DESIGN AND DEVELOPMENT OF A FOUR-LEGGED WALKING ROBOT

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DESIGN AND DEVELOPMENT OF A FOUR-LEGGED WALKING ROBOT

Major Project Report

Submitted in partial fulfillment of requirements

For the degree of

Master of Technology in Mechanical Engineering

(Computer Integrated Manufacturing)

By,

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Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering (Computer Integrated Manufacturing) at Institute of Technology, Nirma University and has not been submitted elsewhere for degree or diploma.
2. Due Acknowledgment has been made in the text to all other material used.

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Undertaking of Originality of Work

I, Mohit Sharma, Roll. No. 15MMCM05, give undertaking that the Major Project Report entitled "Design and development of a four-legged walking robot" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering (Computer Integrated Manufacturing) at Institute of Technology, Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere it will result in severe disciplinary action.

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Date:

Place: Institute of Technology, Nirma University, Ahmedabad

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This is to certify that the Major Project Report entitled **"Design and development of a four-legged walking robot"** submitted by Mr. **MOHIT SHARMA (Roll No. 15MMCM05),** towards the partial fulfillment of the requirements for the award of Degree of Master of Technology in Mechanical Engineering **(Computer Integrated Manufacturing)** of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

The robot with wheeled locomotion has found its applications at many places but still limited due to the requirement of continuous path contact. Due to this limitation, many difficult terrains cannot be travelled using wheel locomotion system. To overcome this limitation, legged locomotion for robots can be thought of from biological inspiration through multi-legged animals. Legs have advantage of isolated foothold that overcome the limitation of wheels i.e. requirement of continuous path. Having saturated research and limited use of wheel locomotion, the research in the field of legged locomotion has immersed in the recent decade. In addition, the development in the field of aerospace science, need of legged locomotion arises as the terrain in the space elements is unknown and difficult.

Looking to the need of era, an attempt is made in this project to develop a four-legged walking robot. Various literatures are studied to identify the walking patterns of the four-legged animals. Through biological inspiration, a four legged robot has been developed that follows various gait cycle. A 3D CAD model is prepared using solid modeling software. The simulation of the CAD model has been carried out in the simulation software. The mathematical model of the robot leg has also been developed. Kinematics and dynamic study of the robot leg has been carried out through mathematical model and the results are compared with that of simulation.

A four-legged walking robot has been fabricated and demonstrated successfully to walk on the flat and inclined surface.

Keywords: CAD model, Four-legged robot locomotion, Mathematical model, Simulation of the CAD model

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Nomenclature

COG = Centre of gravity

α_i = Link twist angle

a_i = Link length

d_i = Joint distance

θ_i = Joint angle

${}^0D_i$ = Position vector

$\dot{\theta}$ = Angular velocity of leg' joint

$\ddot{\theta}$ = Angular acceleration of leg's joint

v =Link velocity

Ji = Jacobian matrix

Chapter 1

Introduction

1.1 Preliminary remarks

In the beginning of the 20^{th} century, the idea of a humanoid robot was come into thought however today; it is currently potential to envision human measured robots with the ability for close human considerations and development. At the point when wheels have vanquished the robot world that time it appears to be to a great degree prevalent. Specialists are under weight to locate a very much mannered trade for wheels which would work in any assortment of a domain. The approach of including legged robots may be an answer for robots which keeps running on uneven terrains.

There are various research recommended that legged movement is the best type of locomotion through various terrains, when contrasted with utilizing wheels. The surface of the terrain might be uneven, delicate, unpleasant, sloppy and by and large unstructured. Legs in the biological condition exhibit noteworthy favorable position in such circumstances. It is on this premise the rationale to advancement of a four-legged walking robot which is propelled from warm blooded creatures.

In this way, other genuinely complex ideas, for example, movement wanting to cross obstructions would be presented that would help in achieving the desired goal, alongside a point by point examination of question following that would enable such a quadruped to explore all the more proficiently.

1.2 Objectives

There are some important objectives of the project as follows-

- Synthesis and analysis of the four-legged walking mechanism,
- Modeling and simulation of robot,
- Fabrication and testing of prototype robot.

1.3 Motivation

It is realized that robots persistently assumes crucial part in our lives with various prerequisites, the requirement for upgraded comprehension of their abilities increments. Scaling in application from household work to bomb disposal, robots are assuming essential parts in the progressed mechanical outskirts. One such imperative part is offering help for the countries' troops on and off the war zone. Soldiers' packs are increasing in weight as their needs in the field develop. Standard issue equipment can achieve upwards of 50 Kg. A conceivable answer for this profound issue is to expel unnecessary items from the soldiers' packs and redistribute these things to robotic convoy. Quadruped robots are one possibility that the military is seeking after to address this issue. Similarly as with robots by and large, the quadruped robots experience suffer from restricted range because of confined on-board control thickness, moderate speeds and obliged versatility.

The biological inspiration has prompted many advances in mechanical autonomy field having a place from cockroaches to lizards; obviously development has idealized these systems to ensure survival. The set of all animals, as a rule, gives a decent beginning stage to fruitful systems that exceed expectations in ranges where robots have concerns. Specifically, speed is not an issue for some creatures and particularly individuals from the natural family Felidae. The individual from this group of intrigue is the Acinonyx jubatus, all the more ordinarily known as the cheetah. This incredible animal has measurements that would make a gearhead dribble not exclusively would it be able to achieve normal velocities of 70 mph, it can quicken from 0 to 60mph in 3 seconds. This mind boggling pace can be connected to its huge rear leg muscles and to another component that all well evolved creatures share to some degree. When viewing a Cheetah in quest for its prey, plainly the spine is not inflexible, but instead a very adaptable piece of the life structures. The essential point of the exploration is to build up an enunciated model of a quadruped keeping in mind the end goal to decide changes in speed, versatility and lively expenses to enhance the working execution. The applications, past military, where a profoundly versatile quadruped robot would be useful, venture into the therapeutic field (for hospice mind, stimulation, hunt, and save operations, and law authorization).

1.4 Methodology

- To prepare a CAD Model of the four-legged robot.
- Kinematic and Dynamic analysis of the four-legged robot.
- Fabrication of the four-legged robot of eight degree of freedom.
- Set programming and simulation with MATLAB for the four-legged robot.
- Set programming of actuators (Servo motor) for the four-legged robot.
- Testing and Analysis of the four-legged robot.

1.5 Thesis organization

The dissertation is made out of a few sections, starting with the foundation. This area gives an overview and brief history of mechanical innovation in robotics, concentrating on the utilization of legs. The biological inspiration for the present study is given specific accentuation on the four-legged animals. The modeling chapter gives the points of interest on the development of the simulation used to demonstrate the speculation, including all imperatives, limits, assumptions and modeling parameters. The outcomes and examination section arrange the results of the required gait cycles to assess the motion planning with wanted step cycle. Ultimately, the conclusions from the review are presented and further research direction tended to.

Chapter 2

Literature Review

The literature review looks at the up-to-date in the four legged robot research and how the current research provides a significant contribution. This chapter is prepared as follows: a history of relevant four-legged robots which have a discussion of the advancement of various modes of legged robots and its comparison over wheeled-robots, and finally, an overview of the robots and models that are pertinent to the development of the current simulation.

2.1 A Brief History

The history of robots is known for its origins from the ancient world. The present concept begins to be urbanized with the commencement of the Industrial Revolution which permitted for the employ of intricate mechanics and the consequent introduction of electricity which made it possible to power machines with small compressed motors. In the starting of early 20th century, the concept of a humanoid machine was come into consideration, but today it is now potential to imagine human sized robots with the competence for near human thoughts and movement.

When wheels have conquered the robot world that time it seem very admired, researchers are under pressure to find a well-mannered replacement for wheels which would work in any variety of an environment and the approach of adding up legs to robots might be an explanation for robots which runs on untrained terrain.

In 1770, Richard Lovell Edgeworth tried to erect a machine he called a "Wooden Horse", but was not too successful afterward in 1878; the Plantigrade Machine by Pafnuty Chebyshev was shown at the Exposition Universelle.

The advance approach of legs was not new to humans or animals but construction of legs for a robot is an intricate face during process. The usually noticed task and unnoticed fact is how a baby learns to amble and the sheer learning curve involved.

Compared to the wheeled robots and tracked robots, legged robots have the talent to walk in a much wider assortment of terrains just like the fact that biological legged animals can contact nearly all of the earth's land surfaces. For example, the gazelle has the well-organized dynamical locomotion performance even in highly intricate environments. Accordingly, the potential of legged robots has motivated a lot of research on legged robots in recent years and because of that legged robots can go to the places that animals can now reach should be constructed for real applications. Although, a great number of achievements in robotics field, legged robots still insulate far behind the capabilities of their bionics.

The exploration of quadruped robots is from 20th century where the study of dynamic locomotion performance for quadruped robots began from the 1980's at that time Marc Raibert and his colleagues have ready to great success in dynamic legged locomotion of one, two, four legged robots.

In 1980, Marc Raibert of Massachusetts Institute of Technology (MIT) [1], and H. Miura and I. Shimoyama of the University of Tokyo approved out a general research on the mammal quadruped robot at first time. He built planar and three-dimensional one-legged hopping machines which is based on the Raibert's three controlling principle of hopping machine, biped and quadruped robots with prismatic legs which can run and jump were subsequently built. 3-dimensional one-legged hopping machine was a landmark of the motion control of dynamic gaits for quadruped robots.

In the duration of 1984-1987, the dynamic walking quadruped robots was come into picture and that time Collie-1 and Collie-2 generated, had been constructed and additional studied under the supervision of Professor Miura and Professor Shimoyama [2] in the University of Tokyo where robots could achieve the trotting and pacing dynamic walking gaits and transition of between trotting and pacing gaits.

In 1990, Martin Snaith & Owen Holland [3] projected three basic approaches to gait control as one of them is simple centrally controlled, state sequenced, second one is local reflexive neural clusters modulated by a loosely coupled oscillator and the last one is local reflexes modulated by training algorithms. From all three approaches, the training techniques used to include a ’genetic type’ approach, a temporal difference learning method, and a simple for best return search. Apart from this, some discussion on theoretical models which gave to along with a description of the experiential study carried out on a small four legged test platform.

In 1991, Kan Yoneda and Shigeo Hirose [4] projected the dynamic and Static Fusion Gait of a quadruped walking vehicle on a winding Path in which the dynamic and static fusion gait approaches under general conditions which can command to drive the vehicle to follow a given uninformed winding path.

In 1992, Marc Raibert and his colleagues founded Boston Dynamics Corporation (BDI) where they restarted the research project of bionic quadruped robot from 2004 and they proposed the first generation of quadruped robot in 2005 is named as “BigDog”.

In 1999, with the advance approach on Central Pattern Generators (CPGs) where the Hiroshi Kimura [5] and his colleagues in Kyoto Institute of Technology investigated the dynamic walking approach for quadruped robots while Kimura also on track with the research of the quadruped robot “Kotetsu” to challenge the general controller for quadruped locomotion with adaptive dynamic walking using phase modulations based on leg loading/unloading in 2009. Scout II quadruped robot is advance form of legged robot which is a dynamically stable running quadruped robot with a very simple mechanical and it was designed to explore the dynamic gaits of mammal animals by Martin Buehler[6] at Ambulatory Robotics Lab (ARL) of McGill University.

In 2000, L.S. Martins-Filho; R.Prajoux [7] proposed a direct calculation of the force distribution in most cases, and with very few iteration at worst. In spite of a loss of optimality sometimes, provides solution that are always sound from an engineering point of view. At that time, C.C. Brown, J.P. Huissoon [8] proposed temporal gait planning for quadruped walking robot to ensuing gait automatically converges to various classical gaits for straight-line, turning and spinning maneuvres, and naturally accommodates transitions between these. Simulation results have shown that this time-based approach yields a very simple yet adaptable controller that can solve complex motion types with minimal deviations from the target speeds and directions.

In 2001, The KOLT named of a legged robot was designed by Kenneth Waldron and his group at Stanford University in collaboration with Ohio State University.

Apart from this, the advance development of legged robot, in 1996, Sunpei Ma of Shanghai Jiaotong University developed a four legged robot named JTUWM-III for the first time at the domestic. Each leg of JTUWM-III robot has three active joints and an amenable joint where DC servo motor was used to actuate the each active joint.

In 2003, The Biobot (biologically inspired robot) named of the legged robot was developed by Xiuli Zhang and her colleagues at Tsinghua University where she proposed a holosymmetric CPG topological network based on the improved Matsuoka's oscillator model also the rhythmic motion and transitions of different gaits were realized. The locomotion capability of Biobot in real environments was improved based on the CPG model.

In 2009, BDI has been awarded a contract by the Defense Advanced Research Projects Agency (DARPA) to develop LS3 and it was the first Legged Squad Support System. LS3 is a dynamic robot intended to go anywhere, Soldiers and Marines go on foot where each LS3 will carry up to 400 lbs of gear and enough fuel for missions covering 20 miles and lasting 24 hours it will not need a driver, because of that type of advancement it will automatically follow a leader using computer vision or travel to elected locations using sensing and GPS.

In 2010, Qi Deng et al. [9] proposed the springy mass model for trotting in which to sum up, running effect on leg performance by means of centrifugal force. Body pitching may lead to greater leg compression; the disadvantages may be offset by the great increase in centrifugal force at high speed. Body mass distribution might not be the main reason for the difference in maximal running speeds.

In 2010, D. Son et al.[9] accessible gait generation algorithm for a mobile robot in which our gait planning was based on inverse kinematics using the Jacobian of the whole body, where the redundancy was solved by defining an object function for the gecko posture to avoid collisions with the surface. A minimizing error term based on real gecko movement and a collision avoidance term were defined in the object function for smooth and natural movement.

In 2011, C.P. Santos and V. Matos[10] proposed Gait transition and modulation in a quadruped robot (Bio inspired architecture) in which to control the velocity and gait selection using one simple command, able to intimate /stop and modulate the rhythmic activity and to improve the stability and the response of the robot during its locomotion for the various velocities.

In 2013, K. Ganesh Kumar, P.M. Pathak [11], is proposed passive dynamics legged locomotion sagital plane control method in which Dynamic modeling of the quadruped is finished by considering different components, for example, masses of the legs ,inclination of the plane , contact , affect constrain and so forth. Relative Derivatives (PD) Control calculation can actualize to acquire the coveted leg touchdown position. Hyunsoo Park and Kyung Joong Kim proposed bio-enlivened learning calculation to produce new practices on a four legged robot against unforeseen body harms (Parallel hereditary calculation) .It is received to quicken the speed of the transformative inquiry which permits the fast adjustment of robot's conduct utilizing different remote sources. Robot has the vision sensor; it is costly to screen entire body's status. It is helpful to foresee the robot's adaptation to internal failure on the distinctive sorts of harms.

In 2014, ZHUANG Yu-feng,et al. [12], is proposed dynamic modeling and analyzing a mobile robot with Denavit-Hartenberg (DH) method, Langrange technique and Adams simulation. The DH method to set up the facilitate framework and reason the turn grid of each arrange. The most extreme torque that counts in view of the dynamic model is bigger than the greatest torque in light of reproduction. Give a decent establishment to the step arranging and the control framework plan of the robot.

In 2015, X. Chen et al. [13], is proposed an algorithm for the fault–tolerant gait to overcome the failure of more than one actuator in which to controlling of optional level of flexibility of the robot body. The arranged directions can even now be acknowledged and the static walking can be kept up. The technique can make full utilization of the rest of the degrees of flexibility and enhance the execution of strolling. M.M. Gor et al. [14], is proposed Control oriented model based simulation and experimental studies on compliant legged quadruped robot with Bond diagram method which can be interfaced with different controller models contains a detail sub model for telescopic compliant legs. The created model is first mimicked for trot gait, and obtained simulation and animation results are contrasted and the test comes about for model approval. Best appropriate consistence esteem for the robot is validation. Best suitable compliance value for the robot is obtained. Alain Segundo Potts et al.[15], is proposed an optimal power consumption algorithms in which easily solve the optimal trajectories for a quadruped legged robot. Techniques to reduce the runtime are being studied.

In 2016, I. Gonzalez-Luchen[16], is proposed Kinetic Momentum Management Algorithm (KMMA) which permits a quadrupedal robot, whose operation is basic and quick, to run utilizing a symmetrical step designs in a wide assortment of situations. It comprises of two undertakings: figuring the lateral position and speed of the fore swinging leg when it next reaches the ground; and controlling the move edge by mean of latency powers utilizing the position legs. L. Wang et al. [17] , is proposed a geometric approach to deal with tackling the stable workspace of quadruped robot with kinematic analysis. By this strategy, the workspace of the under fluctuating stances was broke down which is anything but difficult to unravel the change of mass focus with the position and stance of the robot body and impact of development on dependability in the possible area. T. Lee and C. Shih [18], is introduced a review on the gait control of a quadruped walking vehicle's adaptive gait planning for quadruped robot on flat surface, to discover it with different definitions and fathomed with calculation to overcome from tumbling down. Adaptive gait planning for quadruped robot on inclined surface with formulation which is overcome from tumbling down.

2.1.1 Legged robots

A legged robot is suitable for uneven terrain; it is capable to climb steps, to cross gaps which are as large as its stride and to walk on very irregular terrain where, due to ground irregularities, the use of wheels would not be feasible [1]. To construct a legged robot is movable; each leg must have at least one degree of freedom (DOF). For each DOF one joint is needed, which is usually powered by one servo. According to leg mechanism also known as locomotion mechanism of legged robots are an assemblage of links and joints (a linkage) offers to reproduce the walking motion of humans or animals. Mechanical legs can have one or more actuators which can perform simple planar or multifarious motion. Bionics and Bio-mimetic apply the composition and methods of locomotion of animals to the design of robots for example; the design of Bionic-Kangaroo was based on the method of kangaroos jump.

Types of legged robots

We can classify legged robots on the following basis-

1. On the basis of Legs configuration

2. On the basis of Number of Legs
3. On the basis of Legs orientation

(1) On the basis of legs configuration

On the basis of legs configuration, there are two major types of legged robots which are as follows-

(a) Mammal type

These types of robots are widely applicable for locomotion because of their legs configuration i.e. the locomotion of legs with its body parallel means that the hip and head of robot always move parallel with its leg locomotion.

(b) Insect type

These types of robots are widely applicable for six or more numbers of legs because of their stability with its legs locomotion i.e. the body of the robot is hinged on its legs so the movement of body always parallel to the ground and perpendicular to its legs position.

(a) Mammal type (b) Insects type

Fig. 2.1 Leg configurations of legged robot [23]

(2) On the basis of legs orientation

There are three major important types of legs orientation which are as follows-

(a) Frontal legs orientation

The direction of the robot body is perpendicular to the leg position.

(b) Sagittal legs orientation

Robot body moves parallel to the leg movement.

(c) Circular legs orientation

The legs are positioned radially allowing the mechanism to move any direction.

Fig.2.2 Leg orientations of the legged robot [25], [26], and [27]

(3) On the basis of number of legs

On the basis of number of legs, we can classify legged robots like as-

One-legged robot

As per this approach, the most modest number of legs for a robot to have position on a groundcontact is one. One-legged robots are normally proposed to jump robots (Not certain if there is whatever other system for them to move) where a bouncing robot needs to jump constantly and on the off chance that it stops, then it falls over. These sorts of robots are animatedly steady and adjust themselves by differing its focal point of gravity and applying healing powers to avoid falling when restless. The essential favorable position of one leg is that they can bounce over and move in any sort of territory as they take a running begin and hop once again any deterrents however at times bigger than its optimal stride. Since there is just for one leg, planners can give careful consideration to leg coordination as there is just a single controllable leg. Likewise, one-legged robots are more power proficient contrasted with robots with more number of legs. The impediment is their mind boggling plan and control.

Two-legged robot (Biped)

A two-legged walker/biped is, by a wide margin, the hardest to make. Since at the purpose of walk just a single foot will be in contact with the ground, and the focal point of gravity should powerfully move so as to shield the robot from falling over. While neither as productive nor as straightforward as the wheeled or a followed vehicle, the potential for intersection more troublesome landscape is fundamental. A check can only be ventured over, go between the legs. In any case, there is no excess in the legs. On the off chance that one leg falls flat, the robot can't stroll by any means.

Four-legged robot (Quadruped)

A four-legged robot/quadruped is genuinely basic being used with a case of an industrially accessible quadruped is the Sony Aibo [6]. A quadruped is less difficult to control then a bipedal robot thus long as just a single leg is ever off the ground no complex adjust is required. In any case, a 4 legged robot does not offer any repetition in the legs. On the off chance that a leg comes up short the robot looses the capacity to walk.

Six-legged robot (Hexapod)

The six-legged walker/hexapod is extremely steady. The designer can outline a gait that can take three legs off the floor at any one time leaving a steady tripod. A hexapod is useful for complex territory, and alongside the quadrupeds, it is the most well-known legged frame robot.

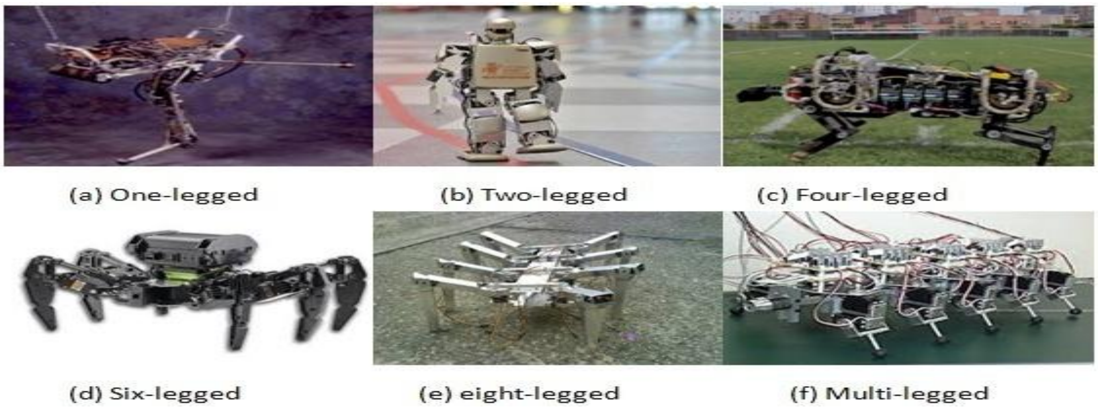

Fig.2.3 Types of legged robot [24]

2.1.2 Comparison of Legged Robots with Wheeled Robots

The principal difference between both, the use of legged robots is improved for motion and adaptation to uneven terrains then wheeled robots which have a inadequate movement in this type of environment.

Compared to the wheeled robots with the legged robots, legged robots have the latent to walk in a much wider assortment of terrains just like the fact that biological legs animals can admittance nearly all of the earth’s land surfaces.

Legged robots have better flexibility and greater efficiency during walk as compare to wheeled robot.

Interact with generic physical environments that are already designed for legged/limbed locomotion (humans). Wheels don't always go where feet do.

Wheeled systems go very fast - faster than anything else, ever. But speed is not always the metric in gauging performance. And speed in linear travel does not translate to speed in change of pose/principle orientation. So, the legged robot is too agile as wheeled robot.

2.2 Summary of the Literature Review

The major project on design and development of a four legged robot is collected of different parts; start with the background which computed on the basis of literature review. This section gives an overview and brief history of robotic technology, focusing on the use of legs. The biological inspiration for the present study is offered with particular importance on the quadruped mammals. The mathematical modeling provides the fine points on the construction of the simulations used to verify the theory, including all constraints, bounds, assumptions and modeling parameters. The Gait analysis organizes the outcomes of the various trials to evaluate the inclusion of the leg position in a quantitative fashion. Lastly, the conclusions from the study of all literature papers are presented and further research directions addressed of a quadruped walking robot as per design criteria.

2.3 Advantages of the four- legged robot

Quadruped robots have been researched more eagerly in recent 20’s years on the basis of its advantages over wheeled robots as explained below-

- It is better in versatility.
- It has enhanced in stability.
- It has capability to move over uneven terrain.
- It has capacity to move even in case of failure of a leg.
- It can distribute its weight and even move its centre of mass without changing the positions of its supports.

2.4 Limitations of the four- legged robot

There are some limitations of quadruped walking robot as follows-

- The design will be more complicated and will have more moving parts.
- Difficult to stable with centre of mass.
- Difficult to set Gait pattern.
- Difficult to control actuators with desire movement.

Chapter 3

Mathematical Modeling

In this chapter, mathematical modeling of four-legged robot is discuss which includes mechanical structure, kinematic modeling, dynamic modeling, and gait analysis.

3.1 Mechanical structure

Mechanical structure of the four-legged robot consists a rigid body; connected with four legs where each leg have two active joints viz. hip joint (θ1) and knee joint (θ2) which allows rotary motion between connected joints whose motion is controlled by servo motors. A four-legged robot has an open serial kinematic chain where upper limb is connected with lower limb for each leg.

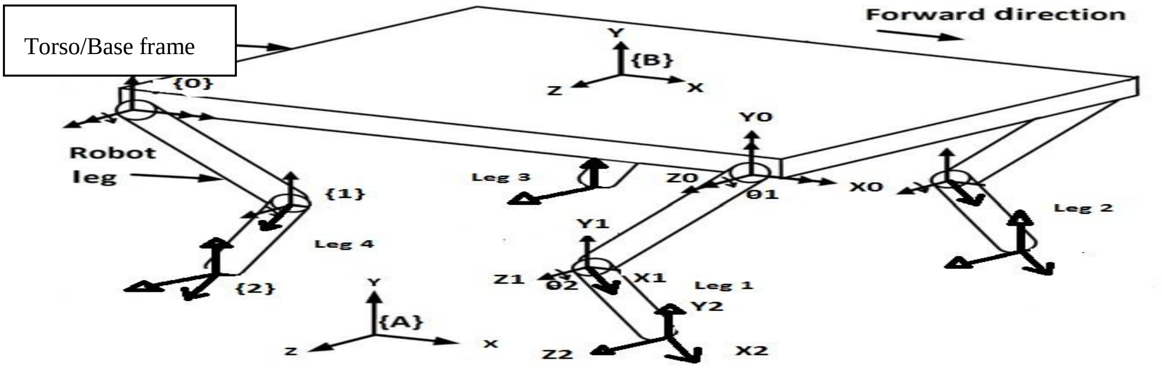

Fig. 3.1 Mechanical structure of the four-legged walking robot

Some important design consideration for quadruped walking robots which are-

- Vertical speed of quadruped should constant if possible while the legs touching the ground (support phase).
- If the foot is not touching the ground, it should move about as fast as possible.
- Steady torque/force input should be considered (or at least no extreme spikes/changes).

- Step height like as enough for clearance, not too much to conserve energy.
- the foot should touch the ground for at least half of the cycle for a two/four leg mechanism or respectively, a third of the cycle for a three/six leg mechanism
- Minimized moving mass.
- Vertical center of mass of the quadruped should always inside the base of support.
- The speed of each leg or group of legs should be discretely controllable for steering.
- The leg mechanism should be permit for forward and backward walking.

There are some important factors for quadruped walking robot as follows-

- The length and design of the legs is essential in robot locomotion, because the trajectory that is implemented in each of the articulation depend on them.
- If the robot moves within the established limits, the collision risk is avoided and the system will be safe.

Assumptions for the quadruped are prepared for the simplicity of analysis -

- There exists a point contact between the foot and the ground.
- The slipping may occurred between the foot and the ground.
- All the mass of the four legs should lump into the body, and the centre of gravity is assumed to be at the Centroid of the body.
- The speed of the robot body when it moves, that time, the average speed of each leg during transfer phase should be constant and considered to be equal.
- Ground should be flat over the region affecting the robot workspace.

Robot specifications

The performance and physical specifications of four-legged robot are decided. Performance specifications describe task related specifications and physical specifications describe robot’s dimensions and weight. In this research work, four-legged robot is able to walk with trot gait over flat and inclined terrain. Robot size and weight are fixed by finalizing actuation system, control system and power pack. Maximum total weight of power pack and control system is assumed to be 0.5 Kg. Dimensions of legs are proportional to dimensions of frame. There are some important specifications of four-legged robot which is described as follows-

Selection of Robot's Leg Number

After computing the device cost and the need for extra control circuits and actuators, a four-legged/ quadruped design is chosen for the project design because it is easier to implement, required fewer controls & actuators, more stable and less cost.

Selection of Robot's Degrees of Freedom

After analyzing the effect of robot's degree of freedom, the two degree of freedom for each leg is chosen because the up-down and forward-back motion is approximately linear which provides a better motion during forward or backward while adjusting to some uneven terrain since one degree of freedom does not present the required capabilities and three degrees of freedom is expensive.

Selection of Actuator

Actuators in robots are like strength in the human body. Without the actuators, the limbs of the robot cannot be in motion. There are many types of actuators existing like Pneumatic, Hydraulic, DC motors, Stepper motor and Servo motors but only Servo motors suit the needs of the project. Servos are selected because of their comparatively low cost and their simplicity of control. The main disadvantage of the servo motor is the loss of feedback position control to the external device providing the control pulse.

3.2 Kinematic modeling

Kinematic model of quadruped robot describes the position and orientation of the legs. The derivatives of kinematics deal with the mechanics of motion without considering the forces that cause it. The relationships between the motion and the forces and/or torques that cause them are the dynamics model.

The problem of manipulator control requires both of direct and inverse kinematic models. The block diagram for both the models is shown in Fig. (3.3), wherein the commonality is the joint-link fixed parameters as well as joint-link variable parameters. The kinematic modeling problem is split into two problems as:

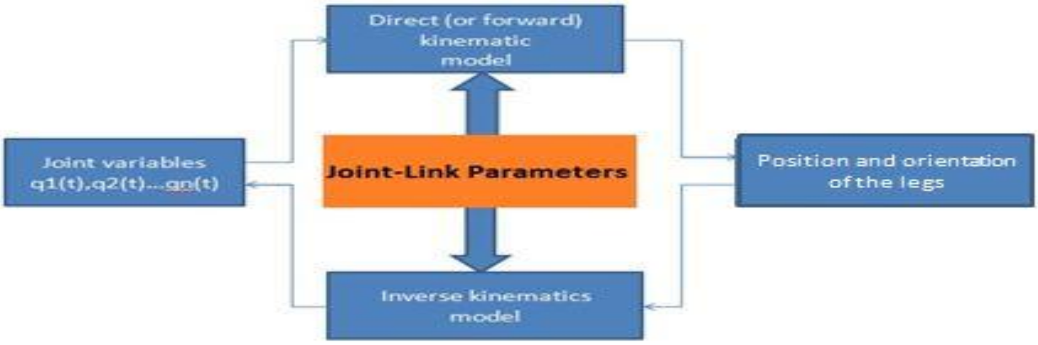

Fig. 3.2 The block diagram for the direct and inverse kinematic model

3.2.1Direct (or forward) kinematic

Give the set of joint-link parameters, the problem of finding the position and orientation of the leg with respect to a known (immobile or inertial) reference frame for a 2-DOF leg of quadruped walking robot. This is referred to as direct (or forward) kinematic model or direct kinematics. This model gives the position and orientation of the leg as a function of the joint variables and other joint-link constant parameters.

From mechanical structure of four-legged robot, there are four joint-link parameters for each leg, one to each leg in an open kinematic chain, was proposed by Denavit and Hartenberg in 1995 which is known as Denavit-Hertenberg (DH) notation. This notation is followed throughout the analysis.

TABLE 3.1 DH Parameters of R-R manipulator for a four legged walking robot

Link i	a_i	α_i	d_i	θ_i	$C\theta_i$	$S\theta_i$	$C\alpha_i$	$S\alpha_i$
0-1	L_1	0	0	θ_1	C_1	S_1	1	0
1-2	L_2	0	0	θ_2	C_2	S_2	1	0

The transformation of frame {i-1} to frame {i} consists of four basic transformations as shown in figure (3.2).

a) A rotation about z_{i-1}- axis by an angle θ_i;
b) Translation along z_{i-1}- axis by distance d_i;
c) Translation by distance α_i along x_i-axis, and
d) Rotation by an angle α_i about x_i-axis.

$$^{i-1}T_i = \begin{vmatrix} C\theta i & -S\theta i C\alpha i & S\theta i S\alpha i & aC\theta i \\ S\theta i & C\theta i C\alpha i & -C\theta i S\alpha i & aS\theta i \\ 0 & S\alpha i & C\alpha i & di \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad 3.1$$

This is an important result for modeling manipulators. The homogeneous transformation matrix $^{i-1}T_i$ describes the position and orientation of frame {i} relative to frame {i-1} and completely specifies the geometric relationship between these links in terms of four DH-parameters (θ_i, d_i, α_i, a_i). Of these four parameters, only one is a variable for link i, the displacement variable q_i (θ_i or d_i) and other three are constant. As shown in the above matrix in which upper left corner sub- matrix of Eq.(3.1) gives the orientation of coordinates axes of frame {i}, while the 3x1 upper right corner sub-matrix shows the position of the origin of frame {i}.

For i=1, the transformation matrix is-

$$^{0}T_1 = \begin{bmatrix} C_1 & -S_1 & 0 & L_1C_1 \\ S_1 & C_1 & 0 & L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.2$$

For i=2, the transformation matrix is-

$$^{1}T_2 = \begin{bmatrix} C_2 & -S_2 & 0 & L_2C_2 \\ S_2 & C_2 & 0 & L_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.3$$

The position and orientation of a quadruped robot’s frame comparative to the base frame can be establish by considering the two consecutive links transformation matrices relating to the adjacent links. Thus,

$$^{0}T_2 = {}^{0}T_1\,{}^{1}T_2 \qquad 3.4$$

$^{0}T_2$ in Eq. (3.4) is known as the kinematic model of the 2-DOF (R-R planner manipulator) of leg’s end point.

Substituting, Eq. (3.2) & Eq. (3.3) into Eq. (3.4) and simplifying as follows-

$$^{0}T_2 = \begin{bmatrix} C_1 & -S_1 & 0 & L_1C_1 \\ S_1 & C_1 & 0 & L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_2 & -S_2 & 0 & L_2C_2 \\ S_2 & C_2 & 0 & L_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{0}T_2 = \begin{bmatrix} C_1C_2 - S_1S_2 & -C_1S_2 - S\ C_2 & 0 & L_2C_2C_1 - L_2S_2S_1 + L_1C_1 \\ C_2S_1 + C_1S_2 & -S_1S_2 + C_1C_2 & 0 & L_2C_2S_1 + L_2S_2C_1 + L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{0}T_2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & L_2C_{12} + L_1C_1 \\ S_{12} & C_{12} & 0 & L_2S_{12} + L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.4$$

Here,

$C_{12} = \cos(\theta_1 + \theta_2)$

$S_{12} = \sin(\theta_1 + \theta_2)$

This overall transformation, Eq. (3.5), is known as transformation matrix of a quadruped walking robot which is similar for each leg.

3.2.2 Inverse kinematics

For a given position and orientation of the leg, with respect to an immobile or inertial reference frame, it is required to find a set of joint variables that would bring the leg in the specified position and orientation. This is the second problem and is referred to as the inverse kinematic model or inverse kinematics.

In other words, the inverse kinematic model is the determination of the joint displacements vector q ranges over the joint-space, as the set of positions and orientations of end point in Cartesian space.

The quadruped walking robot’s transformation matrix T represents the orientation R and position D of the end-effector with respect to the base frame:

$$T = \begin{bmatrix} & R & & D \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.5$$

There are two methods to find out the solutions of the inverse problem, one is closed form solutions and another is numerical solutions. In the closed form solution, joint displacements are determined as open functions of the position and orientation of the legs while in numerical methods, iterative algorithms are used. The numerical methods are computationally exhaustive and by nature slower compared to the correct solution in singular and degenerate cases.

The "closed form" in the present circumstance means a solution where the method is based on analytical algebraic or kinematic approach which gives expressions for solving unknown joint displacements.

$$ {}^{0}T_2 = {}^{0}T_1\,{}^{1}T_2 = T \qquad 3.6 $$

The elements of the left-hand side of Eq. (3.7) are functions of the 2 joint displacement variables. The elements of the right-hand side matrix T are the desired position and orientation of the legs and are either zero or constant. As T matrix equality implies elements by elements equality.

In the inverse kinematic model, the right-hand side of Eq. (3.7) is known, while the left-hand side has 2 unknowns. The left-hand side consists of product of 2 links transformation matrices, that is

$$ {}^{1}T_2 = {}^{0}T_1^{-1}.T $$

$$ and\ T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.7 $$

Where, each r_{ij} has numeric value.

$$ \begin{bmatrix} C_{12} & -S_{12} & 0 & L_2C_{12} + L_1C_1 \\ S_{12} & C_{12} & 0 & L_2S_{12} + L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.8 $$

$$ L_2C_{12} + L_1C_1 = r_{14} \qquad 3.9 $$

$$ L_2S_{12} + L_1S_1 = r_{24} \qquad 3.10 $$

Squaring and adding of Eq. (3.10) & Eq. (3.11) and we get

$$ L_2^{\,2} + L_1^{\,2} + 2L_1L_2(C_{12}C_1 + S_{12}S_1) = r_{14}^{\,2} + r_{24}^{\,2} \qquad 3.11 $$

And then,

$$L_2{}^2 + L_1{}^2 + 2L_1L_2C_1 = r_{14}{}^2 + r_{24}{}^2 \quad 3.12$$

$$C_2 = \left[\frac{(r^2{}_{14} + r^2{}_{24}) - (L_1{}^2 + L_2{}^2)}{2L_1L_2} \right] \quad 3.13$$

$S_2 = \sqrt{1 - (C2)^2}$

$$S_2 = \sqrt{1 - \left[\frac{(r^2{}_{14} + r^2{}_{24}) - (L_1{}^2 + L_2{}^2)}{2L_1L_2} \right]^2} \quad 3.14$$

By dividing Eq. (3.15) by Eq. (3.14) and get

$$\theta_2 = A\tan 2(S_2, C_2)$$

From Eq. (3.10) & Eq. (3.11), we get

$$L_2C_{12} + L_1C_1 = r_{14}$$

$$L_2S_{12} + L_1S_1 = r_{24}$$

And then,

$$L_2(C_1C_2 + S_1S_2) + L_1C_1 = r_{14} \quad 3.15$$

$$L_2(S_1C_2 + C_1S_2) + L_1S_1 = r_{24} \quad 3.16$$

And then,

$$(L_2C_2 + L_1)C_1 + (L_2S_2)S_1 = r_{14} \quad 3.17$$

$$(L_2S_2)C1 + (L_2C_2 + L_1)S_1 = r_{24} \quad 3.18$$

Assume that,

$$L_2C_2 + L_1 = r\cos\phi \quad 3.19$$

$$L_2S_2 = r\sin\phi \quad 3.20$$

Squaring and adding of Eq. (3.20) &Eq. (3.21), we get

$$r = \sqrt{(L_1{}^2 + L_2{}^2 + 2L_1L_2C_2)} \quad 3.21$$

$$\phi = \tan^{-1}\left(\frac{L_2S_2}{L_1 + L_2C_2} \right) \quad 3.22$$

$$[\cos\phi C_1 - \sin\phi S_1] = \frac{r_{14}}{r} \quad 3.23$$

$$[\sin\phi C_1 + \cos\phi S_1] = \frac{r_{24}}{r} \quad 3.24$$

$$\cos(\phi+\theta 1)=\frac{r_{14}}{r} \qquad 3.25$$

$$\sin(\phi+\theta 1)=\frac{r_{24}}{r} \qquad 3.26$$

Dividing Eq. (3.27) by Eq. (3.26), we get

$$\tan(\phi+\theta 1)=\frac{r_{24}}{r_{14}} \qquad 3.27$$

$$\theta_1 = A\tan 2\left(\frac{r_{24}}{r_{14}}\right)-\phi$$

The values of θ_1 and θ_2 are similar for each leg which is attached to quadruped walking robot.

3.3 Jacobian

For the essence of the four-legged robot, not only the final position of the leg's end point is important, but also the velocity. At which, the end point of the legs would move to reach the final location is an equally important criterion. The transformation matrices from joint velocities to the end point of legs velocity is show by a matrix, called the Jacobian which is reliant on leg design. It is a linear mapping from velocity in joint space to velocity in Cartesian space. The Jacobian is one of the significant tools for categorization of differential motions of quadruped walking robot.

The correlation between the infinitesimal (differential) joint motion with infinitesimal (differential) change in end point of the legs position (and orientation) is investigated now. As these changes take place in the infinitesimal (differential) time, we are really looking for a mapping between the instantaneous end point of the legs velocity, V_e (in Cartesian space) to the instant joint velocities (in joint space) and it can be expressed as

$$Ve(t) = J(q)\dot{q} \qquad 3.28$$

Where

$Ve(t)$= 6x1 Cartesian velocity vector,

$J(q)$= 6 x n, a Quadruped walking robot Jacobian or Jacobian matrix,

$\dot{q}$= n x 1, is vector of n joint velocities.

Eq. (3.29) can be written in column vectors of the Jacobian, that is,

$$Ve(t) = [J1(q)J2(q) \dots \dots Jn(q)]\dot{q}(t) \quad 3.29$$

In the Eq. (3.30), $Ji(q)$ is the i[th] column of the Jacobian matrix which explained as,

$$Ve(t) = \begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \dot{d} \\ \dot{\theta} \end{bmatrix} = J(q)\dot{q}(t) \quad 3.30$$

Eq. (3.31) is represented the forward differential motion model or differential kinematics model for a quadruped robot presented in Fig. (3.4), it is similar to the forward kinematic model.

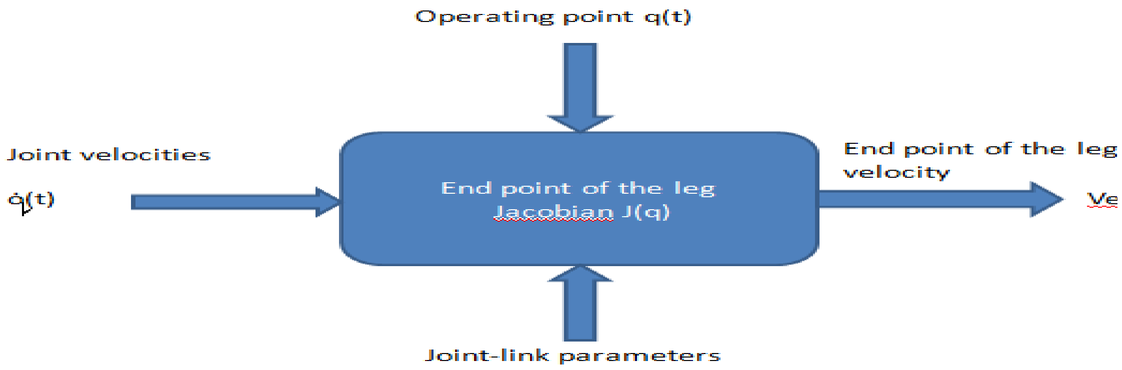

Fig. 3.3 The forward differential motion model for a four legged robot

The first three rows of Jacobian J(q) matrix is associated with the linear velocity of the end point of the legs, while the last three rows keep in touch to the angular velocity, ω of the end point . Each joint of the manipulator, generate some linear and/or some angular velocity at the end point of the leg. Column(i), of Jacobian matrix Ji(q) is, thus, made up from three linear velocity components j_{vi} and three angular velocity components $j_{\omega i}$ and can be expressed as

$$Ji(q) = \begin{bmatrix} jvi \\ j\omega i \end{bmatrix} = \begin{bmatrix} j_{vxi} \\ j_{vyi} \\ j_{vzi} \\ j_{\omega xi} \\ j_{\omega yi} \\ j_{\omega zi} \end{bmatrix} \quad 3.31$$

Where j_{vki} and $j_{\omega ki}$ represents the factor k of linear velocity and angular velocity, respectively, contributed by joint i with k = x, y, or z and i= 1, 2, 3, ……, n.

The involvement of joint to linear velocity of the end point of the legs is $J_{vi}\dot{q}i$ and to angular velocity of the end point of the legs is $J_{\omega i}\dot{q}i$.One simple method of calculation of the Jacobian is to determine J_{vi} and $J_{\omega i}$ for joint i which is carried out in the following sections for revolute joints-

The angular velocity of the link i, also produces a linear velocity at the end point of the leg due to the rotation of all the distal of all distal links along with the end point of the leg about the origin O_{i-1} of frame {i-1}. From O_{i-1}, the end point of the leg frame, frame {n} is defined by a position vector ${}^{i-1}P_n$, the linear velocity generated by ω_i, is

$$v_i = \omega_i\, {}^{i-1}P_n = (P_{i-1}\, {}^{i-1}P_n)\dot{\theta}_i \qquad 3.32$$

For a rotary joint,

$$J_i = \begin{bmatrix} P_{i-1}\, {}^{i-1}P_n \\ P_{i-1} \end{bmatrix} \qquad 3.33$$

Where,

$${}^{i-1}P_n = {}^0P_n - {}^0P_{i-1}$$

$$P_{i-1} = {}^0R_{i-1}\hat{u}$$

${}^0R_{i-1}$ is the 3 x 3 orientation sub-matrix (the rotation matrix) of ${}^0T_{i-1}$.

Note that P_{i-1} is the third column of the rotation matrix ${}^0R_{i-1}$.and the origin of frame {n} at the end point of the leg is $O_n = [0 \quad 0 \quad 0 \quad 1]^T$.

For Jacobian matrix, each column is computed discretely and then all the columns are collective to form the total Jacobian matrix.

The column J_1 of Jacobian matrix is for joint 1, which is a revolute joint and is determined as follows:

The joint axis vector like P_0 (P_{i-1} for i=1) is

$$P_0 = {}^0R_0\hat{u} \qquad 3.34$$

The transformation matrix ${}^0T_0$ and rotation matrix ${}^0R_0$ are the identity matrices. Thus from Eq. (3.34)

$$P_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad 3.35$$

The end point of the leg position vector (for $i = 1$ and $n = 2$) is determined as

$$^0P_n = {}^0T_n O_n - {}^0T_0 O_n = {}^0P_2 = {}^0T_2 O_2 - {}^0T_0 O_2$$

$$^0T_2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & L_2C_{12} + L_1C_1 \\ S_{12} & C_2 & 0 & L_2S_{12} + L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^0P_2 = {}^0T_2 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} - {}^0T_0 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$^0P_2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & L_2C_{12} + L_1C_1 \\ S_{12} & C_{12} & 0 & L_2S_{12} + L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$^0P_2 = \begin{bmatrix} L_2C_{12} + L_1C_1 \\ L_2S_{12} + L_1S_1 \\ 0 \\ 0 \end{bmatrix} \qquad 3.36$$

The first column of Jacobian, is computed by substituted Eq. (3.36) and Eq. (3.37) in Eq. (3.34), for revolute joint. Thus,

$$J_1 = \begin{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \text{X} \begin{bmatrix} L_2C_{12} + L_1C_1 \\ L_2S_{12} + L_1S_1 \\ 0 \end{bmatrix} \\ \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{bmatrix} \qquad 3.37$$

$$\begin{bmatrix}0\\0\\1\end{bmatrix} X \begin{bmatrix}L_2C_{12}+L_1C_1\\L_2S_{12}+L_1S_1\\0\end{bmatrix} = \begin{vmatrix}\hat{i} & \hat{j} & \hat{k}\\0 & 0 & 1\\L_2C_{12}+L_1C_1 & L_2S_{12}+L_1S_1 & 0\end{vmatrix}$$

$$= \left(0-(L_2S_{12}+L_1S_1)\right)\hat{i} - \left(0-(L_2C_{12}+L_1C_1)\right)\hat{j} + \left(0-0\right)\hat{k}$$

$$= -(L_2S_{12}+L_1S_1)\,\hat{i} + (L_2C_{12}+L_1C_1)\,\hat{j} + 0\,\hat{k}$$

$$= \begin{bmatrix}\hat{i} & \hat{j} & \hat{k}\end{bmatrix}\begin{bmatrix}-(L_2S_{12}+L_1S_1)\\(L_2C_{12}+L_1C_1)\\0\end{bmatrix}$$

So,

$$J_1 = \begin{bmatrix}-(L_2S_{12}+L_1S_1)\\(L_2C_{12}+L_1C_1)\\0\\0\\0\\1\end{bmatrix} \qquad 3.38$$

By following similar steps for joint 2 is obtained as,

The joint axis vector P_1 (P_{i-1} for i=2) is

$$P_1 = {}^0R_1\hat{u} \qquad 3.39$$

The transformation matrix (${}^0T_1$) and rotation matrix (${}^0R_1$) is-

$${}^0T_1 = \begin{bmatrix}C1 & -S1 & 0\\S1 & C1 & 0\\0 & 0 & 1\end{bmatrix}$$

$$P_1 = \begin{bmatrix}C_1 & -S_1 & 0\\S_1 & C_1 & 0\\0 & 0 & 1\end{bmatrix}\begin{bmatrix}0\\0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\1\end{bmatrix} \qquad 3.40$$

The end point of the leg position vector (for $i = 2$ and $n = 2$) is determined as

$${}^{i-1}P_n = {}^0T_n\hat{O}_n - {}^0T_{i-1}\hat{O}_n = {}^1P_2 = {}^0T_2O_2 - {}^0T_1O_2$$

$${}^0T_2 = \begin{bmatrix}C_{12} & -S_{12} & 0 & L_2C_{12}+L_1C_1\\S_{12} & C_{12} & 0 & L_2S_{12}+L_1S_1\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix}$$

$$^{1}P_2 = {}^{0}T_2 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} - {}^{0}T_1 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$^{1}P_2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & L_2C_{12} + L_1C_1 \\ S_{12} & C_{12} & 0 & L_2S_{12} + L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} C_1 & -S_1 & 0 & L_1C_1 \\ S_1 & C_1 & 0 & L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$^{1}P_2 = \begin{bmatrix} L_2C_{12} + L_1C_1 \\ L_2S_{12} + L_1S_1 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} L_1C_1 \\ L_1S_1 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} L_2C_{12} \\ L_2S_{12} \\ 0 \\ 0 \end{bmatrix} \qquad 3.41$$

The second column of Jacobian, is computed by substituted Eq. (3.36) and Eq. (3.37) in Eq. (3.34), for revolute joint. Thus,

$$J_2 = \begin{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \text{X} \begin{bmatrix} L_2C_{12} \\ L_2S_{12} \\ 0 \end{bmatrix} \\ \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{bmatrix} \qquad 3.42$$

$$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} L_2C_{12} \\ L_2S_{12} \\ 0 \end{bmatrix} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ 0 & 0 & 1 \\ L_2C_{12} & L_2S_{12} & 0 \end{vmatrix}$$

$$= (0 - (L_2S_{12}))\hat{i} - (0 - (L_2C_{12}))\,\hat{j} + (0 - 0)\hat{k}$$

$$= -(L_2S_{12})\,\hat{i} + (L_2C_{12} + L_1)\,\hat{j} + 0\,\hat{k}$$

$$= \begin{bmatrix} \hat{i} & \hat{j} & \hat{k} \end{bmatrix} \begin{bmatrix} -(L_2S_{12}) \\ (L_2C_{12}) \\ 0 \end{bmatrix}$$

So,

$$J_2 = \begin{bmatrix} -(L_2 S_{12}) \\ (L_2 C_{12}) \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \qquad 3.43$$

By putting of the values of column J_1 *and* J_2 from Eq. (3.39) and Eq. (3.44) in the following equation,

$$V_e(t) = \begin{bmatrix} -\left(L_2 S_{12} + L_1 S_1\right) & -\left(L_2 S_{12}\right) \\ \left(L_2 C_{12} + L_1 C_1\right) & \left(L_2 C_{12}\right) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 1 \end{bmatrix} \mathrm{X} \begin{bmatrix} \dot{\theta}_x \\ \dot{\theta}_y \\ \dot{\theta}_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \qquad 3.44$$

3.4 Dynamic modeling

During the work cycle, the four-legged robot should be accelerate, move at constant speed, and decelerate. The time-varying position and orientation of the four-legged robot is depending on its dynamic behavior. Time-varying torques are applied on the joints (by the joint actuators) to balance the internal and external forces. The internal forces are created by legs motion (velocity and acceleration). Inertial, Coriolis, and frictional forces are the internal forces. The external forces are the forces created by the environment which includes the “load” and gravitational forces. As a result, links and joints have to withstand stresses caused by forces/torques balance across the entire motion.

The mathematical modeling for the dynamic actions of the four-legged robot is developed. The analytical equations, often referred as dynamics, are set of equation of motion (EOM) that described the dynamic response of the four-legged robot to input actuator (servo motor) torques.

The derivation of EOM using LE formulation is carried out in the following subsections, first of all, the leg velocity is computed and then the leg inertia tensor is obtained. These parameters are used to compute the kinetic energy, and then the potential energy is calculated and at last, the Lagrangian is formed, which is substituted to get dynamic model for quadruped walking robot's leg.

EOM of R-R configuration for a four-legged walking robot using LE formulation

The Lagrange-Euler formulation is a systematic approach for obtaining the dynamic model of an 8-DOF manipulator. The derivation of equation of motion using Lagrage-Euler formulation is carried out in the following section.

We know that, the Lagrangian L=K-P is given by,

$$L = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{i}\sum_{k=1}^{i} Tr\left[\left({}^{0}T_{j-1}Q_j\,{}^{j-i}T_i\right)I_i\left({}^{0}T_{k-1}Q_k\,{}^{k-1}T_i\right)^T\right]\dot{q}_j\dot{q}_k + \sum_{i=1}^{n} m_i g\,{}^{0}T_i\,{}^{i}\bar{r}_i \qquad 3.45$$

According to Lagrange-Euler dynamic formulation, the torque τ_i of the actuators at joint I of the manipulator, is given as

$$\tau_i = \frac{d}{dt}\left(\frac{\delta L}{\delta \dot{q}_i}\right) - \left(\frac{\delta L}{\delta q_i}\right) \qquad 3.46$$

By substituting the value of L in Eq. (3.47), we get

$$\tau_i = \sum_{j=1}^{n} M_{ij}(q)\ddot{q}_j + \sum_{j=1}^{n}\sum_{k=1}^{n} H_{ijk}\dot{q}_j\dot{q}_k + G_i \quad \text{for i=1, 2, ……., n} \qquad 3.47$$

Where

$$M_{ij} = \sum_{p=\max(i,j,k)}^{n} Tr\left[d_{pj} I_p d_{pi}{}^T\right] \qquad 3.48$$

$$H_{ijk} = \sum_{p=\max(i,j,k)}^{n} Tr\left[\frac{\partial(d_{pk})}{\partial q_p} I_p d_{pi}{}^T\right] \qquad 3.49$$

$$G_i = -\sum_{p=i}^{n} m_p g d_{pi}\,{}^{p}\bar{r}_p \qquad 3.50$$

and $$d_{ij} = \begin{cases} {}^{0}T_{j-1}Q_j\,{}^{j-1}T_i & \text{for } j \le i \\ 0 & \text{for } j \rangle i \end{cases} \qquad 3.51$$

and $$\frac{\partial d_{ij}}{\partial q_k} = \begin{cases} {}^{0}T_{j-1}Q_j\,{}^{j-1}T_{k-1}Q_k\,{}^{k-1}T_i & \text{for } i \ge k \ge j \\ {}^{0}T_{k-1}Q_k\,{}^{k-1}T_{j-1}Q_j\,{}^{j-1}T_i & \text{for } i \ge j \ge k \\ 0 & \text{for } i < j \text{ or } i < k \end{cases} \qquad 3.52$$

Above equations are the EOM or the dynamic equations of motion for the manipulator.

The dynamic model of the 1 leg of the four-legged robot, 2-DOF planer manipulator is developed using direct approach.

The legs configuration is prismatic shape with uniform mass distribution, that is, the centre of mass of each link of the leg is located at the mid-point of the link. There are some important notations which are as follows-

L_1= Length of upper limb of the legs (meter),

L_2= Length of lower limb of the legs (meter),

m_1= Mass of upper limb of the legs (Kilogram), and

m_2 = Mass of lower limb of the legs (Kilogram),

The LE formulation begins with the kinematic model. The frame assignment is carried out from fig. (3.2) and the joint-link parameters are tabulated from Table (3.1). The link-transformation matrices and the required products of transformation matrices are taken from Eq. (3.3), Eq. (3.4) and Eq. (3.5).

Applying, Q_i matrices for rotary joints 1 and 2 which are given as

$$Q_1 = Q_2 = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad 3.53$$

The inertia tensors I_1 and I_2 for two prismatic links of length with mass m_1 and m_2 at the centroid of the link L_1 and L_2, with respect to the frame {i}, i=1, 2, are computed as,

Where,

h_1=Height of prismatic leg of upper limb (meter),

h_2=Height of prismatic leg of lower limb (meter),

w_1=Width of prismatic leg of upper limb (meter), and

w_2= Width of prismatic leg of lower limb (meter).

$$I_1 = m_1 \begin{bmatrix} \frac{1}{24}\left(L_1{}^2 + h_1{}^2 + 2w_1{}^2\right) & 0 & 0 & \frac{L_1}{2} \\ 0 & \frac{1}{24}\left(L_1{}^2 - h_1{}^2\right) & 0 & \frac{h_1}{2} \\ 0 & 0 & \frac{1}{24}\left(h_1{}^2 - L_1{}^2\right) & \frac{w_1}{2} \\ \frac{L_1}{2} & \frac{h_1}{2} & \frac{w_1}{2} & 1 \end{bmatrix} \quad 3.54$$

$$I_2 = m_2 \begin{bmatrix} \frac{1}{24}\left(L_2{}^2 + h_2{}^2 + 2w_2{}^2\right) & 0 & 0 & \frac{L_2}{2} \\ 0 & \frac{1}{24}\left(L_2{}^2 - h_2{}^2\right) & 0 & \frac{h_2}{2} \\ 0 & 0 & \frac{1}{24}\left(h_2{}^2 - L_2{}^2\right) & \frac{w_2}{2} \\ \frac{L_2}{2} & \frac{h_2}{2} & \frac{w_2}{2} & 1 \end{bmatrix} \quad 3.55$$

The computation of matrices d_{ij} which are required to compute all other coefficients in Eq.(3.49) to Eq. (3.51).

According to Eq. (3.52),

For i, j = 1, 2, the four d_{ij} matrices d_{11}, d_{12}, d_{21}, and d_{22} which are computed now. For i = j =1, then d_{11} is computed as:

$$d_{11} = {}^0T_0 Q_1 {}^0T_1 = Q_1 {}^0T_1 = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \mathrm{X} \begin{bmatrix} C_1 & -S_1 & 0 & L_1C_1 \\ S_1 & C_1 & 0 & L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Note that, ${}^0T_0$ is an identity matrix and the value of this matrix is 1.

$$d_{11} = \begin{bmatrix} -S_1 & -C_1 & 0 & -L_1S_1 \\ C_1 & -S_1 & 0 & L_1C_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad 3.56$$

Similarly, $d_{12} = 0$ (because $j > i$) 3.57

$$d_{21} = {}^{0}T_0 Q_1 {}^{0}T_2 = Q_1 {}^{0}T_2 = \begin{bmatrix} -S_{12} & -C_{12} & 0 & -L_2S_{12} - L_1S_1 \\ C_{12} & -S_{12} & 0 & L_2C_{12} + L_1C_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad 3.58$$

$$d_{22} = {}^{0}T_1 Q_2 {}^{1}T_2 = \begin{bmatrix} -S_{12} & -C_{12} & 0 & -L_2S_{12} \\ C_{12} & -S_{12} & 0 & L_2C_{12} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad 3.59$$

It is applied to compute the elements of inertia matrix $M(M_{ij})$ using Eq. (3.49), i.e.

$$M_{ij} = \sum_{p=\max(i,j)}^{n} Tr\left[d_{pj} I_p d_{pi}^{\ T}\right]$$

Using the d_{ij} and I_i matrices from Eqs. (3.57) to (3.62), the effective inertia coefficients M_{11} and M_{12} are computed, first, as:

$$M_{11} = Tr(d_{11} I_1 d_{11}^{\ T}) + Tr(d_{21} I_2 d_{21}^{\ T}) \quad 3.60$$

Now,

$$d_{11} I_1 d_{11}^{\ T} = \begin{bmatrix} -S_1 & -C_1 & 0 & -L_1S_1 \\ C_1 & -S_1 & 0 & L_1C_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{1}{24}m_1\left(L_1^2 + h_1^2 + 2w_1^2\right) & 0 & 0 & m_1\frac{L_1}{2} \\ 0 & \frac{1}{24}m_1\left(L_1^2 - h_1^2\right) & 0 & m_1\frac{h_1}{2} \\ 0 & 0 & \frac{1}{24}m_1\left(h_1^2 - L_1^2\right) & m_1\frac{w_1}{2} \\ m_1\frac{L_1}{2} & m_1\frac{h_1}{2} & m_1\frac{w_1}{2} & m_1 \end{bmatrix} \begin{bmatrix} -S_1 & C_1 & 0 & 0 \\ -C_1 & -S_1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -LS_1 & LC_1 & 0 & 0 \end{bmatrix}$$

Thus,

$$Tr(d_{11} I_1 d_{11}^{\ T}) = \frac{1}{12} m_1 \left[25L_1^2 + w_1^2\right] \quad 3.61$$

And

$$Tr(d_{21} I_2 d_{21}^{\ T}) =$$

$$\frac{1}{12} m_2 \left\{7L_2^2 + w_2^2 + L_1^2 + 6L_2h_2 + 30L_1L_2C_2 + 6L_1h_2(2C_2 - 3S_2)\right\} \quad 3.62$$

Similarly,

$$M_{22} = Tr(d_{22} I_2 d_{22}^{\ T})$$

$$d_{22}I_2d_{22}^T = \begin{bmatrix} -S_{12} & -C_{12} & 0 & -L_2S_{12} \\ C_{12} & -S_{12} & 0 & L_2C_{12} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$m_2 \begin{bmatrix} \frac{1}{24}\left(L_2^2 + h_2^2 + 2w_2^2\right) & 0 & 0 & \frac{L_2}{2} \\ 0 & \frac{1}{24}\left(L_2^2 - h_2^2\right) & 0 & \frac{h_2}{2} \\ 0 & 0 & \frac{1}{24}\left(h_2^2 - L_2^2\right) & \frac{w_2}{2} \\ \frac{L_2}{2} & \frac{h_2}{2} & \frac{w_2}{2} & 1 \end{bmatrix} \qquad d_{22}^T$$

$$Tr(d_{22}I_2d_{22}^T) = \frac{1}{12}m_2\left[25L_2^2 + w_2^2\right] \qquad 3.63$$

The coupling inertia coefficients are computed as

$$M_{12} = M_{21} = Tr(d_{22}I_2d_{21}^T)$$

$$d_{22}I_2d_{21}^T = \begin{bmatrix} -S_{12} & -C_{12} & 0 & -L_2S_{12} \\ C_{12} & -S_{12} & 0 & L_2C_{12} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} m_2 \begin{bmatrix} \frac{1}{24}\left(L_2^2 + h_2^2 + 2w_2^2\right) & 0 & 0 & \frac{L_2}{2} \\ 0 & \frac{1}{24}\left(L_2^2 - h_2^2\right) & 0 & \frac{h_2}{2} \\ 0 & 0 & \frac{1}{24}\left(h_2^2 - L_2^2\right) & \frac{w_2}{2} \\ \frac{L_2}{2} & \frac{h_2}{2} & \frac{w_2}{2} & 1 \end{bmatrix} d_{21}^T$$

$$Tr(d_{22}I_2d_{21}^T) = \frac{1}{12}m_2\left[25L_2^2 + w_2^2 + 6L_1L_2C_2 - 6L_1h_2S_2\right] \qquad 3.64$$

From the inertia coefficients obtained above, the inertia matrix for leg 1 of quadruped walking robot is,

$$M(\ddot{\theta}) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \qquad 3.65$$

The Coriolis and centrifugal force coefficients (or velocity coupling coefficients), H_{ijk} for i, j, k = 1, 2 are obtained using Equation (3.50),

$$H_{ijk} = \sum_{p=\max(i,j,k)}^{n} Tr\left[\frac{\partial(d_{pk})}{\partial q_p} I_p d_{pi}^T\right]$$

For Equations (3.53) and (3.57) & (3.58), the centrifugal acceleration coefficients are

$H_{111} = 0$

$H_{122} = Tr\left({}^0T_1 Q_2\, {}^1T_1 Q_2\, {}^1T_2 I_2 d^T{}_{21}\right)$

Where, ${}^0T_1\,{}^1T_2 = {}^0T_2$ and,

$${}^1T_0 = \left[{}^0T_1\right]^{-1} = \begin{bmatrix} \left({}^0T_1\right)^T & & & -\left({}^0T_1\right)^T D_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_1 & S_1 & 0 & -L \\ -S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^1T_1 = {}^1T_0\,{}^0T_1 = \begin{bmatrix} C_1 & S_1 & 0 & -L \\ -S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_1 & -S_1 & 0 & LC_1 \\ S_1 & C_1 & 0 & LS_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^1T_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$${}^0T_1.Q_{2.}\,{}^1T_1.Q_2\,{}^1T_2 = \begin{bmatrix} -C_{12} & S_{12} & 0 & -L_2C_{12} \\ -S_{12} & -C_{12} & 0 & -L_2S_{12} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$H_{122} = Tr({}^0T_1.Q_{2.}\,{}^1T_1.Q_2\,{}^1T_2.I_2.d_{21}{}^T) = \begin{bmatrix} -C_{12} & S_{12} & 0 & -L_2C_{12} \\ -S_{12} & -C_{12} & 0 & -L_2S_{12} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} .I_2.d_{21}{}^T$$

$$H_{122} = Tr({}^0T_1.Q_{2.}\,{}^1T_1.Q_2\,{}^1T_2.I_2.d_{21}{}^T) = \frac{-m_2}{2}\left[-L_1L_2S_2 + L_1h_2C_2\right] \qquad 3.66$$

Similarly

$$H_{211} = Tr({}^0T_0.Q_{1.}\,{}^0T_0.Q_1\,{}^0T_2.I_2.d_{22}{}^T) = \begin{bmatrix} -C_{12} & S_{12} & 0 & -L_2C_{12} - L_1C_1 \\ -S_{12} & -C_{12} & 0 & -L_2S_{12} - L_1S_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} .I_2.d_{22}{}^T$$

$$H_{211} = Tr({}^0T_0Q_1\,{}^0T_0Q_1\,{}^0T_2I_2d_{22}{}^T) = -\frac{m_2}{2}\left[-L_1L_2S_2 - L_1h_2C_2\right] \qquad 3.67$$

H_{222}=0 3.68

And the Coriolis acceleration coefficients are,

$$H_{112} = H_{121} = Tr({}^0T_1.Q_{2.}\,{}^1T_1.Q_2\,{}^1T_2.I_2.d_{21}{}^T)$$
$$= \frac{-m_2}{2}\left[-L_1L_2S_2 + L_1h_2C_2\right]$$

3.69

$$H_{212} = H_{221} = Tr({}^0T_0Q_1\,{}^0T_1Q_2\,{}^1T_2I_2d_{22}{}^T) = 0 \qquad 3.70$$

The Coriolis and centrifugal coefficient terms are computed using the series summation.

For i= 1, $H_1 = \sum_{J=1}^{2}\sum_{K=1}^{2} H_{1jk}\dot{\theta}_j\dot{\theta}_k = H_{111}\dot{\theta}_1^{\,2} + H_{112}\dot{\theta}_1\dot{\theta}_2 + H_{122}\dot{\theta}_2^{\,2}$

$$H_1 = \frac{-m_2L_1}{2}\left(h_2C_2 - L_2S_2\right)[\dot{\theta}_1\dot{\theta}_2 - \dot{\theta}_2^{\,2}]$$

And for i = 2, $H_2 = \sum_{J=1}^{2}\sum_{K=1}^{2} H_{2jk}\dot{\theta}_j\dot{\theta}_k = H_{211}\dot{\theta}_1^{\,2} + H_{212}\dot{\theta}_1\dot{\theta}_2 + H_{222}\dot{\theta}_2^{\,2}$

$$H_2 = \frac{m_2L_1}{2}\left[L_2S_2 + h_2C_2\right]\dot{\theta}_1^{\,2}$$

Thus, the Coriolis and centrifugal coefficient matrix H is, therefore,

$$H(\theta,\dot{\theta}) = \begin{bmatrix} H1 \\ H2 \end{bmatrix}$$

It is applied to compute the gravity loading at the two joints. From Equations (3.51) and Equations (3.59) to (3.62),

$$G_1 = -\left(m_1gd_{11}\,{}^1\bar{r}_1 + m_1gd_{21}\,{}^2\bar{r}_2\right)$$

The mass of the links has been assumed to be concentrated at the centroid of the links. The centroid is located from the origins of frame {1} and frame {2} as follows-

$${}^{1}\bar{r}_1 = [\bar{x}_i \quad \bar{y}_i \quad \bar{z}_i \quad 1]^T$$

$${}^{1}\bar{r}_1 = \begin{bmatrix} \frac{L_1}{2} & \frac{h_1}{2} & \frac{w_1}{2} & 1 \end{bmatrix}^T$$

$${}^{1}\bar{r}_1 = \begin{bmatrix} \frac{L_1}{2} \\ \frac{h_1}{2} \\ \frac{w_1}{2} \\ 1 \end{bmatrix}$$

Similarly,

$${}^{2}\bar{r}_2 = [\bar{x}_i \quad \bar{y}_i \quad \bar{z}_i \quad 1]^T$$

$${}^{2}\bar{r}_2 = \begin{bmatrix} \frac{L_2}{2} & \frac{h_2}{2} & \frac{w_2}{2} & 1 \end{bmatrix}^T$$

$${}^{2}\bar{r}_2 = \begin{bmatrix} \frac{L_2}{2} \\ \frac{h_2}{2} \\ \frac{w_2}{2} \\ 1 \end{bmatrix}$$

And the gravity is in negative y-direction giving g_1= [0 -g 0 0]

Hence,

$$m_1 g d_{11}\, {}^{1}\bar{r}_1 = m_1 [0 \quad -g \quad 0 \quad 0] \begin{bmatrix} -S_1 & -C_1 & 0 & -L_1C_1 \\ C_1 & -S_1 & 0 & L_1S_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} L_1/2 \\ h_1/2 \\ w_1/2 \\ 1 \end{bmatrix}$$

$$mgd_{11}\, {}^{1}\bar{r}_1 = \frac{-m_1 g}{2} [L_1(C_1 + 2S_1) - S_1 h_1] \qquad 3.71$$

Similarly,

$$m_1 g d_{12}{}^2\bar{r}_2 = m_1[0 \quad -g \quad 0 \quad 0]\begin{bmatrix} -S_{12} & -C_{12} & 0 & -L_2S_{12}+L_1S_1 \\ C_{12} & -S_{12} & 0 & L_2C_{12}+L_1C_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} L_2/2 \\ h_2/2 \\ w_2/2 \\ 1 \end{bmatrix}$$

$$m_1 g d_{12}{}^2\bar{r}_2 = \frac{-m_1 g}{2}[3C_{12}L_2 + 2C_1L_1 - h_2S_{12}] \qquad 3.72$$

By putting the value of Eq. (3.62) and Eq. (3.63) in the following equation, we get

$$G_1 = -\left(m_1 g d_{11}{}^1\bar{r}_1 + m_1 g d_{21}{}^2\bar{r}_2\right)$$

$$G_1 = -\frac{m_1 g}{2}\left(3C_{12}L_2 + 3C_1L_1 + 2S_1 - h_1S_1 - h_2S_{12}\right) \qquad 3.73$$

Similarly, we calculate G_2

$$G_2 = -\left(m_2 g d_{22}{}^2\bar{r}_2\right) \qquad 3.74$$

$$m_2 g d_{22}{}^2\bar{r}_2 = m_2[0 \quad -g \quad 0 \quad 0]\begin{bmatrix} -S_{12} & -C_{12} & 0 & -L_2S_{12} \\ C_{12} & -S_{12} & 0 & L_2C_{12} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} L_2/2 \\ h_2/2 \\ w_2/2 \\ 1 \end{bmatrix}$$

$$G_2 = m_2 g d_{22}{}^2\bar{r}_2 = -\frac{m_2 g_2}{2}\left(3C_{12}L_2 - S_{12}h_2\right) \qquad 3.75$$

The complete dynamic model is obtained in the final step by substituting the above results. The equation of motion in the vector-matrix form is,

$$\begin{bmatrix} \tau 1 \\ \tau 2 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}\begin{matrix} \ddot{\theta}1 \\ \ddot{\theta}2 \end{matrix} + \begin{bmatrix} H1 \\ H2 \end{bmatrix} + \begin{bmatrix} G1 \\ G2 \end{bmatrix}$$

Above equation known as EOM of R-R configuration for quadruped walking robot which are similar for all four legs.

3.5 Analytical results of mathematical Modeling

A brief description of the equation of motion is formulated which provides the torque values of the single leg of the four-legged robot model. The torque values of single leg is computed on the basis of model’s parameters (dimensions and masses), are shown in Table (3.2). These parameters are similar to rest of three legs. The parameters of four-legged robot are similar to the small-sized dog and it is about half the dimensions and a third of the mass of the Big-Dog robot [5].

TABLE 3.2 Model's parameters of single leg of the four-legged robot

SL. No.	Model Parameters	Variables	Value
1	Length of Upper leg	L_1	0.06m
2	Length of Lower leg	L_2	0.09m
3	Mass of Upper leg	m_1	0.08355Kg
4	Mass of Lower leg	m_2	0.034776Kg
5	Width of prismatic link of upper and lower leg	w_1=w_2	0.025m
6	Height of prismatic link of upper and lower leg	h_1=h_2	0.025m

The equation of motion is characteristically generated using mathematical modeling and the resultant terms are converted into MATLAB to solve for the forward dynamics. The equation of motion is solved numerically using Lagranges-Euler equation and transferred into MATLAB to find torque of each joints of the four-legged walking robot with different-different angle.

TABLE 3.3 Torque values of the single leg of four-legged robot

SL No	Upper limb				Lower limb			
	Hip Joint angle (θ)	Angular Velocity of upper leg (rad/s)	Angular Acceleration of upper leg (rad/s^2)	Torque (N-m)	Knee Joint angle (θ)	Angular Velocity of upper leg (rad/s)	Angular Acceleration of upper leg (rad/s^2)	Torque, (N-m)
1	0	0	0	0.037	0	0	0	0.0153
2	-30	-0.24	0	0.0106	30	0.24	0	0.0150

At initial positions of the single leg (hip joint angle=knee joint angle=0^0), as specified in Table (3.3), the initial velocity and acceleration of the joints are taken zero for an event function which stopped the robot and at that time, all legs on ground. These values of torque during standing position and moving position are an important factor for selection of servo motors.

The model is designed, using SOLIDWORKS-2015; a commercial and general purpose multi-body dynamics software. The model is designed based on the given parameters i.e. moments of inertia, masses, and initial body translational and angular velocities.

3.6 Gait analysis

A gait cycle is an important factor because of its effect on all parameters during locomotion. In our case, we focus on trot gait for robot model which is an improvement gait cycle because of their stability during locomotion and the leg's segment during locomotion shown in Figure (3.4). The left foreleg and the right hind leg are in support position when the right front leg and the left hind leg are in swing position.

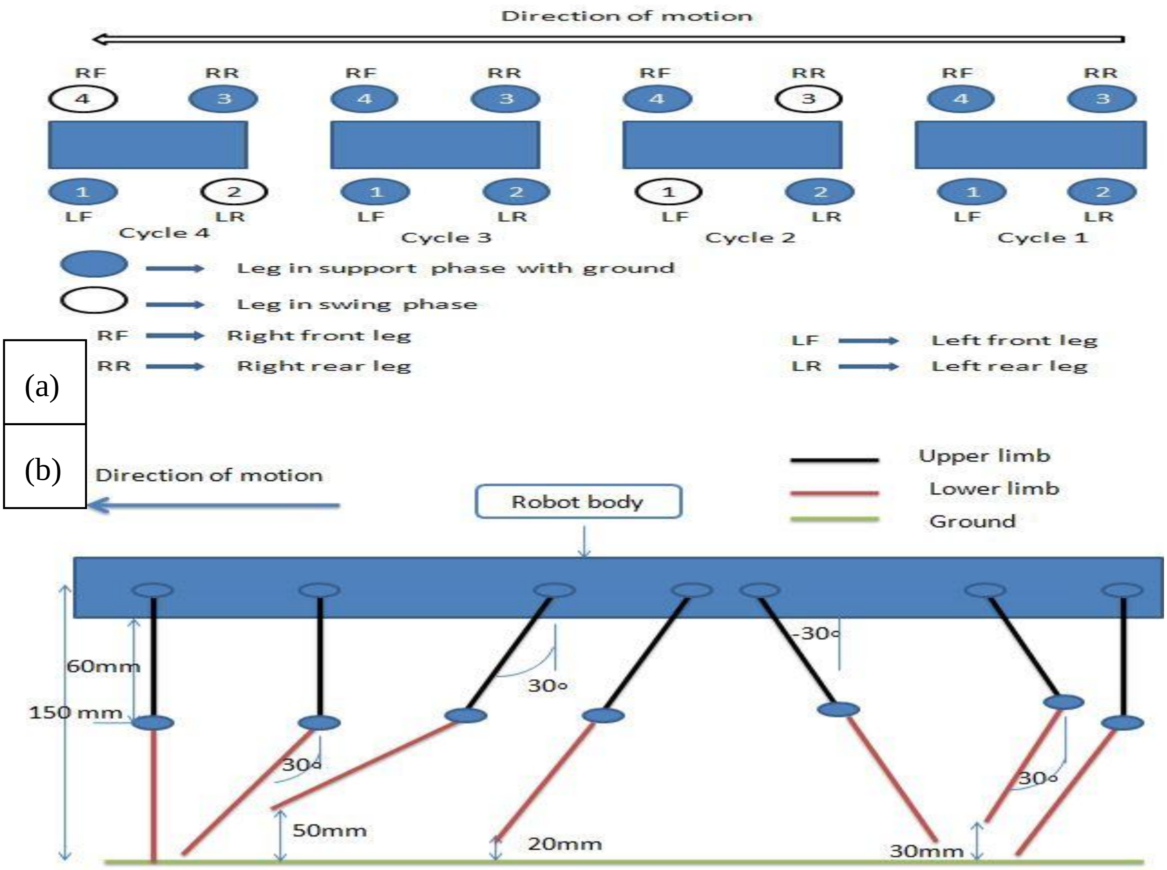

Fig. 3.4 (a) Trot gait locomotion planning of four-legged walking robot, (b) Trot gait segments of single leg of four-legged walking robot.

During forward movement of robot, there are different angles followed by robot's leg which are as follows

TABLE 3.4 Trot gait segments of single leg of four-legged robot.

Cycle Time (sec)	1	2	3	4	5	6	7
θ_1 (degree)	0	0	30	30	-30	-30	0
θ_2 (degree)	0	30	30	0	0	30	30

When the robot is in trot gait cycle, at starting, the robot is in standing position at that time, the angle of upper limb and lower limb with respect to the base frame is 0^0 and the height of the robot, from the ground to the base frame is 150 mm, shown in fig. (3.5). when the robot's leg raises as per set angle from Table (3.4), the robot displace back from initial position to 100 mm and then after getting sufficient force , the robot move forward from 100 mm to -78 mm which make a cubical path and at that time the robot height from ground is 130 mm.

During locomotion, trajectory planning plays an important role because of its way from one location to another location along which robot moves in a controlled manner. In trajectory, along with the trace path, at what time of interval (cycle time) and joint angles (θ_1, θ2) each part of the path must be attained by the robot is also mentioned. Trajectory planning involves generating a time sequence of the robot leg endpoint position attained by the robot leg. In this chapter, robot leg is a planar manipulator thus a 2D curve is the appropriate trajectory. Thus trajectory followed by robot leg endpoint is assumed to be semi-ellipse in 2D plane. In trajectory generation, pairs of front legs and rear legs have been assumed to be 200 mm apart. Torso frame of four-legged robot is maintained at 150 mm from the ground. Cubical trajectory is shown in figure (3.5) below.

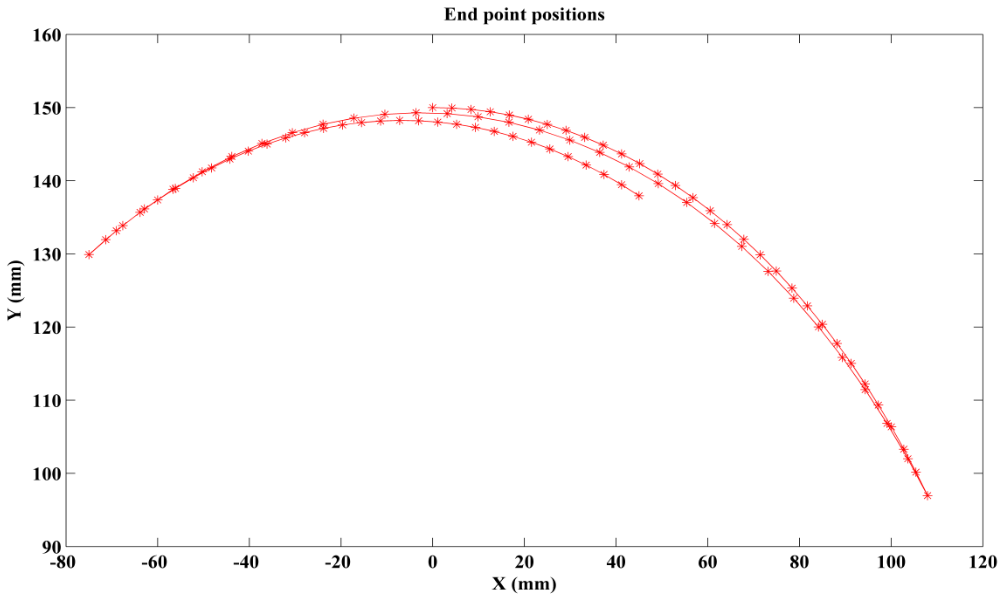

Fig. 3.5 End point positions of single leg during locomotion

To select actuation system for the four-legged robot it is required to estimate the joint torques which varied with joint angles from Table (3.4) i.e. required for locomotion. In this research work, joint torques has been calculated when four-legged robot is stationary and when it performs forward locomotion using trot gait. For calculations, basic principles in mechanics and robotics have been used. To maintain soft home position while standing, four-legged robot is required to maintain 1.06 kg-cm and 1.015 kg-cm torques in clockwise direction at hip joints of front and rear legs respectively. And it requires maintaining 0.15 kg-cm and 0.13 kg-cm torques in counterclockwise direction at knee joints of front and rear legs respectively. Joint torques for legs 1 & 3 and legs 2 & 4 are similar and calculated for trot gait locomotion are shown in figure (3.6) respectively below.

During locomotion of robot, the actuator of upper limb and lower limb raise maximum current at maximum torques of each limb. These torque values of single leg is similar to rest of three legs of robot model.

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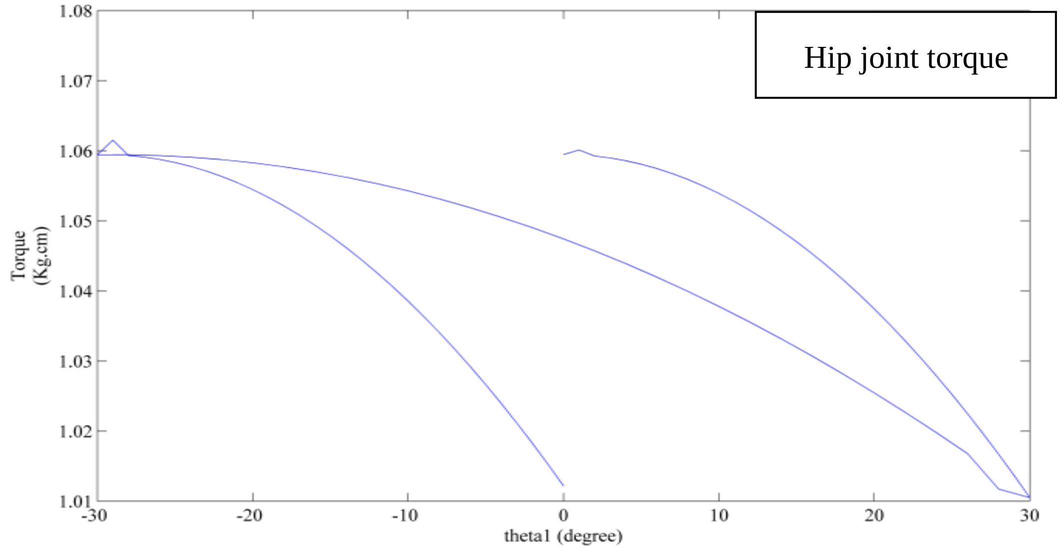


Fig. 3.6 Plot of hip joint angles (θ_1) vs. joint torques of single leg using trot gait throughout locomotion.

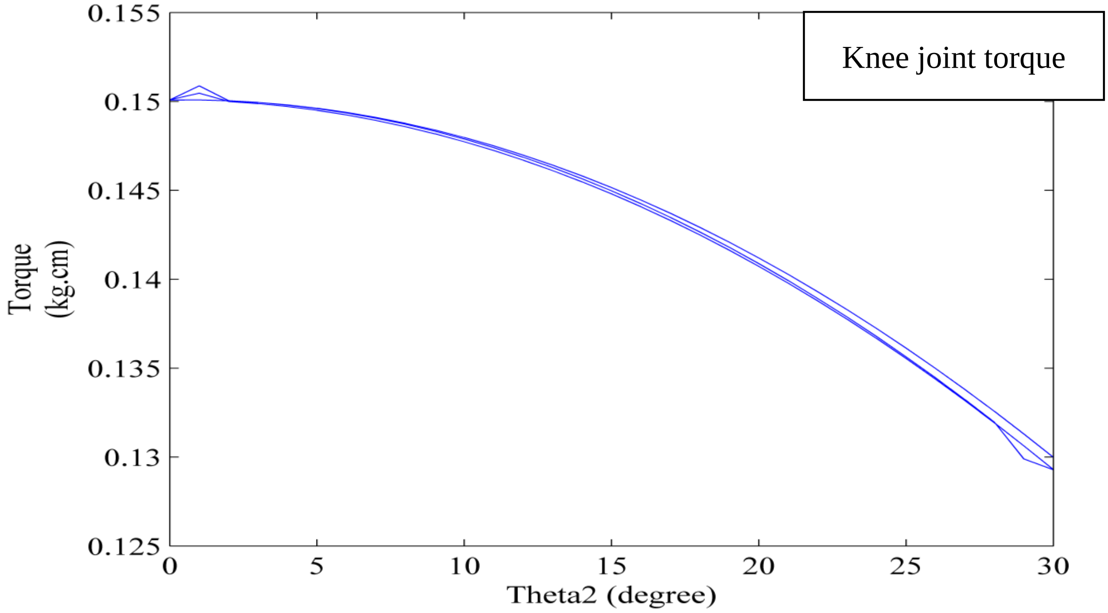


Fig. 3.7 Plot of knee joint angle (θ2) vs. knee torque of single leg using trot gait throughout locomotion

Chapter 4

CAD Model and Simulation

4.1 Introduction

Before the work proceeds from design stage to fabrication stage it is required to develop a CAD model of four-legged robot and then simulate it. In this chapter, CAD model and motion simulation of quadruped robot is developed using SOLIDWORKS-2015 software platform. Development of CAD model helps in fixing dimensions of four-legged robot and calculation of mass properties of four-legged robot.

4.2 3-D Modeling

A mechanical structure of four-legged robot is drafted in SOLIDWORKS-2015. There are some important parts of four-legged robot with specific dimensions and their use in robot model, discuss below-

Torso frame/base frame

The design of torso frame or base frame is inspired from mammals like Dog, Cat, etc. They are characterized on the basis of their torso frame/base frame’s dimensions (length, width & height). In our project, the torso frame/base frame is drafted in design software with dimensions i.e. 300x180x5 mm. There are 4 hip joints’ servo motors (2 for front legs and 2 for rear legs) attached with torso frame.

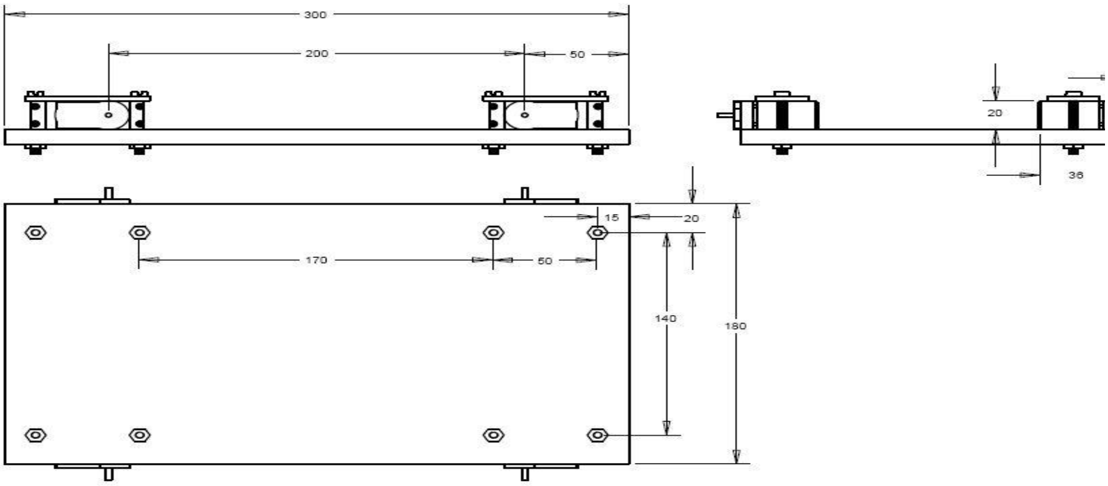


Fig. 4.1 Torso frame/base frame

Leg segments

The leg design of four-legged robot is inspired from mammal's leg configuration which is based on its leg ratio (lower limb length/ upper limb length). There are two leg segments (upper limb and lower limb) required for each leg. From Chapter 2, the leg ratio changes with mammal's leg segments, most of case it is varied from 1.35 to 1.85. The upper limb length is taken from hip joint to knee joint, whereas, the lower limb length taken from knee joint to ground contact. In this project, leg ratio of four-legged robot is 1.5 where upper limb length is 60 mm and lower limb length is 90 mm.

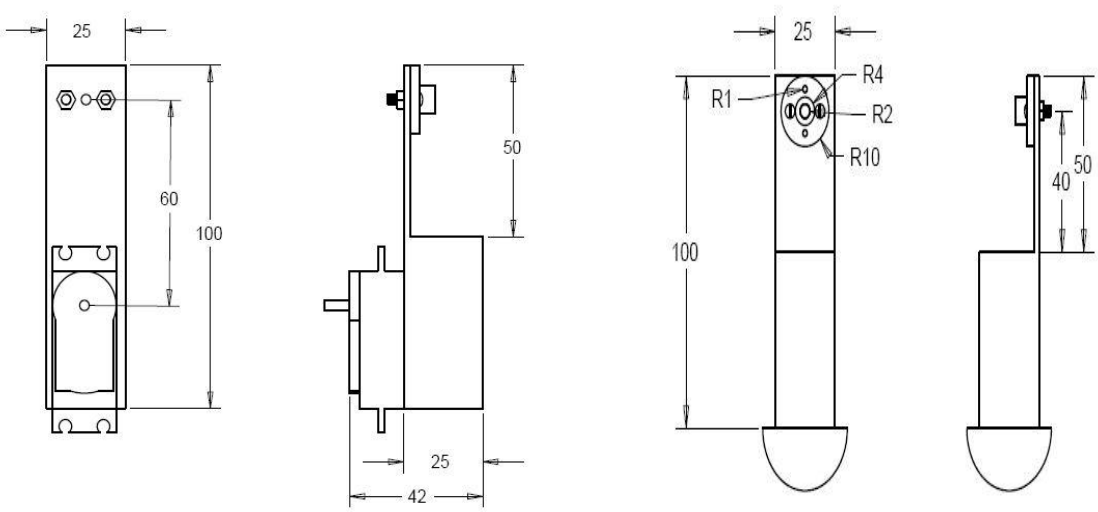


Fig. 4.2 Upper limb and lower limb of four-legged robot

Assembly of leg segments

From figure (4.3), upper limb is attached with motor which has outer spline on its shaft whereas lower limb is attached with a coupler disk which has internal spline. For the assembly of leg segments, the coupler disk's internal spline is attached with the shaft's outer spline . After the attachment of leg segments, it is tightened by a screw of M3x5 mm.

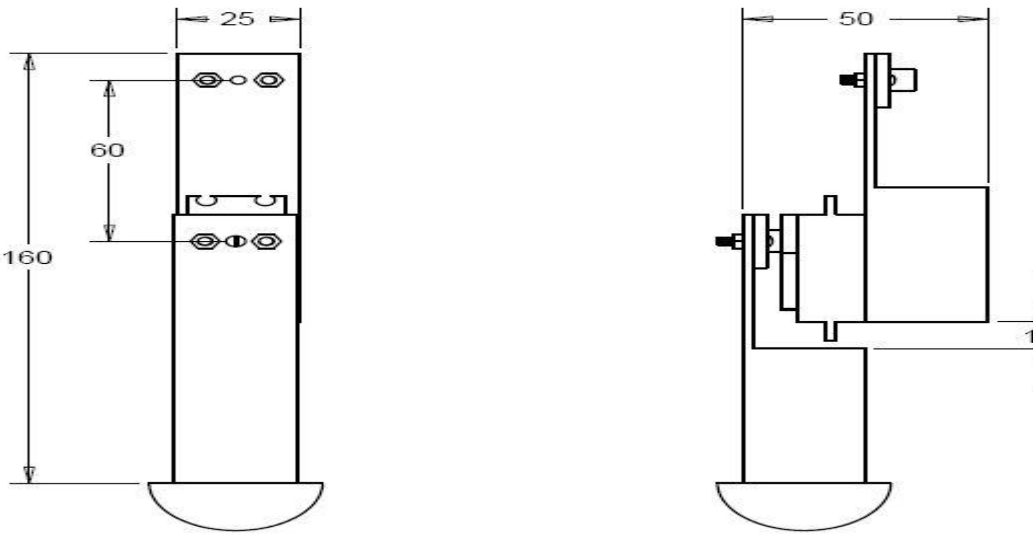


Fig. 4.3 Assembly of legged model

Assembly of four-legged robot model

The assembled model of four-legged robot is required a torso frame/base frame, leg segments. Each leg segments is required two servo motors for locomotion. The first motor drives a hip joint giving to and fro motion of the torso frame/base frame, known as upper limb, Similarly the second motor drives a knee joint creating an up and down motion on the torso, known as lower limb. The hip and knee joints are connected to the servo motors by the use of upper limb and lower limb. The limbs are connected with the help of coupler disk which is mounted on motor's shaft. By simply changing the design parameters in the software, it is able to ensure the motion of the system worked as per requirement.

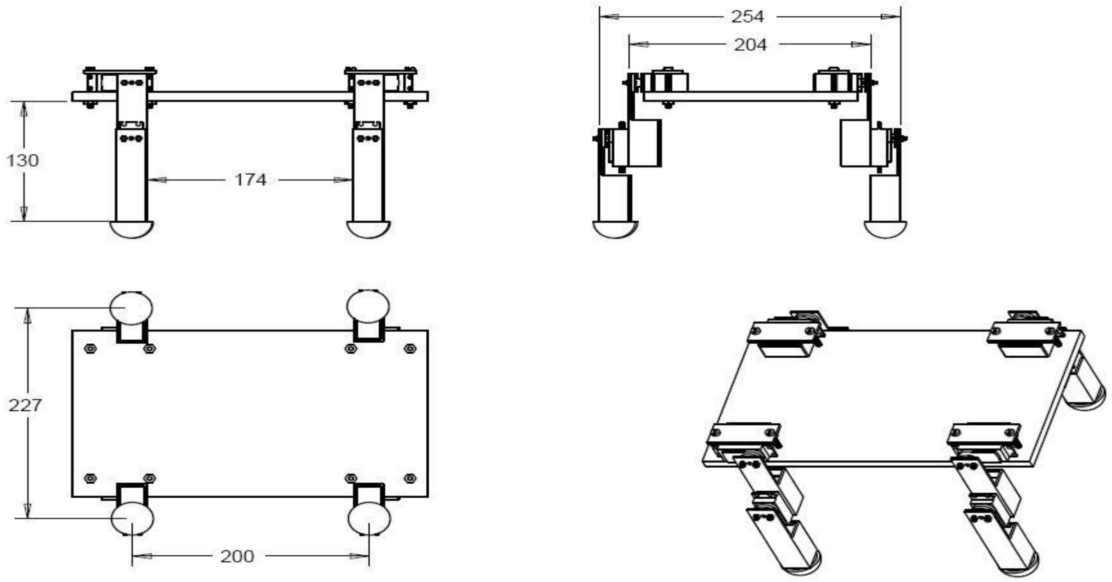


Fig. 4.4 CAD-Model of the mechanical structure

4.3 Motion simulation

The motion simulation of four-legged robot is based on flow chart which is shown in Figure (4.5). During robot simulation, firstly the mathematical modeling give the equation of motion which is used to get torque values of each rotary joint actuated by servo motors. Secondary, on the basis of each leg's parameters of four-legged walking robot (torques, joint angles, angular velocities, angular accelerations, etc.), implementing of programming for actuators and at last for desired gait cycle (trot gait), implementation of simulation phase in SOLIDWORKS-2015 design software.

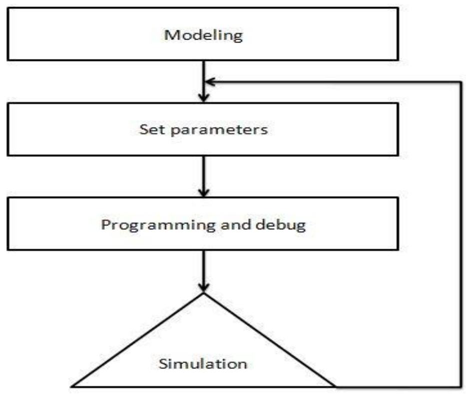
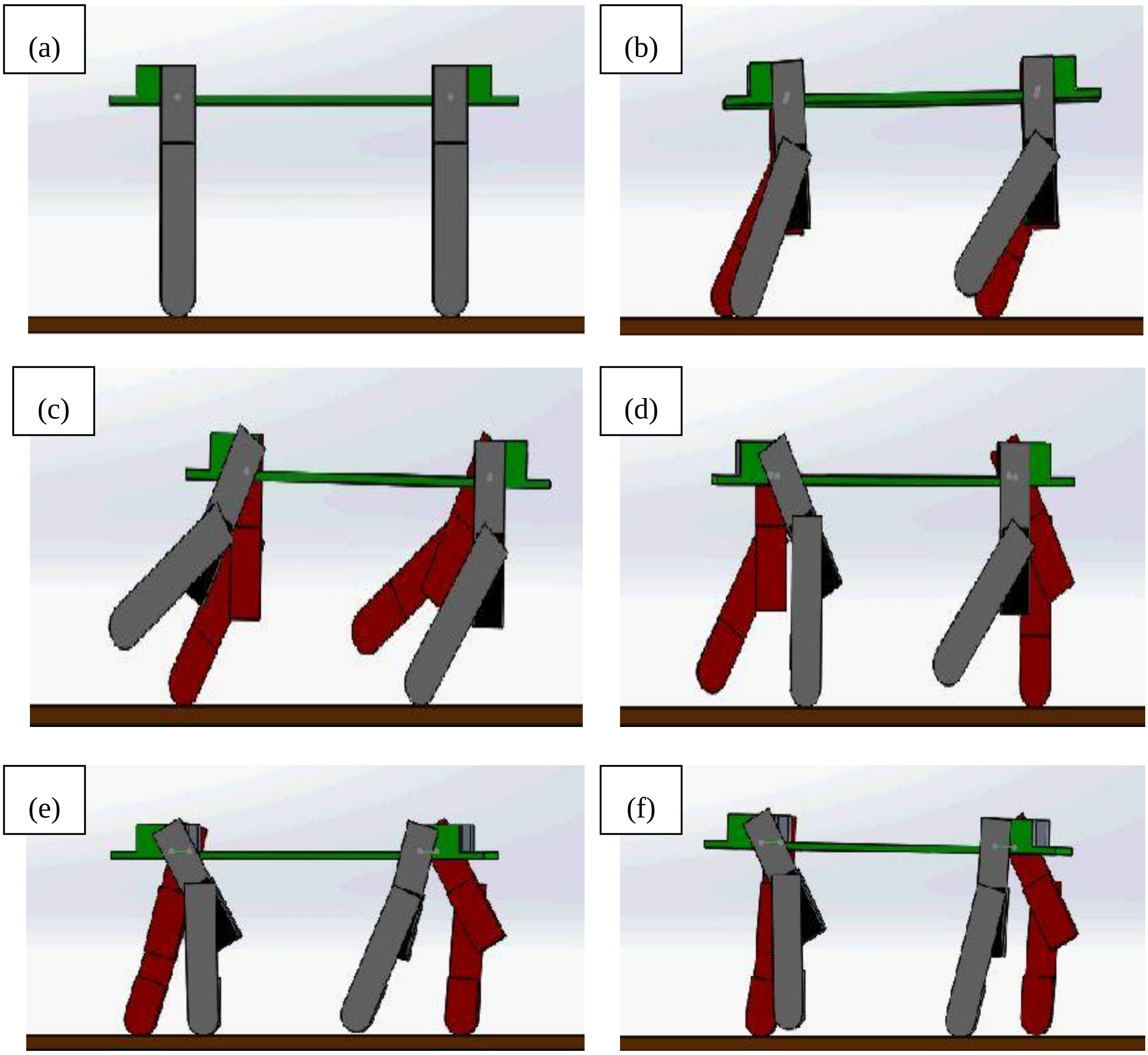


Fig. 4.5 Flow chart of motion simulation [21]

4.3.1 Motion analysis of trot gait

Motion analysis of trot gait shows the position of leg segments during locomotion which is shown in figure (4.6). With the improvement of stability factor during locomotion, leg segment's motion is carried out on the basis of angle of motion. During locomotion, the left front leg and the right rear leg are in support position when the right front leg and the left rear leg are in swing position.

When the robot is in trot, the highest height of leg raise above the earth h = 0.05 m. Hip joint's swing amplitude Ah is 30∘ and knee joint's swing amplitude Ak is 30∘ as the same theory.



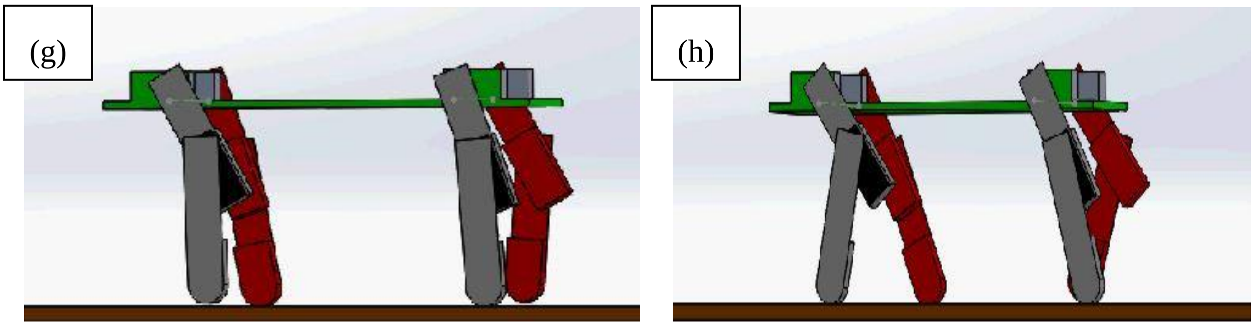
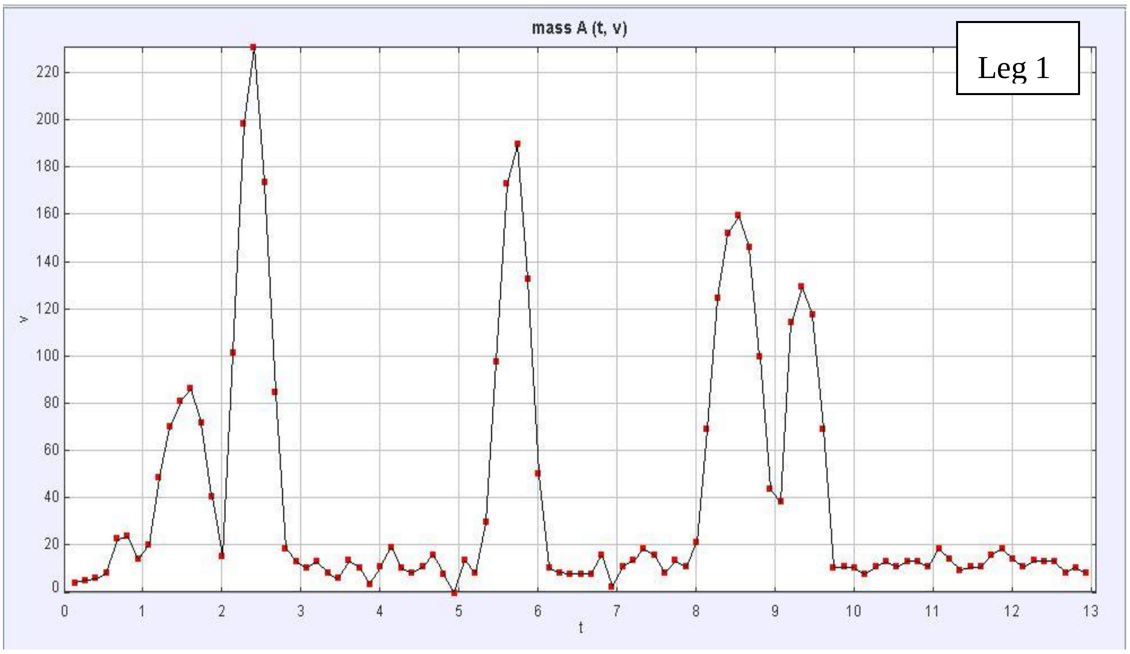


Fig. 4.6 Trot gait simulation on flat surface

4.3.2 Typical velocity transitions of legs

The average velocity of leg 1 and leg 3 are v = 0.24 m/s during locomotion whereas for leg 2 and leg 3 are v = 0.18 m/s, with the adjusting time is about 13 second, shown in Figure (4.7) during gait transition of trot. Gait transition is rapid and smooth throughout the walking with specified time



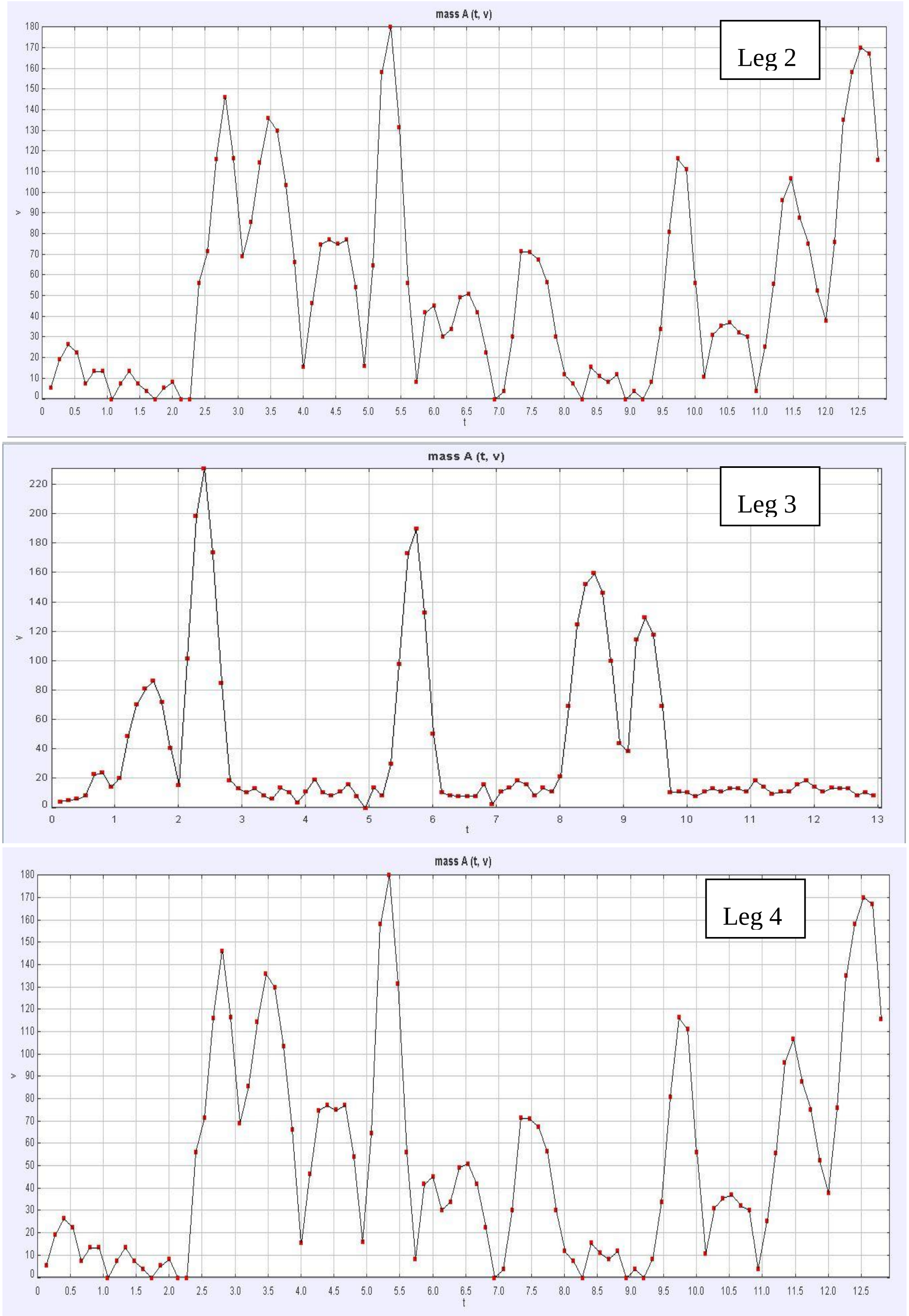


Fig. 4.7 Velocity transitions of trot gait

4.3.3 Stability Simulation

The stability simulation is calculated along the leg length of robot with respect to time, as shown in Figure (4.8) for all legs. The stability of robot decreases when the speed of robot increases. When the speed is up to 1.3v (v = 0.24 ms−1), gaits become disordered because robot's inertia and the impact force of toes increase.

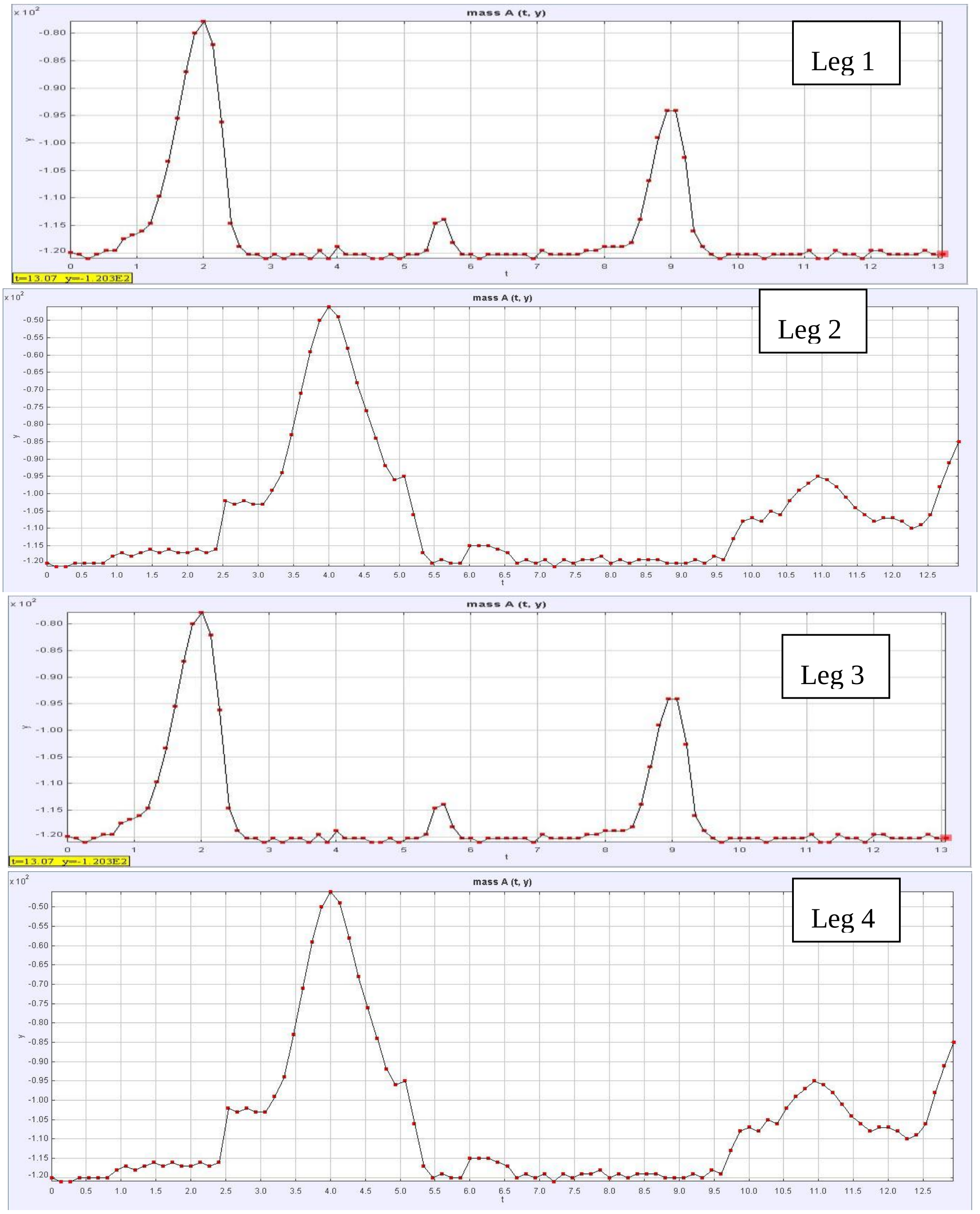


Fig. 4.8 Stability simulation of four-legged robot in y-direction during locomotion

Finally, the robot is in rollover after about one motion cycle. The height of the robot is changes in the direction of y-axis during locomotion which is shown in Figure (4.8).

4.3.4 Real Experiment

For the motion simulation of the four-legged robot over different terrains, it is required to design an assembly including base frame, leg segments and its attachment with base frame, etc in 3D CAD model software, which gives the required layout of the prototype model. After the completion of assembly work, it is simulated in 3D CAD model software viz. SOLIDWORKS-2015. For simulation, it is required to give motors on each joint with required segments, and then after it is simulated in motion analysis with respect to gravity. To evaluate forward motion of the 3D CAD model of the four-legged robot, it is performed some tests under rough terrain using a trot gait. The motion analysis gives the approximate similar cubical trajectory which is found in MATLAB.

Chapter 5

Fabrication and Testing

The CAD model and simulation of the four-legged robot is discussed in Chapter 4 which determines the required dimensions and size of the four-legged robot. On the basis of these parameters, the fabrication work including mechanical structure, electronic circuits and programming is discussed. After completion of the fabrication work, testing of the four-legged robot is performed over different terrains.

5.1 Mechanical structure

Mechanical structure consists of torso frame/base frame, leg segments and their assembly with base frame of the four-legged robot. The fabrication work is completed in the mechanical engineering work-shop. For the mechanical structure, first of all, to prepared a list of the materials, and then began the fabrication process according to list of materials shown in Table (5.1) which are discuss below-

List of the materials of the mechanical structure

TABLE 5.1 List of the materials required for the fabrication

SL. No.	Fabricated parts	Quantity required (Number)	Material/Configuration	Size (mm)	Weight (Kg)
1	Torso/base frame	1	Arcylic sheet	300x180x3	0.01
2	Upper limb	4	Aluminum pipe	100x25x25	0.0823
3	Lower limb	4	Aluminum pipe	100x25x25	0.034
4	Assembled leg	4	Aluminum pipe	150x50x25	0.468

5	Servo motors	8	Metal geared, 180^0 rotation	40x37x20	0.448
6	Torso frame nut/bolts	8	Aluminum	M4x30	
7	Leg's nut/ bolt	16	Aluminum	M3X10	

Torso frame/base frame of mechanical structure

Torso frame/robot body is made of Acrylic material sheet which has certain advantages viz. easily fabricated, low cost, light in weight and better in hardness. There are four servo motor attached as per required dimensions which makes hip joints which is shown in fig. (5.1).

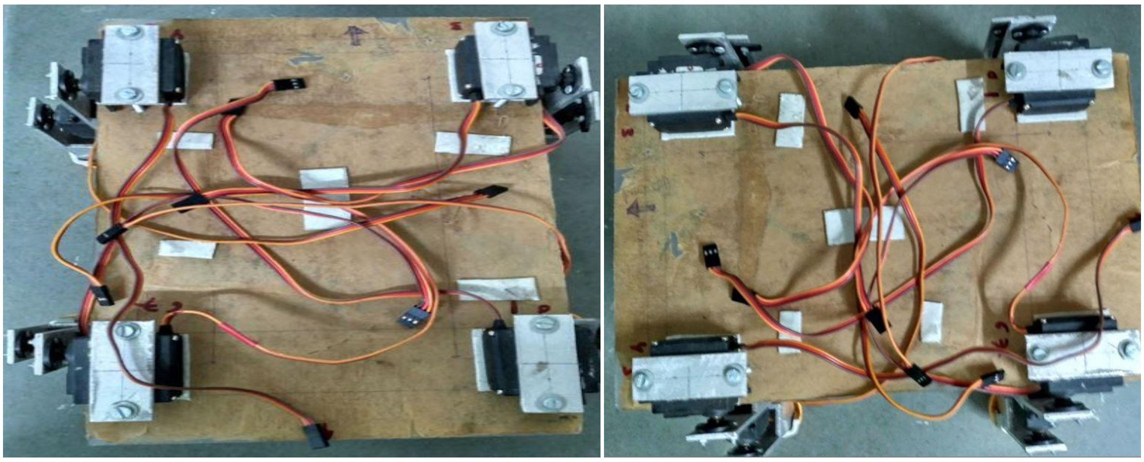


Fig. 5.1 Fabricated model of torso frame/base frame

Upper limb with servo motors

The upper limbs of four-legged robot are fabricated from aluminum pipe which is square in shape. The use of aluminum pipe for leg segments because of its advantages viz. easily available, low cost, easily fabricated and better in strength. Upper limb is assembled with servo motors shown in fig. (5.2) which is used to connect with lower limbs.

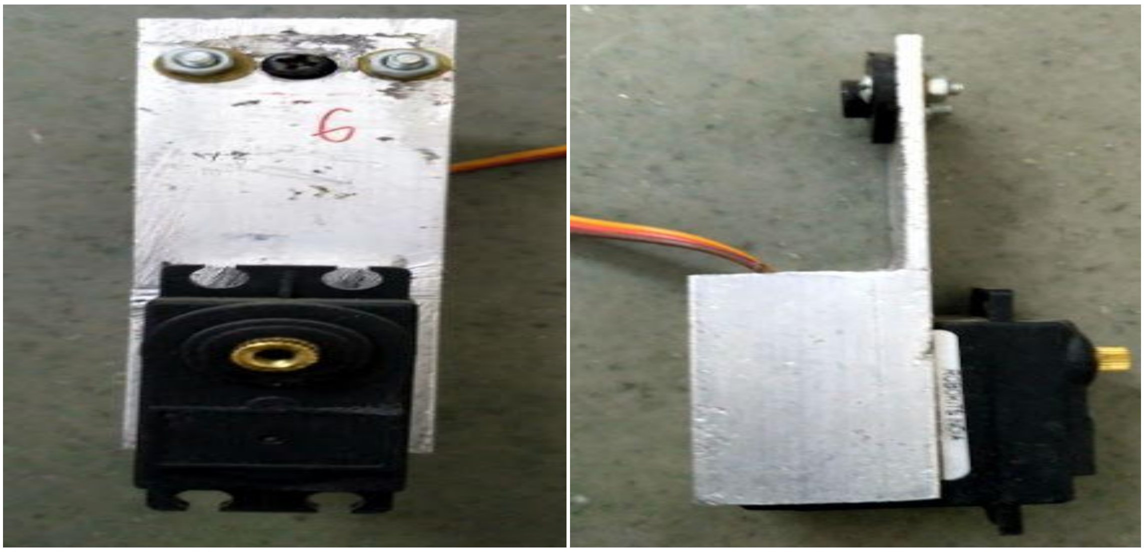


Fig. 5.2 Fabricated model of upper limb

Lower limb

Lower limb is also made from aluminum pipe of square shape and it has similar mechanical properties as upper limb. It is used to give up and down motion to the robot body during locomotion, shown in fig. (5.3)

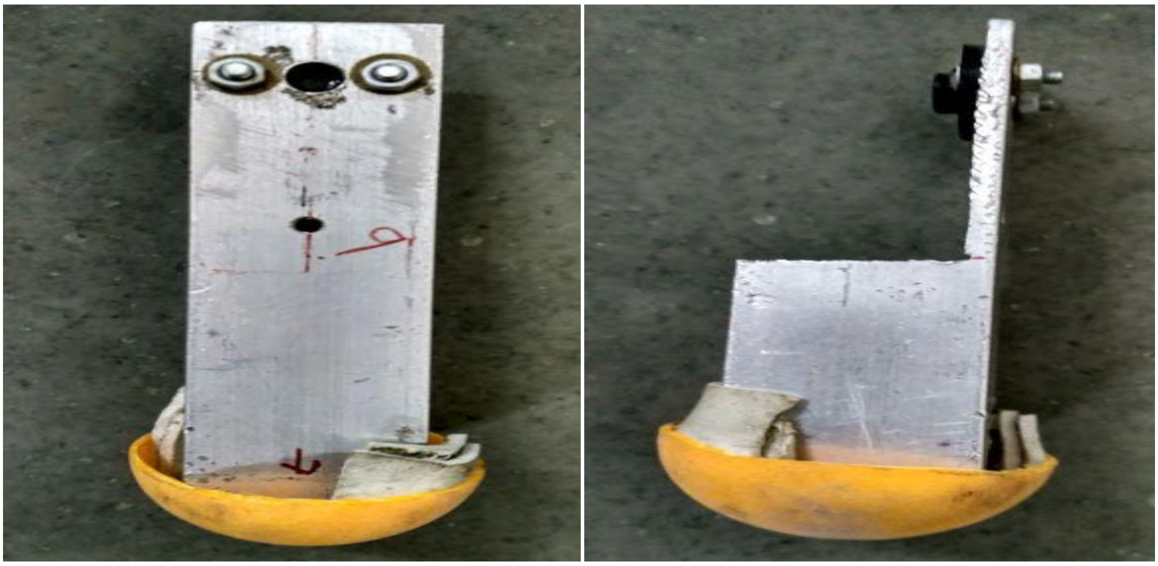


Fig. 5.3 Fabricated model of lower limb

Assembly of leg segments

The lower limb’s internal spline is connected with upper limb’ external spline with the help of coupler disk which is mounted on lower limb, it is shown in fig. (5.4).

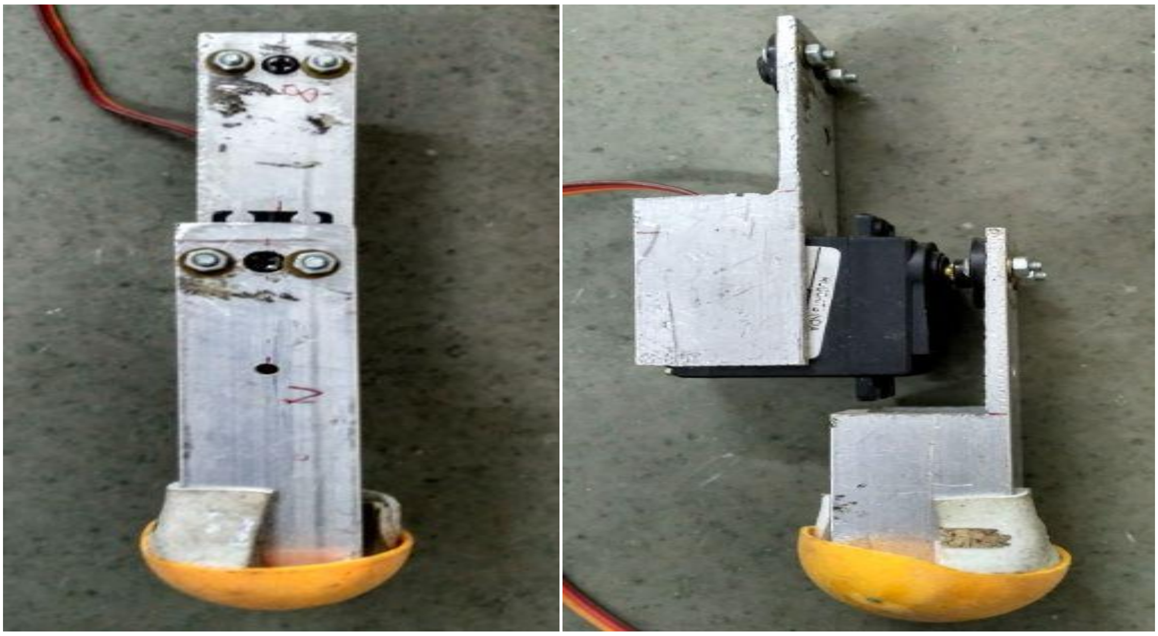


Fig. 5.4 Assembly of leg segments

Assembly of legs with torso frame's servo motor

The assembly is formed by the attachment of internal spline of legs to the external spline of torso frame' servo motor shafts which are shown in fig. (5.5).

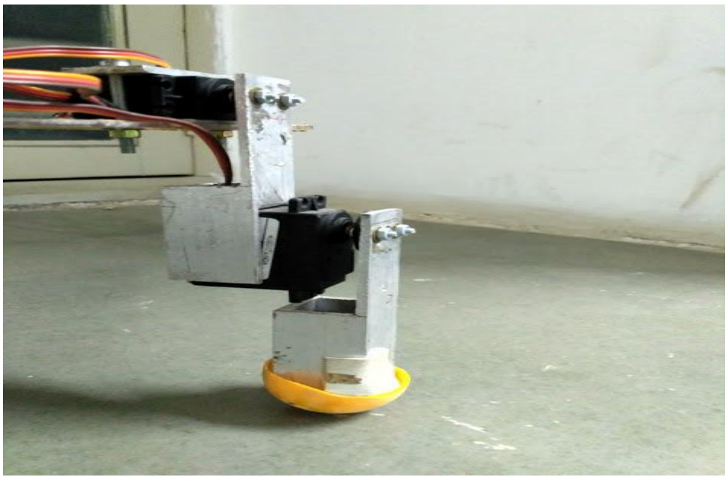


Fig. 5.5 Assembly of leg segment with base frame

Fabricated model of the mechanical structure

The fabrication and assembly of prototype robot is servo motors shaft with the leg's coupler disk. The model of robot including raw materials is manually fabricated in the workshop. During fabrication process, the parts which are discuss in above, is manually crafted. The prototype model of four-legged robot is shown in fig. (5.6).

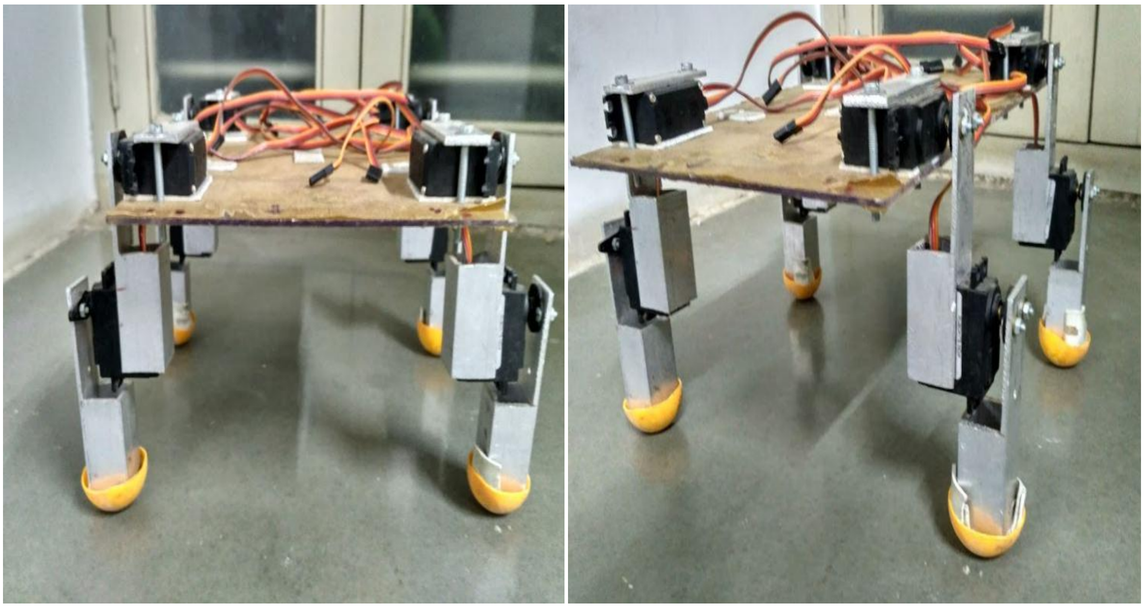


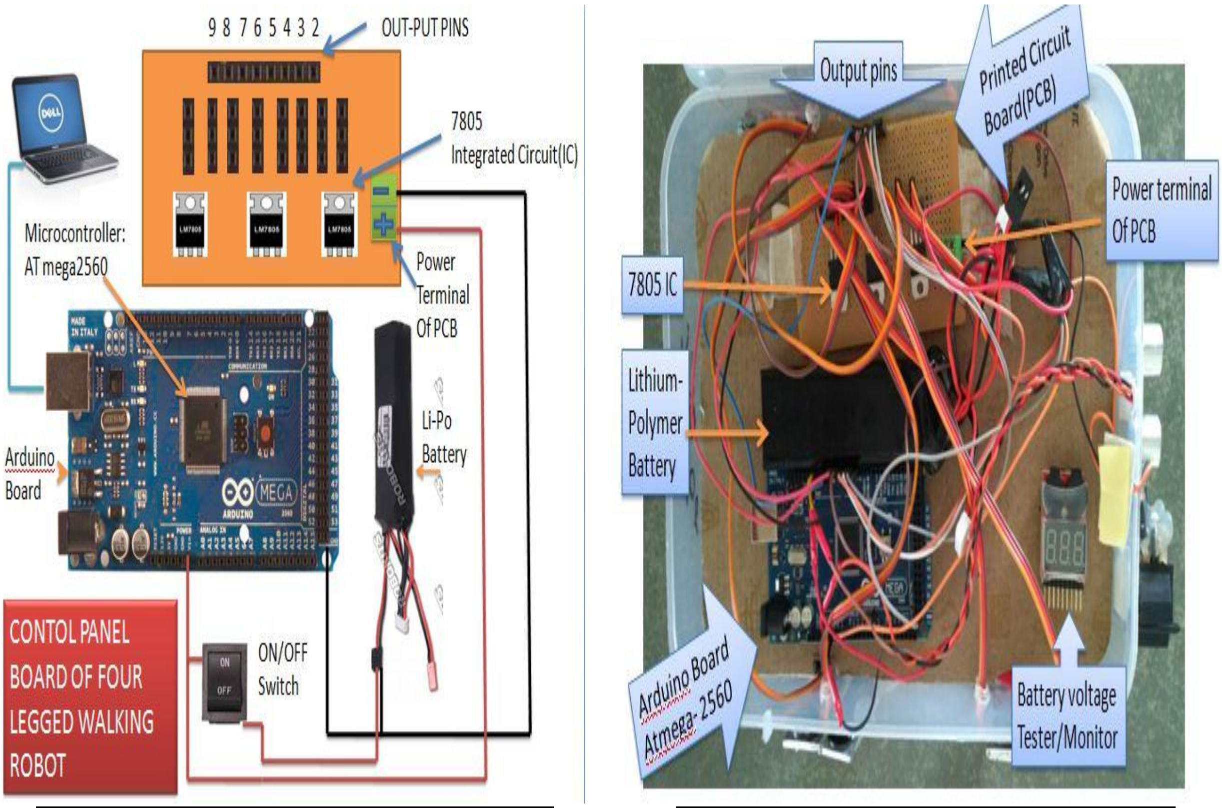
Fig. 5.6 Fabricated model of mechanical structure

5.2 Electronic circuits

Electronic circuits include a control system also known as control panel which is consisting of a controller board, servomotors, printed circuit board (PCB) fabrication and power source.

Control panel board

The control panel is consists of an Arduino controller board which controls all 8 servomotors, shown in fig. (5.7). Each servo motor has separate output pin viz. 2, 3, 4, 5, 6, 7, 8 & 9 which are decided as per Arduino controller board's output pins. A PCB is bridge between servo motors and Arduino controller board. PCB has 8 output pins which are connected with all servo motor's 3-wires pin. Arduino board has 8 output pins which are connected with the 8 input pins of PCB. Arduino board is controlled by programming which is coded in Arduino programming software. Metal geared servomotors are used to actuate the legs. At 4.8 Volts, one such servomotor has stall torque of 11 kg- cm. And at 6 Volts, it has 13 kg-cm stall torque. Servomotor with maximum stall torque little higher than requirement is selected due to losses during its operation. Each of these metal geared servomotors weighs 56 grams. Power sources include Lithium-polymer (Li-Po) of 12 Volts battery which gives 5 Volts to each servomotor, its power controlled by Arduino controller board. Regulated DC power supply also required sometimes because of higher current usage of servomotors.



Design model of control panel board

Actual model of control panel

Fig. 5.7 Control panel board of the four-legged robot

The control panel of electronic circuit is designed from hardware equipments which are discussed below-

List of hardware required for control panel board

TABLE 5.2 List of hardware

SL. No.	Hardware equipment	Quantity	Specification	Weight	Remarks
1	Arduino controller board	1	ATmega2560	5 gm	
2	Li-Po battery	1	12 Volts	30 gm	
3	Servo motors	8	Stall torques of 11 Kg-cm	Each of 56 gm	

4	Integrated circuit (IC) 7805	3	1 Ampere of each IC	-	
5	Ultrasonic sensor	1	Range 4 meter	2 gm	

Controller board

The Arduino Mega-2560 is controller board which has ATmega-2560 microcontroller, shown in fig. (5.8). It has 54 digital I/O pins of which 14 can be used as PWM outputs, 16 analog inputs, 4 UART (hardware serial port), 16 MHz crystal oscillator, an USB connection, a power jack, an ICSP header and a reset button. The board has flash memory of 256KB in which is used 8KB by boot load. The current rating is for DC current per I/O pins of 40Ma and for DC current per 3.3V pin of 50Ma. The controller is timed to utilizing a 20 MHz resonator associated with the oscillator sticks on the ATmega-2560. The MAX-233 level converter chip is utilized to change over TTL rationale to RS-232 flag and the other way around to encourage correspondence between the remote control and the robot.

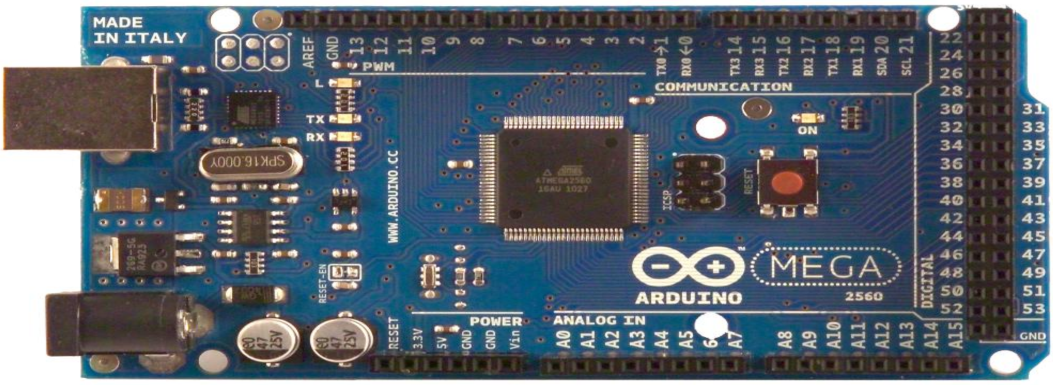


Fig. 5.8 Arduino control board [22]

Servo motor

A servo motor is a DC motor consolidated with position detecting parts which is appeared in fig. (5.9). Servo motor has 3 wires running out from the motor. Two wires are for power and the third wire is for the control input. A pulse width signal is connected to the input which demonstrates the desired position of the motor. The correct connection of pulse width to output shaft location fluctuates by motor display; yet as a standard, all servos moves to the central position with a 1.5 ms input pulse. Inside the servo motor, the segments comprise of a DC motor, a gear train, limits stops, a potentiometer for position feedback and some control hardware. Servo motor works to actualize open loop control system for robots. They expel intricacy from the control system hardware and programming, it is also decrease the aggregate part cost and design time.

Fig. 5.9 Metal geared servo motor [22]

Power source

The four-legged walker is controlled by Lithium-Polymer (Li-Po) battery which is appeared in fig. (5.10). The Li-Po battery is intended for high current drain devices. Because of this way, the motors are drawing a lot of current, the batteries drain rapidly. The battery voltage is decreased it, caused the microcontroller to execute a brown out reset. To cure this issue, Li-Po battery bank is utilized. Just a single battery bank is adequate for logical control and furthermore for motor and hardware is control the robot.

Fig. 5.10 Lithium-Polymer battery of 12 volts [22]

Printed circuit board (PCB)

The robot walker hardware is assembled onto a printed circuit board (PCB) as appeared in Figure (5.11). The PCB design is performed to utilizing schematic programming with the capacity to route follows. The PCB is imprinted onto a transparency for masking. A pre-sentilized single-sided copper-clad board is used, created, and scratched to make the custom PCB. The required part is penetrated onto the holes and individual gadgets soldered into their fitting areas.

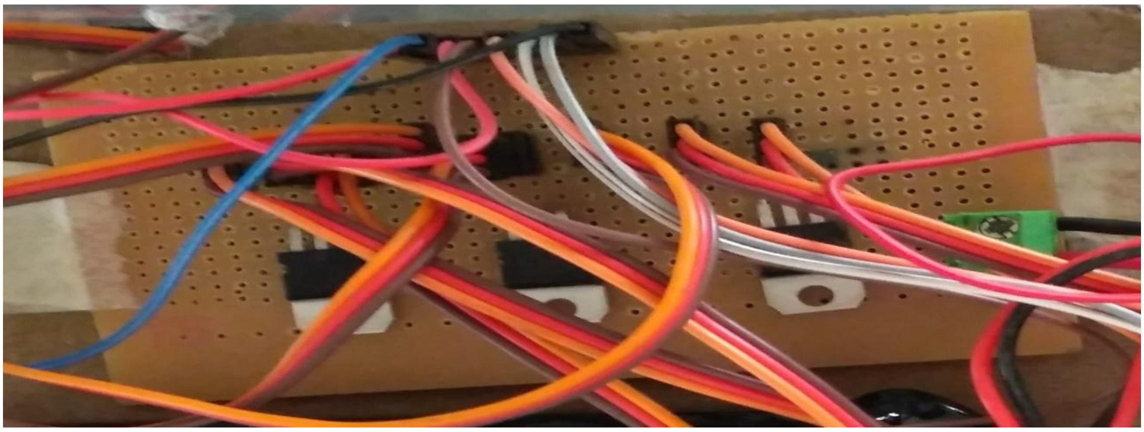


Fig. 5.11 Printed circuit board (PCB) of control panel

Ultrasonic sensor

An ultrasonic sensor is installed on the front of the robot for obstacle avoidance which is shown in fig. (5.11). The Ultrasonic sensor is built to use micro switches with wire extensions to provide adequate reach. By using the servos for the system, the need of the design and implementation of motors are driving circuits where the motor position sensors is removed.

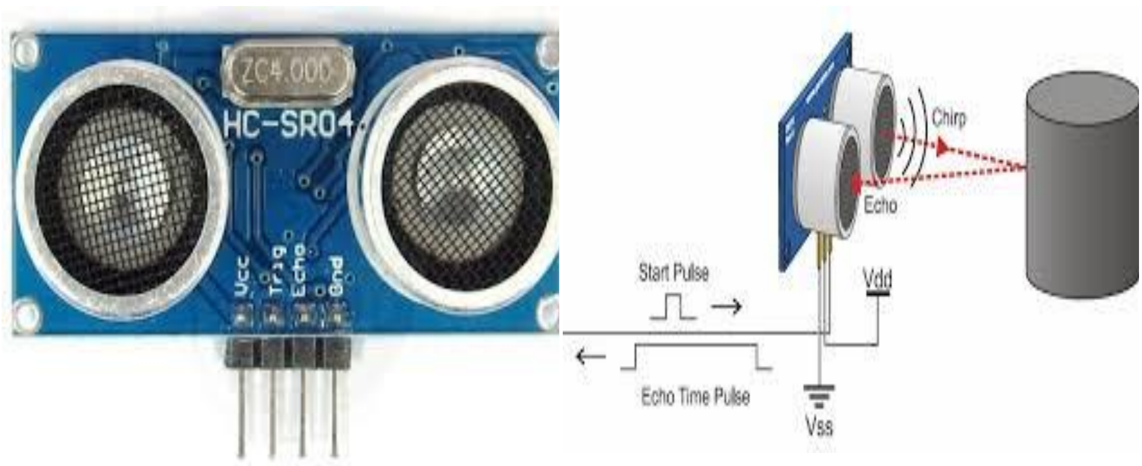


Fig. 5.12 Ultrasonic sensor (HC-SR04) [21]

5.3 Programming

Software includes Arduino programming software. Arduino programming software is available on the Arduino website. A program code is developed in Arduino programming language for trot gait locomotion separately. It is then fed to controller board for use. The Arduino controller board has a PWM signal generator which controls gait cycle. The signal generator is required to control 8 independent output channels each with a variable pulse width for the servo control. Based on the inputs, the gait cycle decides what the leg positions should be to produce desired motion. There are some important aspects for programming of four-legged robot-

Implementation of programming

Programming phase of robot completed with Arduino software where the program is written according to gait cycle which is required for locomotion. At the time of initial condition, the four-legged robot is in standing position at that time each leg have 90^0 angle with respect to the robot body. For end condition, each leg have different range angle for simulating with each other to adjust for locomotion. Following program for initial and end position of eight servo motors.

Eight motors control channels is actualized, utilizing an interrupt on timer with a resolution of 100 mili-secs and 8 digital output pins on the microcontroller. Motor position resolution is not central; however the position must be repeatable. This is on the grounds that the walking movement is constantly done in full strides and the means should dependably be a similar size. A timing resolution of 100 mili-secs is more than satisfactory yielding an accuracy of 30º. Hardware timer interrupts on the Arduino board which is utilized to produce 8 variable pulse width signals. Each pulse width can be autonomously changed from 0 ms to 21 ms in steps of 150µs. The time of each signal is a constant of 21ms. The usage of the flow chart is utilized to deliver the outputs with a single hardware interrupt.

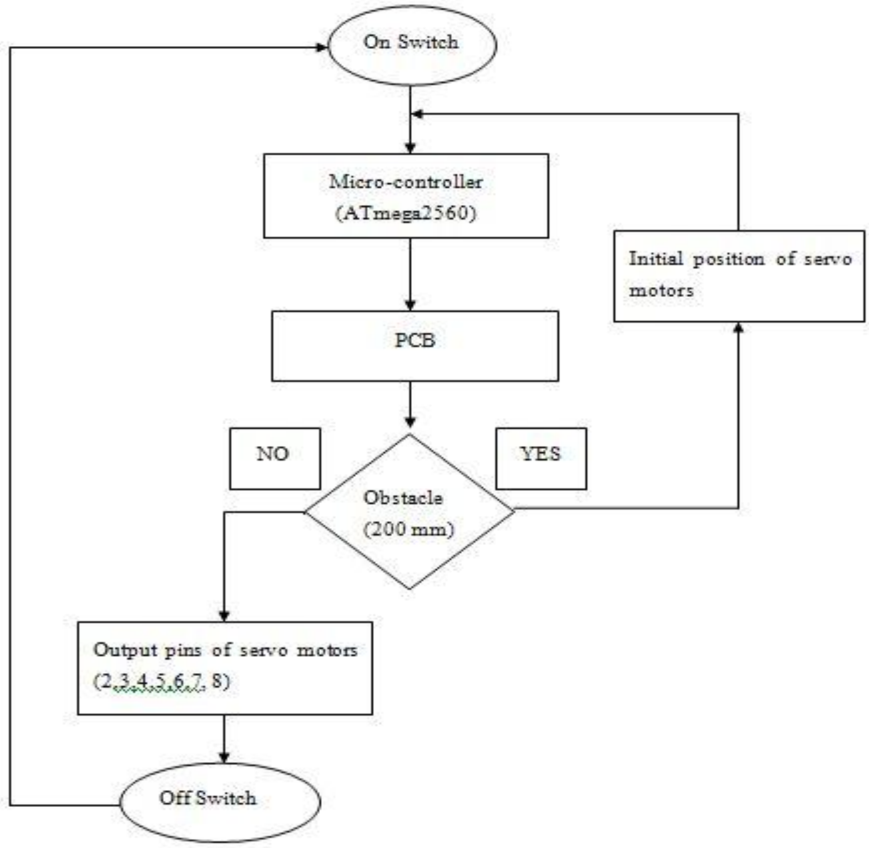


Fig. 5.13 Flow chart of programming

Command cycle for trot gait

To create the selected gait cycle, one for every side is executed with their outputs which is characterizing with joints ought to be moved. A total stride of the robot leg comprises of four joint movements. In this manner the quantity of states in the gait is steps/cycle × 4. The transition between the states happens subsequent to sending 25 identical pulses to the servos, around 0.5 seconds. The walking movement is created by particular gait moves as laid out in Table (5.3). Keeping in mind the end goal to save synchronization, movement sort may just switch amid gait when left and right sides are in a similar state. The quantity of ventures toward any path for the robot to take should likewise control. The command cycle ensures that the change of movement just happens when it will keep up synchronization and that the robot stops after the predetermined number of steps.

TABLE 5.3 Command cycle for trot gait

Action	Left side Gait cycle		Right side Gait cycle	
	Front	Rear	Front	Rear
Walk forward		1	1	
	-1			-1
Stop	0	0	0	0

Note that-
0 => stop motion,
1 => transition in forward direction, and
-1=> transition in reverse direction.

5.4 Experimental Results

A four-legged robot is designed and built from raw materials which are described in chapter 4. There are bunches of work required in the machining and maintenance of the prototype model. The screws and nuts are utilized as pins in the legs of the robot which is ended up being very dangerous. With the expanded detachment in the joints, the legs started to work ineffectively. The coupler plate likewise demonstrated tricky. Within measurement of the coupler is all around coordinated to the external distance across of the motor's pole however motor shafts have internal spline which is utilized to fixed with a screw to the coupler's inward spline, have likewise a dangerous stage due to looseness amid movement. This presented more give in the instrument than what was normal. A more reasonable and better designed system for the joints would have delivered a great deal which is more proficient and hearty robot. Off the shelf robot kits have considered and give all around designed joints which are not degrade with utilization. Although two degrees of freedom for every leg provides motion, two degrees of freedom does not give adequate control and mobility important to explore uneven landscape. Likewise the absence of material input from the legs does not allow the controller to adjust to the landscape. Having a mobile robot with more noteworthy leg mobility and tactile feedback would help the robot in its capacity to explore dangerous territory.

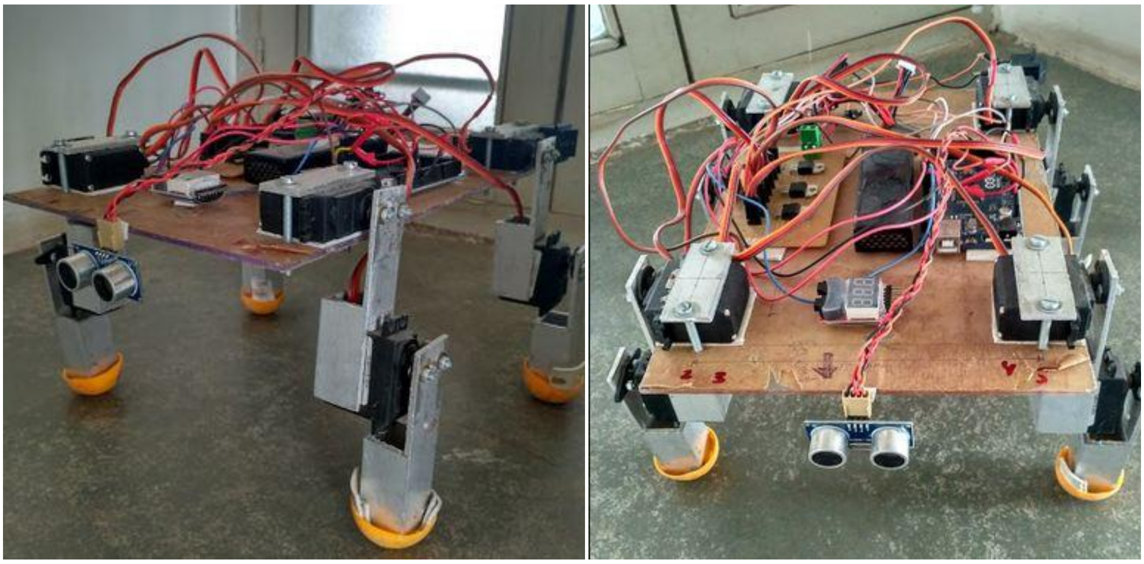


Fig. 5.14 Prototype model of the four-legged robot

For the robot, to navigate the different terrain, more data would be given to the controller. The addition information is originated from utilizing more refined sensors or utilizing extra sensors. With an expanded measure of accessible data a more complex obstruction avoidance system have been executed. The joint and sensor issue wound up noticeably evident towards the finish of the project. Because of time limitations, these issues are not tended to.

5.5 Testing

After the development of four-legged robot, testing of four-legged robot is carried out over flat surface which is shown in fig. (5.15). In the initial position, all the four-legs makes 90^0 angle with the base frame which indicates standing position of the robot, which is shown in fig. (5.15a). When the robot is began to walk forward, at that time, the front left leg or the rear right leg is in forward direction (clockwise), whereas, the front right leg or rear left leg is in reverse direction (counterclockwise), which are shown in fig. (5.15b). In the next cycle of the robot locomotion, the front left leg or the rear right leg is in reverse direction (counter-clockwise), whereas, the front right leg or rear left leg is in forward direction (clockwise), which are shown in fig. (5.15c). The above mentioned cycles are repeated continuously during the forward locomotion.

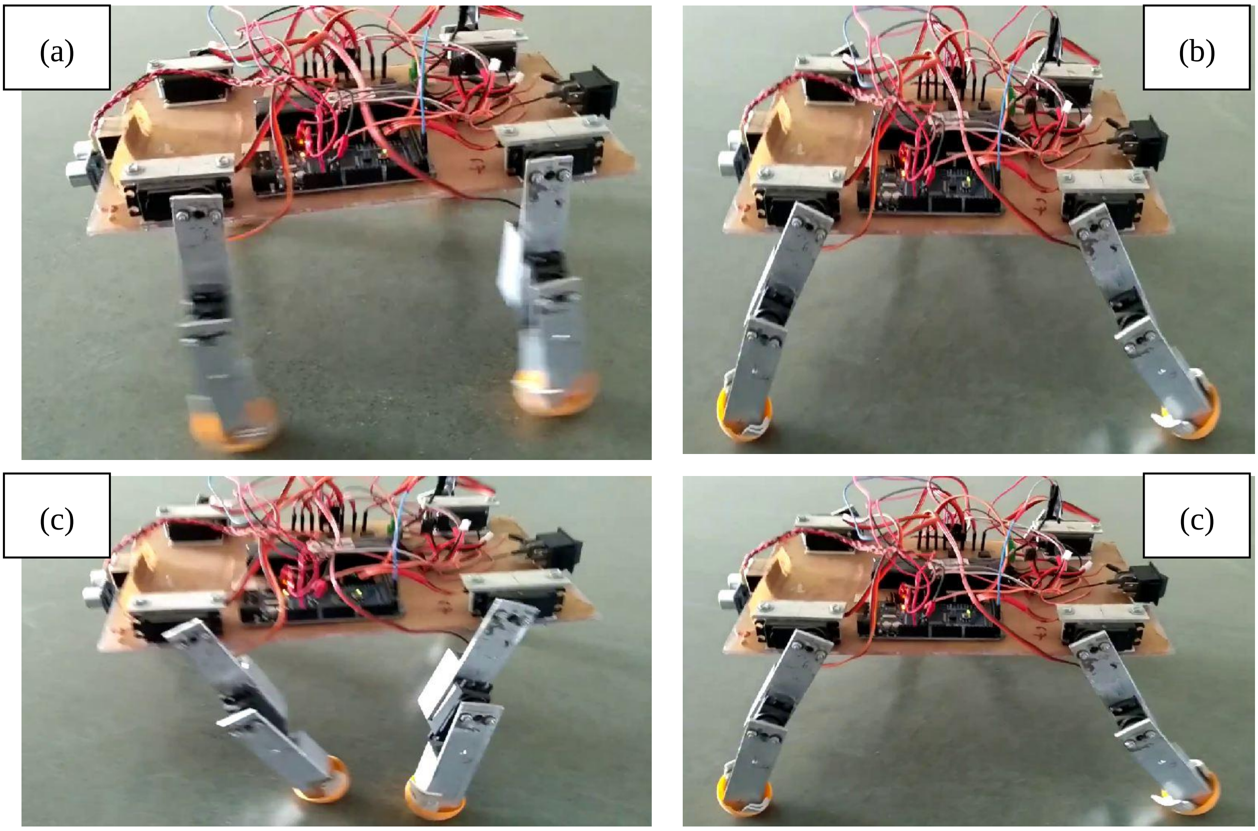


Fig. 5.15 Locomotion of four-legged robot over flat surface

Ultrasonic sensor is enabled to avoid obstacles prior to contact in the range of 200mm. In presence of obstacle, the walker is stopped on its initial position. The robot can adaptively adjust the velocity according to the environment and its posture. Experiment results show the stability controller adapts to the environment change very well.

Chapter 6

Conclusion and Future Work

6.1 Summary

In this report, the literature review is carried out which is focused on the basic concepts related to 3D CAD model, mathematical model i.e. kinematic and dynamic, and gait analysis over different terrains of the four-legged robot. Concurrently, a four-legged robot is designed by analyzing the mathematical modeling concepts and gait analysis and thereafter, prepared its CAD model. After the completion of CAD model, to developed a mechanical structure the four-legged robot with required electronic circuits and programming. After the development of a mechanical structure of the four-legged robot, to prepare a program for trot gait and also for obstacle avoidance (range of 200 mm). After completion of programming, a prototype model of the four-legged robot is successfully tested on the flat surface and inclined surface. It is also successfully tested in the presence of obstacle with the range of 200 mm.

6.2 Conclusion

The walking mechanism for the four legged robot has been synthesized and designed. The detailed kinematic and dynamic analysis of the leg has been carried out through mathematical model. The simulation of CAD model of four legged robot has been carried out using CAD software and the results are compared with that of analytical results and found in good agreement. The prototype robot is fabricated as per the design and demonstrated successfully.

6.3 Future work

The robot is successfully made to walk. However there are some deficiencies, including:

- Poor joints

- Limited maneuverability of legs

- Primitive environmental sensing

- Elementary deterrent evasion.

To cure the poor joints it is suggested that a demonstrated, maybe more convoluted, joint design ought to be utilized. A higher DOF can be utilized to build the mobility in the legs. These mechanical issues could be settled by utilizing an off the rack robot unit. Ultrasonic sensor could be utilized as a more modern technique for detecting obstacle expelling the requirement for physical contact. To encourage a more refined obstacle avoidance system, sensors ought to be added to the back and sides of the robot.

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