B. TECH. PROJECT REPORT

On

Design and Development of a Tree Climbing Quadruped Robot

By

CHAITANYA MEHTA

| 160003028 |

DISCIPLINE OF MECHANICAL ENGINEERING

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Design and Development of a Tree Climbing Quadruped Robot

A PROJECT REPORT

Submitted in partial fulfillment of the
requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
CHAITANYA MEHTA
160003028

Guided by:
Dr. Devendra Deshmukh
Associate Professor

INDIAN INSTITUTE OF TECHNOLOGY INDORE
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CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"Design and Development of a Tree Climbing Quadruped Robot"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr. Devendra Deshmukh, Associate Professor, Department of Mechanical Engineering,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

Chaitanya Mehta

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Signature of BTP Guide(s) with dates and their designation

Dr. Devendra Deshmukh,
Associate Professor

PREFACE

This report on "Design and Development of a Tree Climbing Quadruped Robot" is prepared under the guidance of Dr. Devendra Deshmukh. Through this report, I have tried to give a detailed explanation of the design of the Tree Climbing Quadruped Robot that I developed during my senior year at IIT Indore. While my work was preliminarily focused on development of a kinematic prototype and locomotion and climbing gaits of the robot, it can be carried forward in multiple dimensions in the future as explained in the future scope.

This thesis shall guide all those who wish to continue this project. I have tried to provide all the details of the work that I have done so far for the reference of the students who wish to carry forward. The codes and other material will be submitted to Dr. Deshmukh. I have tried my best to explain the content in lucid manner, whereas if some confusion persists feel free to reach out to me in that regard. I will be glad to help.

Chaitanya Mehta
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore
chaitanya3245@gmail.com

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I wish to thank Dr. Devendra Deshmukh for his kind support and valuable guidance. He has been like a father figure to me and has supported me to pursue my interest and thereby the project in the field of robotics. He has always believed in me and encouraged me to achieve my goals. It is his support that I was able to make this much progress in this project in the given period of time. I would also like to thank Mr. Jagadeesh Kadiyam from Kinematics and Dynamics of Machines (KDM) Lab for helping me with some instruments and technical guidance when and where required. I would like to thank Mr. Anand Petare and the Central Workshop technicians for their kind support in the fabrication process.

Further, it was my family, Mummy, Pappa and Princy (Yashvi) who motivated me to achieve my goals and bear the ignorance due to my dedication towards the project. Their constant support was a key to my success. Without their support this report would not have been possible.

Finally, I would like to thank the God "Jinendra - who has control over all of his senses"- for enlightening me with the knowledge and being my constant source of inspiration.

Chaitanya Mehta
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

ABSTRACT

The aim of this bachelor thesis is to Design and Develop a Tree Climbing Quadruped Robot. The 12-DOF (Degrees of Freedom) Quadrupeds developed have proven their dexterity in traversing variety of terrains and such robots find their application for operations in hazardous environment, disaster rescue operations & defense. But these bio-mimicking robots will only be able to go to places with direct physical access, like road or unstructured terrains, and stairs, etc. and in cases perform some jumps and flips. Enabling them to take support of existing structures and make their way will increase their applications by manifold.

This project primarily targets agricultural application of the robot in fruit harvesting. Many fruit bearing trees are structurally weak to support a human. Traditional methods of harvesting fruits using sticks are cumbersome and quite time consuming as it is difficult to reach some fruits even with long sticks and it involves risk of damaging the fruit during harvest. Using human labor for such process poses threat to very life of the human being. So, the objective has been set to develop a quadruped robot to climb over the tree. The robot will not only be able to climb the trunk, as in case of many wheeled coconut tree climbing robot, but will also be able to transfer from trunk to branches and scale whole length and breadth of the tree. Out of the options available, 11-DOF robot including four 2-DOF legs and a 3-DOF spine has been designed and developed.

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Chapter 1

Introduction

There are some fruit bearing trees, that are not structurally strong, i.e., they cannot support a human. In that case harvesting fruits from these trees becomes difficult. There are some tools available with long sticks with scissors attached on the other side. But still that is too laborious work, and further it is difficult to reach to every fruit and then plucking it. Some big machines available employ the technique to shake the tree rigorously. That way the ripe fruits are cut and the raw fruits which are light in weight or strongly connected with the tree as compared to other fruits stay on the tree. But again, this process is so random, and results in damage to the fruit from impact. Also, segregation of the fruit becomes cumbersome. And the amount of damage is considerably high.

The solution to the above problem is employed for strawberry harvesting robots. These are usually a manipulator arm with one robot per tree, that checks the ripeness of the fruit and then harvests it when it has ripened. This technique is suitable for plants of small size. But not applicable for big trees as the size of the robots will increase significantly. To employ on these big trees, we can use a swarm of the robots. With one robot deployed on each tree, the swarm of such robots can be used for harvesting in orchards and farms. Considering the automation demands of future farms and orchards, this seems the most viable solution.

There are many coconut-tree climbing robots available. All of these robots grip the tree with wheels attached to springs. The springs are pretensioned to provide required grip on the tree trunk, and then the motorized wheels help in climbing up/down the tree trunk. But these robots are suitable for only for the coconut tree, i.e., trees with circular cross section and without branches and irregularities. They are not employable on most of the trees, that have irregular trunk shape with bends, extrusions and branches.

Considering requirements of these robots, it is required to design a robot that is able to climb on any tree. It should be able to deal with extrusion and sharp bends on the tree trunk, should be able to transfer itself from the trunk to branches and vice versa, as well as re-orienting itself on the tree trunk. Also, the robot should be able to traverse uneven terrain on ground and should be able to climb the tree from initial ground level without assistance.

The 12-DOF (Degrees of Freedom) Quadrupeds like MIT Cheetah, Spot Mini (Boston Dynamics), ANYmal (ETH Zurich), have proven their dexterity in traversing variety of terrains. Such robots find their application for operations in hazardous environment, disaster rescue operations & defense. But these bio-mimicking robots will only be able to go to places with direct physical access, like road or unstructured terrains, and stairs, etc. and in cases perform some jumps and flips. Enabling them to take support of existing structures and make their way will increase their applications by manifold. As, it is not always possible to have direct ground access to the destination in hazardous environment.

Therefore, it was decided to develop a tree climbing quadruped robot that has all the following capabilities:

1. Traversing uneven terrains
2. Climbing the tree from initial ground level without assistance
3. Moving up-down the trunk and re-orienting on the trunk
4. Transferring from tree trunk to the branch and vice versa

Monkeys are the animals that can perform these tasks exactly, even we as humans. Taking inspirations from them, a quadruped robot with open loop control was developed and its kinematic model was prototyped at IIT Indore. Various Locomotion and Climbing gaits were implemented and studied.

In the following chapter, Literature review has been performed and the existing research in this domain has been explained in Chapter 2. In Chapter 3, various configurations that can be possible to achieve the Objectives is listed and the choice of the current configuration is explained. Chapter 4 deals with the Hardware Design and prototyping including both electronic components and electrical power supply system. Chapter 5 touches upon the Forward Kinematic Modelling of the robot. Development of Locomotion and Climbing gaits with Inverse Kinematics has been explained in the Chapter 6 and 7 respectively. Lastly, Chapter 8 and 9 deal with Results & Conclusions and Future Scope of the project respectively.

Chapter 2

Concept Design and Selections

Taking inspiration from the nature, for achieving the set objectives, legged robots that can use their limbs as grippers can be the basis for design. In all such animals, if we observe, they have a spine that allows it to orient upper limbs with respect to the lower limbs. So, essentially our requirement brings down to two grippers and one spinal cord joining them, that allows upper gripper to be oriented with respect to the lower gripper.

There are multiple configurations possible for achieving the objectives specified. Some ideas that were considered are explained in the table below.

Table 1. Possible configurations of a tree climbing robot

Sr. No.	Option	DOF	Configuration	Explanation
1	2 Grippers, 6DOF Link	8	1 single DOF Lower and 1 upper gripper, the 6 DOF link as a spine for orienting upper wrt. the lower gripper.	Upper/Lower gripper grips the trunk, climbs and walks like a caterpillar walks on the ground using its 6 DOF Link,
2	2 Grippers, 6 DOF Link + 4 Wheels on the Grippers	12	Gripping material on the circular inside surface of the wheel, using 360° servo for the wheel that can further be used as an actuation servo when the gripper is engaged	Wheeled locomotion over terrains suitable for that, caterpillar like motion when stuck using the spine, Grip the tree from the circular face of the wheel (Continuous rotation Servo on outer side of the chassis)
3	12 DOF Cheetah like robot	12	Gripping surface on the side of the bottom link	Proven dexterity over uneven terrain, re-orientation on trunk might be a bit difficult
4	4*2=8 DOF Legs + 3 DOF Link	11	four 2 DOF legs for walking, 3 DOF spine for balance shift and orienting upper limb wrt lower limb	Link 2 of the 2 DOF Legs can grip the tree and then spine can allow it to position upper/lower limb for climbing
5	4*3=12 DOF Legs + 3 DOF link	15	Four 3 DOF Legs and 3 DOF spine for balance shift and orienting upper limb wrt lower limb	Tip of 3 DOF Legs can grip the tree and then spine can allow it to position upper/lower limb for climbing

The criteria for the selection should be- Light weight, less DOF for lesser cost associated with smaller number of actuators. The idea 1 seems to be with the least DOF. There is a significant advantage of having any orientation and position in the space with 6 DOF spine. But we lose significant advantage of movement over uneven terrains. And caterpillar like crawling gait is too slow on the ground. The next one with the least DOF, is the 11 DOF concept with four 2 DOF legs and 3 DOF active spine. This robot is capable of performing all the objectives. It has quadrupedal locomotion and therefore, capability to traverse uneven terrain. The following figure shows 11 DOF configuration. 1 to 8 servo motors are four 2 DOF legs and 9,10,11 servo motors form the active 3 DOF spine. The next possible choice- MIT Cheetah kind of 12 DOF quadruped. But it would be difficult to implement climbing from initial ground level and re-orientation over the trunk with the existing configuration. Therefore, this 11 DOF concept was chosen for implementation.

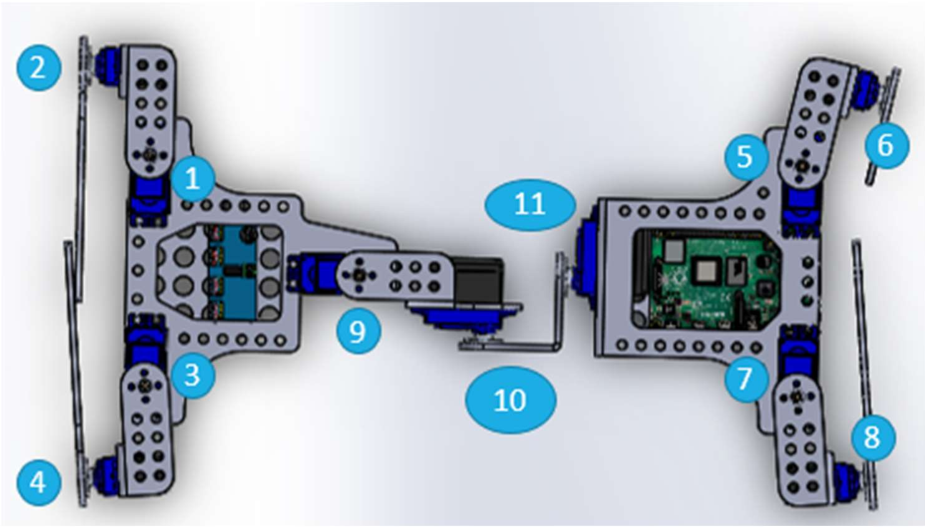


Fig 1. Selected 11 DOF configuration with servo numbers depicted

This Robot works as follows:

- The 4 Arms serve as Legs while walking and gripper while climbing
- The Special friction material on legs help it to clung to the tree
- The Servo No. 9, 10, 11, that make the robot spine helps the upper and lower gripper to re-orient with respect to one another and change its orientation on the trunk. This additional 3 DOF spine will help it to climb the tree from initial ground level and to transfer from Trunk to branch and vice versa! It can position the upper/lower limb towards the branch and allowing it to grip and facilitating the transfer.
- After reaching desired position on tree it can use its front/rear part to reach to the fruit and pluck it using either its arms or with additional tool fixed on the top of it.

Chapter 3

Hardware Design and Implementation

To implement and test the robot, a kinematic model was prepared. Kinematic model, because the actuators used here are hobby servos. These servo motors provide only position control. The speed and torque depend on input voltage and current, which are not controllable.

The main consideration behind the Mechanical Design of the robot was to speed up the fabrication process and reduce the cost, so that more time can be given for the gait development, which was the main aim of the project.

4.1 Mechanical Hardware Design

As stated earlier, the chassis and links were designed to accommodate actuators, electronic components, battery and wirings in the desired position, and provide appropriate free space for actuation. It was taken care that no component hinders the movement of other links.

To speed up the fabrication process, the chassis was made out of sheet metal components and Aluminium was the material chosen because of its lower density, thus reduced weight, and ductility. A 3D model and assembly were prepared in SOLIDWORKS to ensure proper assembly and accurate dimensioning of the components. All the components designed were either planar or had a single 90° bend for ease of manufacturing. Also, all the joints were non-permanent joints with mechanical fasteners, screw and lock nut.

The chassis and links were designed and then were laser cut to achieve desired precision. Further, the components that required bending were bent with the help of forming hammer and die. There were some inaccuracies due to manual bending but the tolerances were in control. M3, M4, M5 bolts, screws and lock-nuts were used as fasteners for the assembly. To maintain require spacing of between top and bottom cover of the chassis, plastic spacers were used with the M5 bolts and lock-nuts.

The specifications of the prototype are as follows:

- DOF: 11
- Weight: 2 Kg
- Servo Max Torque At (4.8 V): 10 kg-cm= 0.98 N.m
- Maximum Diameter of the tree trunk= 40 cm (Considering friction coefficient of 0.7 between bark of the tree and the leg)

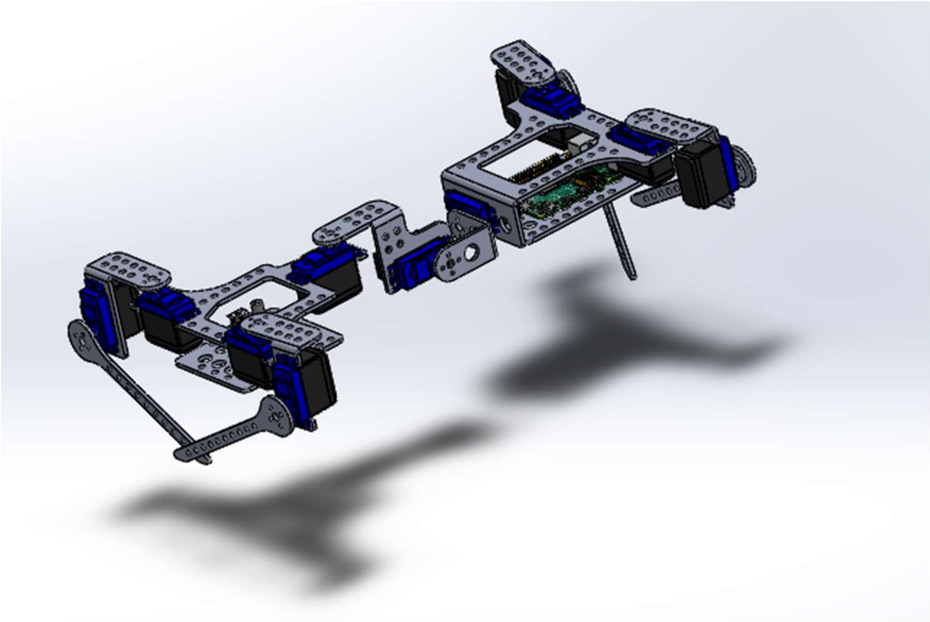


Fig. 2. 3D model of the robot prepared in Solidworks

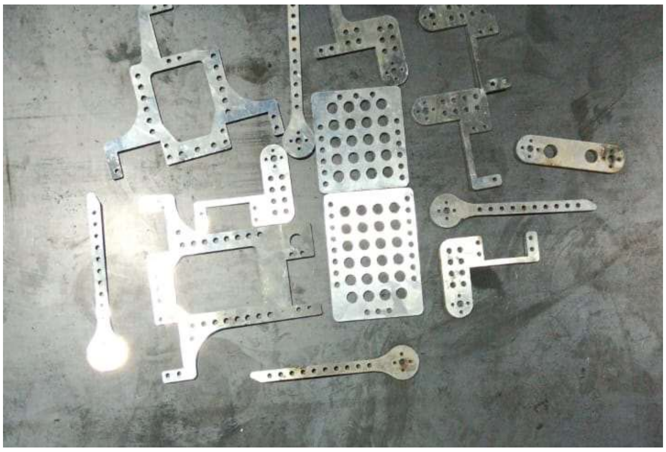


Fig 3. Laser Cut Brackets for chassis fabrication

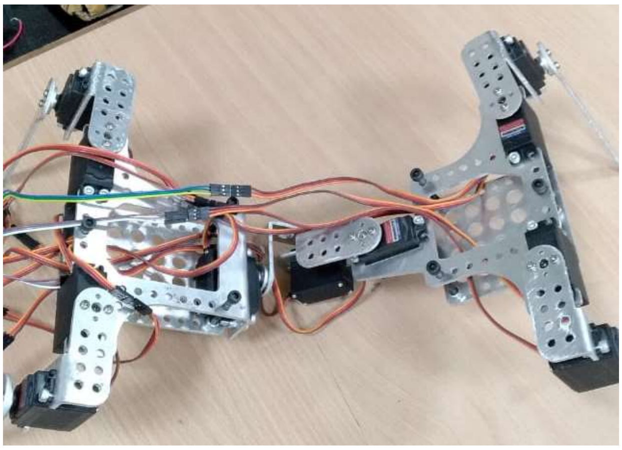


Fig. 4 Assembled Robot

To obtain the maximum diameter of the tree trunk that the robot can grip, an FBD analysis and calculations were performed. For the calculations average friction coefficients were taken from the table below to be 0.7 between rubber of the gripper and the tree bark.

Table 2. Coefficient of Friction of Wood on various surfaces.

Surface Types	Friction Coefficient
soft rubber on dry wood	0.95
hard rubber on dry wood	0.7
soft plastic on dry wood	0.7
hard plastic on dry wood	0.4

4.2 Electronics and Communication

Main components of Electronics and Communication system are:

1. **Raspberry Pi Computer:** Raspberry Pi 4 model B (4 GB) version is chosen as the main computing unit for the robot. It is a mini computer with its Raspbian Operating System. It has built-in Bluetooth, Wi-Fi and Ethernet. Further it is capable for UART, I2C (Inter-Integrated Circuit) communication.

2. **PCA 9685 Servo Controller Module:** The PCA 9685 is an I2C compatible servo controller module. It can control up to 16 servos and up to 62 modules can be chained in the Daisy Chain format. It also has a separate power input for power supply for servo motors isolating it from the Raspberry Pi and providing appropriate protection to it. There is enough documentation, library support for using it with Raspberry Pi or Arduino, that makes its implementation a lot easier.

3. **PS3 Remote Controller:** PS3 Remote Controller has been chosen as it has required number of inputs both digital and analog for controlling the robot. It has 13 Digital Input buttons yielding ON/OFF state, two joy sticks providing total four analog inputs in two axes each, and two triggers for single axes analog input.

   The PS3 Controller is connected with Raspberry pi with Bluetooth connection. It records every event-button press/release/value and sends data to the Raspberry Pi. The python script running on the Raspberry Pi, then uses this data to command the servo to perform the actuation over I2C communication to the PCA 9685 module, which then passes the data to the servo motors. Servo motors with their internal position feedback system tries to reach at the commanded position with the velocity and torque depending on the input power, i.e., voltage and current. The whole system is shown in Fig 5.

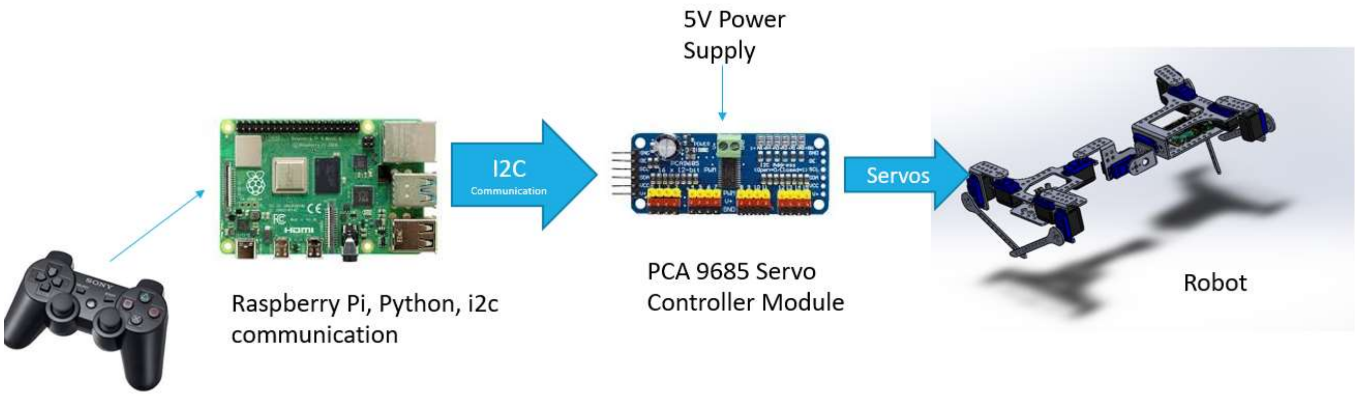


Fig 5. Communication Diagram for open loop control

For establishing I2C communication between the I2C communication between Raspberry Pi and the PCA 9685 Servo controller module, connections were made as shown in Fig. 6.

4.3 Programming

The computer program to command the servos is running as a python script on the Raspberry Pi. The python code uses **evdev library** to fetch the last input from the PS3 controller device received via Bluetooth and that can be used in the conditional loop of the program to execute a certain motion sequence for each command. Currently, the robot is working on totally open loop control system. With no situational/ state awareness or feedback. All the key events have event type (Analog/Button) event code and value (0/1 for button or analog value between 0 to 255 for analog events) associated with them. They are listed in the Table 3. The motion sequences are developed for each command in a separate function and the generation of motion sequence is later explained in detail in in Chapter 5 Locomotion Gaits.

4.4 Electrical Power Supply System Design

In the initial stage of the design, for determining the required current, and to avoid any mis happening with the electronic components, the robot was powered by a DC Power supply system and Raspberry Pi adapter. But to make it capable to perform tasks in remote area, it is necessary to design a remote power supply system. There are mainly 2 power consuming systems, the Raspberry Pi board and the servo motors. Servo motor draws a peak current of 2 A at stall torque. Such 11 servo motors are connected in parallel. So, the current requirement rises to 11*2=22 A. And the Raspberry Pi board works on 5 V 3.1 A DC Adapter. To replace it, a power supply system with equivalent power input must replace the adapter. In sum, the total current requirement rises to 22 + 3.1=25.1 A.

The Servo motors are rated for the voltage of 4.8 V and 6 V. Supplying voltage above this would result in damage to the servo motors. The nearest battery voltage available for supplying the 6V is 7.4 V for rechargeable Lithium Polymer (LiPo) batteries. It is required to step down voltage from 7.4 V to 6V or 5V for safe operation of the Servo motors. For that a DC-DC step-down buck converter is necessary.

Battery capacity and maximum discharge current are also main determining parameters for the selection of the battery. Battery capacity is usually measured in mAh. If the battery capacity is 2500 mAh, it means that it can provide 2.5 A constant discharge current for maximum 1 hour.

The maximum discharge current capacity is usually shown in terms of C rating. If a battery 2500 mAh battery ahs 30 C rating, then it can provide (considering 80% efficiency) 0.8*2500*30/1000=60 Amp constant current discharge. Considering all these factors a battery has been selected. And a DC-DC step down buck converter with required current capacity and power has also been purchased.

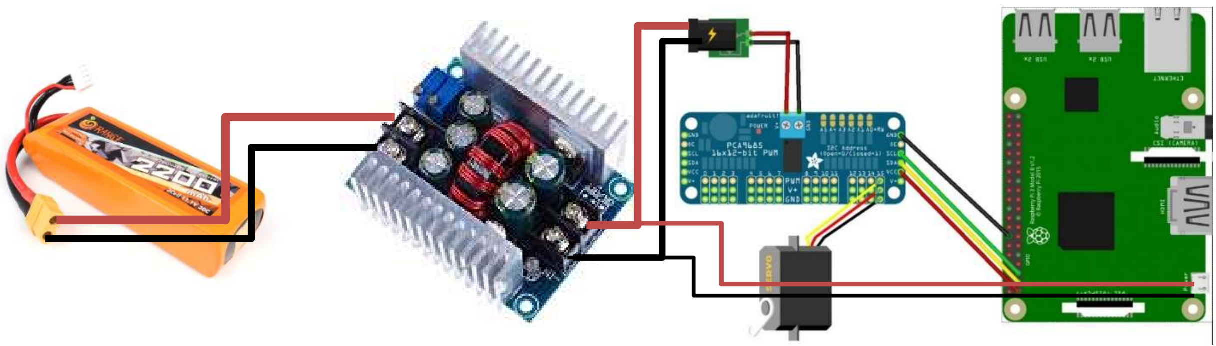


Fig. 6 Electrical Circuit Diagram

Table 3. Event codes and commands for PS3 Controller

Event/Button	Type	Code	Value	Command/Function
Up	Digital	544	0 = Release 1 = Press	Move Forward
Down	Digital	545	0 = Release 1 = Press	Move Backward
Left	Digital	546	0 = Release 1 = Press	Move Left
Right	Digital	547	0 = Release 1 = Press	Move Right
O	Digital	305	0 = Release 1 = Press	Climb Upward
X	Digital	304	0 = Release 1 = Press	Climb Downward
Square	Digital	308	0 = Release 1 = Press	Rear Leg Forward
Triangle	Digital	307	0 = Release 1 = Press	Front Leg Forward
Select	Digital	314	0 = Release 1 = Press	Reset all servo angles to mean position
Start	Digital	315	0 = Release 1 = Press	Turn on the Climbing Mode
Playstation	Digital	316	0 = Release 1 = Press	To connect with the Raspberry Pi
L1	Digital	310	0 = Release 1 = Press	Front Limbs Grip
R1	Digital	311	0 = Release 1 = Press	Rear Limbs Grip
L2 Trigger/ABS_Z	Analog Trigger	312	Press= 255 to Release = 0	Front Grip Release
R2 Trigger/ABS_RZ	Analog Trigger	313	Press= 255 to Release = 0	Rear Grip Release
ABS_X	Left Joystick Horizontal	-	Left=0 Center=127 Right=255	Turn Spine
ABS_Y	Left Joystick Vertical	-	Up=0 Center=127 Down=255	Twist Spine
ABS_RX	Right Joystick Horizontal	-	Left=0 Center=127 Right=255	Up/Down Spine
ABS_RY	Right Joystick Vertical	-	Up=0 Center=127 Down=255	Not yet assigned

Chapter 4

Forward Kinematic Modeling

Forward Kinematic Model of the robot is necessary to determine the current position of the end effectors, in our case the leg tip, and then further use it for further processing and motion planning.

To obtain forward kinematic model of the robot, each leg is treated as a separate manipulator. The front/upper part of the robot where the camera would be fixed in future is kept as the reference for computation of the Denavit- Hartenberg Parameters (D-H Parameters). Therefore, leg 1 and leg 2 has total 2 links and leg 3 & leg 4 has 5 links including 2 links of the leg and 3 links of the spine. The following table shows the D-H parameters of the links.

Table 4. D-H parameters for four legs

	link	a_i	α_i	d_i	θ_i
leg 1	0	0	0	0	0
	1	46	-90	0	θ_0
	2	0	0	0	θ_1
Leg 2	0	0	0	0	0
	1	46	90	0	θ_2
	2	0	0	0	θ_3
leg 3	0	0	0	0	0
	1	65.45	90	0	θ_8
	2	0	-90	0	$-90+\theta_9$
	3	60.9	-90	164.31	$90+\theta_{10}$
	4	46	-90	-2.6	θ_4
	5	0	0	0	θ_5
leg 4	0	0	0	0	0
	1	65.45	90	0	θ_8
	2	0	-90	0	$-90+\theta_9$
	3	60.9	-90	164.31	$90+\theta_{10}$
	4	46	-90	-2.6	θ_6
	5	0	0	0	θ_7

After obtaining D-H Parameters, reference frame is assigned to each joints and transformation matrices are computed. Fig 7 shows the reference frame assignment for each joint. The last reference frame belongs to the end effector (leg-tip).

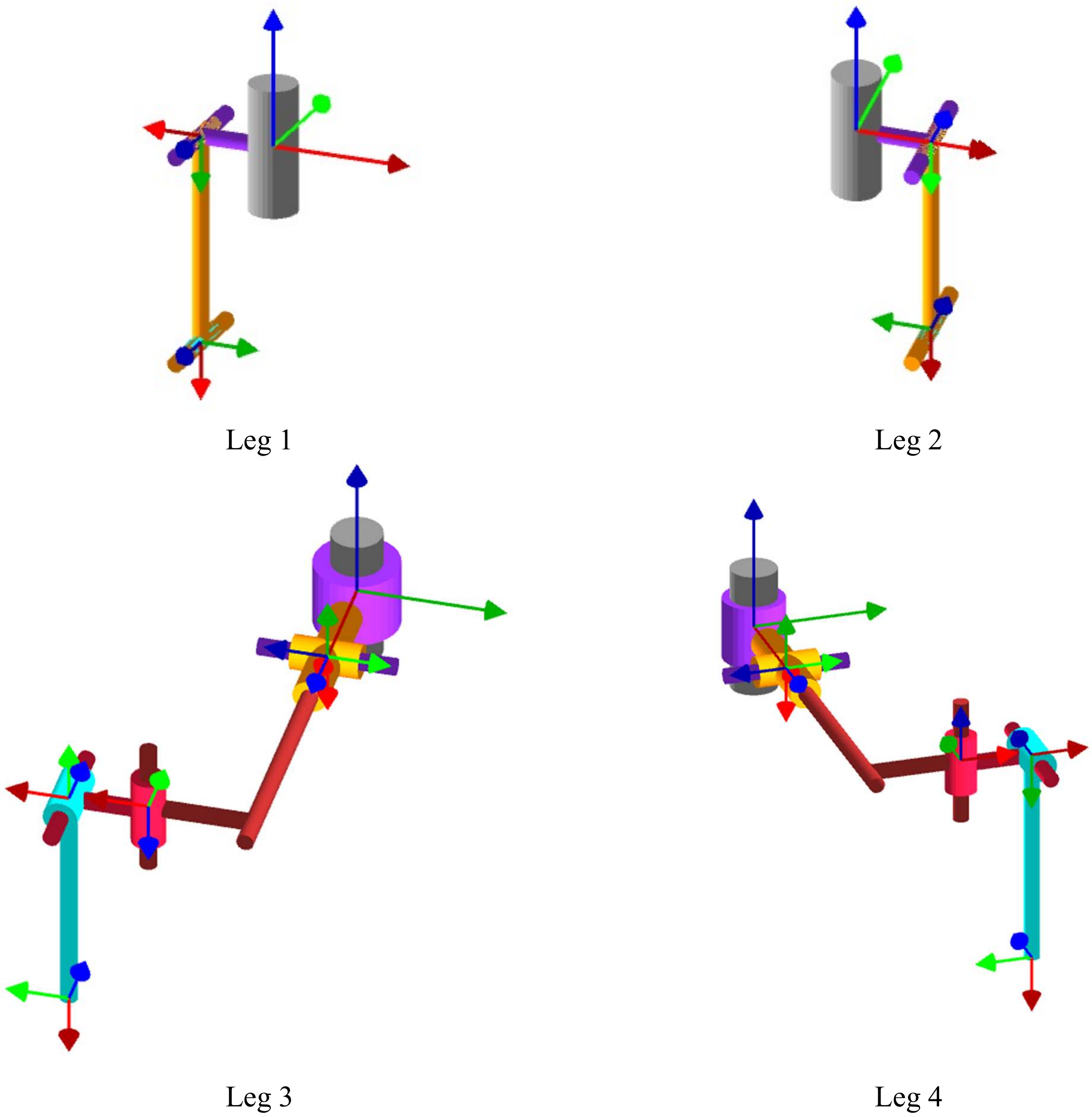


Fig 7. Forward Kinematic Model of each 4 log with assigned reference frames

In the figure above, kinematic model of each leg is shown, with reference frames attached to it. A further transformation to the eye frame (frame of reference of camera) can yield the position of each leg tip with respect to the eye. Further processing on it can help having a situational awareness.

Chapter 5

Locomotion Gaits

5.1 Forward, Backward Walking Gaits

Stability is an important factor to keep in mind while designing gaits for a legged robot. A robot will be stable, i.e. won't topple, if at any given time the projection of its center of gravity on the horizontal plane lies inside the convex support polygon formed by the projection of its support points (leg tips/ footprints) on the same plane. ([2] McGhee and Iswandhi, 1979). Here, horizontal plane is the plane perpendicular to the gravity vector.

Statically stable gaits were developed to simplify the control system. Also, as the robot has open loop control periodic gaits were adopted.

Periodic gaits are of two types:

(1) Continuous gaits: In *continuous gaits,* all legs and body move periodically and continuously.
(2) Discontinuous gaits: In *Discontinuous gaits,* a legs and body move sequentially. A leg is transferred with all other body parts remaining halted. The body is propelled forward while all the legs remain on the ground and move simultaneously for the forward stroke.

The main aspects to be considered while generating discontinuous gaits are as follows:

1. After a leg reaches its rear kinematic limit, it should go through transfer phase and placed at its forward kinematic limit.
2. Body is propelled forward while all the legs remain on the ground. At the completion of the body stroke at least one leg should reach its rear limit to be transferred to its front kinematic limit.
3. The leg- contralateral and non-adjacent (CNA) to the present transfer leg should be placed at such a point that after the placement of the transferred leg, the center of gravity (CG) stays on the other side of the line connecting the CNA leg with the transfer leg. That way, it would be possible to lift the next leg while maintaining the machine's stability.
4. To allow several locomotion cycles to join, the sequence should be periodic.

The following figure shows a two-phase discontinuous gait, that is employed on the robot for forward and backward motion. It follows the 4-2-3-1 sequence to maintain static stability during each transfer phase. This motion sequence is employed on the current robot. It was observed that, due to its rectangular shape, there was really small stability margin between the CG and the line of the support polygon closest to it. That caused the robot to topple towards the transferring leg resulting in the transferring leg not capable to lift itself during the forward stroke and it rather slipped on the floor.

As the quadruped robot essentially mimics the human without hands below elbows and legs below knees, experiments were performed to notice what would be the response of a human subject in that situation. It was noticed that, in that case using spine and the contralateral adjacent (CA) leg to shift the CG inside the support polygon would increase the static stability margin and thus allow the transfer leg to lift and move forward. There were 3 possibilities:

(i) Using the Contralateral Adjacent Leg only by moving it towards the transfer leg
(ii) Using the twist DOF of spine (Servo 11) to shift the CG in the opposite side of the transfer leg
(iii) Both motions combined

After employing and experimenting with all the three possibilities, it was observed that the possibility (ii) provided the smoothest motion allowing the lifting of the transfer leg.

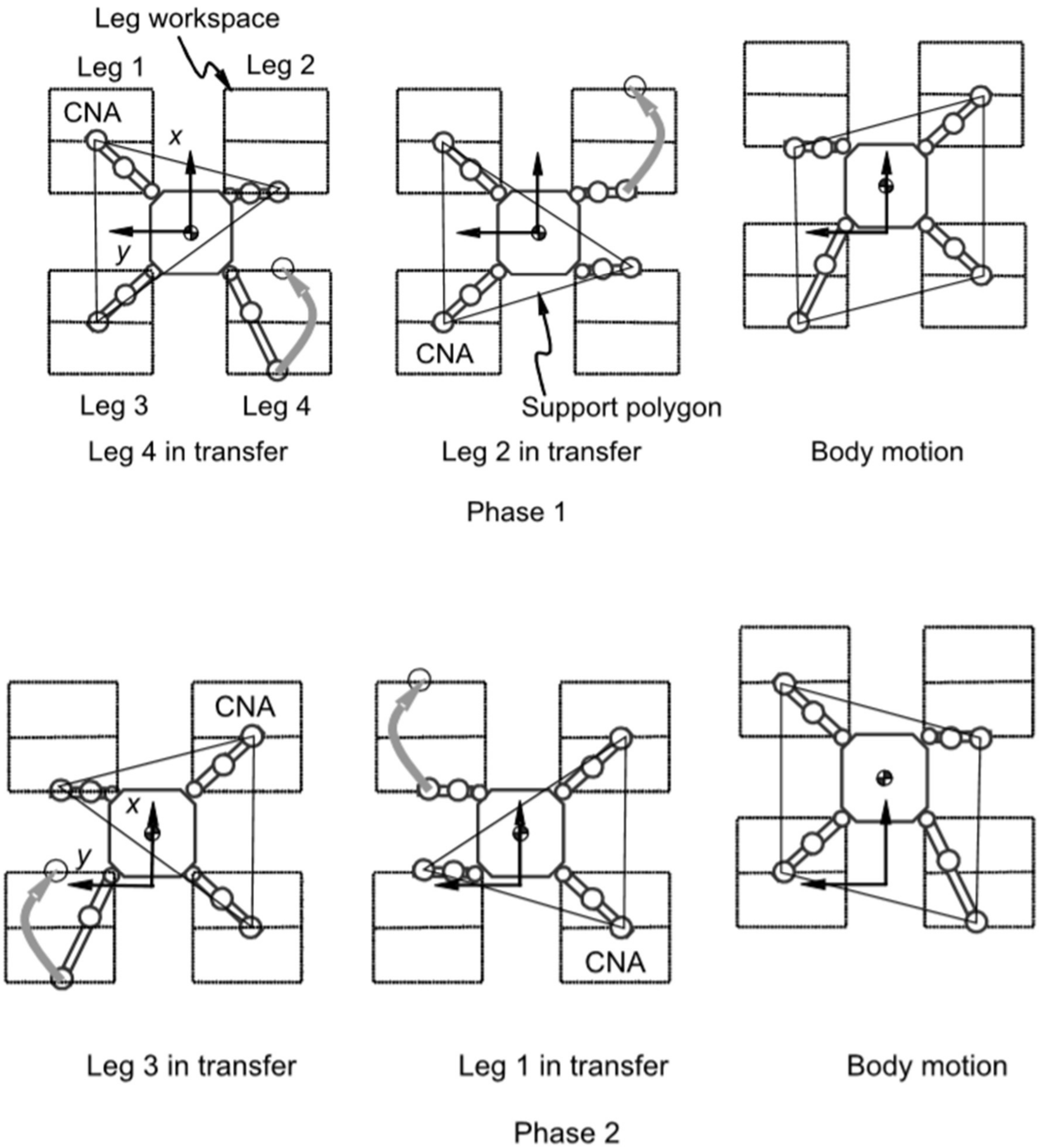
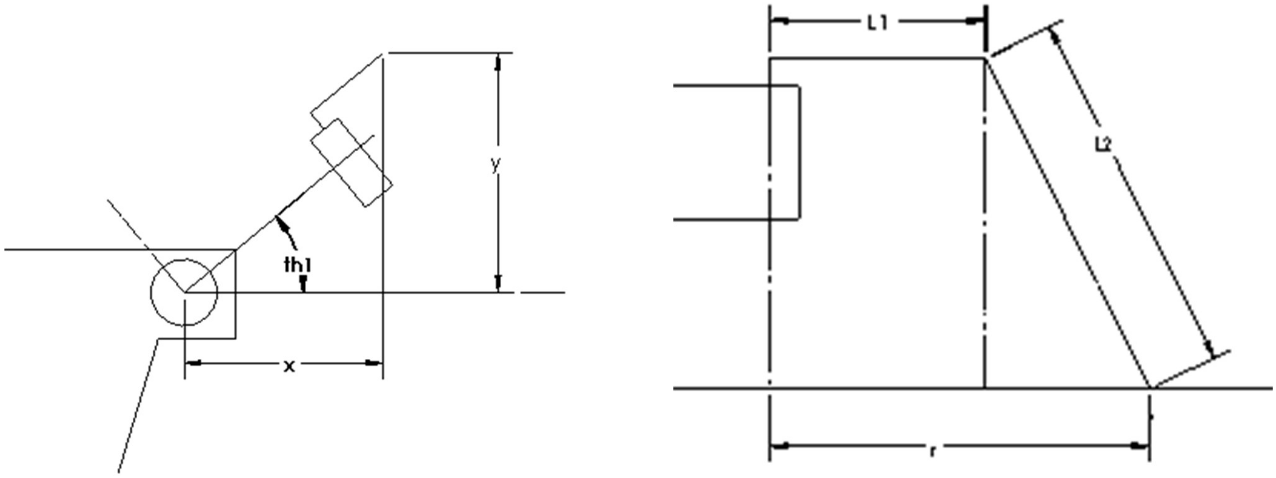


Fig 8. Two phase discontinuous periodic gait for forward motion

Another important factor for stable forward motion without lateral slipping of the legs is that the leg tip follows a straight path during the backward stroke, i.e., the body's forward motion stroke. To ensure this both joints on the legs should work in sync to produce the horizontal straight line during the backward stroke. Therefore, the trajectory of leg tip should be straight line at constant x distance from the joint 1 of the leg with,

x = x (at the start of the backward stroke)

To follow this trajectory inverse kinematics was employed to find the th2 with respect to th1. The th1 would be the stroke with a constant speed from 30° to 90° or 90° to 150° depending on its initial angle. The geometric solution was derived for this inverse kinematics problem which is shown below:



Top View Front View

Fig 9. Geometric solution for Inverse Kinematics problem of locomotion

Geometrically from the figure,

$$r = l1 + l2sin\theta_2$$

$$x = rcos\theta_1, y = rsin\theta_1$$

Solving, we get,

$$\theta_2 = sin^{-1}\left(\frac{x}{l_2cos\theta_2} - \frac{l_1}{l_2}\right)$$

A while loop was implemented for achieving the desired motion.

5.2 Turning Gaits

Similarly, for turning, the same motion sequence is used during turning gaits. But the only difference is that the side it is required to turn the legs on that side would move backwards and the opposite side of legs should move forward. And then for the body stroke, the legs move in straight line in the opposite direction. Left and Right Turning is obtained in this way.

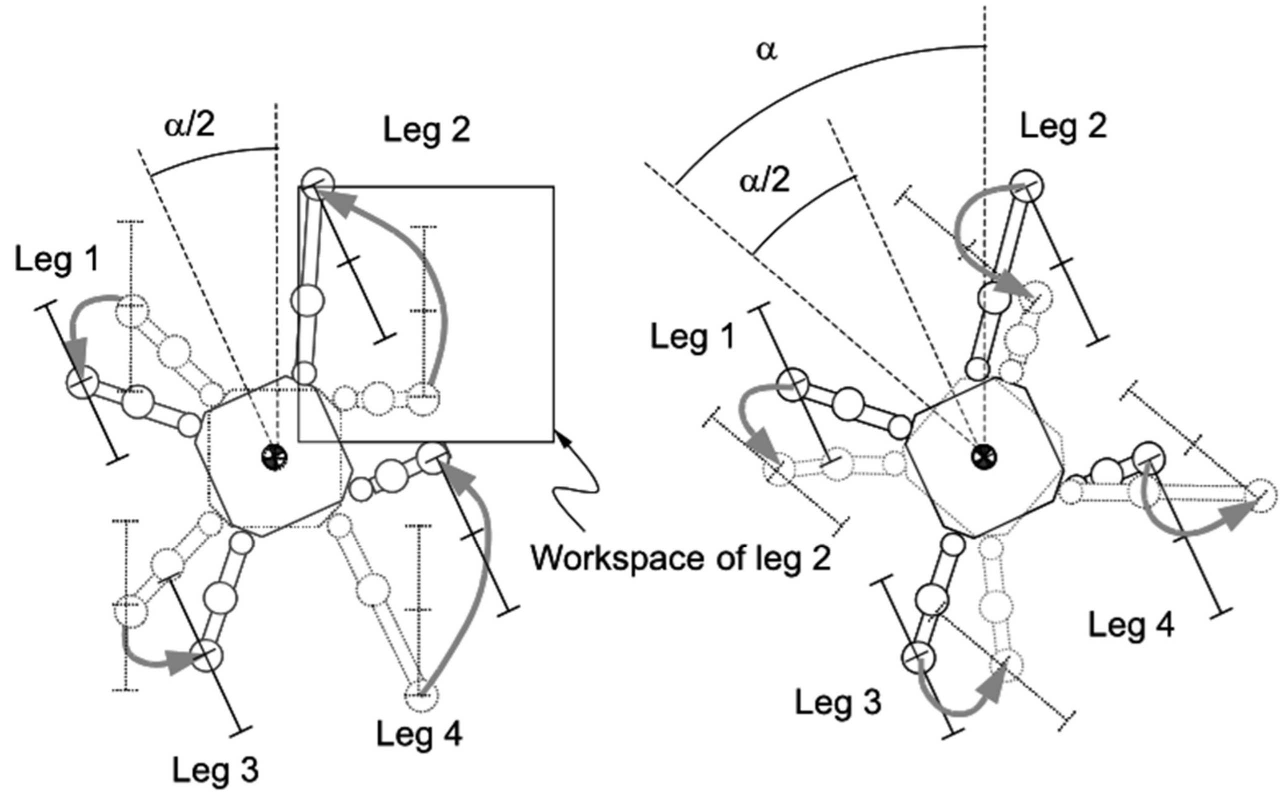


Fig. 10. Sequence for the Turning Gaits

Chapter 6

Climbing Gaits

Climbing is the main specialty of the robot. The objective was to enable the robot to climb the tree from initial ground level. Then it should be capable to climb the tree on the trunk. If the branch is not inline with the climbing side of the robot, it should re-orient itself on the tree trunk so that the branch comes directly in the way of climbing. When it reaches near the branch, it should use its spine to grip the branch from upper limbs and then gradually transfer itself from the tree trunk to the branch. That way the robot will be capable of spanning length and breadth of the tree.

6.1 Motion Sequence for transferring to the trunk from initial ground level

The motion sequence for transferring from the branch to the trunk starts when the robot reaches near the root of the trunk. Then pressing the START button (Enabling climbing mode button) performs a motion sequence. This motion sequence consists of the following steps:

1. Spread the front and rear limbs for better ground support
2. Set the Up/Down Spine servo motor to 90°: During this step, the robot takes support of its belly and the its forward body part lifts from the ground allowing it to grip the tree trunk.

Now, the robot is ready to climb the tree. After this one need to manually control the robot for transferring it to the tree trunk. That involves the steps listed below:

3. Use the L1/R1 button to close the forward limbs and get a proper grip on the tree trunk, this way the forward limbs are now also a part of the support polygon, and we can now lift the robot from the belly while maintaining the static stability.
4. Move the rear leg forward.
5. Perform body forward moving stroke while lifting up the belly
6. Move upper limbs up the trunk while straightening the spine
7. Repeat steps 4, 5, 6 until the rear leg is in the position to climb the tree and the Up/Down Spine motor has moved approximate 90°
8. Then transfer the rear limbs to the tree trunk

This motion sequence may seem tedious and may require some hands on training and experience, but with the integration of closed loop system it will be have a higher degree of automation.

6.2 Climbing Gaits

For climbing, it is required to maintain proper grip on the tree trunk. For that, the legs should maintain constant contact with the tree trunk with force. A solid cylindrical rubber is to be glued on its legs so that the robot can have appropriate friction and grip over the trunk. The cylindrical shape is chosen as compared to any other shape like a fraction of the torus, which seems to provide a better grip. But using the shape like fractional torus will hinder the motion during the body upward stroke. And it will have only single point contact. The contact might also be lost during that forward stroke. Additionally, while the fractional torus would be useful for a specific diameter of the trunk, it will be a disadvantage for the trunk with some other diameter. As we transfer the robot from the tree trunk to the branch this disadvantage will play out.

Therefore, cylindrical design was chosen. During the body upward stroke, while the limbs come down, due to its cylindrical shape, the motion will not cause the contact patch on the trunk to twist, but it will just shift with the rotation of the cylindrical gripper. For maintaining this it is required to synchronize the motion in such a way that a tangent contact is always maintained. Therefore, inverse kinematics were employed for the solution to this problem.

6.3 Inverse Kinematics for Climbing gaits

Following figure shows the cross section of the tree. L1, L2 are the link lengths. L2' is the distance of the contact patch from the joint 2 along L2. R is the diameter of the trunk, b is the width of the body. (th1) and (th2) are the joint angles 1 and 2 respectively.

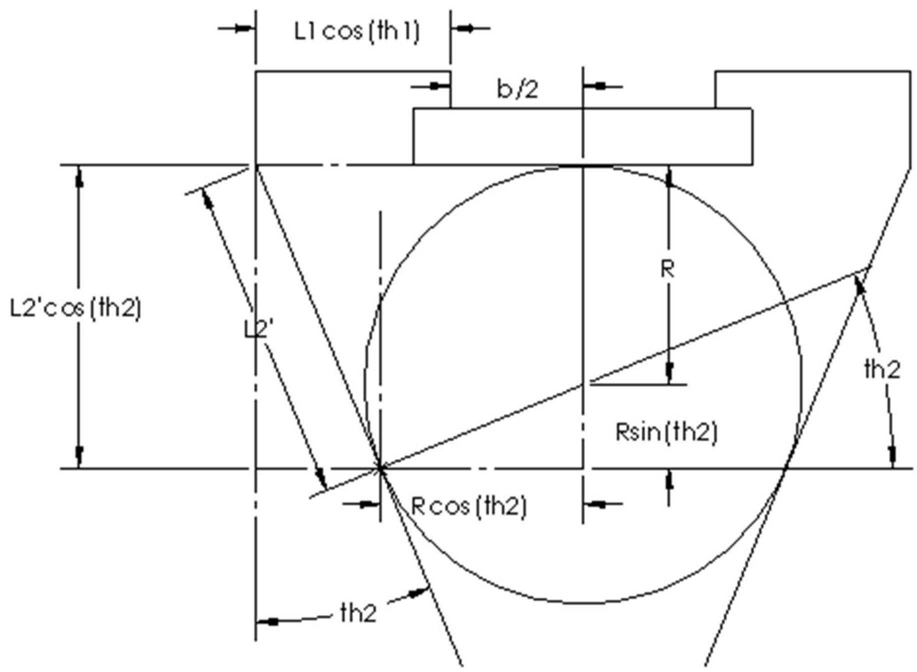


Fig. 11. View form the cross section of the tree for inverse kinematics

A Geometrical solution to the inverse kinematics problem was obtained as follows:

From the figure, in the vertical component of the distance of the contact patch from the body,

$$L_2' cos\theta_2 = R + Rsin\theta_2 \tag{6.3.1}$$

Similarly, geometrically in the horizontal direction

$$\frac{b}{2} + L_1 cos\theta_1 = L_2' sin\theta_2 + Rcos\theta_2 \tag{6.3.2}$$

Substituting L2' from (6.3.1) to (6.3.2), we get,

$$\frac{b}{2} + L_1 cos\theta_1 = R\left(\frac{1 + sin\theta_2}{cos\theta_2}\right) sin\theta_2 + Rcos\theta_2 \tag{6.3.3}$$

Solving,

$$\frac{b}{2} + L_1 cos\theta_1 = R\left(\frac{1 + sin\theta_2}{cos\theta_2}\right) \tag{6.3.4}$$

Further solving using trigonometrical tangent formulae:

$$\theta_2 = 2tan^{-1}\left(\frac{b}{2R} + \frac{L_1 cos\theta_1}{R}\right) - \pi/2 \tag{6.3.5}$$

This motion sequence is implemented with a while loop, commanding th2 with respect to th1 at for each time step. The R can be recorded while the first grip was confirmed.

6.4 Trunk to Branch Transfer

The transfer from trunk to branch or re-orientation over the trunk is done manually in the open loop control. Whenever such operations need to be performed, first it is required that the robot is right below the branch of the tree on the trunk for proper transfer to the branch. To achieve that re-orientation operations over the trunk, need to be performed. For that, the following steps should be followed:

1. Release the grip of upper/lower limbs as suitable
2. Use joysticks to re-orient the released limbs to the new position using the 3 DOF active spine
3. Then grip the trunk/branch in the new position.
4. Release the previously engaged limbs
5. Again, use joy sticks to bring the spine back in its initial straight position while avoiding trunk /extrusions
6. Grip the tree from the remaining limbs

Chapter 7

Results and Conclusions

The tree climbing quadruped robot was developed at IIT Indore and locomotion and climbing gaits were implemented on the robot. Locomotion gaits were refined with the use of active spine together with the legs for higher static stability. An open loop control system was developed for the robot enabling the robot to be controlled by a PS3 controller. The videos for the robot's operation can be found at the following Links:

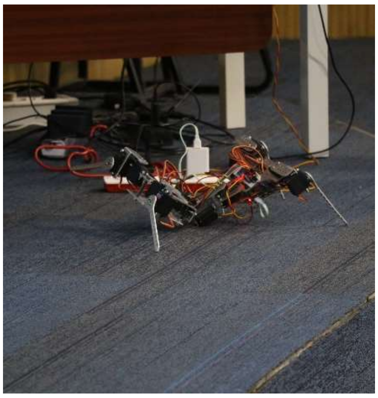
https://www.youtube.com/playlist?list=PLmaBklx_BRHqLehTeFPLsPEGf4zimSC33

Search: Tree Climbing Quadruped Robot on You Tube
Channel Name: Chaitanya Mehta

This robot will have many further applications in the future. In addition to the application for harvesting fruits, it can be employed during disaster rescue missions. Though this project was focused on tree climbing, any cylindrical object can replace the tree. In the industrial environment, for performing inspection and other related operations in the complex piping networks of the plant, such robots can be employed.

The methodology used for developing climbing and walking gaits can be employed on other robots to increase their operational areas significantly. Such robots find their application in defense, surveillance, disaster rescue operations.

This project was demonstrated at **Samsung Innovation Award 2019** in front of a panel consisting of CTO & VP Mr. Aloknath De of Samsung R&D Institute Bangalore, faculty members of IIT Indore. The project won Runner-Up prize of INR 1,20,000/-. Further, the robot was displayed during Convocation 2019.



Chapter 8

Future Scope

Currently, open loop control system has been developed during the course of this B. Tech. Project. The climbing gaits have been developed. With inclusion of gripping material on the legs of the robot it will start climbing on the tree. In future, closed loop control system can be implemented with higher degree of automation. The work has already been started for that with ordering of components for the same. Piezo discs will be used to ensure that required amount of grip has been achieved. Camera and image processing techniques can be used to have better situational awareness, determine radius of the tree, path planning. IMU sensor can be implemented for having a sense of orientation in the world. With the integration of these sensor in the existing system, the robot will become intelligent.

Further, there can be appropriate changes on the hardware front. Considering the short duration for implementation of the project, there were some compromises that were made with the design of the robot. Further, 3D printing can be used for stronger and lighter chassis. Actuators used can be upgraded to better version with position feedback to have a higher order of automation.

In farther future the robots can be totally automated and employed in orchards for full automation of the harvesting process.

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