MODELING AND ANALYSIS ON BIPEDAL WHEEL-LEGGED ROBOT WITH SPRAWLING MECHANISM

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ABSTRAK

Robot mudah alih mempunyai pelbagai aplikasi, ia boleh digunakan bukan sahaja dalam industri perkhidmatan seperti pembuatan, pertanian, penjagaan kesihatan dan bidang khusus lain. Akibatnya, teknologi robot mudah alih telah mendapat perhatian global. Kebanyakan robot mudah alih berkaki menggunakan mekanisme jenis mamalia kerana robot itu boleh berjalan di ruang yang sempit dan boleh berjalan lebih laju daripada mekanisme yang luas. Walau bagaimanapun, robot berkaki jenis ini mempunyai pergerakan jarak lebar yang rendah dan penempatan kaki adalah terhad juga. Selain itu, kestabilan jenis mamalia lebih rendah daripada luas menjadikan konfigurasi ini dapat mengesan pusat gravitinya pada kedudukan rendah dengan poligon sokongan yang lebih luas. Oleh itu, projek ini telah mencadangkan reka bentuk hibrid dan model robot bipedal dengan gabungan mekanisme mamalia dan sprawling. Parameter DH dilakukan dalam penyelesaian kinematik untuk kedua-dua kinematik hadapan dan songsang bagi setiap kaki. Persamaan kinematik ke hadapan digunakan untuk mengukur robot kedudukan Cartesian keluaran daripada isyarat maklum balas setiap sendi setiap kaki. Sebaliknya, kinematik songsang digunakan untuk menterjemah input trajektori Cartesian kepada input sudut untuk setiap sendi setiap kaki. Struktur dinamik berbilang badan robot didekati dalam memodelkan robot ini menggunakan MATLAB SIMULINK-Simscape untuk mensimulasikan gerakan robot dan trajektori kaki gerakan kaki direka untuk ujian sampul kerja kaki robot.

ABSTRACT

Mobile robots have a wide range of applications; they can be used not only in service industries such as manufacturing, agriculture, healthcare, and other specialized fields. As a result, the technology of mobile robots has garnered global attention. Most legged mobile robot use mammal-type mechanism because of the robot can walk at narrow space and can walk faster than sprawling mechanism. However, this type of legged robot has low wide range motion and foot placement is limited as well. Moreover, the stability of the mammal type is lower than sprawling makes this configuration able to locate its center of gravity at low position with wider support polygon. Therefore, this project has proposed a hybrid design and modelled of bipedal robot with combination of mammal and sprawling mechanism. The DH parameters is done in kinematics solution for both forward and inverse kinematics of each leg. Forward kinematics equation is used to measure the output Cartesian position robot from the feedback signal of each joint of each leg. On the other hand, inverse kinematic is used to translate the Cartesian trajectory input to the angular input for each joint of each leg. The multibody dynamic structure of the robot is approached in modeling this robot using MATLAB SIMULINK-Simscape to simulate the motion of the robot and the leg trajectory of the leg motion is designed for robot's leg working envelope test. The dynamic performance angle are observed from the simulation results for each joint and the input angle is same as an output angle. Moreover, the results of trajectory motion and robot workspace is equality with the desired motion.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Classification of robots is based on their operating environment. The most frequently used categorization is that of fixed versus mobile robots. These two types of robots operate in vastly different environments, necessitating the development of vastly different capabilities as shown in Figure 1.1. Fixed robots are primarily industrial robotic manipulators that operate in well-defined robot-friendly environments. In automobile manufacturing plants, industrial robots perform repetitive tasks such as soldering and painting parts. Robotic manipulators are increasingly used in less controlled environments, such as high-precision surgery, as sensors and devices for human-robot interaction improve.

In comparison, mobile robots are expected to manoeuvre and perform tasks in large, ill-defined, and uncertain environments that are not specifically designed for robots. They must contend with situations that are unknown in advance and evolve over time. Unpredictable entities such as humans and animals may exist in these environments. Robot vacuum cleaners and self-driving cars are two examples of mobile robots.

Mobile robots are mainly characterized by a mobile base, enabling the robot to move freely in the environment. In contrast to manipulators, such robots are mainly used in service applications where extensive, autonomous movement capacities are necessary. From a mechanical point of view, a moving robot consists of one or more rigid locomotive systems.

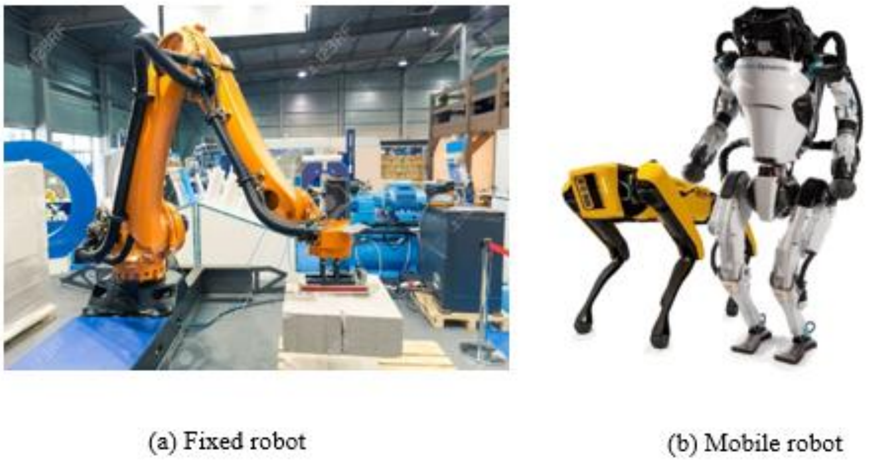
There are two main classes of mobile robots that are wheel and legged robots. Mobile robots with wheels are usually made up of a rigid body (base or chassis) and an earth-moving system with wheels. Mobile legged robots are made of multiple rigid bodies, connected by prismatic joints or more frequently by revolutionary joints. Some of these bodies form lower limbs, whose limbs regularly come into contact with the ground for locomotion. In this class there are a wide range of mechanical structures, often inspired by the study of living organisms, from biped humanoids to hexapod robots to replicate insects' biomechanical efficiency.

A bipedal walking robot is a type of humanoid robot that can be designed to do various activities. For the purpose of simulating human movement, a bipedal walking robot was used. Bipedal robots will be more effective than any other sort of robot in a human setting. It is capable of completing things that would be impossible or risky for a human to perform on their own. Such hazardous applications include fire rescue, poisonous gas or chemical extraction, explosives like land mines, and the assistance of people in difficult jobs that they are unable to complete on their own.

There has been an increase in interest in walking robots that can traverse uneven terrain where wheeled or crawled robots have difficulty. In quadruped robots, there are two types of leg mechanisms: mammal and sprawling as shown in Figure 1.2. Sprawling mechanisms are more stable than mammal mechanisms because they allow the robot to locate its centre of gravity low and have a larger supporting leg polygon. It also has a wide range of motion due to its proximal yaw axis, which allows for a variety of foot placement options.

The study's ultimate goal is to design and analysed on sprawling bipedal wheel-legged robot that is capable of travelling in a variety of environments. This robot is designed to move in a variety of environments using the wheel mechanism on flat ground or slopes and the leg mechanism on uneven ground or steps. This robot has two mode, each mode has a different locomotion. Sprawling mechanism is for leg mode, while the mammal mechanism is for wheel mode. The conceptual design of the sprawling bipedal wheel-legged robot is designed by using Solidworks. Besides, the DH parameters is done in kinematics solution for both forward and inverse kinematics of each leg. Forward kinematics equation is used to measure the output Cartesian position robot from the feedback signal of each joint of each leg. On the other hand, inverse kinematic is used to translate the Cartesian trajectory input to the angular input for each joint of each leg. The multibody dynamic structure of the robot is approached in modelling this robot using

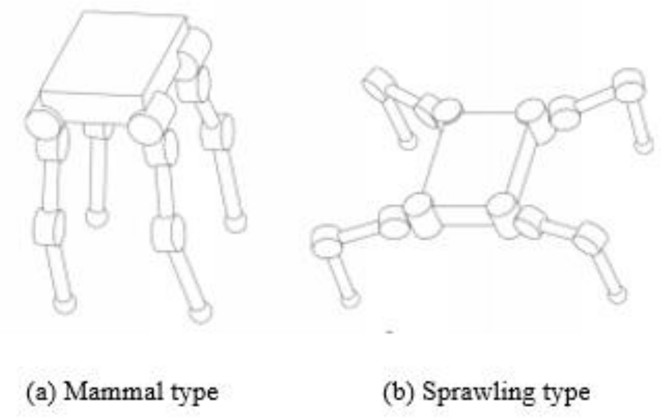
MATLAB SIMULINK-Simscape to simulate the motion of the robot and the leg trajectory of the leg motion is designed for robot’s leg working envelope test.



(a) Fixed robot

(b) Mobile robot

Figure 1.1: Type of robot; (a) Fixed robot and (b) mobile robot [1].



(a) Mammal type

(b) Sprawling type

Figure 1.2: Type of leg mechanism; (a) Mammal-type and (b) sprawling-type [2].

1.2 Problem Statement

With the advancement of robot performance, the mobile robot has the potential to play a significant role in our daily lives in the near future. Mobile robots have a wide range of applications. It can be used not only in service industries such as manufacturing, agriculture, national defence, and healthcare, but also in some extremely dangerous situations such as mine clearance, search-and-rescue in earthquake-prone areas, radiation-prone areas, and other specialized fields. As a result, the technology of mobile robots has garnered global attention. At the moment, two types of mobile robots are being studied which is a wheeled mobile robots and legged mobile robots. Both types have their own advantages and disadvantages. The advantages of the wheeled robot include its rapid movement, high energy efficiency, simplicity of control, and low cost. Although, the disadvantages include a lack of obstacle avoidance ability and a limited ability to adapt to complex terrain. However, legged robots and wheel robots are diametrically opposed in these respects.

Walking robots with many legs, such as bipedal and quadruped robots, have been widely utilised to difficult missions including uneven terrain. The leg structure is responsible for separating the body's locomotion from the foot's motion while overcoming barriers. As a result, the body can retain equilibrium, resulting in an excellent adaptation to the majority of frequent terrains.

Moreover, most bipedal robot use mammal-type mechanism because of the robot can walk at narrow space and can walk faster than sprawling mechanism, but it also has many disadvantages. The leg configuration of the mammal robot has low wide range motion, thus it cannot choose the foot placement widely. The stability of the mammal type is lower than sprawling, since the sprawling can locate its centre of gravity (COG) at low position and it have a wider supporting leg polygon.

1.3 Objective

This project has outlined objectives according to the problem statement as follows:

- To design a bipedal wheel-legged robot with sprawling mechanism as its hips.
- To modelling of a wheel-legged robot with sprawling mechanism and analyse its legged motion from the working envelope.

1.4 Scope of Project

The scope of this project is the design of a bipedal wheel-legged robot with a sprawling mechanism and three degrees-of-freedom (DoF), which is it used in a variety of applications. The project is completed starting with the creation of the conceptual design in Solidworks and ending with the simulation of the model in MATLAB Simulink. In addition, a kinematics model and workspace analysis are carried out in order to determine the motion constraint and limitation of the system.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is discussed about the review of the design of wheel-legged robot and the legged robot with sprawling mechanism. The first discussion is about the review of the legged robot technology and continue with legged robot's configurations and its stability criteria. In addition, latest studies on the bipedal robot system and technology are discussed. For the bipedal robot, the gait pattern and zero moment point are important, hence the locomotion and control have been studied in this chapter.

2.2 Legged Robot Technology

Mobile robots require locomotion technologies that allow them to move freely across their environment. There are numerous ways to move; however, the choice of a robot's locomotion strategy is a crucial part of mobile design. There are research robots in the laboratory that can jump, walk, run, fly, skate, roll, slide, and swim. The locomotion mechanics inspired by biological counterparts are shown in Table 2.1.

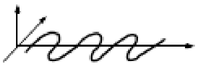
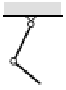
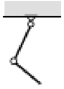
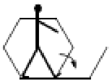
For rough terrain, a legged robot is ideal. It can walk on extremely rough terrain, climb steps, and cross gaps as wide as its stride. When the ground is uneven, it is impossible to utilize wheels. The minimal degree of freedom (DOF) for each leg of a legged robot mobile is two. Each DOF requires one joint, which is normally powered by a single servo or motor. A four-legged robot, for example, requires at least eight servos to move around. Figure 2.1 shows the energy consumption of various locomotion techniques, and it is striking that legged movement consumes roughly two orders of magnitude more energy than wheeled locomotion on a hard, flat surface. As a result, wheeled locomotion requires fewer motors in general than legged mobility.

When the surface becomes soft-wheeled mobility, some inefficiency develops. Because of the higher rolling friction, more motor power is required to move. The legged locomotion consists only of point interactions with the leg and the ground is moved through the air, it is more power-efficient on soft ground than wheeled locomotion, as shown in Figure 2.1. It just requires a single pair of point connections, and the condition of the ground is irrelevant as long as the robot is capable of handling it. However, one of the most difficult problems in legged locomotion, the stability problem, is solved by a single set of point contacts.

A series of point interactions between the robot and the ground characterizes legged mobility. The advantages of legged mobility in tough terrain are adaptability and manoeuvrability. It simply requires a single pair of point connections; the condition of the ground is unimportant as long as the robot is capable of handling it. Furthermore, a walking robot can traverse a chasm or a hole as long as its reach exceeds the hole's breadth. Finally, legged locomotion has the capability of expertly manipulating items in the surroundings. The dung beetle, for example, is capable of rolling a ball while locomotion with its dexterous front legs.

Power and mechanical complexity are two drawbacks of legged locomotion. The leg may have multiple degrees of freedom. Many robots should be capable of lifting and lowering themselves, as well as supporting the entire weight of the robots. Furthermore, high manoeuvrability can only be achieved if the legs have enough degrees of freedom to transmit forces in multiple directions.

Table 2.1: The Locomotion mechanisms used in biological systems [3].

Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel 	Hydrodynamic forces	Eddies 
Crawl 	Friction forces	 Longitudinal vibration
Sliding 	Friction forces	 Transverse vibration
Running 	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum 
Jumping 	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum 
Walking 	Gravitational forces	Rolling of a polygon (see figure 2.2) 

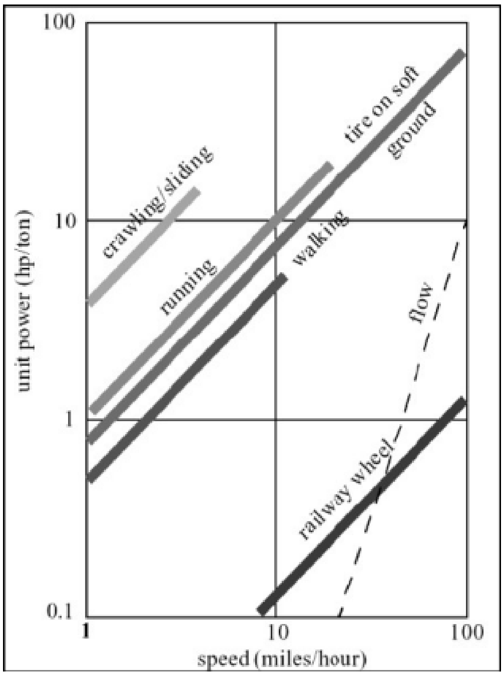


Figure 2.1: Power consumption of several concepts locomotion mechanisms [3].

2.3 Leg Configurations and Stability

Given the biological inspiration for legged robots, it is instructive to investigate biologically successful legged systems. Numerous leg designs have been demonstrated to be effective in a range of creatures as shown in Figure 2.2. Mammalian and reptile-sized creatures have four legs, whereas insects have six or more. Certain mammals have perfected the capacity to walk on two legs. Balance has advanced to the point where we can even jump on one leg, particularly in the case of humans. This extraordinary agility comes at the cost of far more intricate active control required to maintain equilibrium.

In comparison, a species with three legs can maintain a static, stable posture if its centre of gravity is contained inside the tripod of ground contact. Static stability, as illustrated by a three-legged stool, refers to the ability to maintain balance in the absence of movement. When the upsetting force is removed, a minor deviation from stability is passively adjusted back to the stable stance.

When insects and spiders are born, they are immediately capable of walking. For them, maintaining balance while walking is a very simple challenge. Mammals with four legs are incapable of static walking, but can easily stand on four legs. For instance, fauns spend several minutes struggling to stand before finally succeeding, and then several more minutes learning to walk without falling. Humans, having two legs, are incapable of standing still in one spot. Infants take months to develop the ability to stand and walk, and even longer to develop the ability to run, jump, and stand on one leg.

Additionally, due to the intricacy of each individual leg, enormous variation is possible. Again, the biological world is replete with examples from both extremes of the spectrum. In the caterpillar's case, each leg is extended longitudinally via hydraulic pressure by constricting the body cavity and forcing an increase in pressure, and each leg is retracted longitudinally via hydraulic pressure relaxation followed by activation of a single tensile muscle that pulls the leg in toward the body. Each leg has a single degree of freedom that is parallel to the leg's longitudinal axis. The ability to move forward is based on the body's hydraulic pressure, which increases the distance between pairs of legs. Thus, the caterpillar leg is mechanically simple, relying on a small number of extrinsic muscles to perform complex overall movement.

For legged mobile robots, a minimum of two degrees of freedom is often necessary to move a leg forward by lifting and swinging it ahead. More frequently, a third degree of freedom is added to allow for more complicated motions, leading in legs like those seen in Figure 2.3. Recent advances in the development of bipedal walking robots have resulted in the addition of a four degree of freedom at the ankle joint. By actuating the posture of the sole of the foot, the ankle enables more constant ground contact.

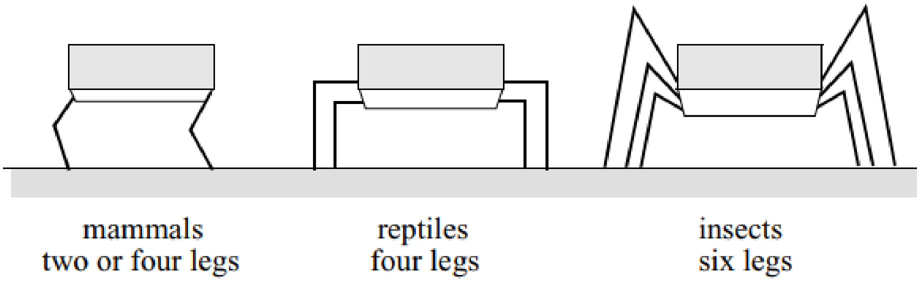


Figure 2.2: Arrangement of several animals' legs [3].

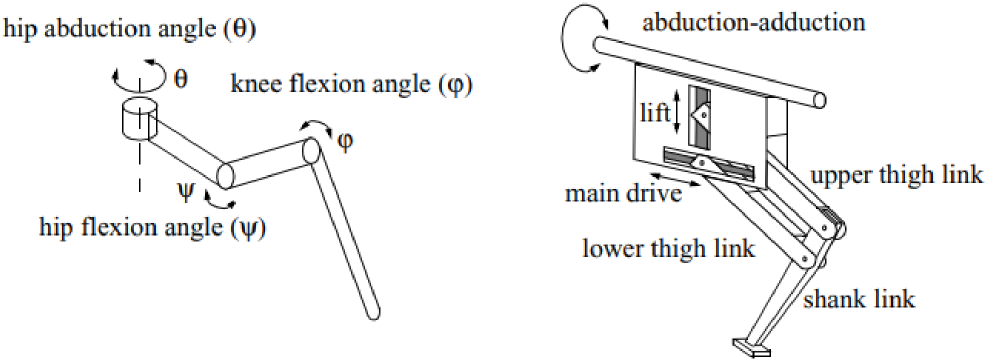


Figure 2.3: The examples of legs with three degrees of freedom [3].

2.3.1 Sprawling Mechanism Leg Robot

According on the categorization of vertebrate limb positions, some writers classify legged robots as mammal-type or sprawling-type. The first category includes machines (or vertebrates) with erect legs that are held under the main frame and are restricted to parasagittal plane motions. They are bioinspired by dogs, cats, and other similar animals, which have their body weight directly over their legs, allowing for increased speed and agility. The second category of walking robots comprises those with locomotion units or legs that are more abducted. Their bioinspiration models are turtles, salamanders, monitor lizards, and other crocodilian animals, in which the femur is nearly parallel to the ground and moves almost entirely horizontally, with the tibia nearly vertical in certain postures during the walking gait, which incorporates significant axial rotation.

To describe a robotic creature as mammal-like, the term "mammal-type robot" is used. Spreading robots have their first leg segment (thigh) horizontal and their second leg segment (shank) vertical in their regular position. In comparison to mammal mechanisms, crawling mechanisms let the robot to lower its centre of gravity and have a bigger polygon of support for its legs, making it more stable. The proximal yaw axis provides a wide range of motion, allowing for a wide range of foot positioning options. The properties of the walking of sprawling organisms have been studied in a number of ways. Pleurobot, a salamander-like robot that closely replicates its biological counterpart, Pleurodeles waltl, is an excellent example of a sprawling walking machine. There are four degrees of freedom in the legs of this quadruped machine [4]. Ancestral terrestrial animals are said to have had their limbs splayed out in a spreading stance. It depends on the sprawl angle σ of the femoral bone, which is measured from the vertical line as shown in Figure 2.5.

As depicted in Figure 2.6, this is another example of a sprawling robot. The researchers created a sprawling-type quadruped robot capable of walking at a fast rate of speed and with minimal energy consumption. They believe that the sprawling-type quadruped robot design is practicable due to its large supporting leg polygons and low centre of gravity [2].

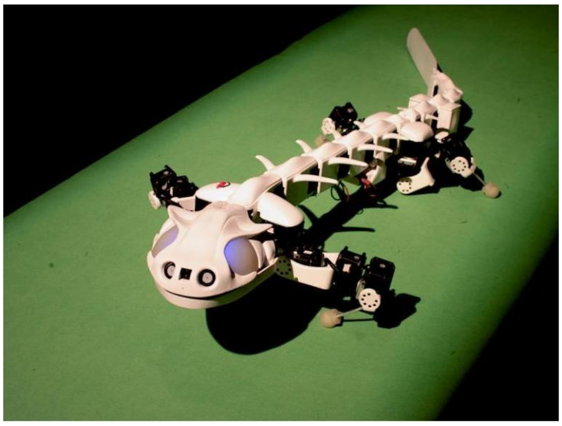


Figure 2.4: Pleurobot with 4-DoF [4].

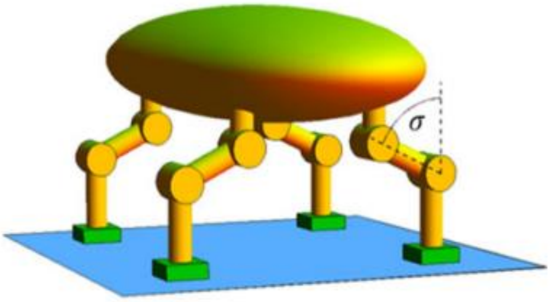


Figure 2.5: Sprawl angle σ in walking machines [4].

Figure 2.6: Sprawling-type quadruped robot [2].

2.4 Wheel-Legged Robot Technology

The wheel has been the most frequently used locomotion mechanism in mobile robots and man-made vehicles in general. As illustrated in Table 2.1, it is capable of achieving exceptionally high efficiencies while adopting a relatively simple mechanical solution. Additionally, balance is rarely a concern in the design of wheeled robots, as they are almost usually manufactured with all wheels in contact with the ground at all times. In order to maintain stable balance, three wheels are required, however two-wheeled robots can also be steady. When a robot has more than three wheels, a suspension system is required to ensure that all wheels remain in contact with the ground when the robot comes into contact with uneven terrain.

As previously stated, a minimum of two wheels is necessary for static stability. Stability may be achieved by a robot with a two-wheel differential drive if the center of mass is below the wheel axle or if a third point of contact with the floor is present. However, these are exceptional circumstances; under normal circumstances, a wheeled robot requires at least three wheels in contact with the ground to achieve static stability. Additionally, the centre of gravity must be completely contained within the support polygon formed by the three wheels in contact with the ground.

Manoeuvrability is critical for a wheeled robot to do its tasks effectively. When a robot is omnidirectional, it can traverse the ground plane in any direction (x, y). This degree of movement frequently necessitates the use of actively powered wheels capable of reversing direction, such as Swedish or spherical wheels. By comparison, vehicles' omnidirectional Ackermann steering mechanism is not omnidirectional. Typically, vehicles configured in this manner have a greater turning radius than the vehicle itself. Additionally, it is unable of driving in reverse, needing repeated parking processes, which include frequent wheel direction adjustments and forward and backward movement. This steering technique is extremely popular in hobby robotics, as it is relatively inexpensive to use a remote control racing car kit as a mobile robot platform.

2.4.1 Wheel-Legged Mobile Robots

As robot performance improves, the mobile robot has the potential to play a key role in our daily lives in the near future. Mobile robots have a wide range of applications; they can be used not only in service industries such as manufacturing, agriculture, national defence, and healthcare, but also in some extremely dangerous situations such as mine clearance, search-and-rescue in earthquake-prone areas, and radiation-prone areas, among others. As a result, mobile robot technology has received global attention. At the moment, two distinct types of mobile robots are being investigated: wheeled and legged mobile robots. Each has a number of pros and cons. The wheeled robot's merits include its rapid movement, high energy economy, ease of operation, and low cost. The disadvantages, on the other hand, include a lack of obstacle avoidance abilities and a restricted capacity for adaptation to varied terrain.

However, legged robots and wheel robots are diametrically opposed in these regards. To maximize the advantages and minimize the downsides, the two types of mobile robots are merged to form a wheel-legged mobile robot, which operates on wheels in flat ground and on legs in difficult terrain. The wheel-legged robot can enhance its mobility and flexibility in certain difficult terrain. Thus, the wheel-legged robot has emerged as a new area of research and development for mobile robots. The wheeled mobile robot has been extensively investigated both domestically and internationally.

Wheel-legged mobile robots (WLMRs) are a hybrid of legged and wheeled mobile robots, Figure 2.7 shows the example of wheel-legged mobile robot. They are highly adaptable because they can choose the method of locomotion depending on the environment. However, because the height of the centre of gravity of these robots is high, they have a high risk of falling. To avoid falling, most WLMRs move statically. However in this case, WLMRs can meet only one of the expectations which is the adaptability [5].

An additional illustration of this is the rescue robot's three degrees of freedom leg mechanism, which is based on serial–parallel and wheel-legged mechanisms and is composed of two Universal joint–Prismatic joint–Spherical joint serial–parallel mechanisms plus one Universal joint and Revolute joint serial–parallel mechanism, as shown in Figure 2.8. The structural model of the wheel-legged rescue robot is shown in Figure 2.9. The robot is built using the same structure and four legs as the previous one.

The robot has two modes of movement, legged and wheeled. In the legged mode, the lower legs make contact with the ground, simulating the gait of a quadruped. Each leg is a (2-UPS+U) &R serial–parallel mechanism comprised of an upper and a lower leg, with the leg mechanism having three degrees of freedom. In wheeled mode, the lower legs retract and the wheels make contact with the ground, simulating a four-wheel mobile robot with a high top speed. At the present, each leg is a parallel construction with two degrees of freedom, giving the robot the benefits of a big load and high stiffness, while also improving its flexibility and carrying capacity significantly [6].

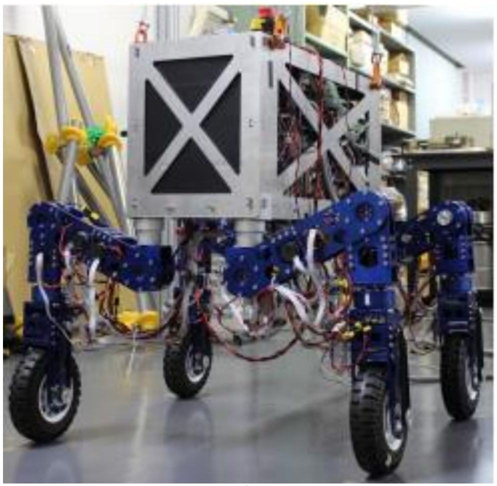


Figure 2.7: Overview of wheel-legged robot [5].

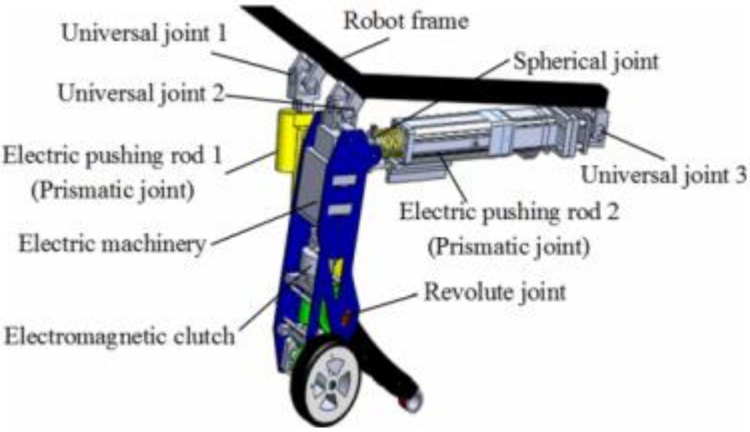
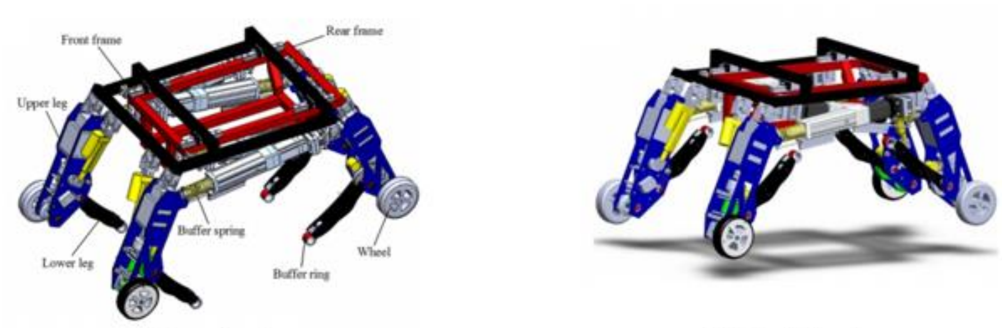


Figure 2.8: Single leg wheel-legged rescue robot [6].



(a) Legged mode (b) Wheeled mode

Figure 2.9: Structure model of the wheel-legged rescue robot; (a) Legged mode and (b) Wheeled mode [6].

2.5 Bipedal Robot System and Technology

Only humans and birds use bipedal mobility in the ensemble of living beings. In unusual circumstances, certain insects, reptiles, and mammals walk on two legs. Bipedal animals first arose in the Mesozoic era among a huge number of dinosaur reptiles. These animals' legs have a relatively similar anatomic structure, consisting of a thigh, a leg, and a foot. Each lower limb is articulated by three major joints: the hip, the knee, and the ankle. The hip is a spherical joint that may move in three directions. The knee is a one- or two-degree-of-freedom joint (DoF). The ankle combines two major ranges of motion. The relative length of the foot and its typical position during walking are significant differences that can perceptibly alter the extreme values of joint angles.

Walking and running are the two primary bipedal gaits. Walking, one of the two locomotive limbs is always in contact with the ground at any one time. During a run, the body is propelled forward by a grounded monopodial impulse, which then shocks the other locomotive limb. Kinetic energy from this ballistic phase is partially recovered during renewal support because tendons, muscles, and joints are elastic. New contact with the earth helps to partially recover the energy required for a leap. The lower limbs alternately shift weight from left to right.

As a result, Agility Robotics developed Cassie, a bipedal robot, as illustrated in Figure 2.10. The robot's design is inspired by the ostrich. Cassie is a dynamic bipedal robot capable of walking and running in a manner reminiscent to humans or animals. It is capable of navigating varied and challenging terrain, making it ideal for search and rescue missions or parcel delivery. Several studies describe the Cassie robot model and demonstrate how solving a trajectory optimization issue with constraints and physical limitations results in realisable locomotion [7].

However, MIT researchers have developed a novel type of teleoperation system that enables a two-legged robot to "borrow" the physical abilities of a human operator in order to move more agilely, as illustrated in Figure 2.11. Little Hermes is the name given to the bipedal robot. They suggest a solution for this bilateral feedback policy that would enable a bipedal robot to walk, leap, and take steps in sync with a human operator. This dynamic synchronisation was accomplished by real-time scaling of the fundamental components of human locomotion data to robot proportions and applying feedback pressures to the operator proportionate to the difference in relative velocity between human and robot. Human motion was sped up to keep up with a quicker robot, or drag was induced to keep the operator in sync with a slower robot. The researcher concentrated on frontal plane dynamics and employed an external gantry to steady the robot in the sagittal plane [8].

Figure 2.10: Cassie robot from Agility Robotics [7].

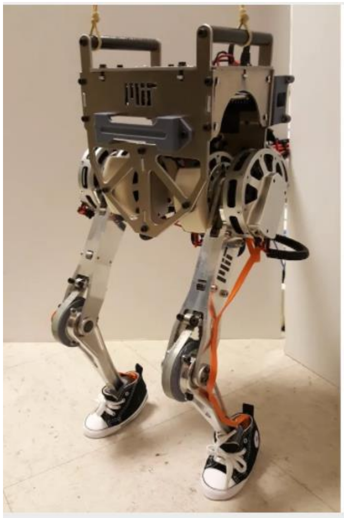


Figure 2.11: Little Hermes from MIT Robot [8].

2.6 Bipedal Robot Locomotion and Control

Many academics and engineers are interested in developing a biped robot that can walk like a person. One advantageous use is to have biped robots do tasks for humans in hazardous or risky situations. Additionally, research on biped robot mobility might yield useful discoveries that could aid in the development of prosthetic legs for disabled individuals. In comparison to mobile robots, a biped robot is more adaptable to less organised terrain. However, the dynamics of a biped robot are extremely nonlinear and statically unstable. Its movement is tough to regulate. Before biped robots may be extensively and effectively employed, extensive study is required [9].

2.6.1 Bipedal Robot Gait Pattern

Recent literature [10, 11] indicates that a number of researchers are examining the stability of biped systems with a single point foot, i.e., bipeds without a foot-link. Due to the lack of a foot-link (and support polygon), stability notions such as ZMP do not apply to these systems. Orbital stability and periodicity are helpful notions for analysing the stability of such bipedal systems. The effectiveness of Raibert's control rule for a one-legged hopper [11] inspired others to analyse the stability of point-foot biped systems analytically. Due to the lack of a statically stable posture during the single-support phase, research of point-foot biped systems focus on periodic activities such as walking, running, hopping, or jogging.

When the contact point between the foot and the ground changes while walking, the biped robot transitions to a new walking phase with significantly altered dynamic properties, posing several control challenges. Recent research has concentrated on implementing the so-called "heel off and toe support" on a biped robot. As a result, the bipedal robotic stride is simplified somewhat from the human walking pattern. To begin, it is assumed that the double support phase is instantaneous. Second, when the swing foot makes contact with the ground, the sole is parallel to it. The ideal robotic walking action may thus be divided into three phases: heel support, toe support, and instantaneous double support (or impact phase) [12]. The bipedal robotic walking pattern seen in Figure 2.12 includes a state transition event.

As a result, the heel support phase (HSP) begins when the swing leg's toe rises off the ground. It is expected that the entire foot of the stance leg remains level and immobile on the ground without sliding. Simultaneously, the swing leg swings forward. The biped robot is completely actuated during this phase due to the fact that it has the same amount of degrees of freedom (DOF) and actuators.

Following then, the Toe Support Phase (TSP) begins when the stance leg's heel rises off the ground. The stance foot turns around its toe, which is almost completely parallel to the ground, while the swing leg continues to swing forward. Because there is no actuation between the stance foot and the ground, the biped robot is under-actuated.

Additionally, the Impact Phase (IP) begins when leg roles are exchanged during this phase. When the swing foot makes contact with the ground, the swing leg becomes the new stance leg, while the previous stance leg rises to become the swing leg.

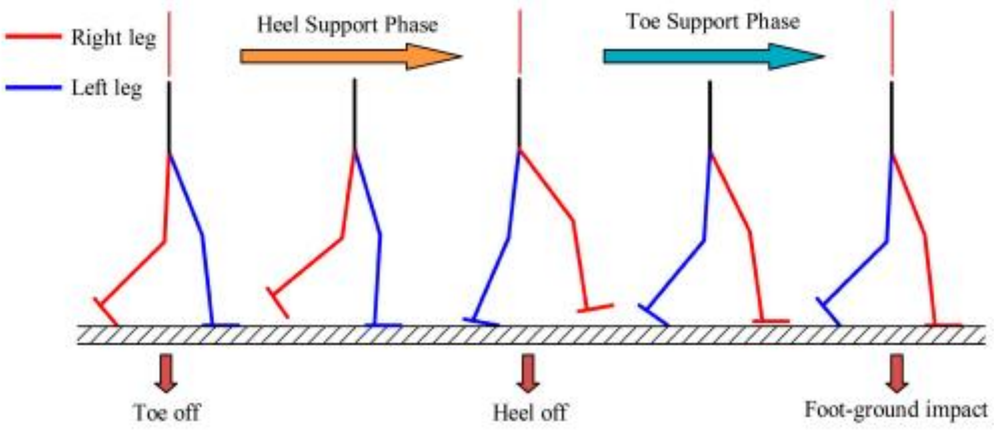


Figure 2.12: The bipedal walking pattern [12].

2.6.2 Zero Moment Point in Bipedal Robot Stability

The existence, form, and size of the feet all contribute to the postural stability of bipedal systems. The support polygon is the convex hull of the foot-support area. Postural stability of bipeds is frequently determined by the placements of certain reference points on the surface upon which the biped is standing. These ground reference points are determined by the biped's dynamic properties and mechanical structure. Numerous ground reference sites have been used to test the postural stability of biped locomotion in the literature. The Zero-Moment-Point (ZMP) [13] is the most helpful ground reference point for the investigation of bipedal postural stability.

When such principles are used, the likelihood of support foot rotation is frequently interpreted as a loss of postural balance. Stability ideas such as ZMP examine the feasibility of this type of foot rotation during locomotion. The rotational stability of the foot link is referred to as the foot's "rotational equilibrium." In a few of the studies published, point-foot bipeds are employed to analyse anthropomorphic gait [10, 11]. The idea for such biped models is that an anthropomorphic walking gait should include a fully actuated phase during which the stance foot is flat on the ground, followed by an underactuated period during which the stance foot heel lifts off the ground and rotates about the toe. The bipedal model with point-footed feet is less complex than a more comprehensive anthropomorphic gait model.

For systems with a non-trivial area of support polygons, postural stability is frequently determined using the Zero-Moment-Point method (ZMP). ZMP is defined as the location on the ground at which the net moment of inertial and gravitational forces is zero along the horizontal axis. For steady (static) locomotion to occur, the ZMP must remain within the support polygon at all phases of the locomotion gait.

Besides the contact between the foot and the ground (which may be regarded an extra passive DOF), all of the biped mechanism joints are powered and directly programmable except for the contact between the foot and the ground, where only the mechanism and environment interact. This touch is critical for the walk's reality since the mechanism's location in relation to the environment is determined by the foot/relative feet's position to the ground. The foot cannot be controlled directly, but can be controlled indirectly by ensuring that the mechanism above the foot has the proper dynamics. Thus, the overall indication of a mechanism's behaviour is the point at which all forces operating on it may be replaced by a single force. The Zero-Moment Moment (ZMP) was coined to refer to this point [13].

Additionally, the most often used criteria for quasi-dynamic walking is based on Vukobratovic's idea of ZMP. ZMP denotes the point on the ground at which the ground reaction force acts. A stable gait may be obtained by ensuring that the ZMP of a bipedal robot remains contained inside the convex hull of the foot support region while walking. ZMP is commonly used as a reference for creating reference walking trajectories for a variety of bipedal robots [14]. Figure 2.13 illustrates the ZMP criteria.

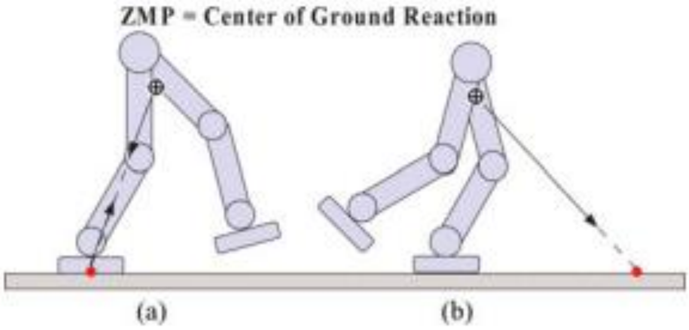


Figure 2.13: ZMP stability criterion. (a) Stable ZMP position. (b) Unstable ZMP when it goes out of the foot support [14].

2.7 Summary

To maximize the benefits and minimize the drawbacks, the two types of mobile robots are merged to produce a wheel-legged mobile robot that can operates on wheels in flat terrain and on legs in rugged terrain. The wheeled robot's mobility and flexibility can be enhanced in certain difficult terrain. Thus, the wheel-legged robot and bipedal robot has arisen as a new area of mobile robot research and development. The combination of bipedal robot, wheel-legged robot and sprawling mechanism design has been develop in this project.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter is focusing the methodology of sprawling bipedal wheel-legged robot. The fundamental of each joints are the most important part to ensure the project is successful. The operational for this project is using Solidworks and MATLAB. The design of this robot was visualized with using Solidworks software to sketch the conceptual design. The simulation part is completed by designing the multibody model of the robot using Simscape Multibody Link. Moreover, the kinematics and workspace system is discussed in this chapter.

3.2 Project Methodology and Workflows

The design of this project has made from many source and research to gain more perspective of ideas. The project design has been decided based on its safety and functionality. Hence, the project completed accordingly step by step. For ensuring output and objective from the project successful, a workflow process is listed as shown in Figure 3.1, to be a guideline in development of the whole project. The listed process has been fulfilled to ensure the understanding of the project working principal.

In this project, the workflow process is start with designing the conceptual design using Solidworks. Next, Simscape Multibody Link is exporting the model design to MATLAB Simulink for creating multibody of the robot. The kinematics design is created to develop the trajectory motion and workspace of the robot.

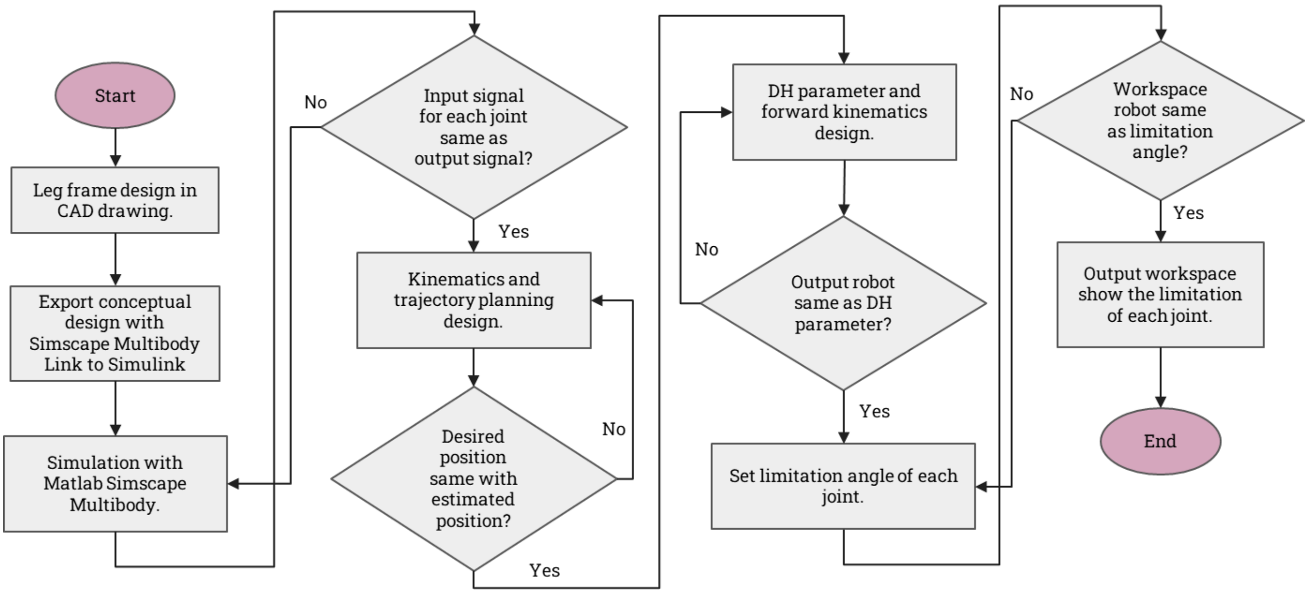


Figure 3.1: Workflow process and phases of the project.

3.3 Conceptual Design

The sprawling bipedal wheel-legged robot has been designed by using Solidworks. The design has 3 joints, which are joint base (Joint 1), joint upper leg (Joint 2) and joint lower leg (Joint 3). Wheel also has been designed with suitable dimension for the robot. Both wheel is positioned outside the link, which has no effect on the lower leg's range of motion. This is preferable to having it placed on the foot-end. Figure 3.2 shows the conceptual design of the robot for leg mode, it shows the movement of the sprawling motion at the joint 1. However, Figure 3.3 shows the wheel mode of the robot, the joint 2 and joint is moving upward and downward.

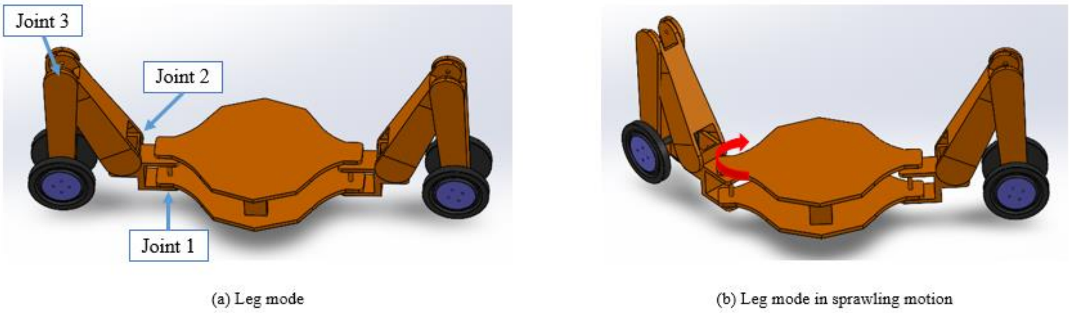


Figure 3.2: Leg mode design, (a) Leg mode and (b) Leg mode in sprawling motion.

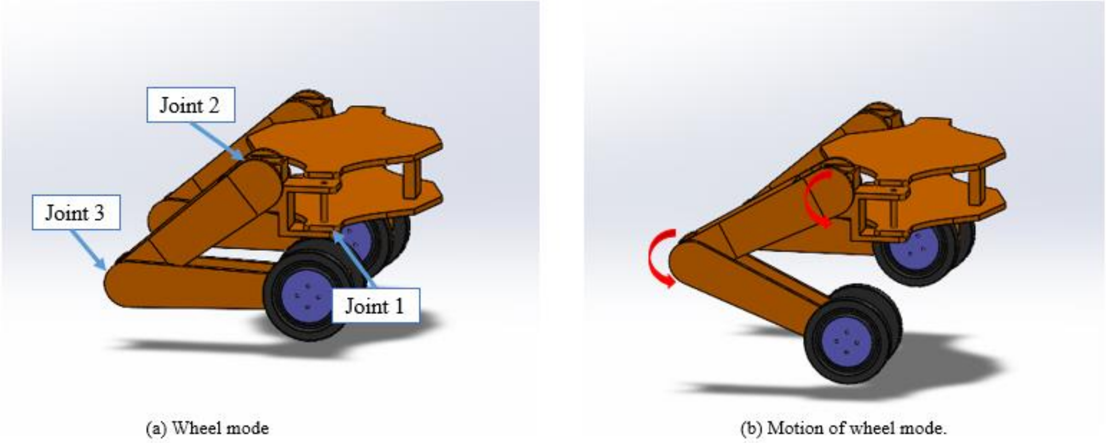


Figure 3.3: Wheel mode design, (a) Wheel mode and (b) Motion of wheel mode.

3.4 Multibody Dynamics Design

Simulating the dynamics of multibody systems is a typical engineering and scientific topic. Numerous programmes are available to do this task, including symbolic computation programmes for deriving and solving dynamical equations of motion, as well as numerical computation tools for computing dynamics on the basis of a 3D-CAD model. Simulink's multibody dynamics are seen in Figure 3.4. Simscape Multibody Link is used to export the CAD design to Simulink. Simscape Multibody includes a library of blocks, simulation and control interfaces, and a command line interface for integrating Simscape designs with the Simulink environment. Simscape blocks are used to describe mechanical systems made up of solid entities joined by joints with translational and rotational degrees of freedom. Simscape configures reference systems automatically and generates a strategy using mathematical solutions.

The CAD files are arranged to assemble a virtual structure that complies with the requirements of conversion to .xml file and send it to Simulink for its respective virtual control. The components that makes up the final assembly are distributed by subassemblies that make up unique pieces. These subassemblies are the fixed base and rotational part as shown in Figure 3.5, while the design that has been import to Simulink as shown in Figure 3.6. In Figure 3.7 shows the properties of the revolute joint which is the joint 2 of the right leg. For the actuation, motion and angular position of this joint was provided and the actuation torque required for this model to achieve that motion was calculated. The joint motion inputs were calculated based on the slider gain. The slider is move to get a suitable position of the robot such as wheel mode and leg mode.

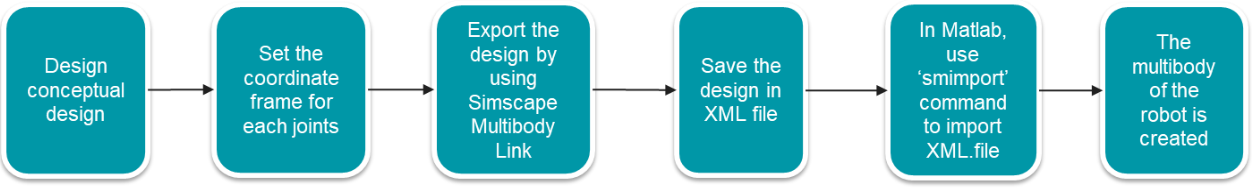


Figure 3.4: Exporting design from Solidworks to MATLAB Simulink.

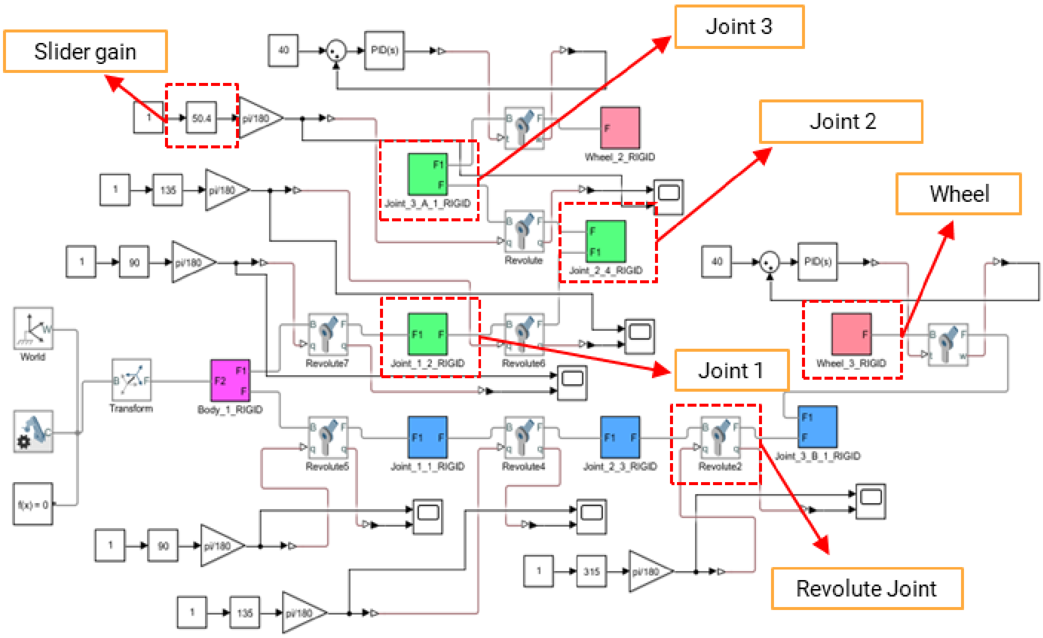


Figure 3.5: Multibody dynamics design of sprawling bipedal wheel-legged robot.

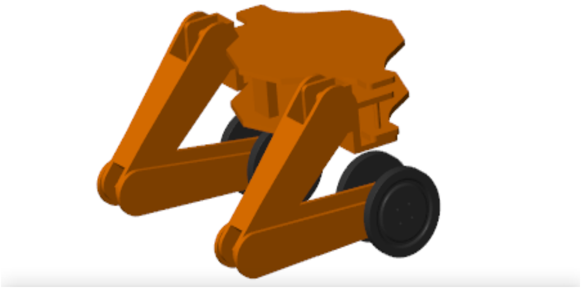
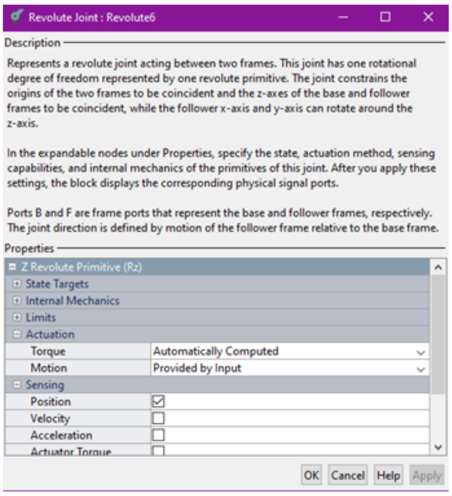


Figure 3.6: The robot design that has been import from Solidworks to MATLAB Simulink.



Revolute Joint : Revolute6

Description

Represents a revolute joint acting between two frames. This joint has one rotational degree of freedom represented by one revolute primitive. The joint constrains the origins of the two frames to be coincident and the z-axes of the base and follower frames to be coincident, while the follower x-axis and y-axis can rotate around the z-axis.

In the expandable nodes under Properties, specify the state, actuation method, sensing capabilities, and internal mechanics of the primitives of this joint. After you apply these settings, the block displays the corresponding physical signal ports.

Ports B and F are frame ports that represent the base and follower frames, respectively. The joint direction is defined by motion of the follower frame relative to the base frame.

Properties

- Z Revolute Primitive (Rz)
  - State Targets
  - Internal Mechanics
  - Limits
  - Actuation
    - Torque: Automatically Computed
    - Motion: Provided by Input
  - Sensing
    - Position: ☑
    - Velocity: ☐
    - Acceleration: ☐
    - Actuator Torque: ☐

Figure 3.7: Example of properties setting of the revolute joint that represent joint 2 of right leg of the robot.

3.5 Kinematics Design

In this part is discussed about the kinematics modelling and the overall connection system of a robot. Kinematics is the branch of mechanics concerned with the motion of a body or system of bodies without concern for its mass or the forces acting on it. Serial link manipulators are constructed from a series of mechanical links and joints. Each joint has the ability to shift its outer neighbouring link relative to its inner neighbour. Generally, one end of the chain, called the base, is fixed, while the other end, called the end-effector, is free to move in space and holds the tool or end-effector.

3.5.1 Forward Kinematics

For a sprawling bipedal wheel-legged robot, the forward kinematics are identified by the x-axis position (Px), the y-axis position (Py), and the z-axis position (Pz) of the end effector in relation to the joint variable of the 3-DoF robot system (n), where n = 1,2, and 3. The right-hand grip rule and the right-hand rule are used to calculate the rotational and Cartesian coordinates of each robot joint, as well as the reference for rotation axes as in Figure 3.8. Additionally, the right-hand rule is used to identify the axis (x,y,z) of each joint in the robot system.

The Denavit-Hartenberg or D-H, convention is a widely used standard for choosing frames of reference in robotic applications. Each homogeneous transformation Ai is represented using this approach as a product of four fundamental transformations, where the four ai, αi, di, and θi are connected with link i and joint i. The four parameters ai, αi, di, and θi respectively referred to as link length, link twist, link offset, and joint angle. Table 3.1 shows the DH parameter of sprawling bipedal wheel-legged robot. Below is the forward kinematics equation (A_0^3) that calculated from DH parameter table:

$$A_0^3 = \begin{bmatrix} C_1C_{23} & C_1S_{23} & -S_1 & C_1(a_3C_{23} + C_2a_2) \\ S_1C_{23} & S_1S_{23} & C_1 & S_1(a_3C_{23} + C_2a_2) \\ S_{23} & -C_{23} & 0 & a_3S_{23} + S_2a_2 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.1}$$

Table 3.1: Denavit-Hartenberg (DH) parameter for sprawling bipedal wheel-legged robot.

Joint	$\boldsymbol{\theta}$	∝	**d**	**a**
1	θ_1	90°	d_1	0
2	θ_2	0	0	a_2
3	θ_3	90°	0	a_3

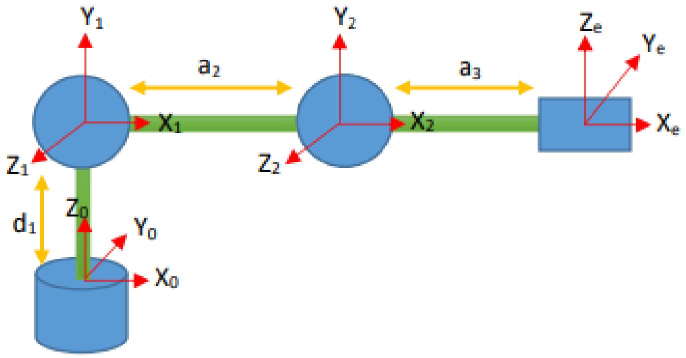
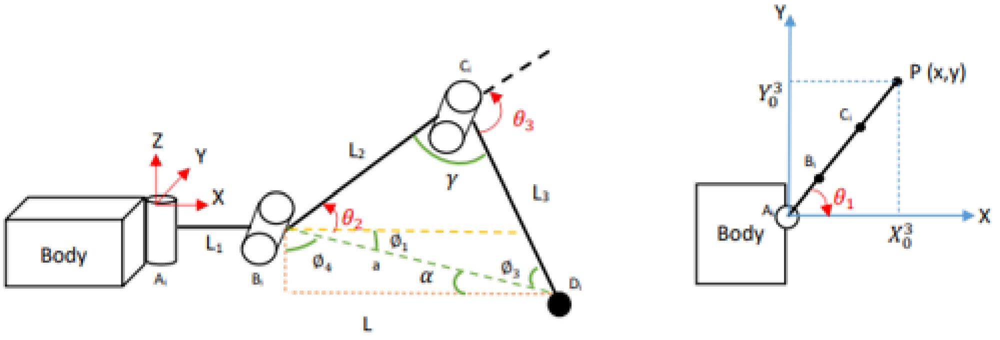


Figure 3.8: Coordinate frame of sprawling bipedal wheel-legged robot.

3.5.2 Inverse Kinematics

One of the most challenging issues in robotics programming is inverse kinematics, which involves determining the values of joint angles $\theta_1 : \theta_n$ that allow the robot to reach the given position x, y, z with a particular orientation $\theta_x, \theta_y, \theta_z$. The forward kinematics problem is the converse of the inverse kinematics problem. Forward kinematics has a fairly easy solution in comparison to inverse kinematics, which requires the solution of a large number of equations with a highly complicated form. The difficulty of the inverse kinematics issue is determined by the geometrical properties of the robot arm and the nonlinear equations that define the mapping between the joint and Cartesian space. Figure 3.9 shows the front and top view of the robot, the angle for each joint has been determined in Table 3.2.



(a) Front view (b) Top view

Figure 3.9: Cartesian of the robot, (a) Front view and (b) Top view.

Table 3.2: Equation of angle for each joints.

Joint	**Equation**
Joint 1 (Base)	$\theta_1 = \tan^{-1}\left[\frac{Y_0^3}{X_0^3}\right]$
Joint 2 (Upper Leg)	$L = \sqrt[2]{x^2 + y^2}$ $a = \sqrt[2]{(L - L_1)^2 + z^2}$ $\emptyset_1 = \cos^{-1}\left[\frac{a^2 - L_2^2 - L_3^2}{2a \,.\, L_2}\right]$ $\emptyset_4 = \cos^{-1}\left[\frac{L - L_1}{z}\right]$ $\theta_2 = \emptyset_1 + \emptyset_4 - 90°$
Joint 3 (Lower Leg)	$\emptyset_3 = \cos^{-1}\left[\frac{-a^2 + L_2^2 + L_3^2}{2L_3 \,.\, L_2}\right]$ $\theta_3 = 180° - \emptyset_3$

3.6 Robot Workspace

Kinematic indicator is important in the working space of a robot. The precise estimation of the border shape and volume or area of the manipulator workspace is important for the optimal design and application of the manipulator system. The robot workspace for the robot has been developed and discussed in this part. The trajectory motion design has been developed as shown in Appendix A.

3.6.1 Leg Trajectory Motion

The planning of the robot's trajectory is important for robot movement. Effective planning results in increased efficiency because it maximizes generated movement while minimizing the energy expended to generate it. With this in mind, a polynomial trajectory is a suitable option to legged movement. The trajectory simulation has been designed in Simulink. In Figure 3.10 shows the multibody of mechanical model for the right leg sprawling bipedal wheel-legged robot. The trajectory equation has been calculated. There are a difference trajectory equation for horizontal motion and vertical motion as shown in Table 3.3. The trajectory for each motion is react as an input for the robot and continuing to inverse kinematics, robot mechanical model and lastly forward kinematics as shown in Figure 3.11. The trajectory motion is divided into three type, which is leg mode of horizontal motion and vertical motion, and wheel mode in vertical leg motion.

Table 3.3: Trajectory equation of sprawling bipedal wheel-legged robot.

Motion	Trajectory Equation
Horizontal Leg Motion (Leg Mode)	$x = -1\,cos[\left(\frac{2\pi}{5}\right)u + \frac{\pi}{2}]$ $y = -1 + 1.5\,sin[\left(\frac{2\pi}{5}\right)u + \frac{\pi}{2}]$ $z = 0$
Vertical Leg Motion (Leg Mode)	$x = -1\,cos[\left(\frac{2\pi}{5}\right)u + \frac{\pi}{2}]$ $y = 0$ $z = -1 + 1.5\,sin[\left(\frac{2\pi}{5}\right)u + \frac{\pi}{2}]$

Horizontal Wheel Motion (Wheel Mode)	$x = 0$ $y = -1\ cos[\left(\frac{2\pi}{5}\right)u + \frac{\pi}{2}]$ $z = -1 + 1.5\ sin[\left(\frac{2\pi}{5}\right)u + \frac{\pi}{2}]$

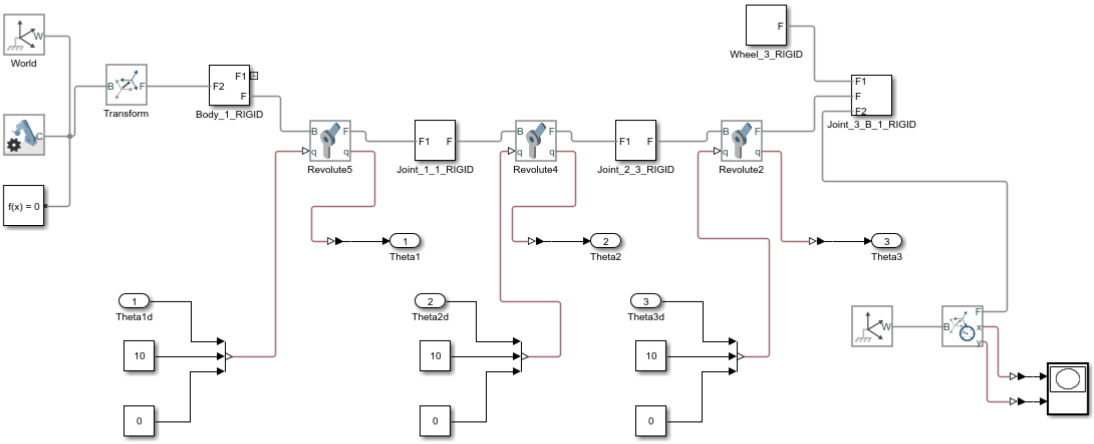


Figure 3.10: Multibody of mechanical model for the right leg sprawling bipedal wheel-legged robot.

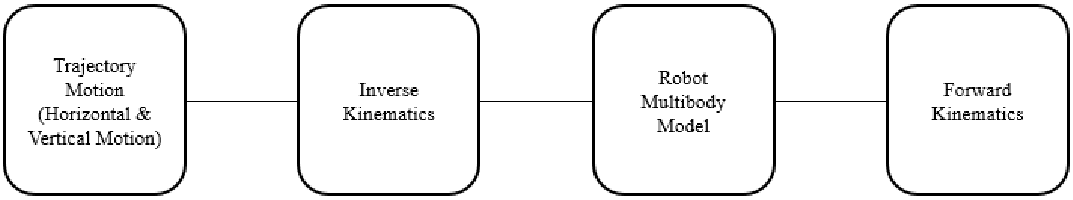


Figure 3.11: Trajectory motion design of the robot.

3.6.2 Working Envelope

The work envelope defines the space around a robot that is accessible for the end effector. As a robot moves around the limits of its reaches it traces out a specific shape. The work envelope of sprawling bipedal wheel-legged robot has been design by using the data from the trajectory motion results for each joint in MATLAB Simulink. The limitation angle for each joint has been calculated based on the trajectory motion. Figure 3.12 illustrated the desired workspace of the robot,

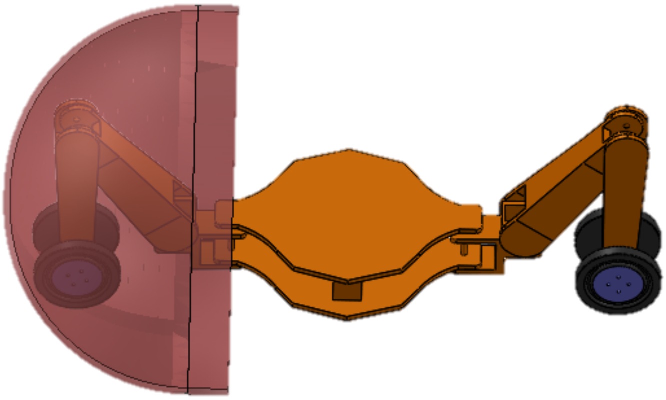


Figure 3.12: The desired workspace of the robot.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

As overall the sprawling bipedal wheel-legged robot comprise three main axes as joint base, joint upper leg and joint lower leg. Kinematics is the branch of mechanics concerned with the motion of a body or system of bodies without concern for its mass or the forces acting on it. This chapter is discussed about the result simulation of the model structure analysis and workspace analysis by using MATLAB Simulink.

4.2 Model Structure Analysis

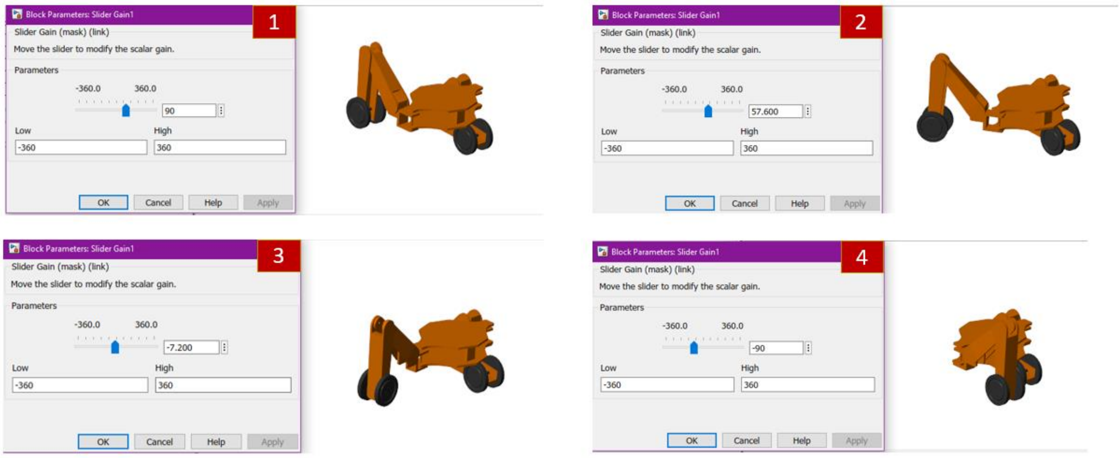
In addition to predicting mechanical system performance, trajectory of motion, collision detection, peak load, and so on, multibody dynamics simulation can also be used to analyze and optimize numerous factors, such as safety and comfort. A complicated multibody system may be constructed using blocks representing bodies, joints, constraints, force elements, and sensors in the MATLAB Simscape Multibody software. It formulates and solves the motion equations for the entire mechanical system and generates 3D animation automatically.

4.2.1 Angular Analysis

Multibody dynamics for the angular analysis of the robot has been designed. Each joint has been analyze using the slider gain for the joint’s motion. In Figure 4.1 shows the motion of the joint 1 in a leg mode. The motion of the robot shows the sprawling movement which is joint 1 move from 90° to -90°. Next, Figure 4.2 shows the motion of the joint 2 in a wheel mode. The joint move from 135° to 50°. Meanwhile, Figure 4.3

shows the motion of the joint 3 in a wheel mode. The motion of the robot move like a mammal, the joint 3 move from 315° to 295°.

Apart from that, each joint movement has been thoroughly examined in terms of input and output angles. The angular location of the joint 1 in radians versus time is represented in Figure 4.4. The joint is capable of forward and backward movement. While Figures 4.5 and 4.6 illustrate the angle of joint 2 and joint 3 as they move upward and downward, respectively. Due to the fact that the input and output signals are equal, the steady state error is zero in this scenario.



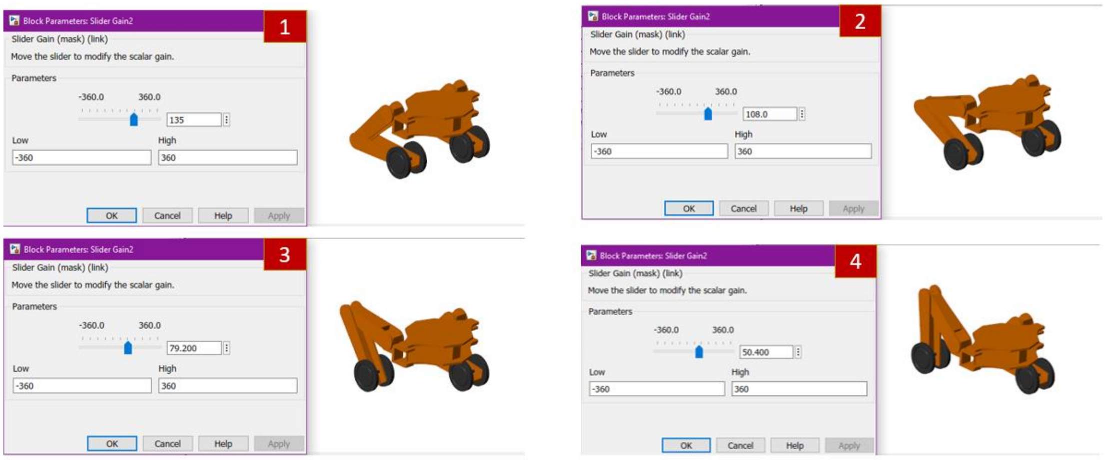
1
Block Parameters: Slider Gain1
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
90
Low -360
High 360

2
Block Parameters: Slider Gain1
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
57.600
Low -360
High 360

3
Block Parameters: Slider Gain1
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
-7.200
Low -360
High 360

4
Block Parameters: Slider Gain1
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
-90
Low -360
High 360

Figure 4.1: The movement of joint 1 in leg mode.



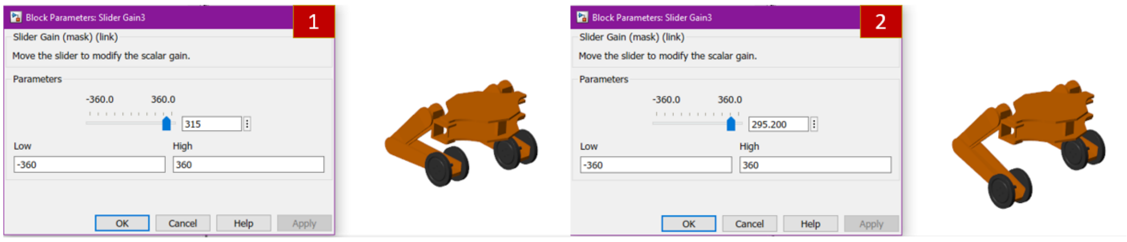
1
Block Parameters: Slider Gain2
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
135
Low -360
High 360

2
Block Parameters: Slider Gain2
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
108.0
Low -360
High 360

3
Block Parameters: Slider Gain2
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
79.200
Low -360
High 360

4
Block Parameters: Slider Gain2
Slider Gain (mask) (link)
Move the slider to modify the scalar gain.
Parameters
-360.0 360.0
50.400
Low -360
High 360

Figure 4.2: The movement of joint 2 in wheel mode.



1

Block Parameters: Slider Gain3

Slider Gain (mask) (link)

Move the slider to modify the scalar gain.

Parameters

-360.0 360.0

315

Low: -360

High: 360

2

Block Parameters: Slider Gain3

Slider Gain (mask) (link)

Move the slider to modify the scalar gain.

Parameters

-360.0 360.0

295.200

Low: -360

High: 360

Figure 4.3: The movement of joint 3 in wheel mode.

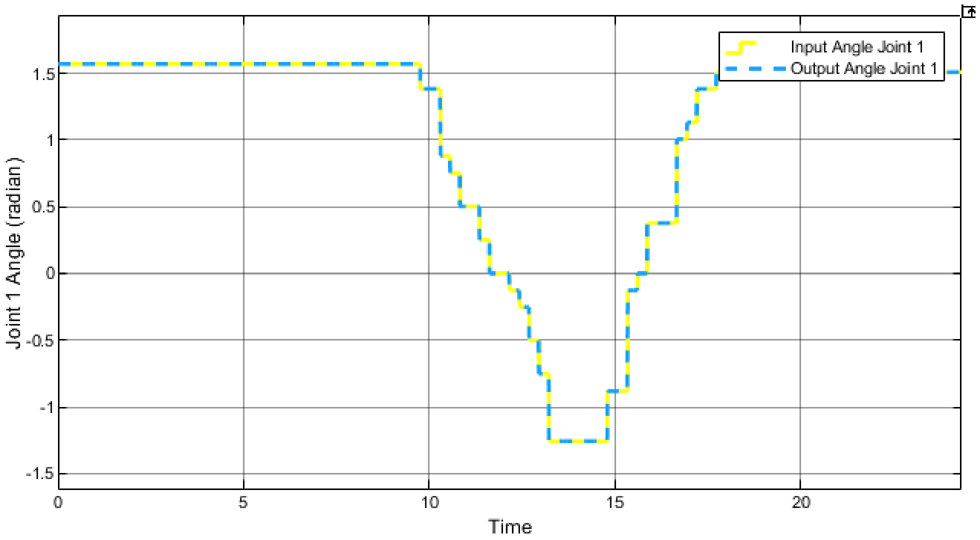


Figure 4.4: The angular position of joint 1.

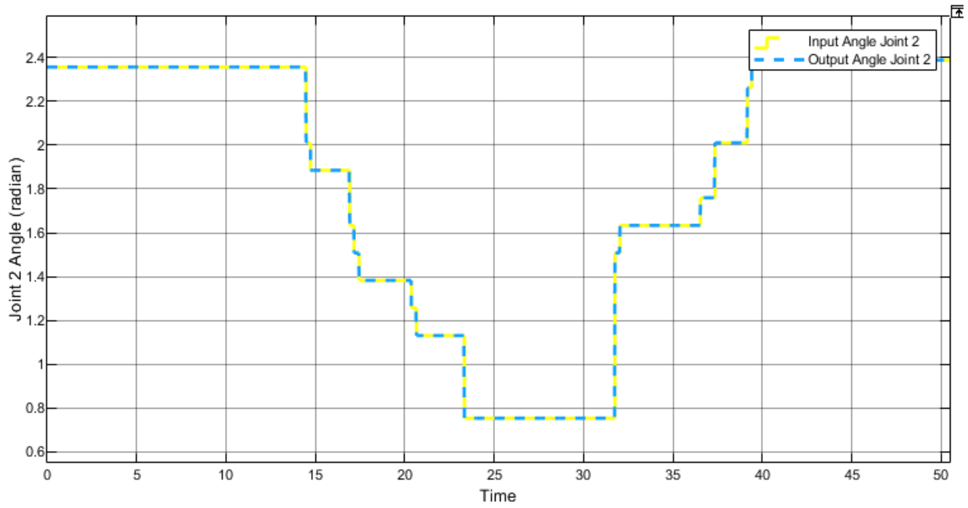


Figure 4.5: The angular position of joint 2.

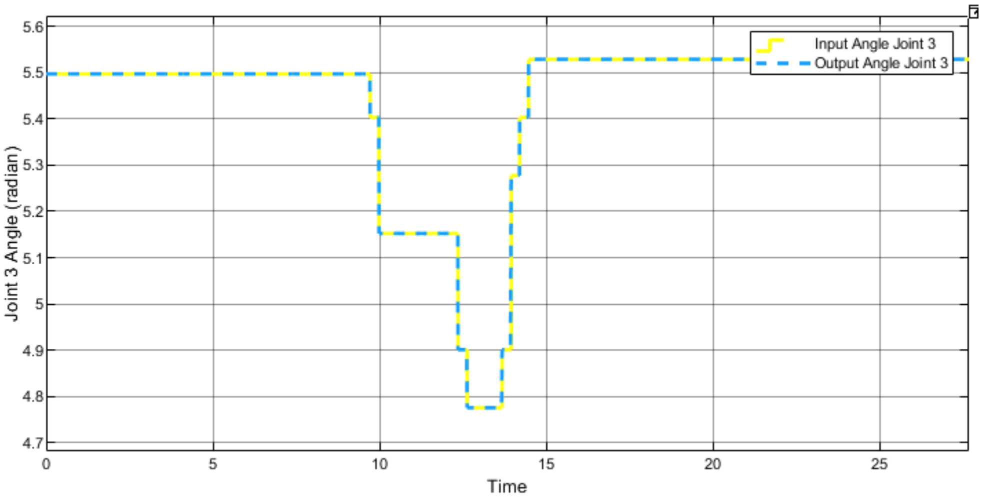


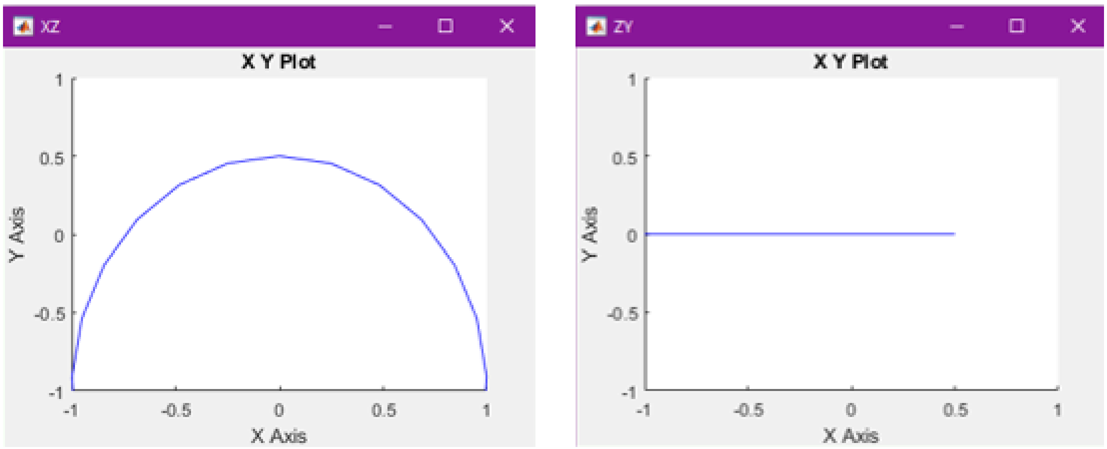
Figure 4.6: The angular position of joint 3.

4.3 Workspace Analysis

Workspace analysis consists of trajectory motion of the robot and robot workspace. The trajectory of the robot has been analysed with two different motion, which is horizontal motion and vertical motion. Work envelope of the robot has been created based on the trajectory motion of the robot.

4.3.1 Robot Trajectory of Horizontal Motion

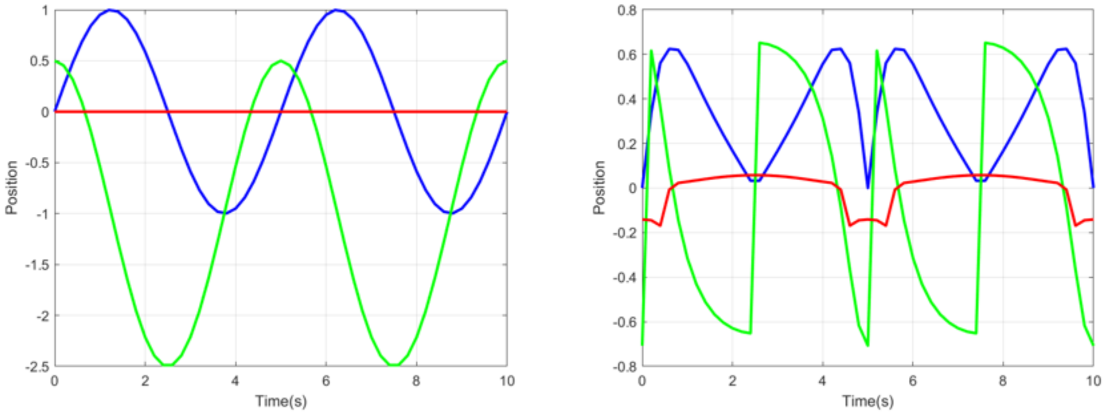
The trajectory pattern as shown in Figure 4.7 is designed for robot’s leg motion of leg mode that emphasized on x and y-axis since, for this scope of the study, the z-axis is set to zero. In Figure 4.8 shows the trajectory motion of leg mode from xyz-axis trajectory and the angular trajectory each joint from the multibody dynamic model. However, the trajectory pattern as shown in Figure 4.9 is designed for the wheel mode that emphasized on y and z-axis, while the x-axis is set to zero. The xyz-axis trajectory and the angular trajectory each joint for wheel mode is plotted in Figure 4.10.



a) XZ View

b) ZY View

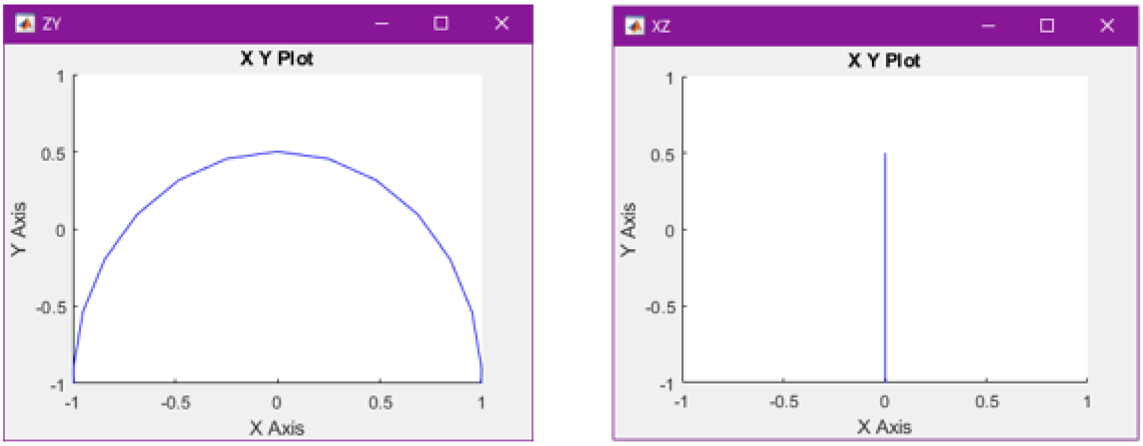
Figure 4.7: Trajectory pattern of leg mode. (a) XZ view and (b) ZY view.



(a) XYZ Trajectory

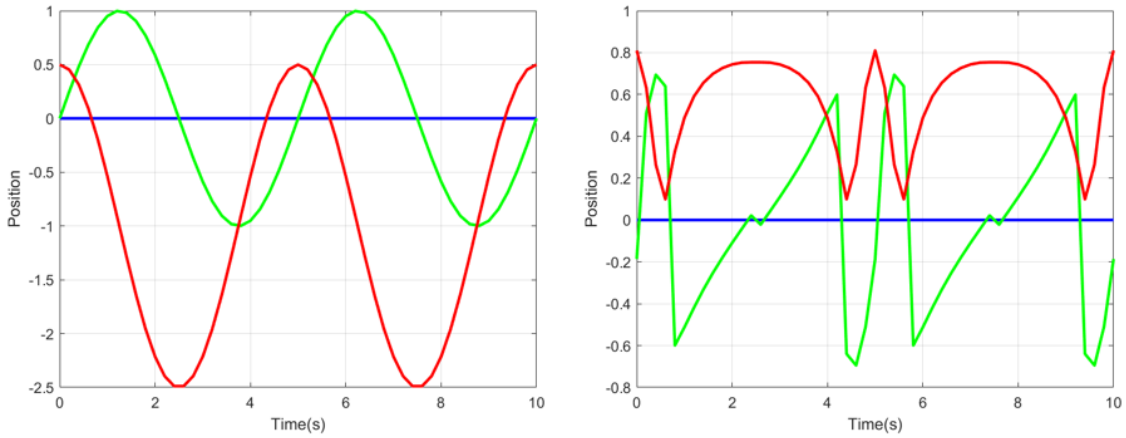
(b) Trajectory Angle

Figure 4.8: Trajectory motion of leg mode. (a) XYZ Trajectory and (b) Trajectory angle.



a) ZY View b) XZ View

Figure 4.9: Trajectory pattern of wheel mode. (a) ZY view and (b) XZ view.

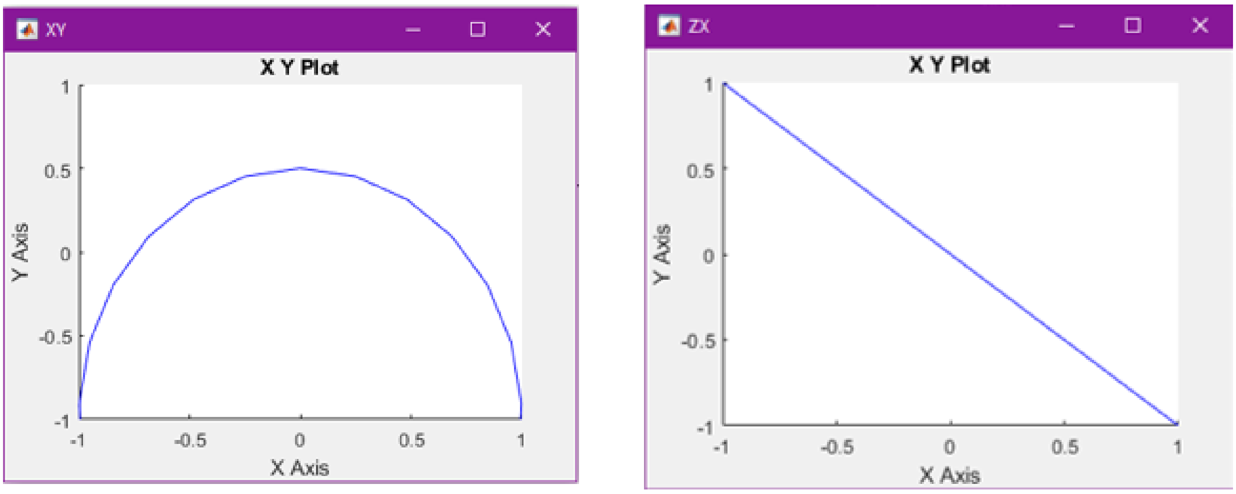


(a) XYZ Trajectory (b) Trajectory Angle

Figure 4.10: Trajectory motion of wheel mode. (a) XYZ Trajectory and (b) Trajectory angle.

4.3.2 Robot Trajectory of Vertical Motion

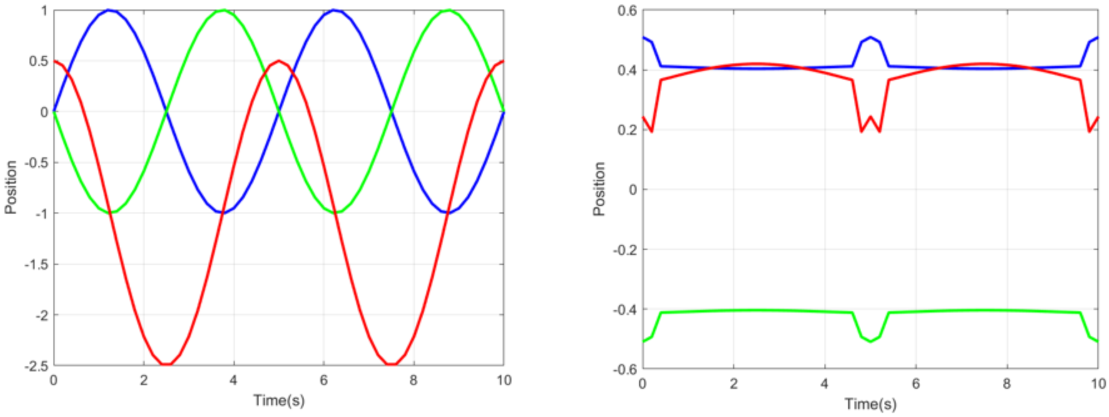
The vertical motion includes x, y and z-axis for the robot's trajectory motion. Figure 4.11 shows the trajectory pattern of the vertical motion. In Figure 4.12 shows the trajectory motion of vertical motion from xyz-axis trajectory and the angular trajectory each joint from the multibody dynamic model.



a) XY View

b) ZX View

Figure 4.11: Trajectory pattern of vertical motion. (a) XY view and (b) ZX view.



(a) XYZ Trajectory

(b) Trajectory Angle

Figure 4.12: Trajectory motion of vertical motion. (a) XYZ Trajectory and (b) Trajectory angle.

4.3.3 Robot workspace

By using the trajectory motion and inverse kinematics equations and specifying the movement limitations of the sprawling bipedal wheel-legged robot, it is possible to obtain the workspace of the system that as shown in Figure 4.13. The green line is for limitation of horizontal motion which is for the leg mode of the robot. However, the red line is for limitation of vertical motion in leg mode. Result of the workspace is equal with the desired motion.

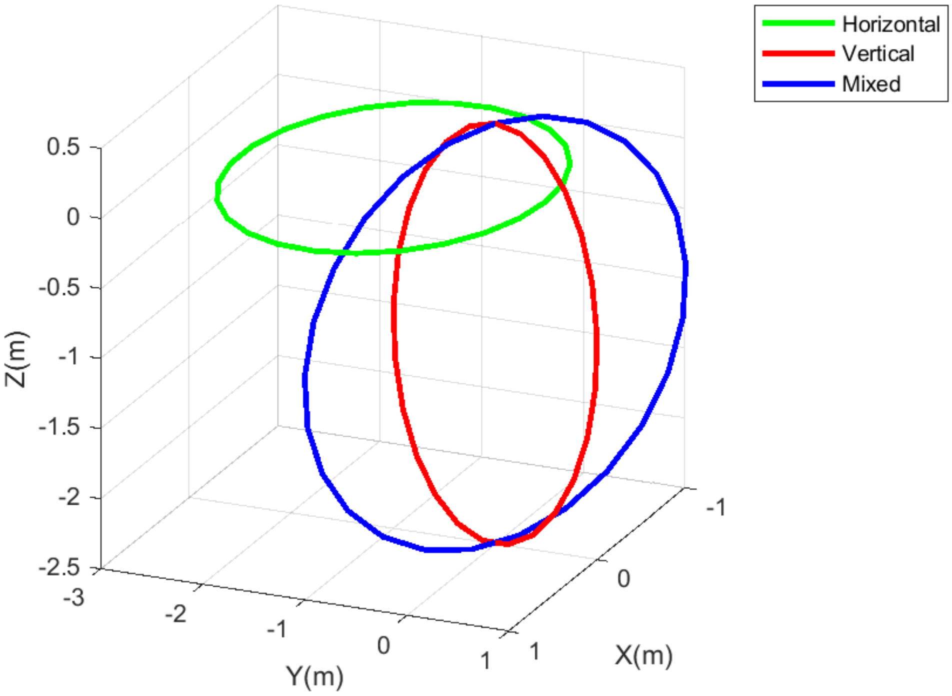


Figure 4.13: Workspace of the robot.

CHAPTER 5

CONCLUSION

5.1 Conclusion

In conclusion, the sprawling bipedal wheel-legged robot has a three-degree-of-freedom design. This robot is meant to navigate a range of terrains by utilising the wheel mechanism on level ground or slopes and the leg mechanism on uneven ground or steps. This robot has two modes of operation, each with its own unique movement. The kinematic design was constructed using a schematic representation of the robot's CAD model and assigned D-H parameters. Kinematics is used to analyse the workspace of a trajectory and a robot. The simulation was carried out in MATLAB Simulink and Simscape Multibody Link using the SolidWorks platform's export of the 3D CAD model. The dynamic performance angle for each joint is determined by the simulation results. The modelling and simulation of a robot using Solidworks and Simscape demonstrates that design and structural changes may be made very easily depending on the results of the simulated dynamic analysis. Thus, constructing a robot with the necessary configuration has been made more affordable and straightforward as a consequence of this ground-breaking study.

5.2 Future Recommendation

There are several interactions between robot mechanics and drives, and the mechatronic approach must be taken into account while designing these systems. For the mechatronic technique described above, a foundational tool like computer modelling is available. It is vital to know the required torque and rotational angle of each motor when creating a robot's control, to visualise the robot's behaviour and to build a mathematical model of each part.

The walking robot gait pattern relies heavily on robot stability. Walking in a static position uses a lot of energy. Dynamic stability, on the other hand, allows a robot to remain upright while moving. In order for a robot to be stable, its centre of gravity (COG) must be within the projection area of its points of contact onto the surface, which is called the polygon of support.

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APPENDIX A
CODE

Multibody Design for Trajectory Motion: