arthropod. Robot begini selalunya dibangunkan sebagai robot yang boleh bergerak sendirian tanpa perlukan pengawasan untuk mempunyai lebih banyak kebaikan berbanding dengan robot beroda. Tambahan lagi robot ini mampu mengawal kestabilan dan statik dalam pergerakannya. Di dalam projek ini, sebuah robot berbilang kaki 'Hexapod-to-Quadruped' (Hexaquad) difokuskan untuk menambah baik kestabilan kakinya dan bentuk pergerakkanya. Tambahan lagi, projek ini memfokuskan untuk mencipta tapak kasut baharu untuk kaki robot ini berjalan di atas tanah yang rata. Sebuah papan unit kawalan disediakan dengan mikropengawal 32-bit sebagai unit pemprosesannya dalam reka bentuk kawalan. Papan pengawal ini menggunakan Simulink untuk mengawal projek ini dalam masa nyata. Hasil dari projek ini adalah menyediakan dan mewujudkan pergerakan asas untuk setiap kaki robot ini dan menyediakan penyelarasan kaki robot ini kepada kedudukan asal.

ABSTRACT

The multi-legged robot is a biologically inspired robot that mimics insect or arthropod creatures. This robot is commonly developed as a mobile robot for a crewless operation that can surpass what a wheeled robot does not. Moreover, this robot can hold both static and dynamic stabilities in its locomotion. In this project, a configurable multi-legged robot named Hexapod-to-Quadruped (Hexaquad) robot is focused on improving with stable leg motion and gait pattern. Moreover, the project focuses on developing a new leg shoe for flat terrain on land locomotion. A centralized control unit board is prepared with a 32-bit microcontroller as its processing unit in the control design. The embedded controller design used Simulink code for the real-time and hardware-in-loop method. The project's outcome provides basic motion for each robot's leg including leg reset setting for initial position.

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
CoG	Centre-of-Gravity
DC	Direct Current
DoF	Degree of Freedom
FTG	Foot-to-Gripper
Hexaquad	Hexapod to Quadruped
IO	Inputs/Outputs
DIO	Digital input/output
PWM	Pulse with modulation
VS	Versus
COM	Centre of Mass
POS	Polygon of support
CPU	Central processing unit
A/D	Analog/Digital
D/A	Digital/Analog
ASV	Active suspension vehicle
PID	Proportional Integral Derivative

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

To cross unstructured terrain successfully and safely, almost all terrestrial animals evolved with sturdy, nimble legs. Thus, robotic expertise has made multiple attempts over the last several decades to produce bio-inspired legged robots that are as lifelike as feasible in synchronizing and coordinating the robot's body to leg joints. As a result, many robots and machine designs in the automotive technology industry select wheels because of their energy efficiency and mobility. Nevertheless, it is essential to remember that only vehicle systems with legged mechanisms can operate as a legged creatures capable of navigating unstructured terrain [1]. Additionally, because a legged robot requires only discrete touch with the terrain surface, this robot can step over obstacles and maintain stability by altering the height of its legs.

On the other hand, the wheeled robot must maintain constant contact with the flat surface to navigate steadily. This feature highlights how a legged robot may reduce damage to terrain structures while enhancing mobility in any situation, particularly in applications where the ground must stay undisturbed for specific reasons [2]. Until recently, developed legged robots were employed to demonstrate their competency in a range of important applications, such as underwater research [3], planetary or space exploration [4], nuclear power plant operations [5], and search and rescue operations [6].

Multi-legged robots are frequently impacted by living organisms such as humans, animals, and insects. multi-legged robots follow a predetermined gait pattern/algorithm when walking. Multi-legged robots are being used to transfer payloads and investigate rugged terrain. Big Dog, a multi-legged robot created by Boston Dynamic, is an example. It has a top speed of 4 miles per hour (mph) and can climb slopes up to 35 degrees in inclination [7]. To perform a joint movement, robots require drive systems, and all robot designers desire/need accurate joint actuation [8]. It is possible to better regulate the robot's movement and walking pattern (gait) with precision control.

Without a proper controller for robot leg's, the incoming development for the robot may be crippled in a particular situation. Excellent and stable, reliable feet are needed to ensure the robot can stand on itself without any problem. Any part movement of the robot needs to be optimized and scrutinized to ensure the robot's movement is precise to avoid any future error that may harm the robot or its surroundings.

1.2 OBJECTIVES AND SCOPES

Concerning the problem statements outlined in the previous section, the objective is listed below:

I. To reconfigure the controller and drive unit of the Hexaquad robot.
II. To design a basic motion/movement of the Hexaquad robot.
III. To design a new shoe on the robot's foot for flat terrain mode walking.

The scope of the project should be focused on:

I. Design and developed a driven module for every Hexaquad leg with a controller.
II. Design a stable leg movement program for Hexaquad to develop its walking pattern.
III. Design and prepare a flat shoe for each robot's foot to disable each gripper.

1.3 THESIS OUTLINE

This thesis is organized as follow:

Chapter 1:
On this chapter of this proposal will explain this SDP, covering the project's introduction, objective, scope, and thesis outline. The introduction will discuss the Hexaquad current problem and provide background information on the project.

Chapter 2:
This chapter includes a literature review about the previous development of the Hexaquad robot. In addition, the current information on Hexaquad and its work process will be discussed in this chapter. This chapter will also discuss the development of robot legged and the type of robot walking pattern.

Chapter 3:
This chapter will give detail about the methodology used to complete the project. The method for completing the work and a description of the tools, resource utilisation, and general flow of the project are covered in length in this part. References to related knowledge will be explored, and the project details will be discussed.

Chapter 4:
This chapter will show the result from the driver setup and the Simulink program made. This chapter will also discuss the output graph from Simulink to understand the detail in Hexaquad leg movement. The chapter explains the overall developed control and the result after the implementation.

Chapter 5:
The project's results and comments will be provided here to validate the proposed solution. In addition, the problem encountered will be described, as well as the remedy if available.

CHAPTER 2

LITERATURE REVIEW

2.1 REVIEW ON RESEARCH AND DEVELOPMENT OF LEGGED ROBOT

As with manipulators, the legged robot needs interaction with the surrounding environment and its robotic leg for sensing and foot placement, particularly in unstructured terrain (complex) that may contain unanticipated obstructions or have varying ground stiffness. The key to maintaining the robot's body posture and stability in a legged robot is to recognize and regulate the impacts that occur during leg landing into the surface and transfer force onto the surface to move the robot's body. Thus, compliance components like suppleness and flexibility are incorporated into motion control to provide a stable body posture and adaptation to the surroundings for a legged robot during locomotion. For a non-compliant (stiff) robot, the end-effector is constructed with preset and set locations or trajectories in mind. Even when an external force is applied to the manipulator, the robotic end-effector will perfectly follow the specified route. At the same time, a compliant end-effector may relocate the manipulator linkage or end-effector location when a different force is applied to it [9]. There are two ways to ensure that the robot complies with environmental regulations: passive compliance and active compliance. Passive compliance can be achieved by rebuilding the robot's body, focusing on the leg structure, modifying the leg's joint actuation mechanism, or by equipping the leg with springs, dampers, or both as a compliant device. It is distinct from passive compliance control, which gained extra active compliance by incorporating force feedback or joint torque feedback into the robot's leg end-effectors to dynamically manage the system's behavior, such as precise force control and impedance management. Both approaches to developing an environment-compliant robot will provide flexibility for a legged robot to adapt, particularly during locomotion over unstructured terrain or when confronted with ground stiffness while retaining the robot's body's stability.

2.2 MULTI-LEGGED ROBOTS

Multi-legged robots or active suspension vehicles (ASV) provide several advantages over motion control, particularly when coping with uneven and steep terrain. Leg manipulation stability is crucial since it determines how well a robot leg can move. Each robot's leg is simply a manipulator unit (a single robot arm) that is generally set up with fixed design motion during mobility. The robot arm manipulator is particularly adept at applying force to items to move them across the workspace in terms of object interaction. For a legged robot's reliable mobility, compelling trajectory tracking in leg manipulation is essential. For the leg to perfectly follow the needed motion during trajectory tracking, each leg's joints must have a robust closed-loop control. Certain nonlinear situations, such as the windup phenomenon and gravity effects, should be considered while designing a closed-loop control. Close-loop control inputs such as the proportional integral derivative (PID) control input ($u(t)$) accrue and continue to increase when the physical variable approaches its saturation point due to the action of the integral element. As a result, one or more leg joints may be involved in raising and lowering the leg to complete the position control, or some joints may be static while others keep the system moving. During these leg motion phases, particularly during foot planting, gravitational influence can cause an internal disruption to each leg's joint [10].

2.3 OVERVIEW OF HEXAQUAD ROBOT

The paper explored the many types of multi-legged robots. The walking robot mechanism mentioned is the leg-type mobile robot. The Hexaquad robot is a legged robot. Compared to crawler and wheel type robots, the leg type robot has several benefits, including the flexibility to choose the ground contact point, which means it will be more adaptable to the terrain with which its leg comes into touch. In addition, the capacity of a legged robot to walk and navigate without sliding is critical for positional stability. The method of multi-legged robot walking is classified into two types: static walking and dynamic walking. For instance, static walking in a four-legged robot means that just one leg swings while the other three remain in a supporting posture, but dynamic walking always requires one or two supporting legs [11].

Hexapod-to-Quadruped (Hexaquad) is a reconfigurable multi-legged robot with a bioinspired design that will be used for underwater operations. Hexapod is a configuration of multi-legged robots that is statically stable, whereas quadruped is a configuration of multi-legged robots that is dynamically stable. In terms of robot configuration, multi-legged robots are extremely adaptable, and their greater gait stability [12] enables them to travel to locations/terrains where a robot with conventional wheels would ordinarily fail. While multi-legged robots offer several benefits over propeller-based robots for underwater operation, the benefits of legged robots include their ability to undertake underwater walking and manipulation in the face of strong tidal currents and their manoeuvres at the bottom, as mentioned in[13], will have a lower influence on muddying the sea water. It is feasible for the robot to climb at a specific incline by having a suitable walking algorithm (gait pattern) [14]. As seen in Figure 2.1, the dimension of Hexaquad is given

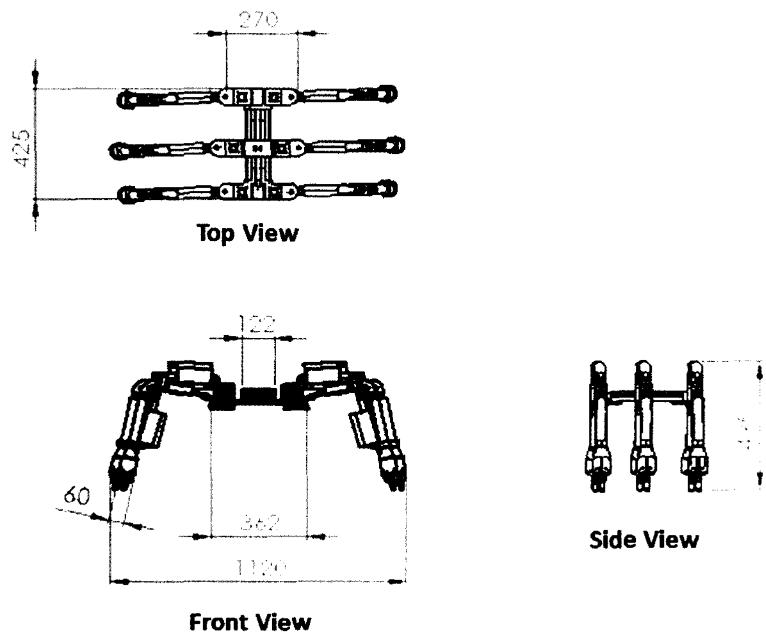

Figure 2.1: Dimension of Hexaquad [15]

Each of the six Hexaquad legs is configured identically. Each of them has two joints, the Merus, and the Carpus (both parallel actuated by linear actuator). A dual driver is employed to drive the Merus and Carpus joints two linear actuators. Figure 2.2 illustrates the real design Hexaquad Leg configuration and connection.

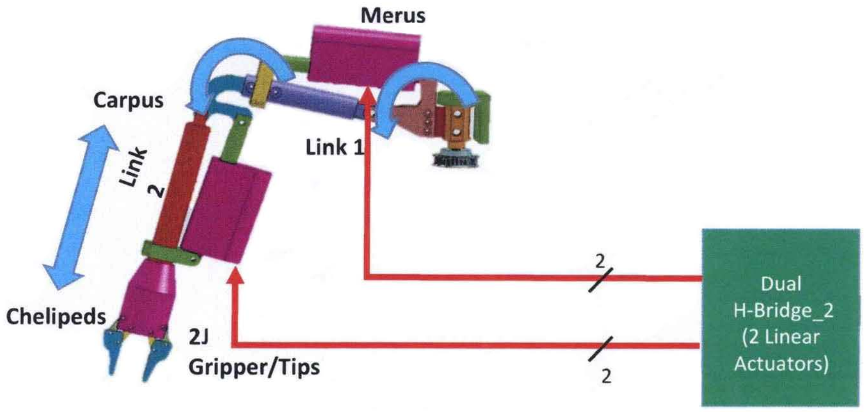

Figure 2.2: Hexaquad leg configuration and connection [15]

The component (actuator) needed to control the Hexaquad robot was included in the set detailed in [15]. The article described the sort of actuator used for the Hexaquad robot and how it met the requirements for performing leg actuation. The article conducted simulations and estimated the torque requirements for each joint [15]. The Hexaquad Robot's design is summarized in Figure 2.3 and Figure 2.4.

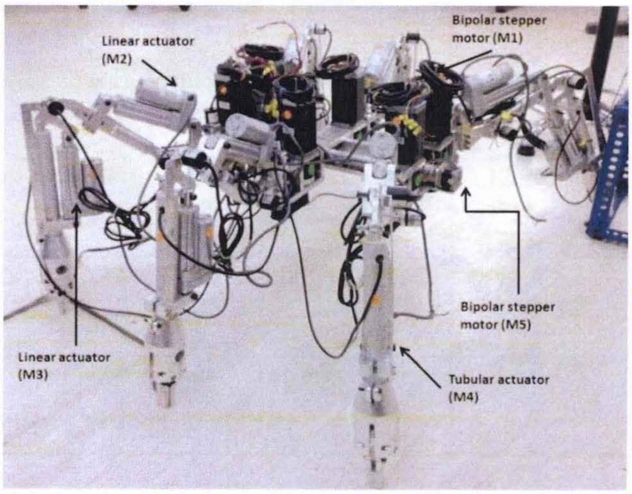

Figure 2.3: Hexaquad Robot Design Overview.[15]

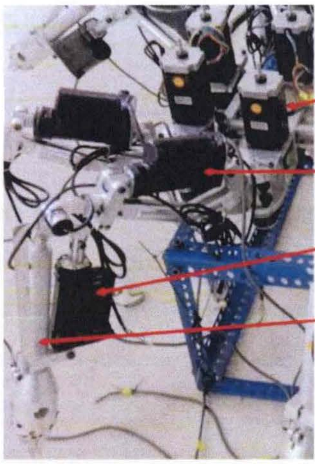

Figure 2.4: Actuator and respective joint

The specification of the robot leg and the size are discussed in Table 2.1 below. The detail of this discussion can be referred to the previous journal [15]

Table 2.1: Hexaquad specification

Item	Value	Unit Total
Length (m)	0.9	-
Width (m)	0.42	-
Height (m)	0.43	-
Total weight (Kg)	50	-
Potentiometer	-	12
Linear actuator Load (N), Voltage (V) and Current (A)	200,12,2	6
Tubular actuator Load (N), Voltage (V) and Current (A)	12,200,12	12
Bipolar Stepper, Torque (N/m), Voltage (V) and Current (A)	54,4.5,3	6
Bipolar Stepper Motor (Body), Torque (N/m), Voltage (V) and Current (A)	3,5.4,0.8	1

2.4 MULTI-LEGGED ROBOT CONTROL

Because of their enormous mobility capabilities, multi-legged walking robots are ideal platforms for unstructured and rugged terrains. Compared to wheeled robots, these are redeemed by more sophisticated control and energy-demanding mobility. The unfavourable ratio between the robot body weight and payload capacity is problematic for electrically operated multi-legged walking robots. Furthermore, the locomotion speed and endurance ratio are much inferior to wheeled robots.

The power consumption of multi-legged robots can be decreased by the specific robot morphology and leg design and by locomotion control, gait parameterization and foot contact force optimization with further explicit planning of the robot trajectory and the suitable footholds. The ability to move quickly is crucial in large-scale contexts. In general, it is determined by the robot's morphology, leg dynamics, locomotion control technique, and the possible leg swing length. It is important to note that longer swing lengths result in higher joint torques, which impact power consumption and payload capacity.[16]

2.5 SUMMARY

Hexaquad is a well-designed robot with a high torque linear actuator as its leg, based on the previous work. The robot's system is nearly complete, with only a few minor details remaining. To ensure that all Hexaquad legs can be run, creating its joint leg and walking pattern is critical. Allowing the Hexaquad legged robot to roam its workspace properly requires a stable leg movement control system that allows it to walk in a predetermined motion. Because all robotics legs must lift and lower while preserving discrete contact and correcting for gravity forces during locomotion, gravity is a nonlinear element contributing to the loss of position control. The legged robot will traverse flat terrain easily if it has a flawless trajectory that closely matches the programmed motion. Mechanical impedance control can be utilized to adapt the location of the legend effector to the terrain structure or boost the leg movement speed.

CHAPTER 3

DRIVEN MODULE DESIGN, CONTROLLER UNIT SETUP AND HEXAQUAD LEG NEW SHOES DESIGN

3.1 MODULE DRIVEN SYSTEM DESIGN

The main controller used for Hexaquad is Arduino Mega 2560 microcontroller. This microcontroller consisted of 54 (39 DIO +15 PWM) and 16 ADC +10 external ADC channels. In Figure 3.1, can be seen the block diagram connection of the 6 joint leg of Hexaquad to microcontroller.

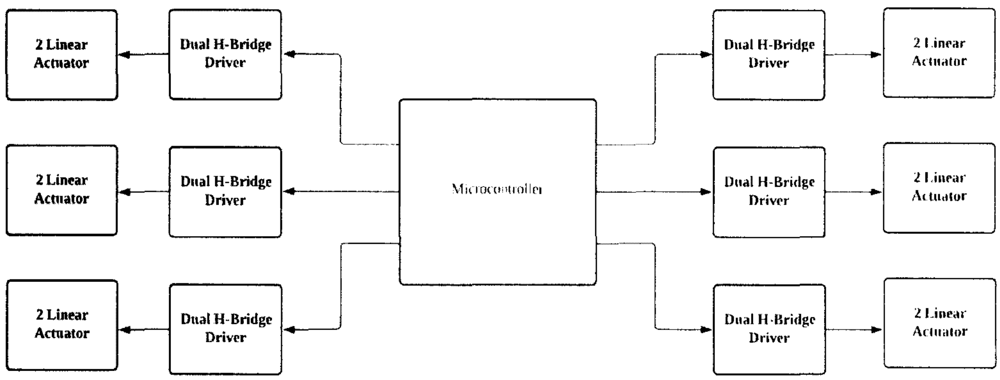

Figure 3.1: Block diagram of 6 leg of Hexaquad to microcontroller

As stated, before Hexaquad are using microcontroller to control its whole leg operation. Dual H-Bridge drivers are required to manipulate a single leg of Hexaquad. This driver will be connected straight toward two linear actuators of the leg. Hexaquad is composed of 12 adjustable joints that require a response from the data collecting system. This data is used to manage the location of the 3 joints of Coxa, Merus and Carpus. Figure 3.2 shows the control system connection of the Hexaquad robot's leg system.

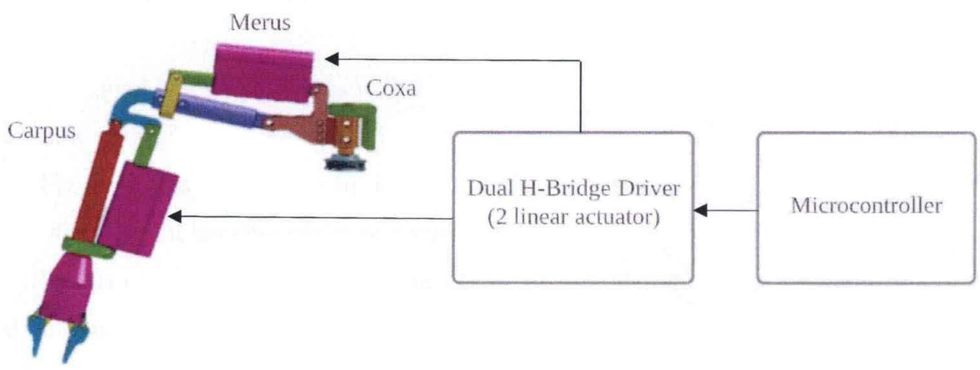

Figure 3.2: Diagram connection of 1 joint leg of Hexaquad to microcontroller.

To control the two linear actuators, the experiment will use 4 Digital pins on the microcontroller. In Table 3.2 below, the example of how one linear actuator run is given an example. The digital pin number is random.

Table 3.2: One linear actuator logic input

Pin as in Figure 4.1		Motor rotation
Pin 4	Pin 6	
Steady state	Steady state	No rotation
0	0	Motor Stop
1	0	Clockwise
0	1	Counter-clockwise
1	1	Motor Stop

3.2 CONTROLLER UNIT SETUP

Hexaquad has six joint legs with 12 linear actuator motors, with each leg having two linear actuator motors. Each leg has four digital pin outputs connected to the motor driver. Figure 3.3 shows how to identify each leg of Hexaquad. With each leg identification, it will become easier to connect to the microcontroller. Figure 3.4 shows the digital pin connection from the motor driver to the microcontroller. A total of 24 digital outputs are needed to control all Hexaquad legs. A new customize compact shield has been developed to be used with multiple motor drivers. Figure 3.5 shows the actual connection from the PCB shield driver to the motor driver and connected to the Hexaquad leg.

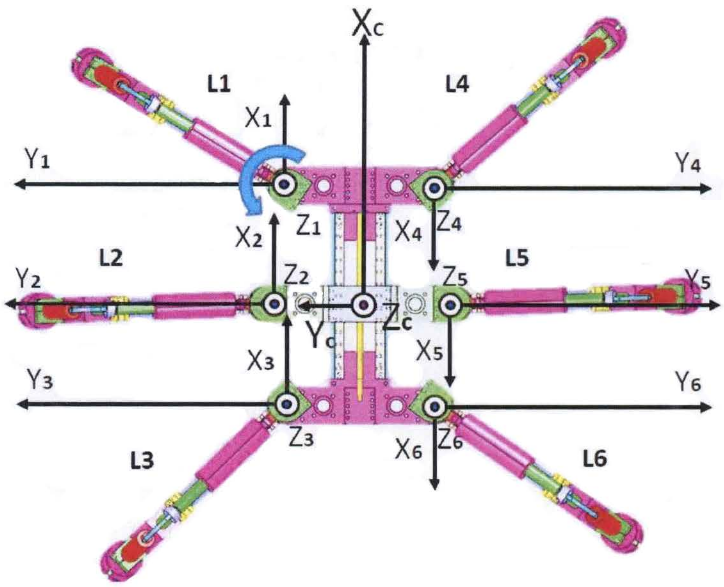

Figure 3.3: Hexaquad leg coordination

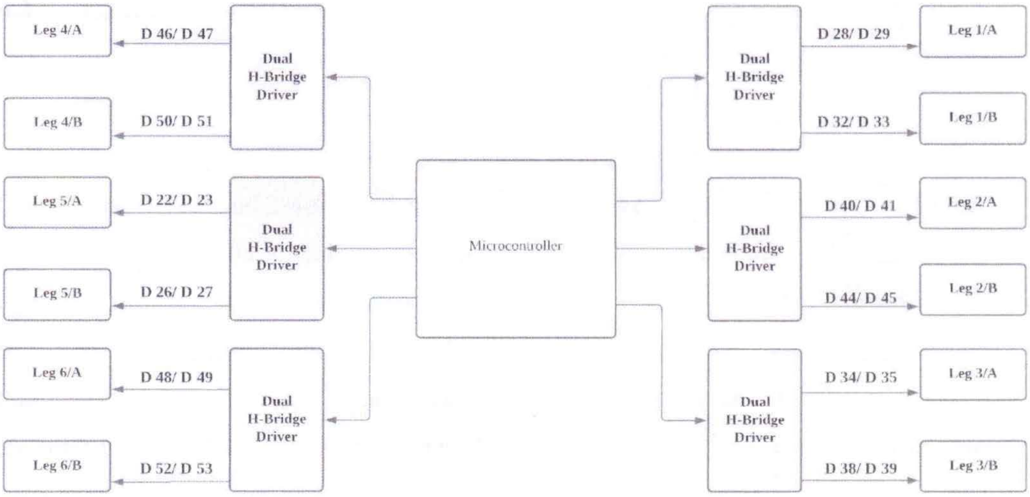

Figure 3.4: General Controller Unit Schematic

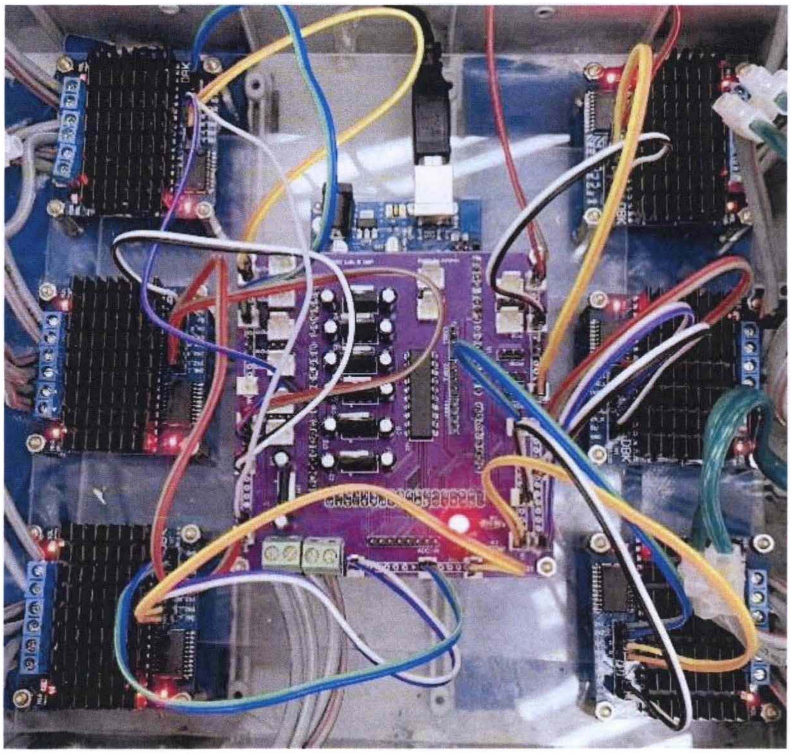

Figure 3.5: Controller unit with new customized compact shield for multiple motor drivers.

3.3 LEG SYNCHRONIZATION

To develop a walking pattern for the Hexaquad, an inverse kinematic trajectory will be used to achieve this purpose. The leg of the Hexaquad robot will be grouped by 2, where 1-3-5 legs and 2-4-6 are combined. A precision control movement of both group legs will generate a basic walking pattern movement. This group of leg only need to be 360 degrees different between each other. To develop the walking pattern, a few problems need to be solved. The first problem is where, Hexaquad does not have a feedback system, thus making it harder to control the trajectory for each leg. To fix this, block timing delays are used to control the timing movement for each leg to achieve the trajectory that has been planned. However, each leg timing movement is very different, and a specific trial and error test needed to be done to achieve the perfect timing movement for every leg. By adjusting the value of block timing delay, the speed of the leg to move will be significant. This value depends on each leg timing movement.

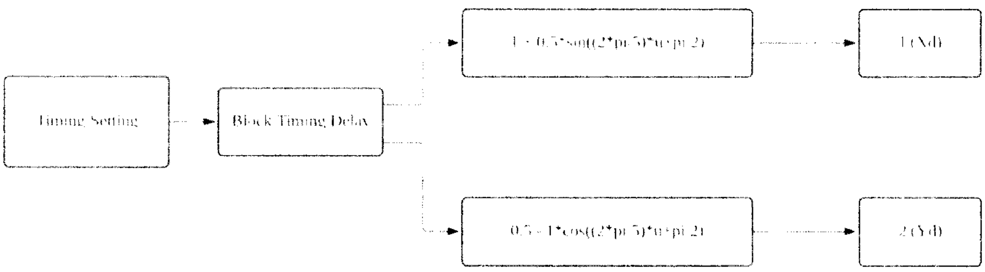

Figure 3.6: Hexaquad block timing delay structure

3.3 HEXAQUAD NEW LEG SHOES DESIGN

To make sure Hexaquad can stand on the ground in idle mode, it needs to have a stable leg to make sure Hexaquad can stand on the ground in idle mode. The foot of Hexaquad needs to be reliable and steady when it stands itself on the ground. The shoes for Hexaquad have been developed by custom and trimmed a 50 mm PVC end cap. Figures 3.5 shows the product use. Figure 3.6 shows the result after the Hexaquad leg fits with the PVC end cap. The back of the end cap is also stuck with 5mm sponge tape to make it more stable.

Figure 3.5: 50 mm PVC end cap

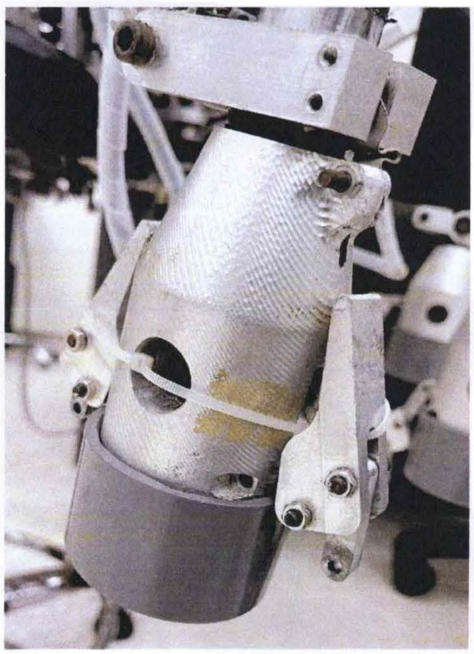

Figure 3.6: Hexaquad leg fit with the PVC end cap.

CHAPTER 4

RESULT AND DISCUSSION

4.1 HEXAQUAD JOINT LEG SIMULINK CONTROL

Simulink are used in this project to control the Hexaquad legs—an example in the Figure below shows how to control one Hexaquad joint leg simultaneously. Logic 1 and 0 are given to move both linear actuator motors. Figure 4.1 shows that the Hexaquad leg is in standing/idle mode. After the leg has received a logic signal from Simulink, both will move according to the coding created.

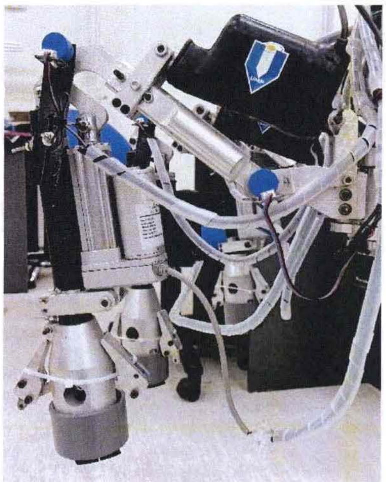

Figure 4.1: Hexaquad stand/idle mode

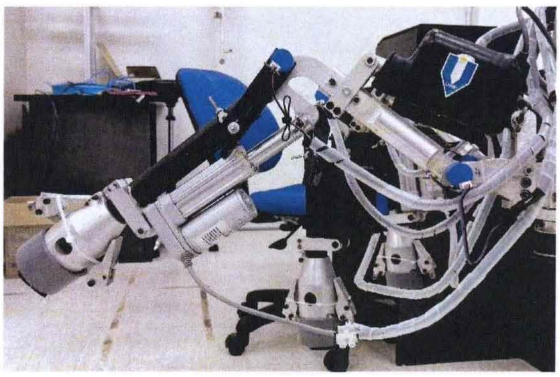

Figure 4.2: Leg movement after receive logic signal.

In Figure 4.3, the generated graph shows the leg signal received. The red one is the signal from the Hexaquad leg 1/A, and the blue one is from the Hexaquad leg 1/B. In the idle position, the Hexaquad 1/A are in logic 1, and when the signals are well received, it will go down to zero, and the movement will be made, as shown in Figure 4.2. The same goes for the Hexaquad leg 1/B; in the idle position, it is in logic 1, and when the signals are well received, it will go up to 1, and the movement will be made.

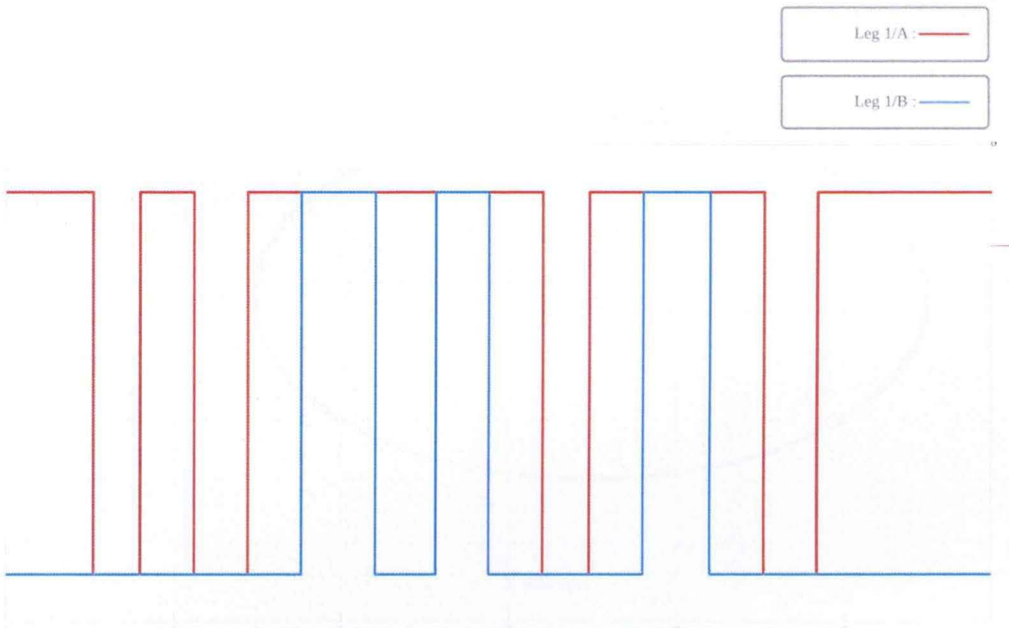

Figure 4.3: Experimental result from the leg 1 movement.

4.1 ANALYSIS OF LEG 1-3-5 AND 2-4-6 TRAJECTORY

A stable and reliable leg trajectory needs to be developed to create a stable walking pattern. The X-axis and Y-axis of legs 1-3-5 and 2-4-6 trajectory must be simultaneous, so the walking movement is not crippled. The simulation and analysis are done using the trajectory for positions X-axis and Y-axis of the leg 1 and 2. Figure 4.4 shows the trajectory for both legs.

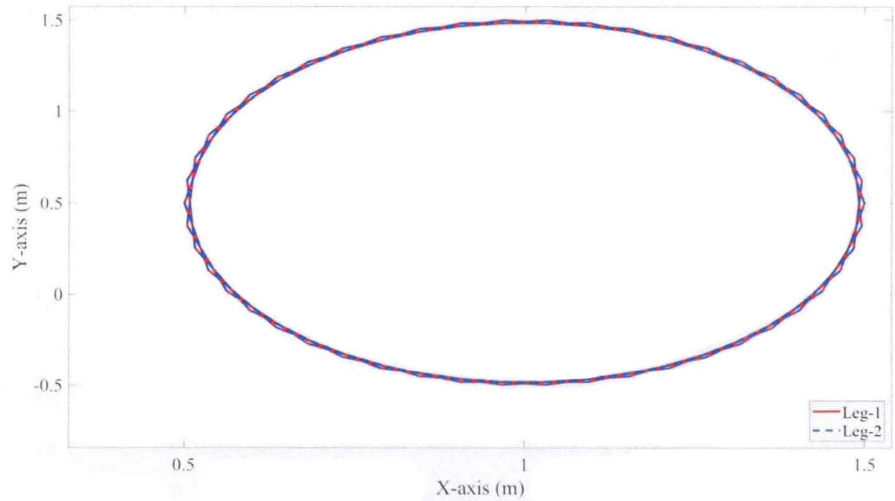

Figure 4.4: Trajectory axis of leg 1 and 2.

Furthermore, the analysis of tita-1 of legs 1 and 2 is made. As shown in Figure 4.5, the maximum angle the tita-1 leg one and leg two ever achieve is at 0.535 radians or 30.7°, and the minimum it ever reaches was -1.594 radians or 268.7°. There are 2 points where they collide through each other, as shown in point A and point B. The first point is at -0.424 radian or 335.7°, and the second was at -0.337 radians or 340.69°.

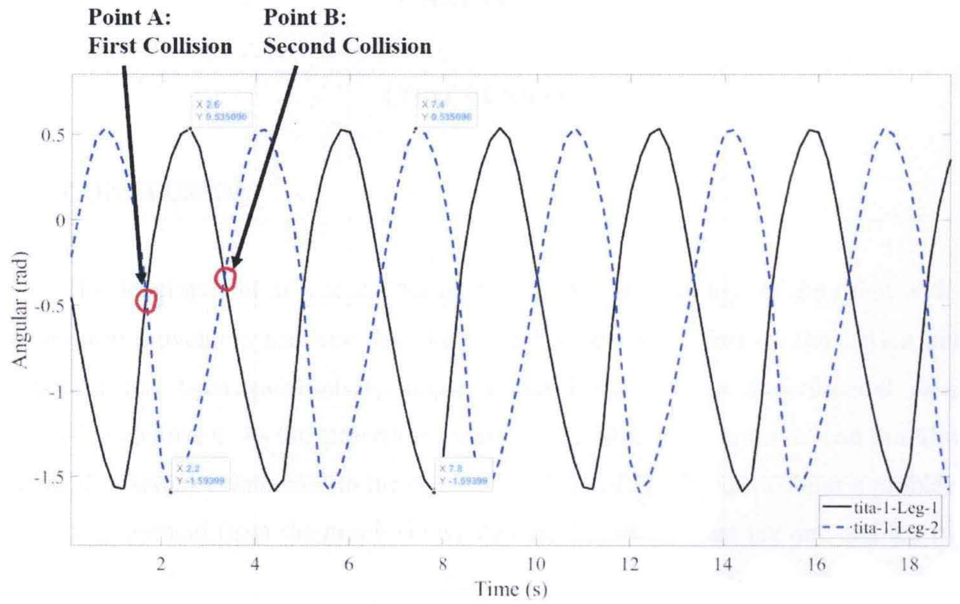

Figure 4.5: Tita-1 of leg 1 and 2

Moreover, the analysis of tita-2 of legs 1 and 2 are also made. As shown in Figure 4.6, the maximum angle the tita-2 leg one and leg two ever achieve is at 2.572 radians or 147.4°, and the minimum it ever reaches was 0.768 radians or 44.0°. There are 2 points where they collide through each other, as shown in point A and point B. The first point is at 2.4 radian or 137.5°, and the second was at 1.313 radians or 75.2°.

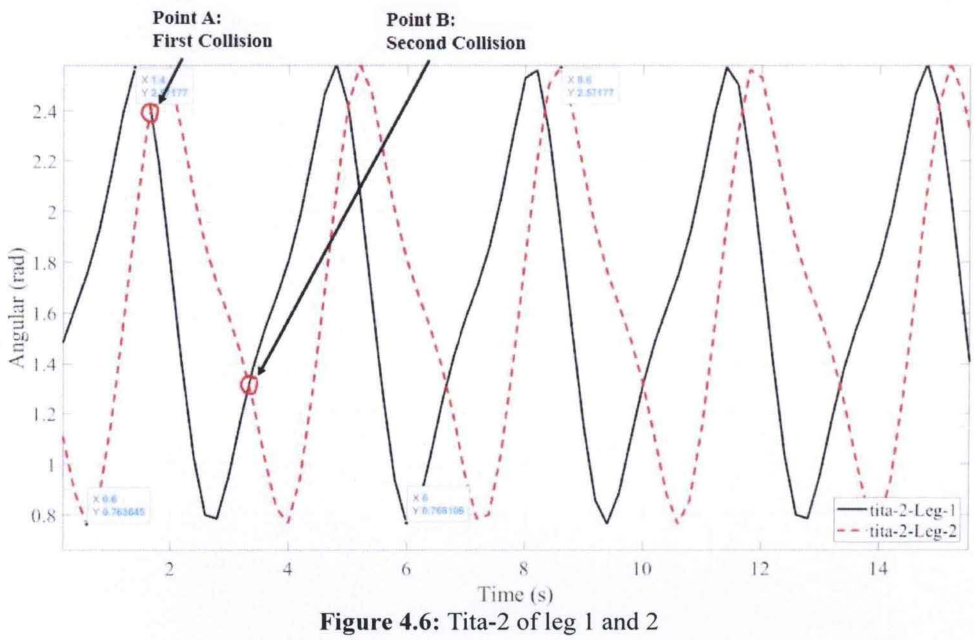

Figure 4.6: Tita-2 of leg 1 and 2

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

The development of a controller unit for 2-DoF and six legs of the robot with a basic motion movement and new leg shoes for Hexaquad to stand on flat terrain land locomotion has been successfully implemented based on the experimental result discussed in chapter 4. As the experiment was conducted, the motor driver and Simulink embedded program create able to move each joint leg of Hexaquad without a problem. The value generated from the graph shows that the trajectory from leg one and leg two has reached the desired position; thus, creating a walking pattern for the Hexaquad can be achieved in the future.

5.2 RECOMMENDATION FOR FUTURE RESEARCH

For future research and development on the improvement of the Hexaquad robot, it can use another approach to generate a walking pattern by using a feedback control system connected to a potentiometer instead of block timing delay. With a feedback system, it will become easier to control the trajectory for each leg and can be done without a hassle.

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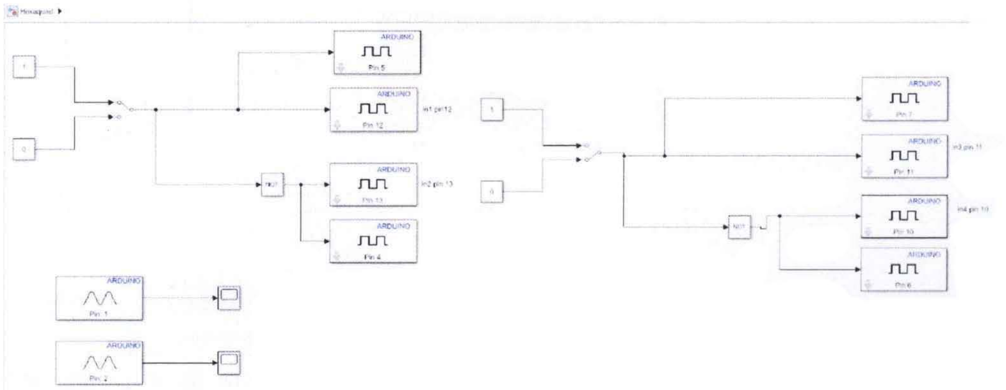
APPENDICES

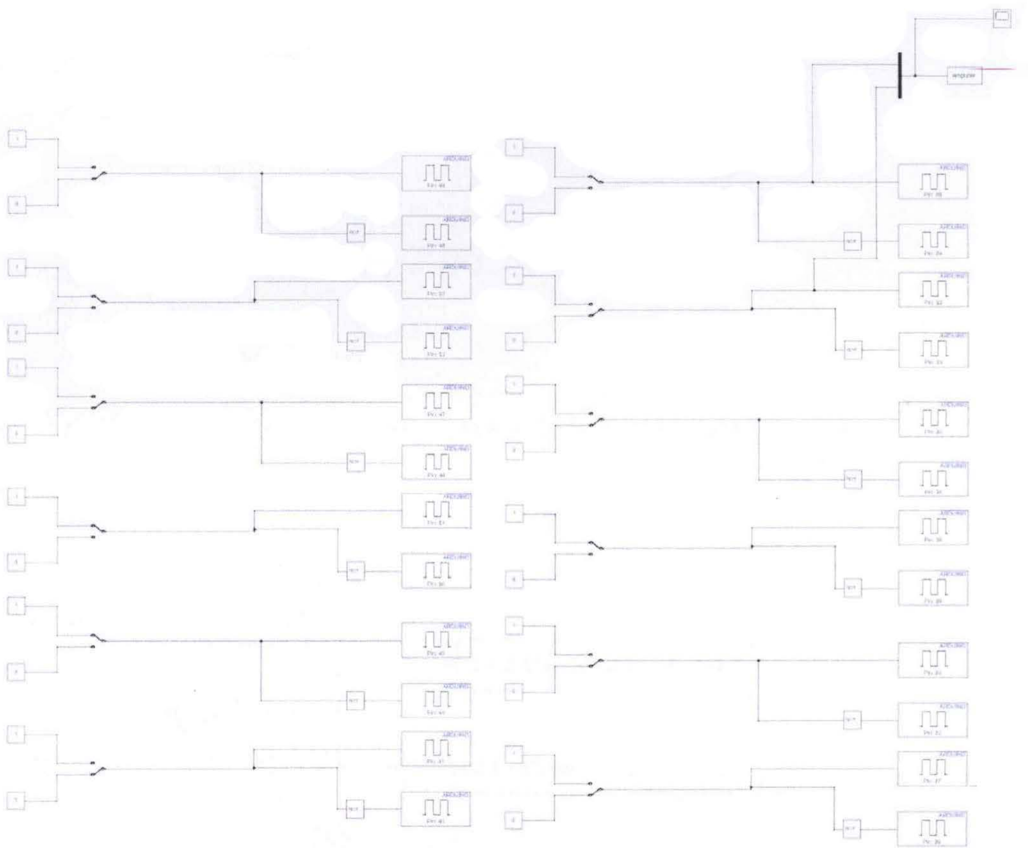
Appendix A: Gantt Chart

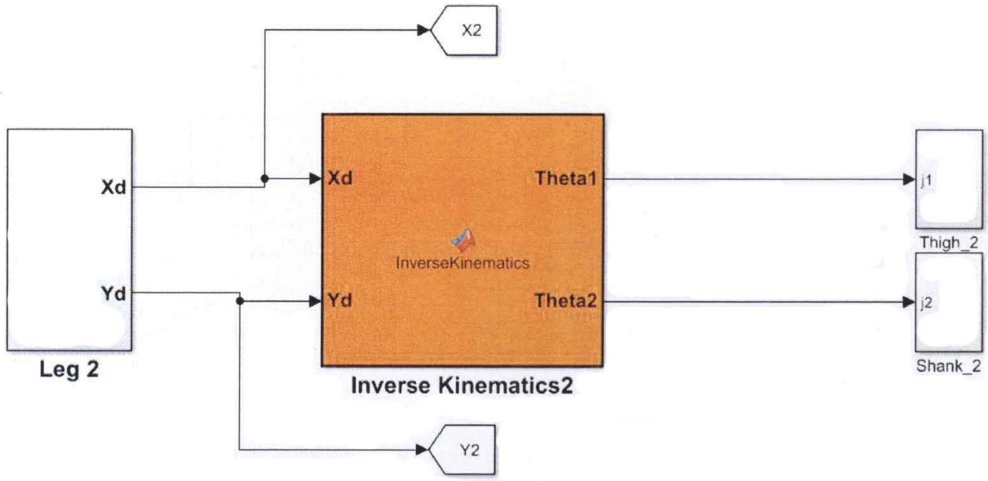
Development of Multi-legged Robot Controller with Remotely Controlled System																																		
	MAR.21		APR.21				MAY.21				JUNE.21				JULY.21				AUG.21				SEP.21				OCT.21				NOV.21			
TASK	W1	W2	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4
Planning	■	■																																
SDP title selection		■	■	■																														
Discussion details on project and roles of team memebers		■	■	■	■	■																												
Finf the root cause problem						■	■																											
Clarify the objectives, discuss the main target of the project							■	■	■																									
Specific scope of the project						■	■	■	■	■	■	■	■	■																				
Design																																		
Design the product and circuit diagram									■	■	■	■	■	■																				
Conceptual and design detailing									■	■	■	■	■	■	■	■																		
Programme																																		
Programme and install Arduino MEGA 2560															■	■	■	■																
Programme and install the monitoring the output															■	■	■	■	■	■														
Fabrication																																		
Measure the material																					■	■	■	■										
Assembly part																					■	■	■	■	■									
Check the electrical and mechanical part																					■	■	■	■	■	■	■							
Test the Project																																		
Testing and troubleshooting programming of the system																												■	■	■	■			
Testing and troubleshooting programming of monitoring system																												■	■	■	■	■		
Development of Remote controller																															■	■	■	■

Appendix B: Software Part

The software part contains the series of Block Programming for the controller implementation of Hexaquad joint leg control using Simulink MATLAB







PREPARE NAVIGATE CODE COMPILE SIMULATE

Inverse Kinematics2

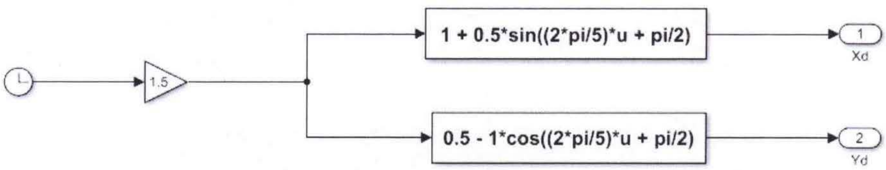
Leg1 ▶ Inverse Kinematics2

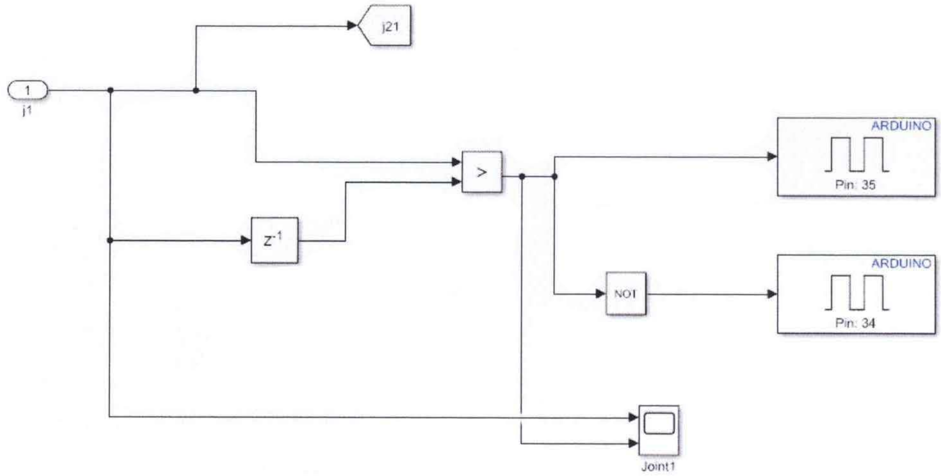
```
function [Theta1,Theta2] = InverseKinematics(Xd,Yd)
% l1= 0.105;
% l1= 0.2;
% l2 =0.405;
% l4= 0;
l1 = 1;
l2 = 1;

Theta2 = acos((Xd^2 + Yd^2 -l1^2 - l2^2)/(2*l1*l2));

s_Theta2 = sin(Theta2);
c_Theta2 = cos(Theta2);

Theta1 = atan2(Yd,Xd) - atan2(l2*s_Theta2,(l1+l2*c_Theta2));
```




j21
1
j1
>
ARDUINO
Pin: 35
z-1
NOT
ARDUINO
Pin: 34
Joint1