

**DEVELOPMENT OF WALKING GAITS FOR QUADRUPED ROBOT  
(4-LEGGED ROBOT)**

by

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Dissertation submitted in partial fulfillment of  
the requirements for the Bachelor of Engineering (Hons)  
(Mechanical Engineering)

JUNE 2010

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CERTIFICATION OF APPROVAL

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8170

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Mechanical Engineering Programme  
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in partial fulfilment of the requirement for the  
BACHELOR OF ENGINEERING (Hons)  
(MECHANICAL ENGINEERING)

Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS  
TRONOH, PERAK  
JUNE 2010

## CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(HOUNG NAI HUI)

## **ABSTRACT**

The project outcomes of this project are to develop the walking gaits for the quadruped robot including trotting gait, to produce printed circuit board (PCB) for the electronic parts of the robot and to improve on the motor torque for better lifting capability and to model the gaits and implementation of the quadruped robot on ADAM software. This project is the continuation of the project completed by Mr. Yee Yuan Bin whereby he managed to develop the control system that enables the robot to perform crawling gait on the flat and horizontal surface. The control system designed involves gait control, stability control and motor control. Therefore, the existing crawling gait is to be improved into trotting gait. Besides, the modelling of the quadruped robot is to be performed using ADAMS software and the PCB for the electronic parts of the robot is to be produced in order to reduce the weight of the body. This project is split to two phases. Phase 1 is to be carried out during semester FYP 1 while Phase 2 is commenced during FYP 2. The work aspects of phase 1 are on producing printed circuit board (PCB), modelling the walking gaits using ADAMS software and also to learn about C programming for PIC18. Phase 2 is the testing stage with the presence of servomotors and circuit board as well as improvement and development of the walking gaits. At the end of project, the quadruped prototype is meant to perform forward trotting gait on flat and horizontal grounds.

## **ACKNOWLEDGEMENT**

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Besides, all the help and support received from my supervisor, Pn Rosmawati Mat Zain throughout the whole period of completing the final year project cannot be neglected as well. Her guidance and advices are very much appreciated and I really wish to thank her for all that she has done. Besides, I would like to thank my seniors Mr Yee Yuan Bin and also Mr Kanopathy a/l Murugayah in assisting me to complete this project especially in completing the circuit and also the development of the Excel simulator.

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# **CHAPTER 1**

## **INTRODUCTION**

This chapter will highlight the background study, problem statement, the main objectives of the project, scope of study and also significance the project.

### **1.1 BACKGROUND STUDY**

Robot is a virtual or mechanical artificial agent. It is usually an electro-mechanical machine which is guided by computer or electronic programming, and it is able to perform certain limited tasks on its own. There are assorted types of robots today, either mobile or stationary robot, for instance, robot manipulator, wheeled robot, legged robot or etc. Generally, legged robots can be categorised into biped (2-legged), quadruped (4-legged), hexapod (6- legged) and octopod (8-legged) robots. Quadruped robots basically imitate the unique walking gaits of the mammals and insects such as crawling, trotting, climbing and etc.

### **1.2 PROBLEM STATEMENT**

The wheeled robots have been by far the most popular locomotion mechanism in the robotics research and development particularly when flexible motion capabilities are required on reasonably smooth grounds and surfaces. When designing a wheeled robot, balance is not usually a major concern as the wheeled robots are designed in such a way that all wheels are in ground contact at all times.

However, when comes to rugged terrain or uneven surfaces, the problems of traction and stability, maneuverability and control surface. Wheeled robot has less than satisfactory of maneuverability and mobility on rugged terrain [1]. Besides vibration of wheeled robot moving on uneven surface has also cost the robot's lifespan and

stability. Therefore the idea of quadruped robot has come in to overcome such situation as it is able to maneuver on various surfaces.

### **1.3 OBJECTIVES**

The objectives that have been identified for this project are as below:

- a) To improve on the motor torque for better lifting capability.
- b) To model the gaits and implementation of the quadruped robot on ADAMS software.
- c) To develop the walking gaits for the quadruped robot including trotting gait.

### **1.4 SCOPE OF STUDY**

The scopes of study include:

- a) Develop trotting gait for quadruped robot in which the center of gravity (COG) will be constrained by its static or dynamic stability margin. EXCEL spreadsheet will be used to create gait simulator.
- b) Study on the microcontroller and learn about programming microcontroller in C language as it provides higher flexibility in executing program instructions.
- c) Model the quadruped robot in ADAMS software to simulate the gaits implementation. Graphical result and analysis will be done on the simulation model to determine the feasibility of the quadruped model.
- d) The quadruped equipped with motor controller will be tested on flat and horizontal ground to observe its mobility and maneuverability when performing different gaits.

## **1.5 SIGNIFICANCE OF STUDY**

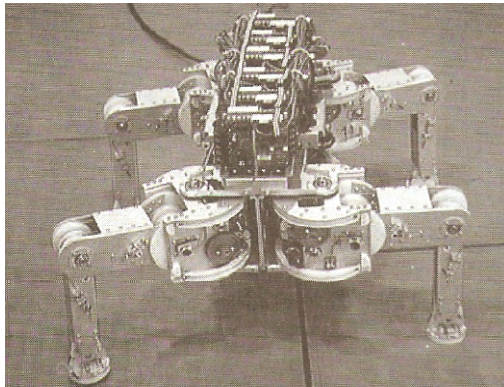
This project will be able to produce an enhanced quadruped robot which is able to manoeuvre over various surfaces, such as even ground, rugged terrain, slope or even stairs by performing various walking gaits including crawling and trotting gaits. Due to the unique nature of quadruped robot, it has the strength to carry out extreme duty such as bomb and landmine retrieval at war zone, search and rescue operation at earthquake-hit area, outer space and seabed exploration.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 QUADRUPED ROBOT**

A quadruped robot is basically a 4 legged robot that imitates the walking gait of an animal or insect. The robot is able to perform gaits such as walking, crawling, trotting, climbing, turning and etc. By adjusting the gait movement and the body position, a quadruped robot can easily adapt to the environment by stabilizing itself. Thus, quadruped robot is favored for the research of all terrains including the rough and unstructured terrains and also avoiding obstacles.



*Figure 1 Titan VIII, a quadruped robot developed at Tokyo Institute of Technology.*  
[1]

#### **2.2 GAIT ANALYSIS**

Gait analysis normally is the process of quantification and interpretation of animal locomotion (in this case the robot locomotion) [2] using the eye and the brain of observers, augmented by instrumentation for measuring body movements, body mechanics and the activity of the muscles (in this case the actuators of the robot). [3] Gait analysis is used to assess, and to plan robots' movement. The main purpose

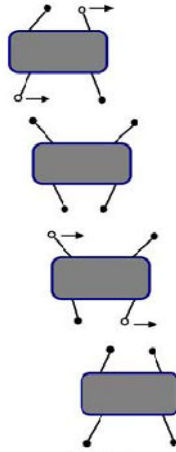
of the gait analysis for the quadruped is to plan the walking gait in order to come out with the most effective and clash-free movement.

### **2.2.1 Walking Gaits**

The term “walking gait” is used in describing legged robot’s moving pattern. Gait is literally describing the sequence of the lifting and the placing of the legs and the relative time between these movements [4]. Gait is assumed to be cyclic and only one leg is lifted once per cycle [4]. In other words, legs are lifted up in a manner of one leg per cycle and one leg after another. Such manner of gait is to adjust the body motion in an attempt to maintain its stability. For a quadruped robot, just like a 4 legged animal, it is able to perform slower gaits and faster gaits. The slower gaits include creep (crawl), walking, and trotting while faster gaits include running and galloping. [2]

The creep, sometimes known as crawl, is a slow meticulous movement of one leg at a time with the body low slung to the ground. This causes the gait to be “potentially” very stable, since three legs form a stable support tripod whenever any one leg is suspended. However, there are several factors such as the length of the legs with respect to the body can affect the stability of the body for the centre of gravity (COG) may not be contained within the stability triangle formed by the three down legs. Overall, creep stability relates to: body length, body width, leg length, leg angles, foot positions, and general distribution of weight on the body. [2]

The trot is the faster gait of the waking gait. It is a two-time gait, LR (Left Rear) + RF (Right Front) alternating with RR (Right Rear) + LF (Left Front) as shown in Figure 2.



*Figure 2 Walking or trotting gait of a legged animal or robot. [9]*

The trot gets its stability by using alternating “diagonal bracing” under the torso and it is an example of dynamic stability where the animal could not hold its balance when stopped. However, because the trot always keeps the COG of the torso straddled by diagonal bracing, and the order of stepping is similar to that of the walk, the gait would be easily implemented in a quadruped robot. [2]

### **2.2.2 Stability**

In this project study, the stability and also the torque of the motor in order to lift the robot are taken into considerations. Generally, all the walking robots confront with the stability problem of what is the suitable distance that each leg transfer in order to maintain its stability [5]. Therefore, how and where does the center of gravity (COG) lie has becoming an important factor in maintain the robot’s stability. There are two types of stability for a walking robot, namely static stability and dynamic stability. Static stability is meaning as the robot’s center of gravity (COG) is always within the polygon formed by its supporting leg. The gait performed under such stability condition is called static gait, for instance a walk or crawl [6]. Whereas, the dynamic stability which performing dynamic gait such as a trot or gallop does not necessarily have the center of gravity (COG) lies within the supporting polygon; it involves a much more difficult balancing task [6].

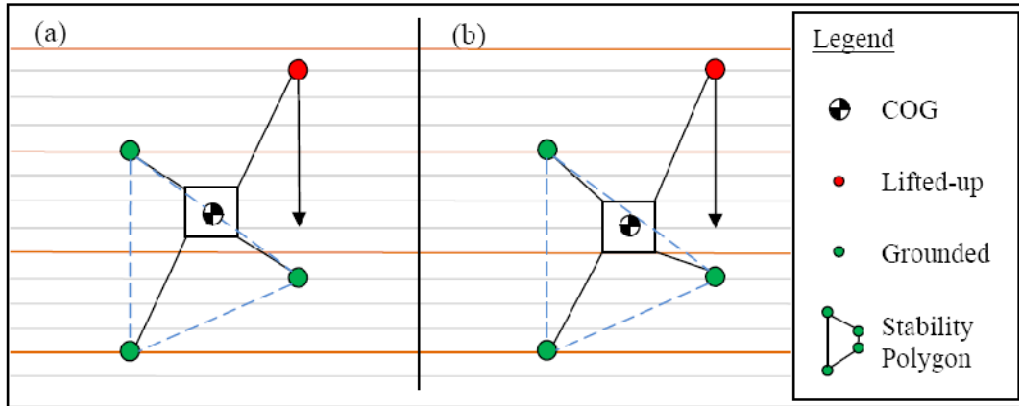


Figure 3 a) COG is within the supporting polygon, thus stable. b) COG outside the supporting polygon thus involves dynamic stability.

One important fact is that a legged robot is not statically balanced if fewer than three legs are on the ground. When two legs are lifted in the air at one time, in this case trotting or walking gait, dynamic stability needs to be considered.

The factors to be considered in this project are the motor torque in order to lift the robot up and to mobilise the robot, the sequence of the legs movements, and also the centre of gravity (COG) of the robot.

### 2.3 ADAMS SOFTWARE

ADAMS (Automatic Dynamic Analysis of Mechanical Systems) software is complex CAD (Computer Aided Design) software. It is a motion simulation solution for analyzing the complex behavior of mechanical assemblies and it can be used to test virtual prototypes and optimize designs for performance, safety, and comfort, without having to build and test numerous physical prototypes.

ADAMS is a family of interactive motion simulation software modules. A core package (Adams/View, Adams/Solver, and Adams/PostProcessor) allows user to import geometry from most major CAD systems or to build a solid model of the mechanical system from scratch. A full library of joints and constraints is available for creating articulated mechanisms. Once the virtual prototype is complete, ADAMS checks the model and then runs simultaneous equations for kinematic, static, quasi-static, and dynamic simulations. Results are viewable as graph, data



plots, reports, or animations. The results (loads created from different types of motion) of ADAMS simulation studies to provide loads for many different FEA programs to optimize the structure of a design.

### **2.3.1 CONSTRUCTION OF ADAMS MODEL**

Firstly, one first *builds* a model (representative of the one being tested). Then a *test* simulation of the model is run and the computer result with those taken from an actual test will be *validated*. In a process of *refining* a model, the computer model will become more and more accurate. After the model is fixed then tests changing parameters and variables are able to be *iterated* to *optimize* the model. This saves time in that one can run many simulations that are cheap, accurate, and can be done quickly.

### **2.3.2 APPLICATION OF ADAMS TO THE PROJECT**

In designing and improving the quadruped robot, it is important to observe how the 4 legs move and interact with one another. This will help the author to develop the suitable walking gait that is stable especially in trotting gait. Through ADAMS, the mechanism of the 4 legs movement can be simulated and possible clashes or mechanical failure can be identified. Besides, ADAMS can help to determine what forces (*noise, vibration, and harshness*) that can be generated by the quadruped robot during operation. This will help the author in improving the design of the robot in terms of mechanical and electronic hardware.

### **2.3.3 DESIGN PARAMETERS**

In the project, there are several parameters to be considered while modeling the model for the quadruped robot using the ADAMS software.

The parameters involve the physical dimensions, motion generators, torques produced by the motors, the gravity, the walking envelope of the robot, the weight of the robot, and the types of joints such as revolute joints or translational joints.

## **2.4 ELECTRONIC HARDWARE**

Some basic electronic components are utilized in a legged robot project, for example servomotors, microcontrollers, and etc.

### **2.4.1 Servomotors**

Servomotors are motors used in a closed-loop servo system. Closed loop servo systems are systems that use internal sensors to see how well they are doing their jobs. The motor portion of a servomotor can be a DC motor, an AC motor, a stepper motor or even a hydraulic motor. The advantage of a servomotor is it includes some type of feedback system for accessing how well it is doing its task. The feedback control system will automatically adjust the rotor back to the desired position. [7]

Generally, servomotors are able to position at a range of 90 degrees rotation (clockwise 45 degrees rotation or anti-clockwise 45 degrees rotation) depends on the manufacturer's specification. However, the range of position can be extended to 180 degrees by adjusting the control signal. Servomotor has three wires, where two of them are for power of +5V and GND, while the third wire is for position control signal input. The position of the servomotor rotor is controlled by pulse-width modulation (PWM) signal which is a variable width of signal-ON pulse ranged from 1 to 2 milliseconds. A 1 millisecond PWM signal places the rotor at the extreme anticlockwise position (-45 degrees) while 2 milliseconds PWM signal places the rotor at the extreme clockwise position (+45 degrees). A 1.5 millisecond signal will place the rotor at the neutral position (0 degree). The PWM signal for servomotor is usually configured at 50 to 60 Hz which set the pulses period to be approximate 16 to 18 milliseconds.

### **2.4.2 Microcontrollers**

Microcontrollers are pre-programmed electronic devices that are able to perform particular output based on electronic input. A microcontroller has a CPU (a microprocessor) in addition to a fixed amount of RAM, ROM, I/O ports, and a timer all on a single chip. In other words, the processor, RAM, ROM, I/O ports, and timer are all embedded together on one chip; therefore, the designer cannot add any external memory, I/O, or timer to it. The fixed amount of on-chip ROM, RAM, and number of I/O ports in microcontrollers make them ideal for many applications in which cost and space are critical. [8]

### **2.4.3 PIC18F Microcontroller**

The main reason PIC microcontrollers manufactured by Microchip are chosen in this project because of its availability at the electronic store of UTP and most importantly, UTP has the programmer of PIC which allows reprogramming of a PIC. Many PIC18 chips have on-chip program ROM in the form of flash memory. The flash version uses the letter F in the part number to indicate that the on-chip ROM is flash. PIC18F458 is an example of PIC18 with flash ROM. The flash version is ideal for fast development because flash memory can be erased in seconds compared to the 20 minutes or more needed of the UV-EEPROM version.

To use the PIC18F to develop a microcontroller-based system requires a ROM burner that supports flash memory; however a ROM eraser is not needed because flash memory is an EEPROM (Electrically Erasable PROM). [8]

## 2.5 C PROGRAMMING ON PIC18

Compilers produce hex files that are downloaded into the ROM of the microcontroller. The size of the hex file produced by the compiler is one of the main concerns of microcontroller programmers for two reasons: [8]

1. Microcontrollers have limited on-chip ROM.
2. The code space for the PIC18 is limited to 2M.

While Assembly language produces a hex file that is much smaller than C, programming in Assembly language is often tedious and time consuming. On the other hand, C programming is less time consuming and much easier to write, but the hex file size produced is much larger than if we used Assembly language.

The following are the major reasons for writing programs in C instead of Assembly:

1. It is easier and less time consuming to write in C than in Assembly.
2. C is easier to modify and update.
3. Codes available in function libraries can be used.
4. C code is portable to other microcontrollers with little or no modification.

## **CHAPTER 3**

### **METHODOLOGY**

This chapter will cover the analysis techniques, the project flow chart, and also the full FYP I and FYP II Gantt Charts for the progress of the project.

#### **3.1 RESEARCH METHODOLOGIES**

Throughout the research for the project, the author referred to report and documents prepared by Mr. Yee Yuan Bin, online journals, software manuals, technical reference books, lecture notes as well as websites from the internet.

As the project is the improvement of the existing project, first of all the author was required to understand the mechanical mechanism as well as the electronic structure of the existing quadruped robot.

Then, a simulator is developed for the trotting gait by using Microsoft Excel to predict the movement of the quadruped robot by calculating the positions and coordinates of the legs of the robot.

After that, the author is to gather the necessary data such as through the usage of ADAMS software to determine the factors that might affect the movement of the robot and also to determine the feasibility of the gait movement.

With the data gathered, the programming of the PIC18 can then be modified and developed to enable the robot to perform the trotting gait.

## 3.2 Final Year Project I

### 3.2.1 Flow Chart

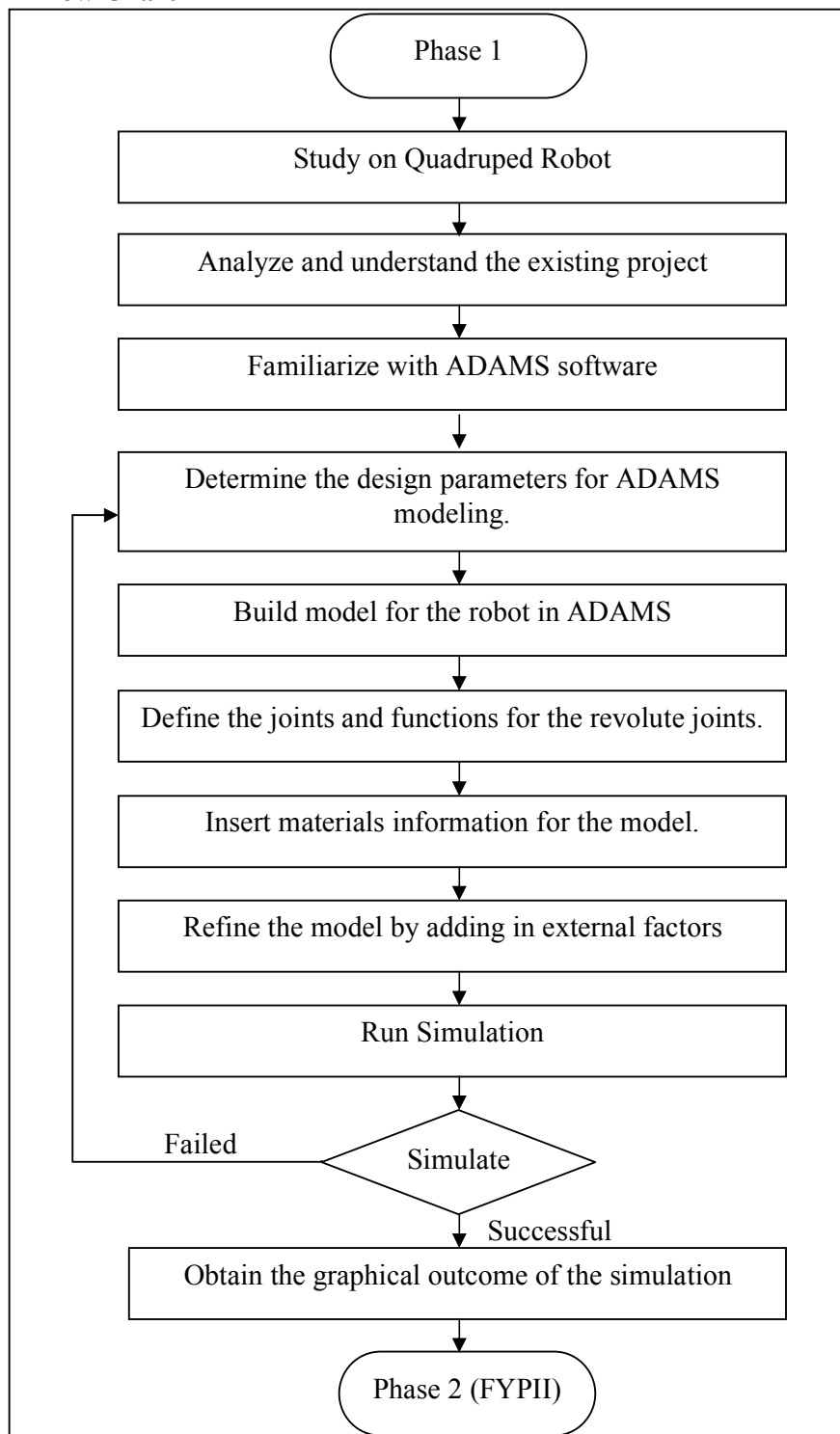


Figure 4: Flow Chart for FYPI

### 3.2.2 Understanding and Analyzing Existing project

A thorough study has been conducted on the existing project including understanding the concept involved and also the report produced by the previous author. Some improvement has been done by changing the servomotors to improve the lifting capability of the robot. A feasibility study has been conducted to justify the quadruped robot will be able to produce sufficient torque to support itself while standing still and also while performing the gaits.

### 3.2.3 ADAMS Software

In order to simulate the motion of the quadruped while performing trotting gait, ADAMS software has been used. As the simulation is required to be performed in 3D for the quadruped robot, “CONTACT” function is used in the simulation.

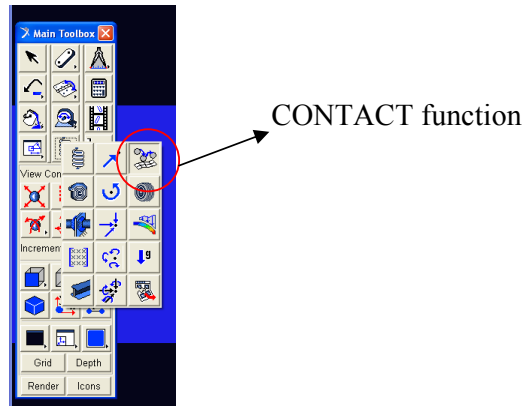


Figure 5 CONTACT Function icon in ADAMS software

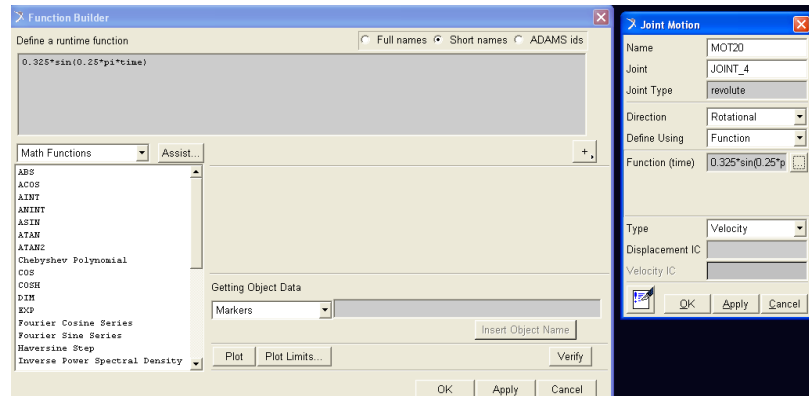


Figure 6 Joint Function pop up window to define the motion function.

The parameters such as the physical dimensions, motion functions, the gravity, the walking envelope of the robot, the weight of the robot, and the types of joints such as revolute joints or translational joints are defined for the model in ADAMS. The motion functions are modified accordingly to perform crawling gait or trotting gait.

#### **3.2.4 Simulation Results**

After the simulation is run successfully, graphical result can be obtained or generated from the software. The graphical result will depict the distance travelled and also the motion of the quadruped robot model. The simulation will be repeated after changing the motion functions of the model in order to obtain the most optimal motion for the gait movement.



### 3.3 Final Year Project II

#### 3.3.1 Flow Chart

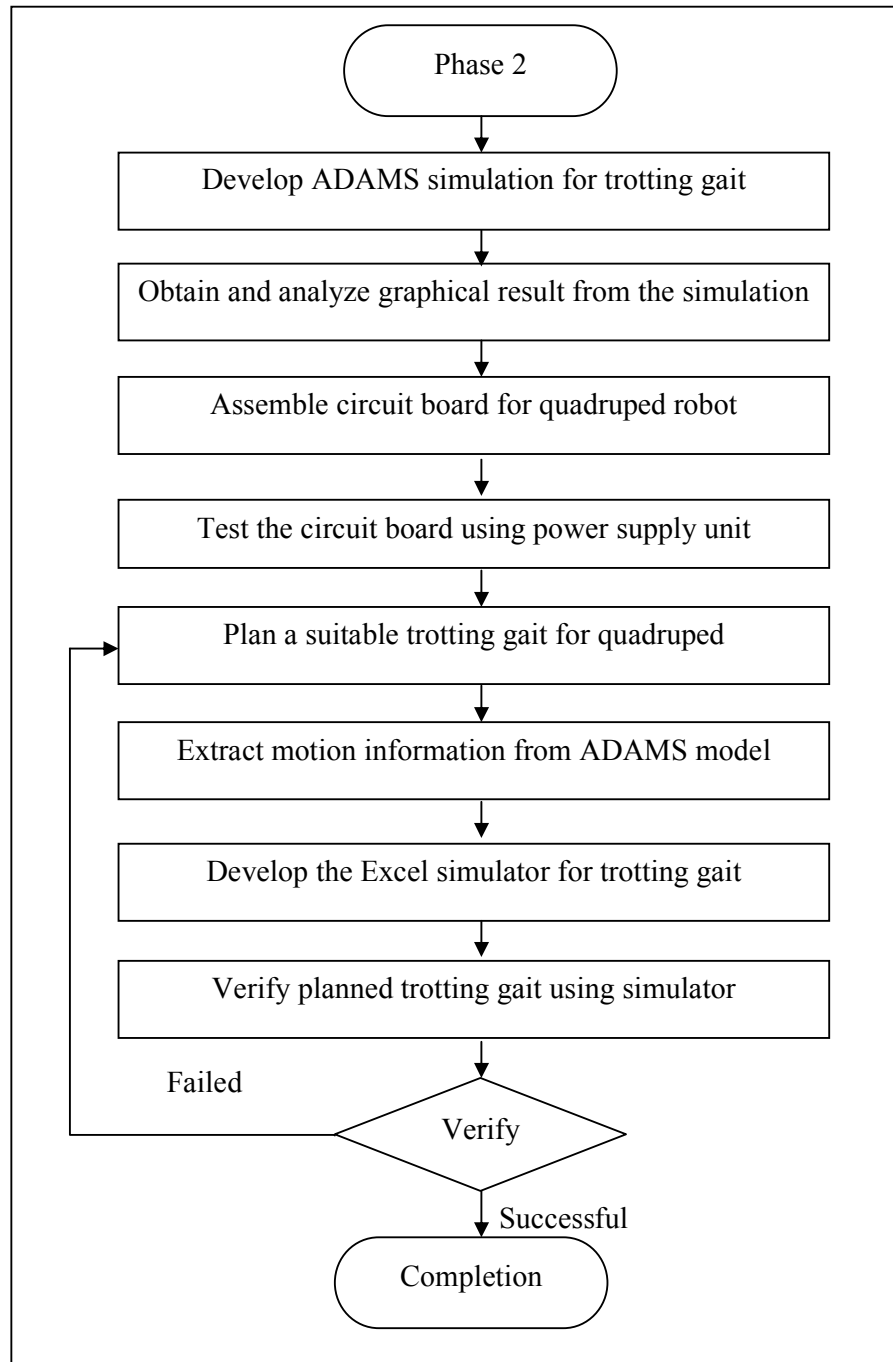


Figure 7: Flow Chart for FYPII

### **3.3.2 ADAMS simulation**

The trotting gait is simulated using the constructed ADAMS model. The motion functions will be refined through trials and errors in order for the model to perform the gait with most optimal stability by achieving acceptable speed and distance. The graphical result is generated to show the motion type of the robot and also the distance travelled by the robot in the simulation. Besides, the stability of the robot can also be seen through the simulation.

### **3.3.3 Excel Simulator development**

By extracting the information and also the data from the simulation model, the Excel simulator is developed using the Microsoft Excel software. The purpose of this simulator is to calculate the coordinate of each joint and also the joint angle of each leg. Coordinates of each joint are labeled with specified notations, which are the global coordinates. Each joint consists of x-axis, y-axis, and z-axis coordinates with COG of quadruped defined as the origin of all axes, i.e. (0.0.0). The global coordinate notation in top view is defined in *Appendix 3*.

### **3.3.4 Servomotors**

In order to improve the existing lifting capability of the robot, 4 BizChip SV003 servomotors and 8 Hitec HS 322HD servomotors are used. This is because BizChip SV003 servomotors have higher torque (13 kgcm) compared to Hitec HS 322HD (3.7 kgcm).

Hitec HS 322 HD servomotors operate in a way that the rotor position +/- 45 degrees by manipulating the pulse width from 1 to 2 milliseconds and basically operate from the voltage of 4.8 to 6.0 V with 4.8 V generating output torque of 3kgcm while 6.0 V generate output torque of 3.7 kgcm. While for BizChip SV003 servomotors, the moving range is from 0-180 degrees and they operate from the voltage of 4.8 to 6.0

V with 4.8 V generating output torque of 13kgcm while 6.0 V generate output torque of 14 kgcm.

The example of BizChip SV003 and Hitec HS 322HD servomotors are show as below:



*Figure 8 BizChip SV003 servomotor*



*Figure 9 Hitec HS-322HD servomotor*

### **3.3.5 Circuit Assembly**

From the existing circuit produced by Mr Yee Yuan Bin, some modification has been done to improve the efficiency of the circuit in controlling the servomotors. Power buses for the servomotors have been connected to the power source directly to give enable the motors to function at full torque. Besides, the use of voltage regulators and capacitors are reduced due to redundancy.

The new produced circuit is then constructed on a veroboard instead of a breadboard in order to ensure the circuit will be able to function consistently and also to reduce the weight factor exerted on the robot thus improving the lifting capability of the robot.

### 3.4 GANTT CHARTS

Detail	WEEK														
	1	2	3	4	5	6	7	8	9		10	11	12	13	14
Submission of Project Topic	█	█													
Preliminary Research Work		█	█	█	█										
Submission of Preliminary Report					█										
Research and understanding of previous project					█	█	█	█	█						
PCB design and production						█	█	█	█						
Submission of Progress Report								█	█						
Seminar								█	█						
Test run existing prototype									█		█				
ADAMS modeling											█	█	█	█	
Interim Report Submission														█	
Oral Presentation															

MID-SEMESTER BREAK

STUDY WEEK

Figure 10: Gantt Chart for FYP I

Detail	WEEK																
	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16
ADAMS Model completion	█	█	█	█	█	█	█		█	█	█	█	█				
Control circuit assembly			█	█	█												
Progress Report 1 submission			█	█	█												
Simulator development				█	█	█	█		█	█							
Progress Report 2 submission									█	█							
Seminar									█	█							
Test run prototype									█	█	█	█	█	█	█	█	
Poster Submission													█				
Dissertation Draft submission																█	
Oral Presentation																	█
Project Dissertation submission																	█

MID SEMESTER BREAK

Figure 11: Gantt Chart for FYP II

### **3.5 TOOLS USED**

Throughout the completion of the project, the tools (software and hardware) required are:

- PIC Compiler for compiling program in C language and generate hex code.
- MPLAB to simulate and troubleshoot the program before burning the program into microcontroller.
- Universal PIC Serial Programmer, BIZ011 for programming the codes unto the PIC18.
- ADAMS Software for modeling the movements
- Power Supply Unit for supplying power to the circuit.

## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 WORK COMPLETED

##### 4.1.1 Existing Robot Feasibility Analysis

A critical analysis has been done on the existing robot to calculate the torque produced by the motors. This is to determine whether the torque generated by the motors used on the four legs of the robot is able to support the weight of the robot and to mobilize the robot.

##### Calculations:

$$\begin{aligned} \text{Weight of the robot} &= \text{weight of the legs} + \text{weight of the body} + \text{electronics} \\ &\quad \text{components} + \text{weight of motors} \\ &= 1478 \text{ g} + 400\text{g} \\ &= 1878 \text{ g} \\ &= 18.42 \text{ N} \end{aligned}$$

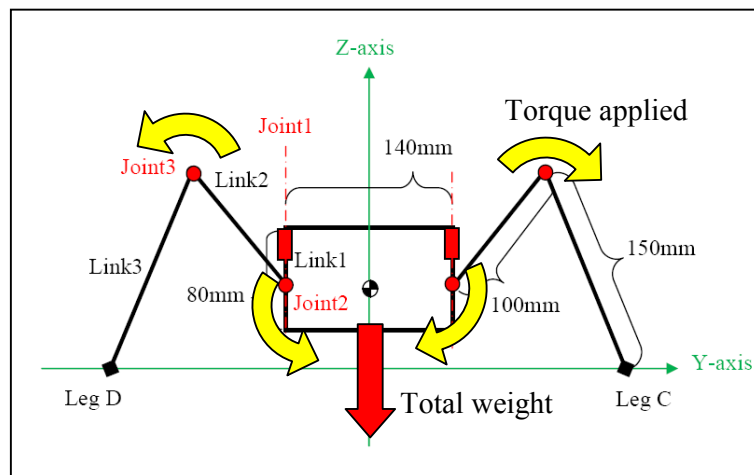


Figure 12 The schematic diagram showing the torque applied by the motors and the weight of the robot

Two types of servomotors are used:

- BizChip SV003 (Torque,  $T_2 = 13 \text{ kgcm}$ ) at Joint 2
- Hitec HS 322HD (Torque,  $T_3 = 3.7 \text{ kgcm}$ ) at Joint 3

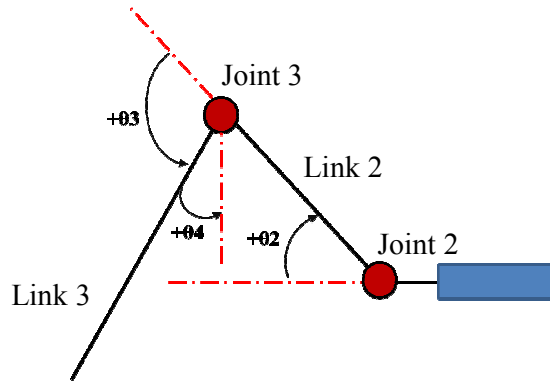


Figure 13 the schematic diagram of the leg showing the angles

Table 1 The angles for leg C and D while not moving.

Step 0	$\theta_2$	$\theta_3$	$\theta_4$
Leg C	$39.27^\circ$	$110.25^\circ$	$19.02^\circ$
Leg D	$44.36^\circ$	$134.05^\circ$	$0.31^\circ$

Leg C = Leg A

Leg D = Leg B

$$\begin{aligned}
 \text{Vertical forces for Leg A \& C} &= \left( \frac{T_3}{\text{link 3}} \sin \theta_4 + \frac{T_2}{\text{link 2}} \sin \theta_2 \right) \times 2 \\
 &= \left( \frac{3.7 \times 9.81}{15} \sin 19.02^\circ + \frac{13 \times 9.81}{10} \sin 39.27^\circ \right) \times 2 \\
 &= 17.72 \text{ N}
 \end{aligned}$$

$$\begin{aligned}
 \text{Vertical forces for Leg B \& D} &= \left( \frac{T_3}{\text{link 3}} \sin \theta_4 + \frac{T_2}{\text{link 2}} \sin \theta_2 \right) \times 2 \\
 &= \left( \frac{3.7 \times 9.81}{15} \sin 0.31^\circ + \frac{13 \times 9.81}{10} \sin 44.36^\circ \right) \times 2 \\
 &= 17.86 \text{ N}
 \end{aligned}$$

Total vertical forces (for 4 legs on the ground) = 35.58 N

Total vertical forces (for 3 legs on the ground) = range of 26.65N to 26.72N

Total vertical forces (for 2 legs on the ground) = range of 17.91N to 18.21N

Thus, it is justified that with the usages of two different types of motors with different torques can help the robot to stand alone while moving or while standing still.

### 4.1.2 ADAMS Model

The ADAMS model has been constructed successfully using ADAMS/View of the MSC Software Corporation.

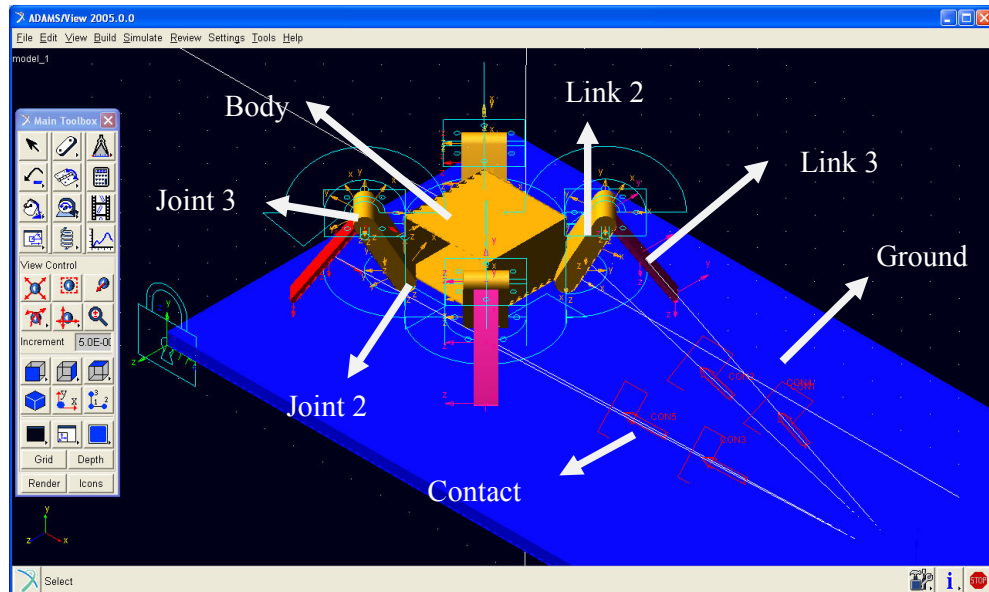


Figure 14: Rendered view of the ADAMS quadruped robot

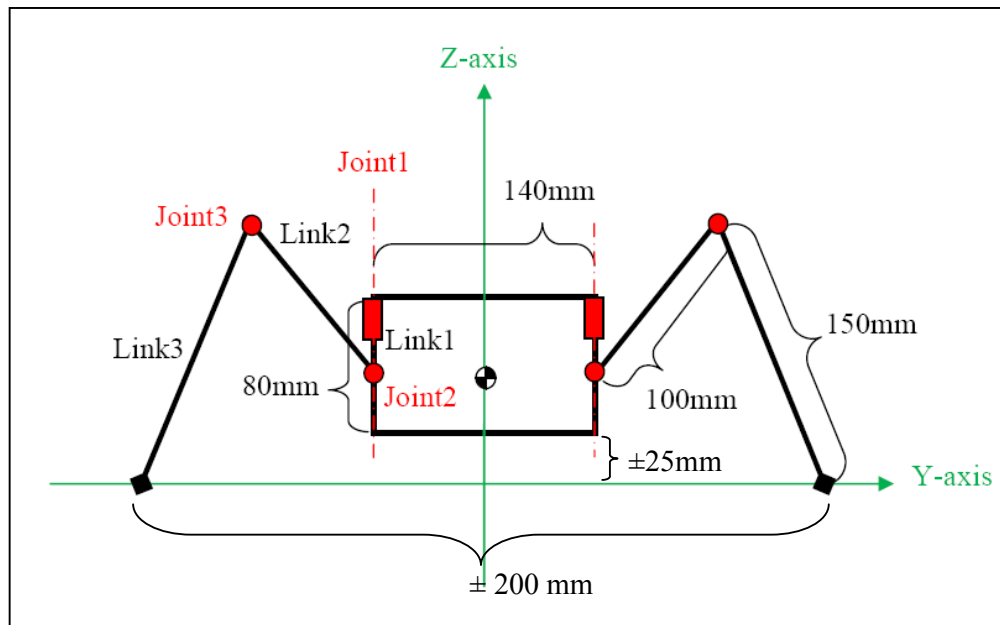


Figure 15 Schematic Design for Quadruped Robot (Right Hand Side View) [7]



During the ADAMS model construction, the design parameters are used as shown in the figure above. Besides those shown in the schematic diagram above, the remaining parameters are:

- Link 2
  - Width: 56mm
  - Thickness: 28mm
- Link 3
  - Width: 30mm
  - Thickness: 7mm
- Torque for each link : 35kg.mm or 130 kg.mm
- Density of material (Aluminum) :  $2700\text{kg/m}^3$
- Walking envelope :  $\pm 200\text{mm} \times \pm 200\text{mm}$
- The minimum distance between the bottom surface of the robot and the ground :  $\pm 25\text{mm}$
- Height of the robot:  $\pm 140\text{mm}$

Figures above depict the outcome of the ADAMS modeling. As shown in the Figure 14, the revolute joints have been defined between the links including between the links and the body (Joint 2 and Joint 3). The body is built to be hollow in order to reduce the weight of the body, collaborate with the real design of the quadruped robot prototype whereby two aluminum plates are used to construct the body.

The density of the material (Aluminum) of  $2700\text{ kg/m}^3$  has been defined in the information for the materials. Besides, each link (Link 3) has been defined with the Torque of 3.5kg.cm as the torque produced by the servomotor on each link in the real prototype. While for Link 2, torque of 13kg.cm is being defined for each link.

Procedure of developing a quadruped robot using ADAMS/View: [10]

1. To open the ADAMS package Adams/View and to enter the edit mode
2. To set the environment parameters, for example the original of the coordinate system, the size of workspace, etc
3. To build the models of four legs (each leg consist of Link 2 and Link 3) and a body of the robot as shown in Figure 7. Each part of the robot can be seen as a link that is offered by ADAMS. After building the link, the researcher can modify the physical parameters such as length, width, mass and inertia momentum, etc.;
4. Kinematics constraint is exerted on each joint of the robot. There are many kinds of constraint in ADAMS, such as revolute joint, universal joint, spherical joint, etc. In this ADAMS model, revolute joints are used for all the joints of the robot.
5. When the robot moves, a leg is in contact with the ground in stance phase. So, the ground model should be built in ADAMS. The box/platform is used for the ground model.
6. The contact model between four legs of the robot and the ground is built. The IMPACT function should be used for the contact model in ADAMS.
7. Functions are defined for each revolute joint to simulate movements of the robot.

#### 4.1.2.1 Simulation result for trotting gait

A simulation of the trotting gait has been done using the ADAMS model constructed. In order to simplify the simulation of the ADAMS model, only two motors movement are taken into consideration, which are the angles of  $\theta_1$  and  $\theta_3$ .

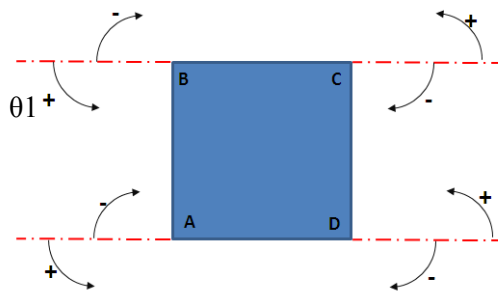


Figure 16: Plan view of the quadruped robot schematic diagram.

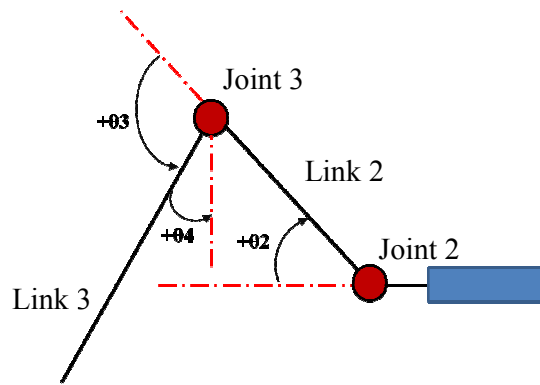


Figure 17: Side view of the quadruped robot schematic diagram

For each complete step, one leg will rotate  $\theta_1 = 18.62^\circ = 0.325$  rad. While for  $\theta_3$ , each complete leg will rotate  $\theta_3 = 5.73^\circ = 0.100$  rad. The simulation is set for 30 seconds.

Therefore, the functions defined are:

For Joint 2 for Leg A and D,

$$f(t) = 0.325 \sin\left(\frac{1}{4}\pi t\right)$$

For Joint 3 for Leg A and D,

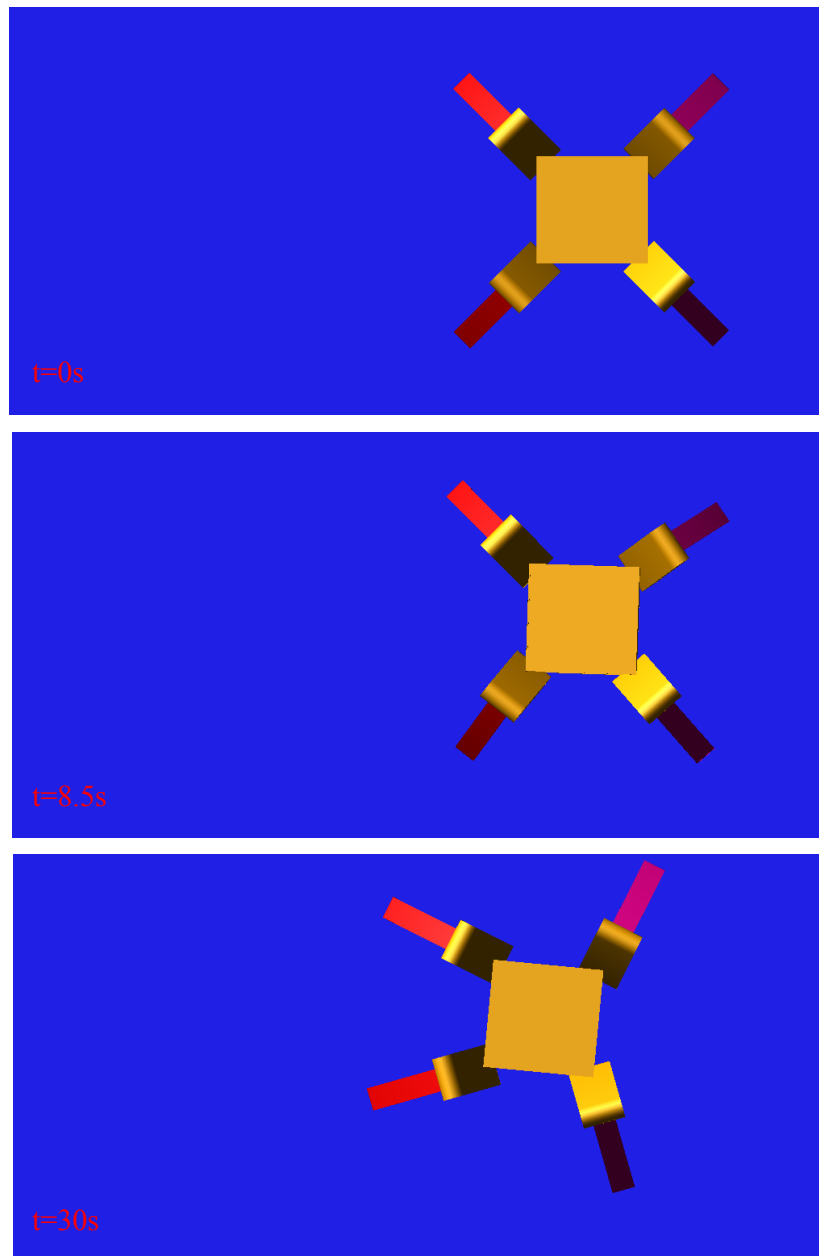
$$f(t) = 0.10 \sin\left(-\frac{1}{4}\pi t\right)$$

For Joint 2 for Leg B and C,

$$f(t) = 0.325 \cos\left(\frac{1}{4}\pi t\right)$$

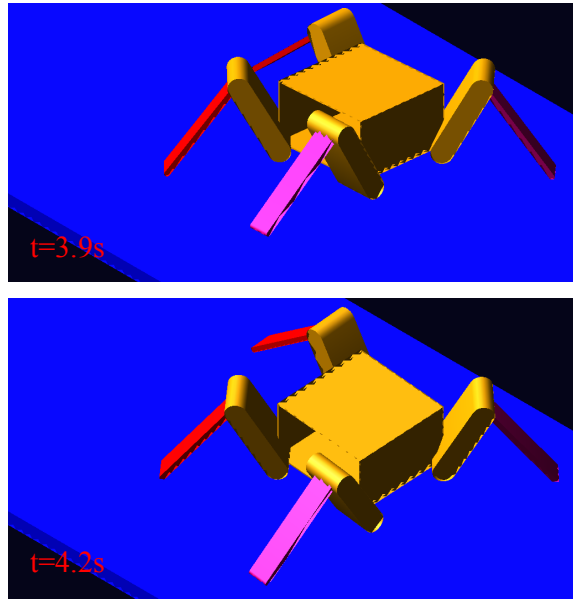
For Joint 3 for Leg B and C,

$$f(t) = 0.10 \cos\left(-\frac{1}{4}\pi t\right)$$

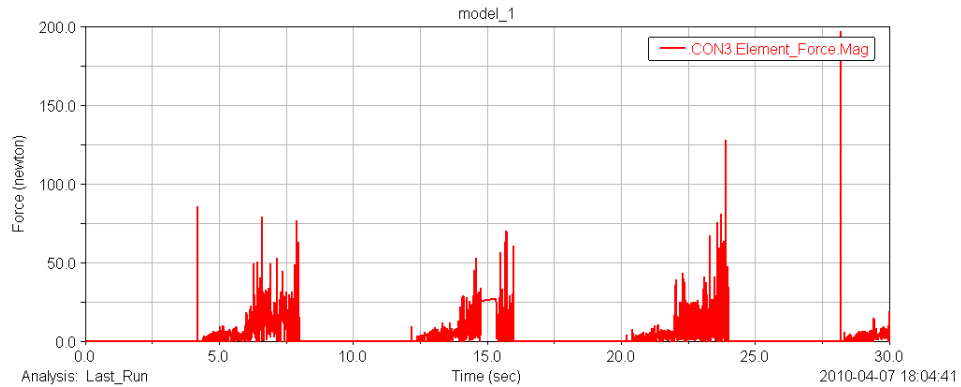


*Figure 18 Position of robot model at  $t=0s$   $t=8.5s$  and  $t=30s$*

Figure 18 shows the robot did not trot in a straight line despite the fact that the certain displacement is achieved. This is due to the less ideal coordination of the legs and also the time of landing and lifting of the legs. Nevertheless, the stability of the robot is one of main causes of the problems as well.



*Figure 19 State of the robot at  $t=3.9s$  and  $t=4.2s$  shows the instability and tendency to flip over.*



*Figure 20 Element forces on the legs of the robot during simulation.*

From the simulation, it is shown that the robot is not stable as the robot tends to partially flip over thus causing the robot to have certain unnecessary impact on the ground while performing the trotting gait. This can be seen in Figure 19 and the situation happened between  $t=3.9s$  and  $t=4.2s$ .

From Figure 20, it shows the sudden increase of the forces exerted on the legs of the robot. The impact caused might harm the connection of the electronic components of the servomotors controller and also the mechanical structure of the robot.

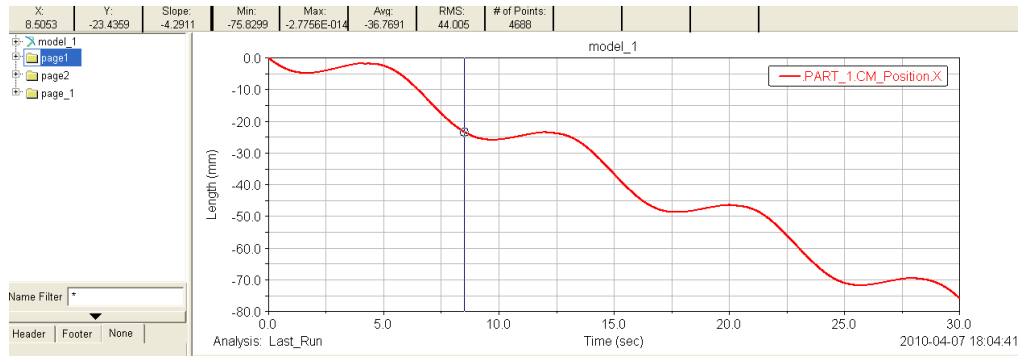


Figure 21 Plot of the CM position for X component for the gait simulation using ADAMS PostProcessor

From Figure 21, it is shown that the model has moved 75.83mm in 30 seconds of the simulation. The wavy plot shows that the robot did not move with consistency and also high instability. This shows trotting gait is a gait with dynamic stability and the COG might not be within the stability polygon all the time. This is because in trotting gait, two legs are lifted up at one time thus the robot will require more complicated balancing task.

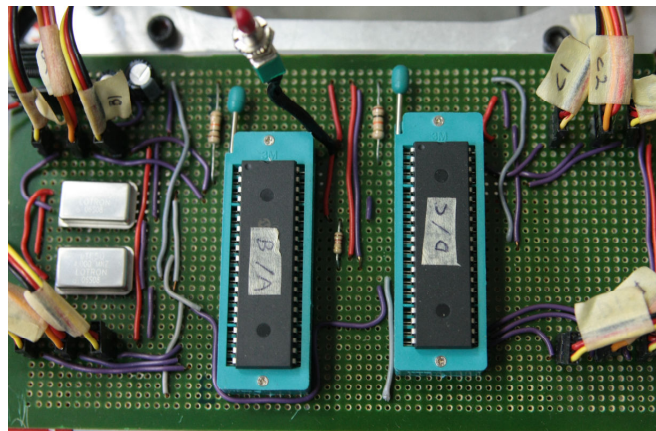
#### 4.1.3 Excel Spreadsheet Simulator development

The Excel Spreadsheet simulator developed for crawling gait has been modified and updated in order to perform the simulation for trotting gait. For trotting gait, only 8 steps will be developed instead of 16 steps for crawling gait. The result of the developed simulator is defined in *Appendix 4*. The simulation is able to provide the simple structure for the motor controller such as joint angles, the coordinates of the legs and so on and the information can be used to modify the program code for the PIC.

The simulation is adjusted by referring to the real dimensions of the prototype. The necessary information such as turning angle and distance travelled are extracted from the ADAMS simulation. The outcome of the simulator is to provide the joints angles, or motor rotational angles that are required in programming the servomotors controller.

#### 4.1.4 Circuit Assembly

Instead of PCB board, veroboard has been used to build the circuit in order to reduce the overall weight of the robot. As shown in Figure 22, veroboard which has the same weight factor as the PCB board is used to construct the electronic circuit.



*Figure 22 Completed circuit board*

The circuit board is configured according to wiring diagram shown in Figure 23 and is to be tested using power supply unit at 6 to 9 volt to ensure the sufficient voltage and current are supplied to the servomotors. From the test result of the power supply unit, the servomotors will be able to function optimally and perform the gaits efficiently at range of voltage from 6.7V to 7.2V. Power supply higher than the range will cause the servomotors to malfunction and exert excessive torque thus causing the robot unable to walk perfectly.

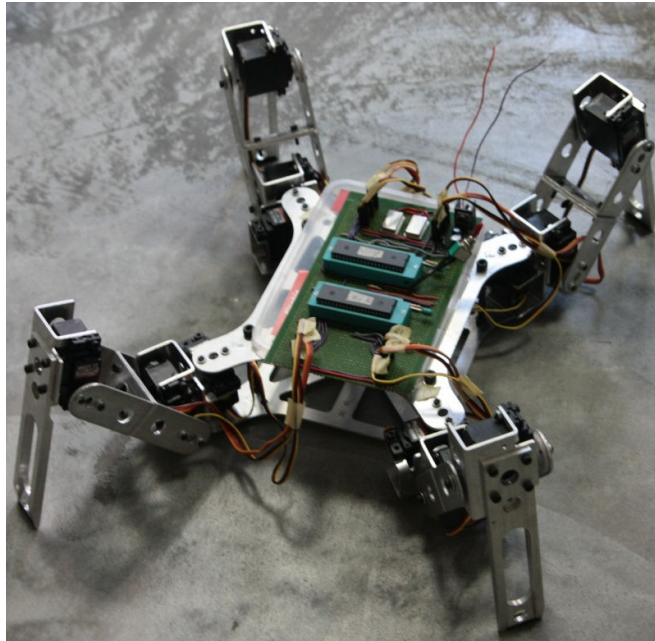
There are two microcontrollers (PIC18F458); one for controlling leg A and B (6 servomotors) while another one is for controlling leg C and leg D (6 servomotors). Two 4 MHz crystals (oscillator) are used in the motor controllers; one is used to provide time base for timer RTCC and TIMER1 (both internal clocks) of both microcontrollers while another one is for timer TIMER3 (external clock). Besides, one power regulators (78L05) is used in order to provide steady power supply of 5 volt to each microcontroller as the PIC requires at least 5 volt to initiate the programs inside it. Heat sinks are attached to the power regulators in order to dissipate heat and prevent component from failure.





#### 4.1.5 Prototype

The prototype is completed by mounting the servomotors as well as the completed circuit board using the veroboard. Thus, the robot is now a functioning robot and able to perform crawling gait.



*Figure 24 Quadruped Robot prototype*

## **CHAPTER 5**

### **CONCLUSIONS AND RECOMMENDATIONS**

#### **5.1 Conclusion**

The objectives of this project is to improve on the motor torque for better lifting capability, to model the gaits and implementation of the quadruped robot on ADAMS software, to develop the walking gaits for the quadruped robot including trotting gait and to produce printed circuit board (PCB) for the electronic parts of the robot.

As a conclusion, the ADAMS model for the trotting gait of the quadruped robot has been successfully constructed and simulations have been run successfully. The quadruped robot is proven to be able to perform trotting gait despite the instability involved. From the simulation, it is shown that trotting gait involved dynamic stability and more complicated balancing task or capability needed to be added to the robot in order for the robot to perform trotting gait efficiently.

The Excel Spreadsheet simulator has been developed for the trotting gait and instead of 16 steps, 8 steps are developed for a complete cycle. The information such as joints angles are used to develop the program codes for PIC of the prototype.

The printed circuit board (PCB) has been replaced with veroboard as the veroboard has the same weight factor as the PCB. This will not only reduce the cost of producing the PCB, but will also achieve the main objective which is to reduce the overall weight of the quadruped robot. Therefore, the electronic parts are being assembled on the board and the circuit board is to be tested using the power supply unit. With the power supply of 6.7V to 7.2V, the prototype is able to perform crawling gait without any support.

Nevertheless, the prototype is yet to perform trotting gait as from the ADAMS simulation, it is shown that with the current configuration and design of the prototype, the robot will not be able to perform trotting gait efficiently and with high stability. Besides, the sudden increase of impact forces and vibration on the prototype will cause harm to the mechanical structure of the robot as well as disconnection to the circuit board of the servomotors controller.

## **5.2 Recommendations**

Therefore, it is recommended to perform some changes to the design of the current prototype. As shown in the ADAMS simulations, trotting gait involves dynamic stability of the robot and complicated balancing task will be required to perform a stable and efficient trotting gait. Thus, some addition features such as force sensor, gyrometer, etc in order to help the robot to perform advanced balancing task.

Alternatively, different gait which does not require dynamic balancing can be developed for the quadruped robot. Such gaits include crawling gait with higher speed, or called the walking gait, and also gait performed on inclined or rugged surface. In order to develop gaits on inclined or rugged surface, some components with high frictional factor should be incorporated to the base of the legs of the prototype so that the robot will be able to have higher grip on the surface. Besides, some modification on the circuit will be required in order to incorporate all the addition to the prototype.

Lastly, instead of PIC control, the quadruped can implement manual control such as using Bluetooth or Wireless transmission from the user in order to execute direct control of the quadruped to perform moving pattern according to user's will. This will assist the user to order the quadruped to perform any task on rugged or incline surface with more flexible and easier control.

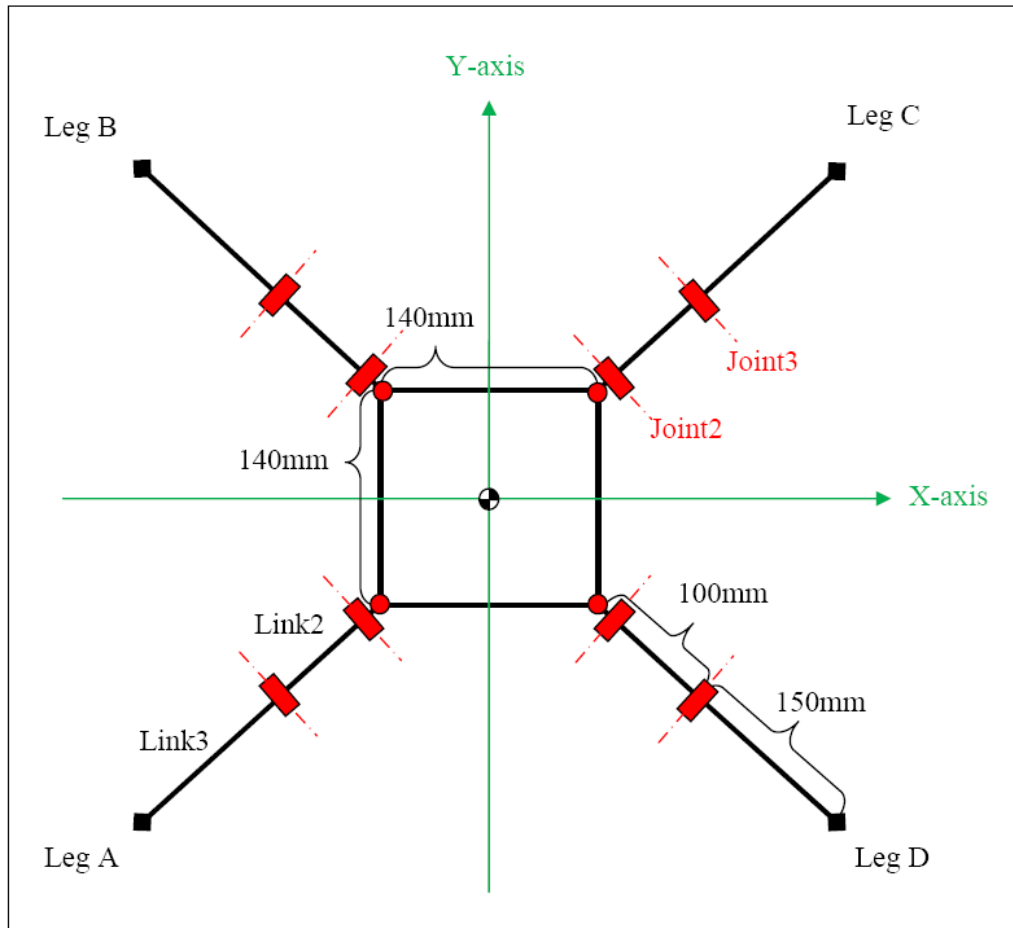
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8. M. A. Mazidi, R. D. Mckinlay & D. Causey. 2008, *PIC Microcontroller and Embedded Systems: Using Assembly and C for PIC18*, Prentice Hall, New Jersey

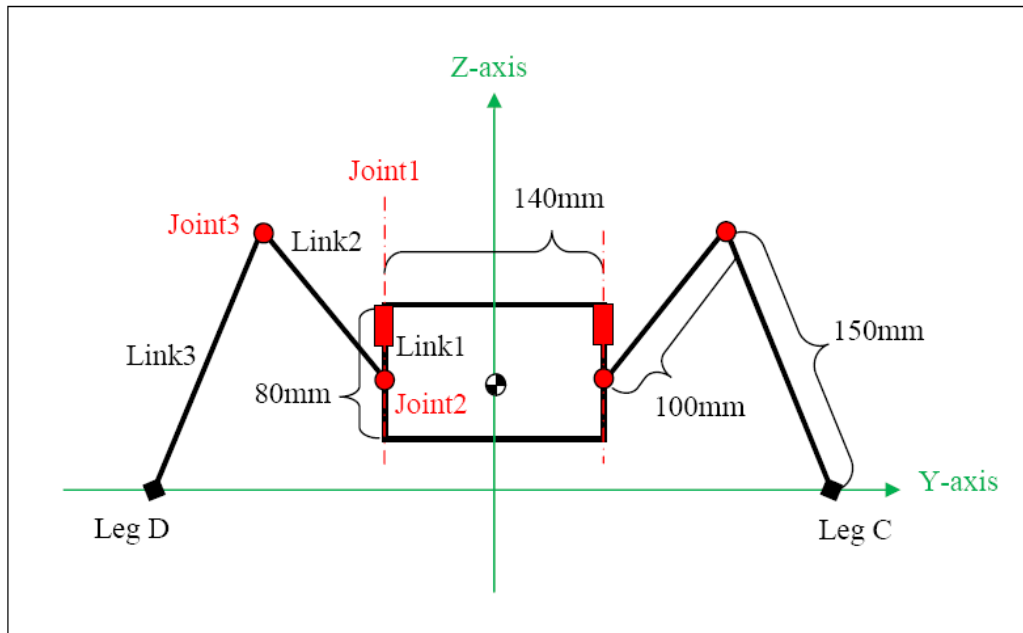
9. Thanhtam Ho, Sunghac Choi, Sangyoon Lee. 2007, “Development of a Biomimetic Quadruped Robot”, *Journal of Bionic Engineering 4 (2007)* 193–199.
  
10. Hangxin Wei, Wei Wu, Mingzhi Liu. 2008, “Simulation of the Humanoid Running Robot Based on ADAMS”, *Tenth International Conference on Computer Modeling and Simulation*.

# APPENDICES

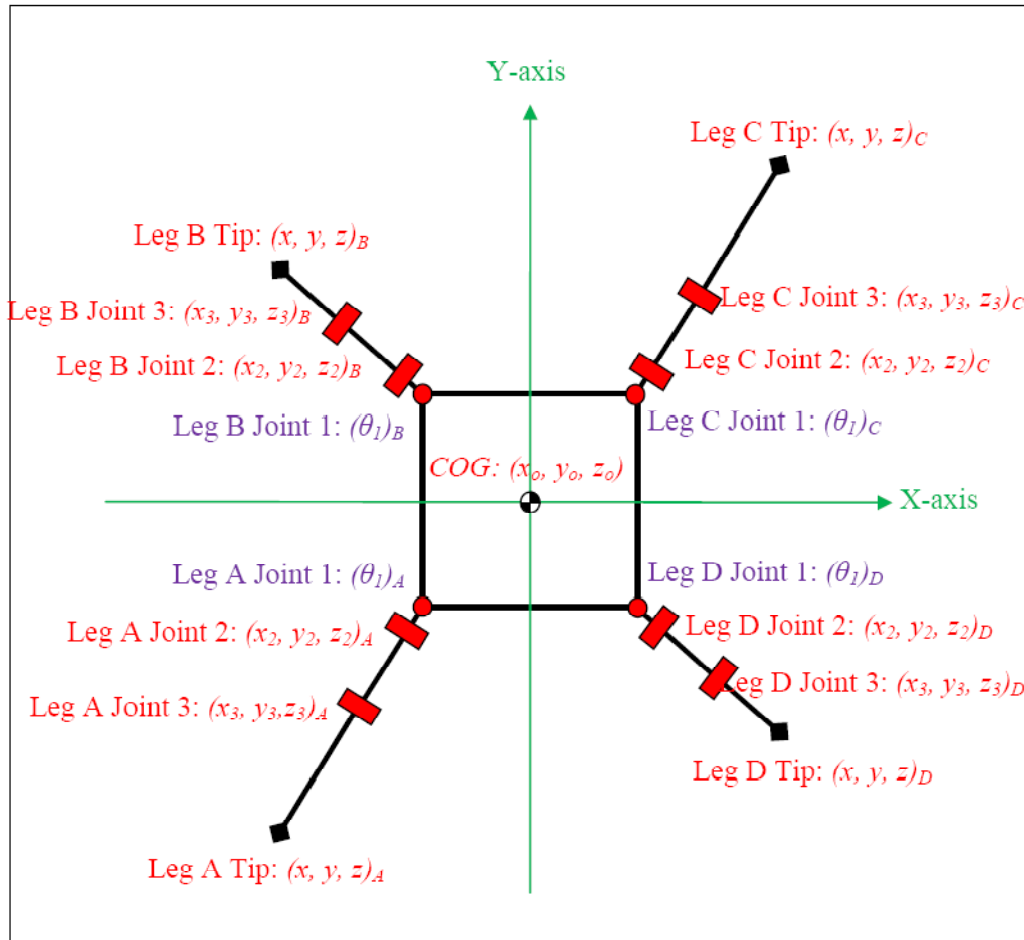
## Appendix 1: Schematic Design of Quadruped (Top View)



## Appendix 2: Schematic Design of Quadruped (Right Hand Side View)



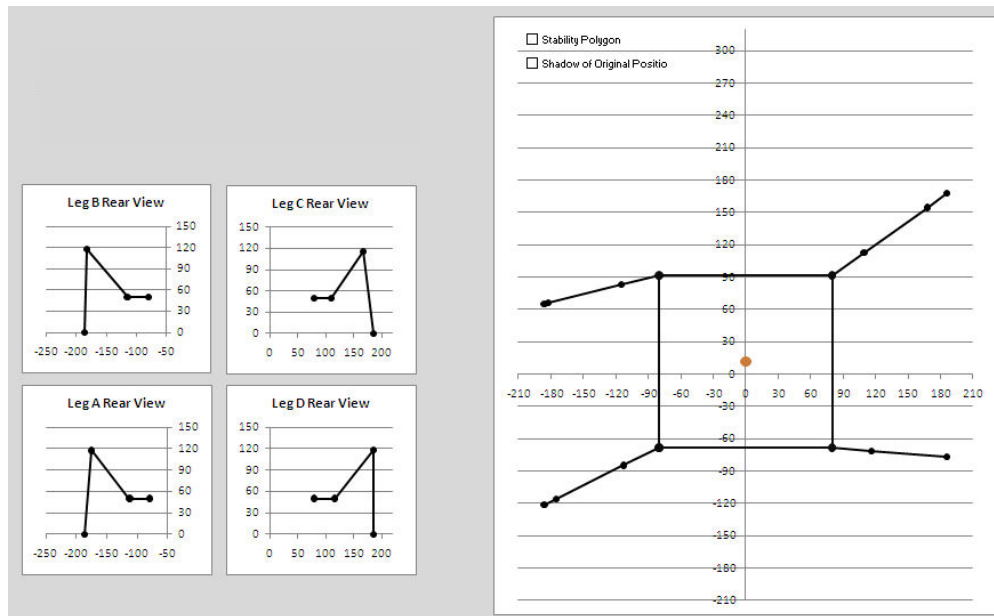
### Appendix 3: Global Coordinate Notation of Quadruped Robot (Top View)





## Appendix 4: Trotting Gait Simulation using Excel Spreadsheet

### Step 0



\* Red solid line represents lifted-up legs.

Leg	Joint	Joint	Joint	Tip
B	1	2	3	
x	-80.0	-115.2	-182.7	-186.1
y	91.7	82.9	66.1	65.3
z	50.0	50.0	117.9	0.0

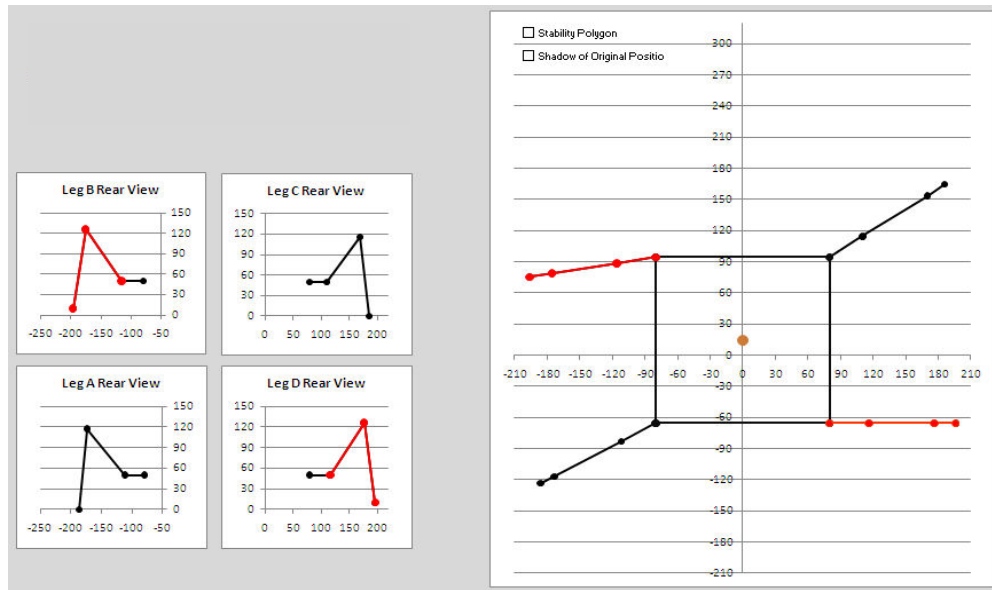
Leg	Joint	Joint	Joint	Tip
C	1	2	3	
x	80.0	109.4	167.6	186.1
y	91.7	112.8	154.6	167.9
z	50.0	50.0	115.8	0.0

Leg	Joint	Joint	Joint	Tip
A	1	2	3	
x	-80.0	-112.5	-175.3	-186.1
y	-68.3	-84.4	-115.6	-120.9
z	50.0	50.0	117.4	0.0

Leg	Joint	Joint	Joint	Tip
D	1	2	3	
x	80.0	116.1	185.4	186.1
y	-68.3	-71.2	-76.9	-76.9
z	50.0	50.0	118.0	0.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	26.4	14.0	35.7	-4.6
$\theta_2^\circ$	43.9	44.3	42.6	44.4
$\theta_3^\circ$	128.0	132.6	121.5	134.1

## Step 1



\* Red solid line represents lifted-up legs.

Leg	Joint	Joint	Joint	Tip
B	1	2	3	
x	-80.0	-115.8	-175.5	-196.1
y	94.6	88.8	79.0	75.6
z	50.0	50.0	126.1	10.0

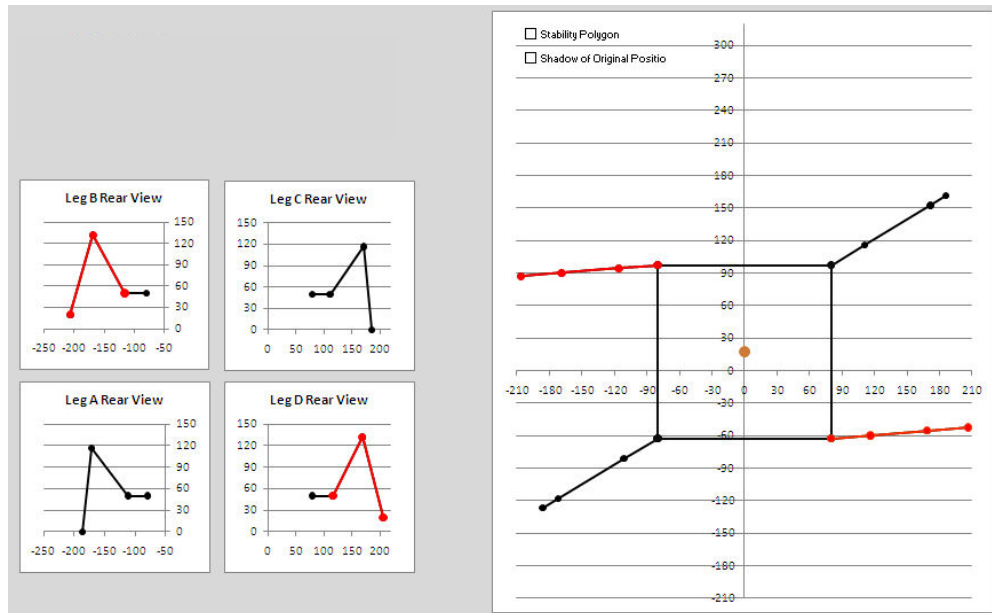
Leg	Joint	Joint	Joint	Tip
C	1	2	3	
x	80.0	110.3	169.7	186.1
y	94.6	114.6	153.7	164.5
z	50.0	50.0	116.4	0.0

Leg	Joint	Joint	Joint	Tip
A	1	2	3	
x	-80.0	-111.8	-173.5	-186.1
y	-65.4	-82.8	-116.6	-123.5
z	50.0	50.0	117.1	0.0

Leg	Joint	Joint	Joint	Tip
D	1	2	3	
x	80.0	116.2	176.5	196.1
y	-65.4	-65.4	-65.4	-65.4
z	50.0	50.0	126.4	10.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	28.7	9.3	33.4	0.0
$\theta_2^\circ$	43.7	51.5	43.0	51.7
$\theta_3^\circ$	126.7	131.3	123.4	132.2

## Step 2



\* Red solid line represents lifted-up legs.

Leg	Joint	Joint	Joint	Tip
B	1	2	3	
x	-80.0	-116.1	-168.5	-206.1
y	97.6	94.6	90.3	87.3
z	50.0	50.0	131.8	20.0

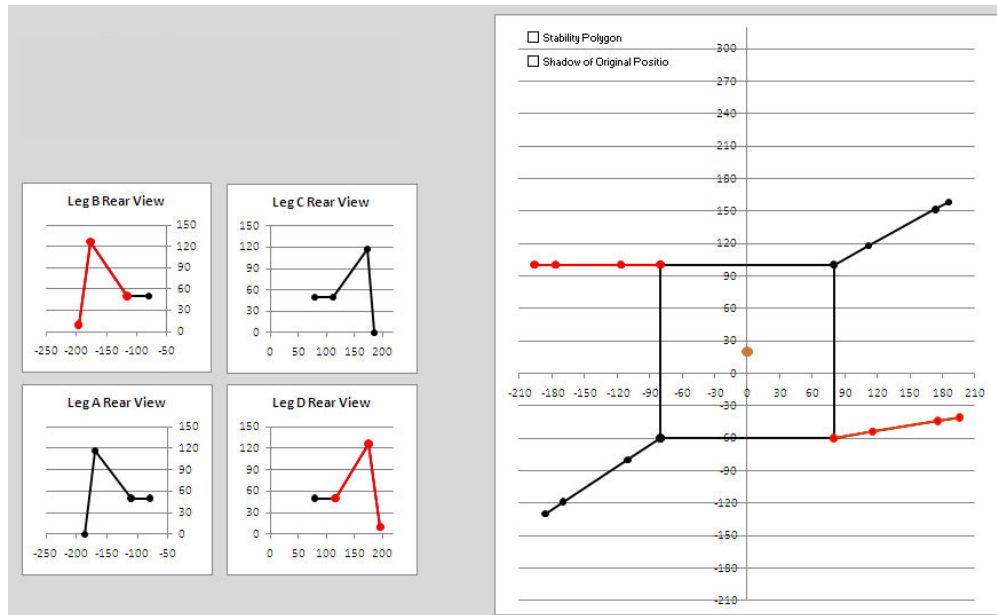
Leg	Joint	Joint	Joint	Tip
C	1	2	3	
x	80.0	111.1	171.6	186.1
y	97.6	116.2	152.7	161.4
z	50.0	50.0	116.8	0.0

Leg	Joint	Joint	Joint	Tip
A	1	2	3	
x	-80.0	-111.1	-171.6	-186.1
y	-62.5	-81.1	-117.6	-126.3
z	50.0	50.0	116.8	0.0

Leg	Joint	Joint	Joint	Tip
D	1	2	3	
x	80.0	116.1	168.5	206.1
y	-62.5	-59.5	-55.2	-52.2
z	50.0	50.0	131.8	20.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	31.0	4.7	31.0	4.7
$\theta_2^\circ$	43.4	57.3	43.4	57.3
$\theta_3^\circ$	125.2	128.7	125.2	128.7

### Step 3



\* Red solid line represents lifted-up legs.

Leg	Joint	Joint	Joint	Tip
B	1	2	3	
x	-80.0	-116.2	-176.5	-196.1
y	100.5	100.5	100.5	100.5
z	50.0	50.0	126.4	10.0

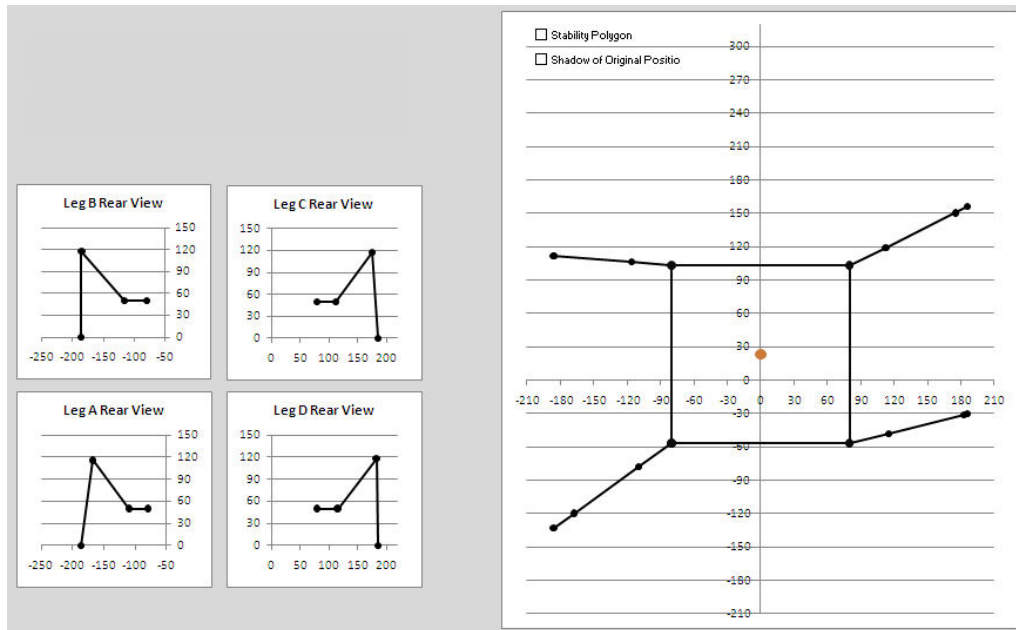
Leg	Joint	Joint	Joint	Tip
C	1	2	3	
x	80.0	111.8	173.5	186.1
y	100.5	117.9	151.7	158.6
z	50.0	50.0	117.1	0.0

Leg	Joint	Joint	Joint	Tip
A	1	2	3	
x	-80.0	-110.3	-169.7	-186.1
y	-59.5	-79.5	-118.6	-129.4
z	50.0	50.0	116.4	0.0

Leg	Joint	Joint	Joint	Tip
D	1	2	3	
x	80.0	115.8	175.5	196.1
y	-59.5	-53.7	-43.9	-40.5
z	50.0	50.0	126.1	10.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	33.4	0.0	28.7	9.3
$\theta_2^\circ$	43.0	51.7	43.7	51.5
$\theta_3^\circ$	123.4	132.2	126.7	131.3

### Step 4



\* Red solid line represents lifted-up legs.

Leg B	Joint 1	Joint 2	Joint 3	Tip
x	-80.0	-116.1	-185.4	-186.1
y	103.4	106.3	112.0	112.0
z	50.0	50.0	118.0	0.0

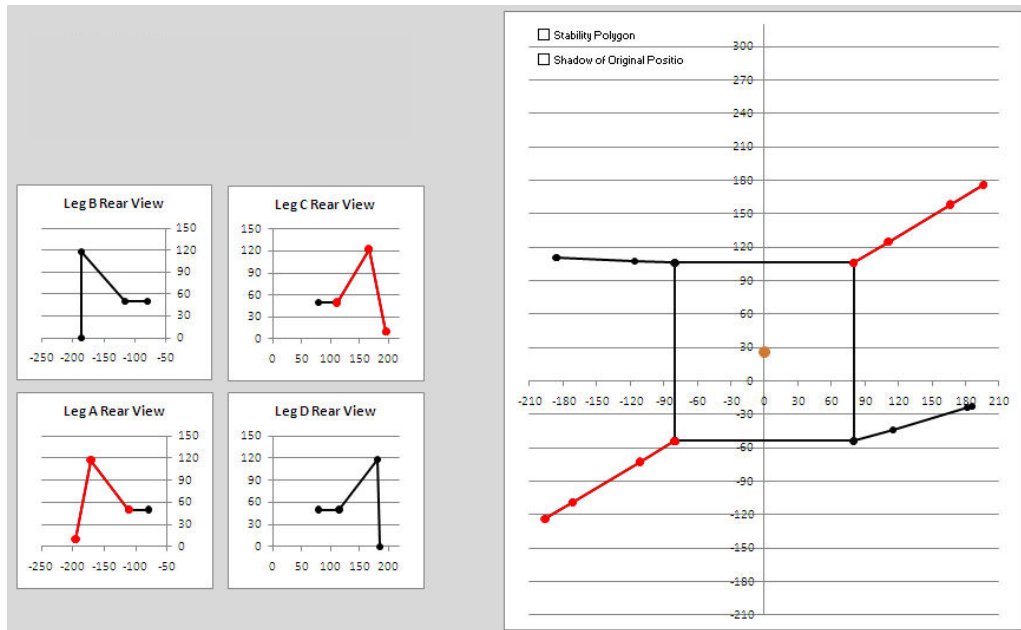
Leg C	Joint 1	Joint 2	Joint 3	Tip
x	80.0	112.5	175.3	186.1
y	103.4	119.5	150.7	156.0
z	50.0	50.0	117.4	0.0

Leg A	Joint 1	Joint 2	Joint 3	Tip
x	-80.0	-109.4	-167.6	-186.1
y	-56.6	-77.7	-119.5	-132.8
z	50.0	50.0	115.8	0.0

Leg D	Joint 1	Joint 2	Joint 3	Tip
x	80.0	115.2	182.7	186.1
y	-56.6	-47.8	-31.0	-30.2
z	50.0	50.0	117.9	0.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	35.7	-4.6	26.4	14.0
$\theta_2^\circ$	42.6	44.4	43.9	44.3
$\theta_3^\circ$	121.5	134.1	128.0	132.6

## Step 5



\* Red solid line represents lifted-up legs.

Leg	Joint	Joint	Joint	Tip
B	1	2	3	
x	-80.0	-116.2	-185.7	-186.1
y	106.3	107.8	110.6	110.6
z	50.0	50.0	118.0	0.0

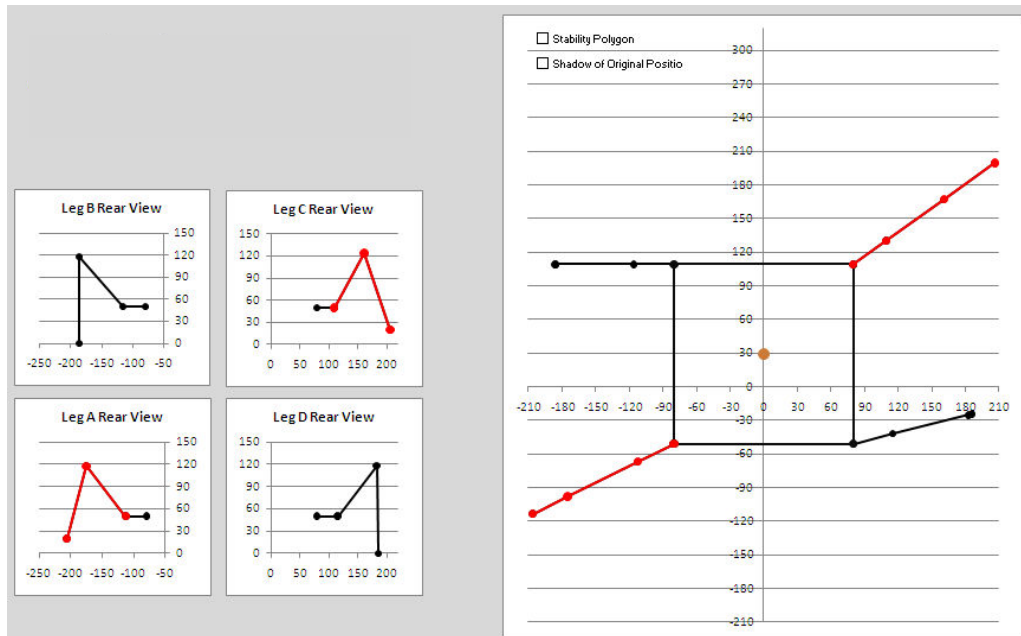
Leg	Joint	Joint	Joint	Tip
C	1	2	3	
x	80.0	111.1	166.3	196.1
y	106.3	125.0	158.3	176.2
z	50.0	50.0	122.8	10.0

Leg	Joint	Joint	Joint	Tip
A	1	2	3	
x	-80.0	-111.1	-171.3	-196.1
y	-53.7	-72.4	-108.6	-123.5
z	50.0	50.0	117.1	10.0

Leg	Joint	Joint	Joint	Tip
D	1	2	3	
x	80.0	114.8	181.6	186.1
y	-53.7	-43.5	-24.0	-22.7
z	50.0	50.0	117.9	0.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	31.0	-2.3	31.0	16.3
$\theta_2^\circ$	43.7	44.4	48.5	44.3
$\theta_3^\circ$	121.3	134.2	121.3	132.0

## Step 6



\* Red solid line represents lifted-up legs.

Leg B	Joint 1	Joint 2	Joint 3	Tip
x	-80.0	-116.2	-185.8	-186.1
y	109.3	109.2	109.2	109.2
z	50.0	50.0	118.0	0.0

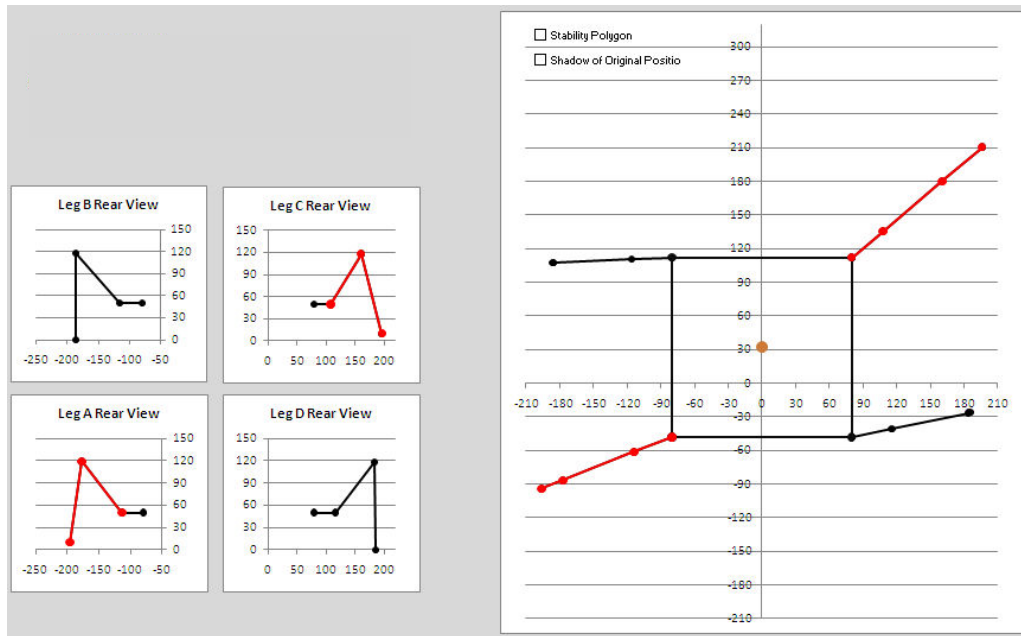
Leg C	Joint 1	Joint 2	Joint 3	Tip
x	80.0	109.4	160.7	206.1
y	109.3	130.4	167.2	199.8
z	50.0	50.0	124.0	20.0

Leg A	Joint 1	Joint 2	Joint 3	Tip
x	-80.0	-112.5	-175.1	-206.1
y	-50.8	-66.9	-97.9	-113.3
z	50.0	50.0	117.7	20.0

Leg D	Joint 1	Joint 2	Joint 3	Tip
x	80.0	115.2	182.7	186.1
y	-50.8	-42.0	-25.2	-24.4
z	50.0	50.0	117.9	0.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	26.4	0.0	35.7	14.0
$\theta_2^\circ$	44.1	44.4	49.5	44.3
$\theta_3^\circ$	120.3	134.2	111.3	132.6

## Step 7



\* Red solid line represents lifted-up legs.

Leg B	Joint 1	Joint 2	Joint 3	Tip
x	-80.0	-116.2	-185.7	-186.1
y	112.2	110.7	107.9	107.8
z	50.0	50.0	118.0	0.0

Leg C	Joint 1	Joint 2	Joint 3	Tip
x	80.0	107.6	160.4	196.1
y	112.2	135.6	180.5	210.8
z	50.0	50.0	118.3	10.0

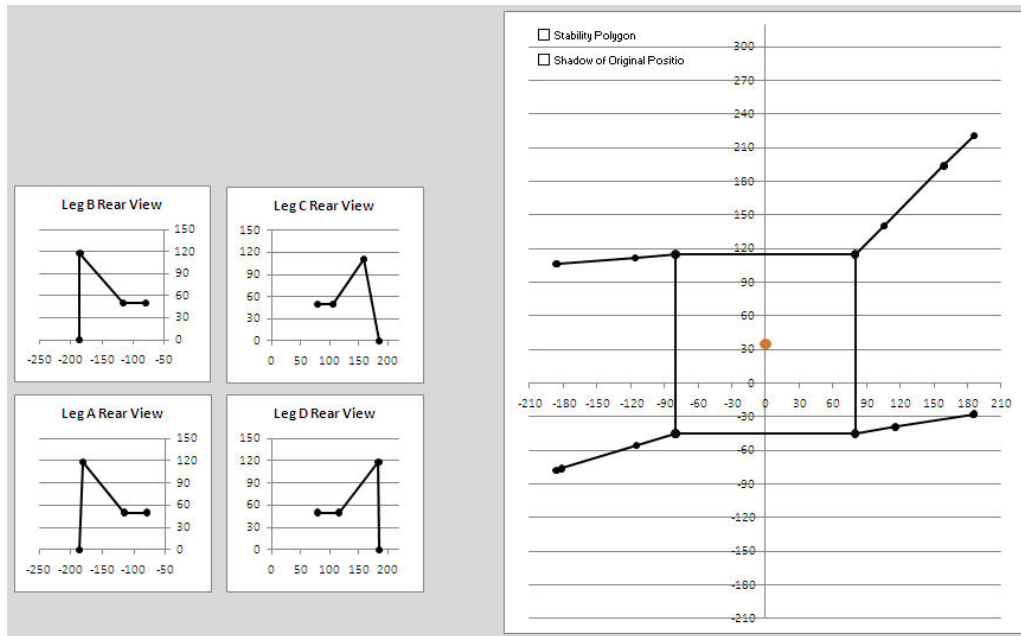
Leg A	Joint 1	Joint 2	Joint 3	Tip
x	-80.0	-113.7	-177.3	-196.1
y	-47.8	-61.2	-86.6	-94.1
z	50.0	50.0	119.1	10.0

Leg D	Joint 1	Joint 2	Joint 3	Tip
x	80.0	115.5	183.6	186.1
y	-47.8	-40.5	-26.5	-26.0
z	50.0	50.0	118.0	0.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	21.7	2.3	40.3	11.6
$\theta_2^\circ$	45.3	44.4	44.6	44.3
$\theta_3^\circ$	127.3	134.2	111.2	133.1



## Step 8



\* Red solid line represents lifted-up legs.

Leg	Joint	Joint	Joint	Tip
B	1	2	3	
x	-80.0	-116.1	-185.4	-186.1
y	115.1	112.2	106.5	106.4
z	50.0	50.0	118.0	0.0

Leg	Joint	Joint	Joint	Tip
C	1	2	3	
x	80.0	105.6	158.9	186.1
y	115.1	140.7	194.0	221.2
z	50.0	50.0	111.6	0.0

Leg	Joint	Joint	Joint	Tip
A	1	2	3	
x	-80.0	-114.7	-181.2	-186.1
y	-44.9	-55.5	-76.0	-77.5
z	50.0	50.0	117.9	0.0

Leg	Joint	Joint	Joint	Tip
D	1	2	3	
x	80.0	115.8	184.4	186.1
y	-44.9	-39.0	-27.8	-27.5
z	50.0	50.0	118.0	0.0

Angles	Leg A	Leg B	Leg C	Leg D
$\theta_1^\circ$	17.1	4.7	45.0	9.3
$\theta_2^\circ$	44.3	44.4	39.3	44.4
$\theta_3^\circ$	131.8	134.1	110.2	133.5