Objectives:

The objective of this course project is to develop a Quadruped Robot and implementing the following features:

1. An eight actuator system (2 actuators per leg)
2. Ability to climb up inclined planes and step on raised platforms
3. Fabricating a control system and Implementing various gaiting systems for locomotion
4. Setup a basic navigation system capable of taking input from the surroundings

Motivation:

Our primary motivation for this project was ABU-Robocon 2019. This year, the problem statement includes the development of a quadruped robot. Therefore, we decided to develop a robust fully-operational quadruped robot which can act as the autonomous robot for Robocon and can be further utilised as a platform for future research work.

Approach:

The following steps were proposed to approach the project:

1. Manufacture a prototype
2. Develop control systems for the prototype
3. Implement gaiting systems on the prototype
4. Prepare a CAD of an improved design
5. Identify and procure suitable materials, components and actuators for final design
6. Fabricate the final design
7. Develop control system and gaiting systems for the final model

Progress:

The major points of development are mentioned below:

1. Research and finalization of design for Quadruped Robots
2. Studied various designs and ranked based on viability with respect to ROBOCON, ease of manufacturing, controllability, stability, maneuverability and agility
3. Literature review of finalized design – Ghost Minitaur
4. Studied the structure of the leg, gaiting system and control system
5. Development of CAD model for final model
6. Manufacturing a prototype with the available material
7. Fabrication of electrical circuit and control system
8. Development of Walking Gait, Turning Gait
9. Development of Stepping and Climbing gaits for obstacle clearance
10. Manufacturing of joints for the final leg design
11. Assembly of the legs, chassis and motor subsystem
12. Modified inverse kinematics and trajectory calculations adhering to the updated leg design
13. Fabrication of a new electrical layout
14. Development of a packet serial library for achieving the control of leg actuators

We will discuss each of the above points in detail subsequently in this report.

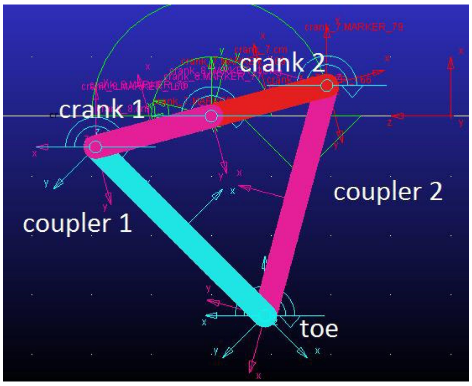
Design:

The design of the robot is based on 'Minitaur' by Ghost Robotics.

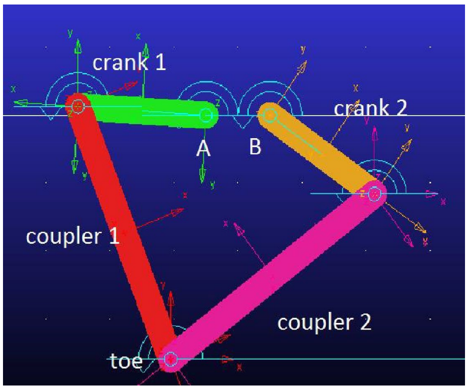
Ghost Minitaur

The leg design in the Ghost Minitaur had co-axial motor shafts for actuation. Minitaur's leg is a five bar mechanism with 2 degrees of freedom (both rotational). This allows the toe achieve any position in its plane. It is a direct driven bot using electric motors with each leg having two motors actuating crank 1 and crank 2 shown in the figure below.

We conceptualized a leg design with non-coaxial motor shafts to avoid complex geometry. This facilitated the manufacturing of a closed five bar mechanism with five revolute joints, with 2 of the joints actuated[1].



Co-axial Design



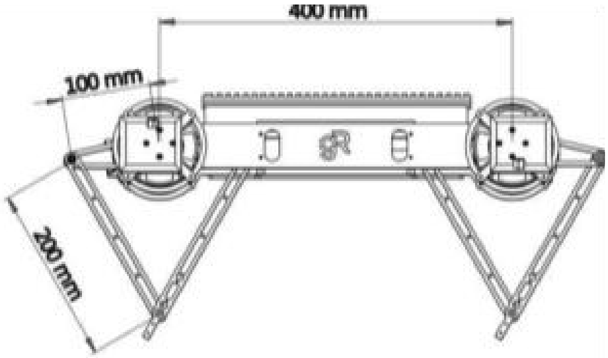
Eccentric Design

By controlling the 2 joints, we can make the toe of the leg follow a desired trajectory. After some literature review, we decided that the coupler length should be double that of the crank. To improve the traction at the toe, we extended one of the couplers beyond the joint and decided to attach a rubber stub at the tip of the extended coupler[2].

Advantages of 5 bar legs:

- The direct link to leg system allows for the production of high frequency gaits.
- The leg configuration allows the motors to be located at the hip of the robot, thereby decreasing leg mass and reducing the inertial effects during these high speed motions.
- The high torque motors and 5-bar legs also reduce the necessity for a gear box by producing variable transmission rates.

Dimensions of the prototype:
Length of crank 1 and crank 2 = 100 mm
Length of coupler 1 and coupler 2 = 200 mm
Width of all links = 10 mm
Distance between the pivot points A and B, i.e., between parallel axes = 50 mm
Vertical distance from the toe to line AB during stroke = 180 mm

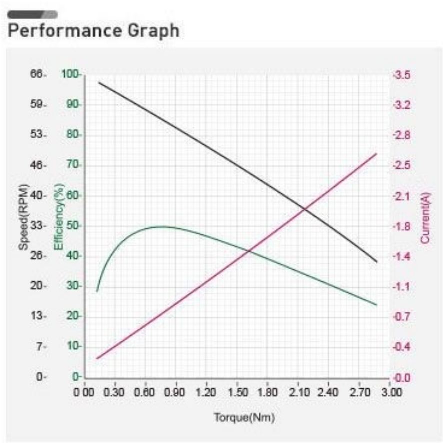


Actuators:
Hobby servo motors with the following specification were used for the actuation of the legs of the prototype

- 1200 mA stall current at 7.0 volts
- Stall torque upto 12kg-cm

These motors are capable of providing high torque while being light. They also provide internal feedback for precise angular control and are readily available.
On the final prototype these motors are replaced by Dynamixel MX 64T Servos which are more suitable motors to the specifications of bigger robot. These are high performance actuators with a fully integrated DC Motors, reduction gearhead, controller and driver, all in one servo module. These actuator provide independent speed control, position control and torque control modes. The specifications of the motor are as follows:

- Operating Voltage : 10 ~ 14.8V
- Stall Torque: 6.0N.m (at 12V, 4.1A)
- No load RPM: 63rpm (at 12V)



Materials:

We exclusively used square aluminium tubes for the fabrication of the prototype. The chassis of the prototype was manufactured of 20mm x 2mm square tubes which provides enough strength for 8 servo motors to be mounted steadily (with the help of laser-cut acrylic mounts). The legs of the prototype were manufactured by 10mm square channels in order to keep the inertia of the leg to the minimum. Joints of the prototype were fabricated using 4mm hex-bolts acting as shaft for revolute motion. Rubber strips were attached at the toe to improve its traction against ground.

For a more sophisticated final robot, we plan to use carbon fiber reinforced plastics for manufacturing as it is a lightweight high-strength material. We intend to use square tubes of the proposed material for fabrication. Specialized joints, consisting of a flange bearing were designed for final model of robot which provide frictionless motion to the legs. The joints at the toe were extended to provide for a space to mount rubber stubs. Legs of the improved model are also to be manufactured with carbon fiber reinforced plastics. A sheet of sunboard or double-railed polystyrene would be mounted on chassis to provide space for placing of circuitry of the robot[3].

Electrical Circuit:

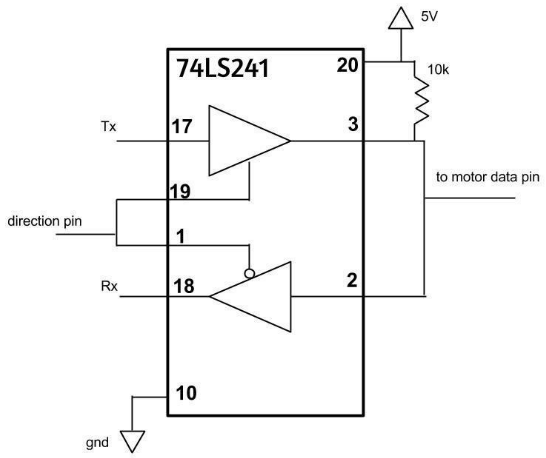
The electrical circuit for the prototype consists of the following setup:

1. LM2596 IC provides regulated power supply for powering up servos. It steps down 12 volts input to 7 volts with upto 3 Amps continuous current. The system consists of 4 of these units, each being used to power 2 motors.
2. Raspberry Pi is used as the initial microcontroller. Its Linux based OS (Raspbian) provides multi-threading capabilities and faster computational speed. This is planned to be later replaced by a more powerful Nvidia Jetson board which can be used for capturing and processing input from the camera sensor.
3. The power board used has a low pass filter to reduce noise from the power supply. A fuse (rated 15 Amps) has been included to prevent damage due to short-circuiting. We have also fabricated compact UCBs to reduce wires and improve aesthetics of the robot.

For the final robot, there have been a few changes from the previous robot:

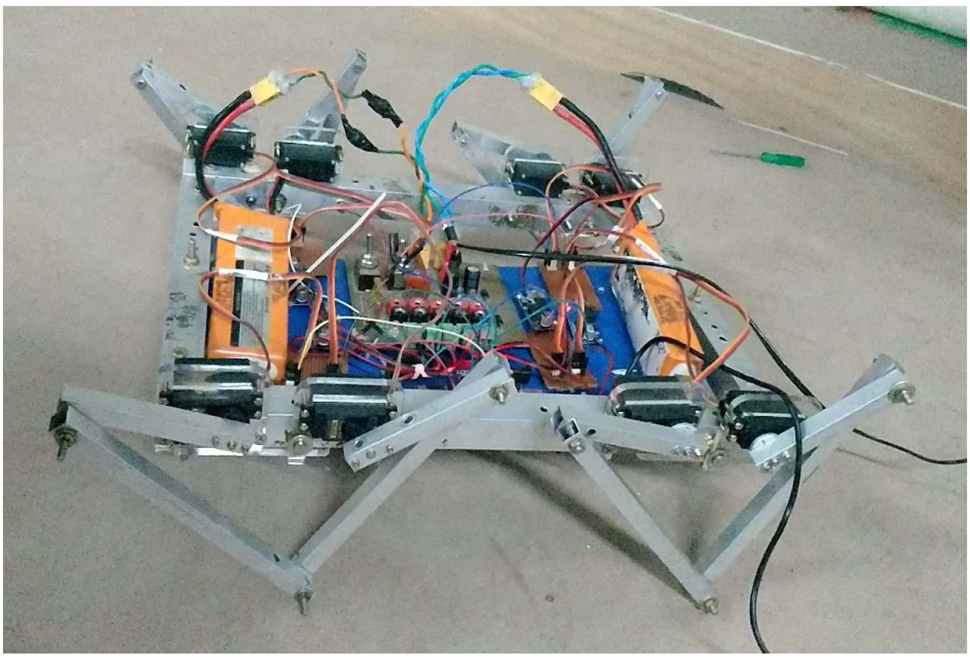
1. The microcontroller is Raspberry Pi which is same as the one chosen for the prototype. However, this time the power to RPi is provided by an onboard power bank which provides a steady 5V ~ 2.1 Amps. Previously the power was being provided externally.
2. The Dynamixel actuators used operate on 12V. Now, instead of using two 3-cell LiPo batteries, only a single 12V Lipo battery is used. This will greatly reduce the weight of the robot.
3. These motors use a half duplex Asynchronous Serial Communication Protocol for communication while RPi has provisions for a full duplex serial communication. This means that the data is sent to and received from the motor on the same wire, in contrast to the typical serial communication where data where the TX wire is dedicated for transmission and RX is dedicated to reception. To counter this issue, the full duplex signals from the Raspberry pi had to be converted to half duplex. A

74LS241 IC was used for this purpose. The circuit used for the purpose is shown below. By controlling the signal to the direction pin, the motor data pin can be made to switch from RX to TX and vice versa



Full Duplex to Half Duplex conversion

4. A daisy chain was created to control the motor through RPi. Since serial communication is used to send commands to the motor, 8 serial connections would be required to control the motors individually which is not feasible. So instead, the motors were connected on the same serial bus and the address of each motor was set to be different. This made sure that the command sent was executed by the correct motor even though the command was received by all the motors.
5. A BNO055 sensor was integrated to the system to measure the orientation of the robot and to precisely control its motion. It is a 9-axis IMU and is used to track the orientation of the robot and to monitor its stability by measuring the acceleration of the robot in the vertical direction.



Initial Prototype

Toe Trajectory:

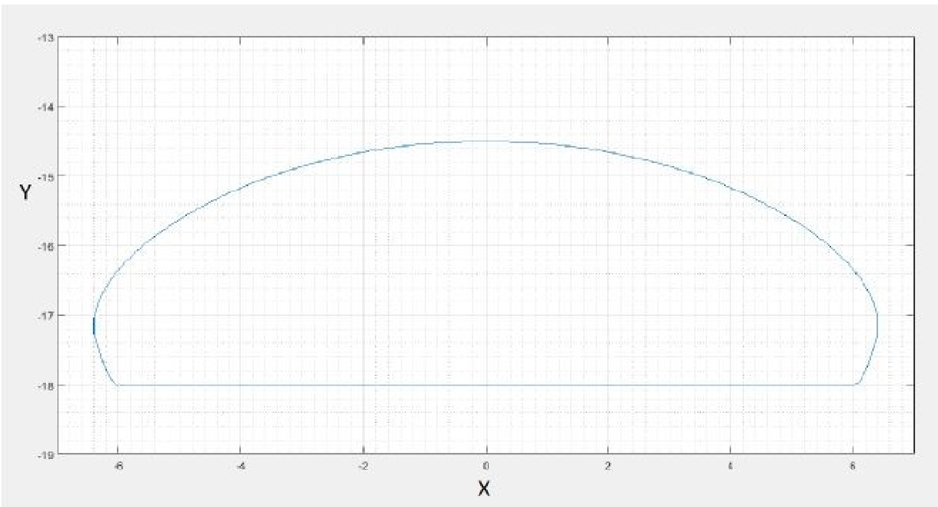
The toe trajectory is the curve traced by the the toe during a complete cycle of the leg. It is defined by the following parameters[4]:

1. Time period - Time required to complete one cycle of the leg
2. Stance time - The period during which the toe is in contact with the ground
3. Stride - The backwards movement of the toe to complete the cyclic curve
4. Duty factor (β) - Ratio of stance time to the Time period
5. Stroke - Distance covered during stance
6. s1 - Part of the stroke beyond the front edge of the robot
7. Stride Height - The maximum height off the ground achieved by the toe during stride

The following values were chosen based on literature review and by considering the static stability criteria:

- The stroke was chosen to be symmetric with a stroke length of 12cm.
- The stroke occurs 18 cm below the base of the bot.
- The motion of the robot was tested for strides of height – 3.5cm, 5cm and 6cm. The 3.5 cm stride seemed to provide most stable motion.
- A duty factor of 0.8 (> 0.75) was used to generate the toe trajectory. This duty factor provides enough time to the leg to settle down after the stride and ensures stability.

We used a third degree polynomial for the path to ensure continuity and differentiability at the end points. ‘y coordinate’ vs. ‘x coordinate’ plot of the path of the toe was obtained using Matlab and is as shown below:

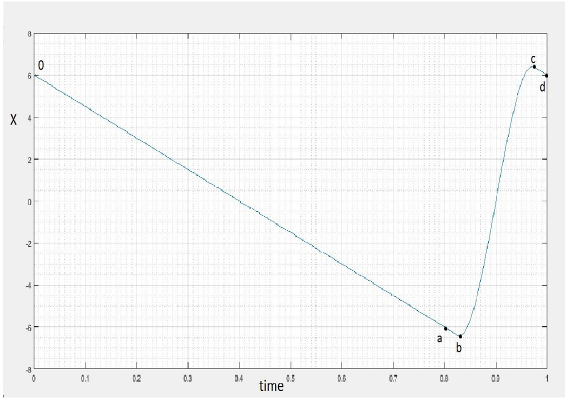


Path of the Toe

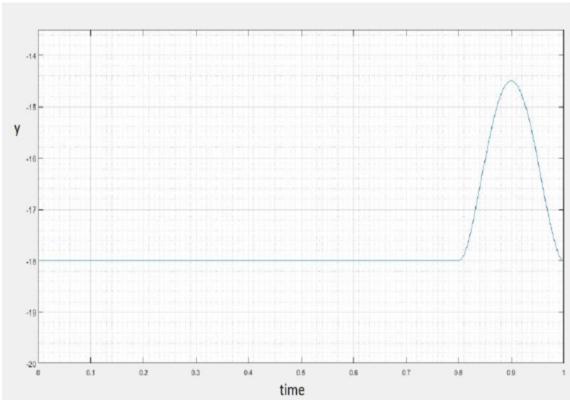
From this path, we need to generate the trajectory of motion of the toe as a function of time. The toe trajectory as a function of time were obtained using:

- Duty factor = 0.8
- Time Period = 2 seconds

The x-coordinate vs time and the y-coordinate vs time plots of the trajectory were subsequently obtained and shown as below:



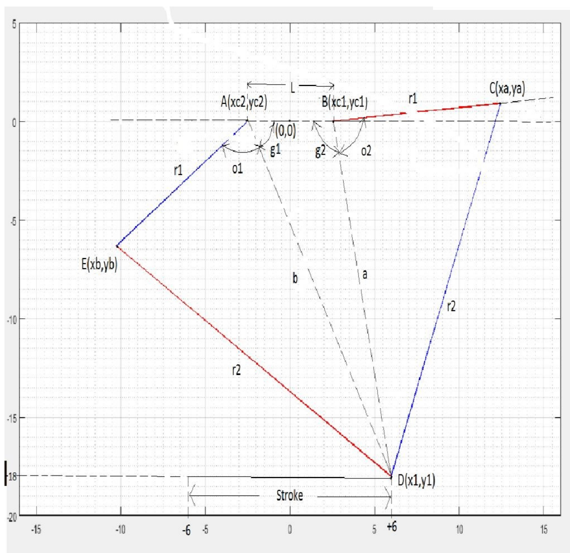
x-coordinate vs time



y-coordinate vs time

Inverse Kinematics:

This generated trajectory was to be achieved by providing appropriate angles by the actuators. The points on the trajectory were to be traced back to the crank angles by using geometric relations. The inverse kinematics of this 5R-5 bar mechanism is discussed below[5]



1) Triangle AED $\quad o1 = arccos((-r_2\hat{}2 + r1\hat{}2 + b\hat{}2)/(2*r1*b))$
2) Triangle AEB $\quad o2 = arccos((-r2\hat{}2 + r1\hat{}2 + a\hat{}2)/(2*r1*a))$
3) Triangle ABD $\quad g1 = arccos(-(a\hat{}2 - L\hat{}2 - b\hat{}2)/(2*L*b))$
$\quad g2 = arccos(-(b\hat{}2 - L\hat{}2 - a\hat{}2)/(2*L*a))$

Where a = sqrt((xt - xc1)^2 + (yt - yc1)^2)
b = sqrt((xt - xc2)^2 + (yt - yc2)^2)
xt = x-coordinate of the position of the toe
yt = y-coordinate of the position of the toe

Input angle with respect to co-ordinate system
Q2 = - (g1+o1)
Q1 = - (π-(g2+o2))

These relations were used to calculate the actuator angles Q1 and Q2.

The coordinates of the toe was calculated using the developed toe trajectory equations at various points of time. These values were put in the above inverse kinematics relations to obtain the angular position of the cranks. Since the time interval between two successive points was very less compared to the time period, the trajectory thus achieved by the toe was smooth. It was not feasible to calculate motor angles by performing these calculations in real time as they were complex and therefore time consuming. Since these angle values were being repeatedly used, they were calculated and stored in the form of a lookup table which can be accessed by the controller during runtime.

For the final model we followed a similar approach to generate the crank angles to produce the required toe trajectory. However since the design of the leg has been changed and a new link has been added to the 5R - 5Bar mechanism in the new model, the inverse kinematic relations were slightly modified.

Gaiting Methods:

Types of Gaits:

- Static - Stability when a minimum of 3 legs are on the ground at any time instant(low speeds)
- Dynamic - Stability when lesser than 3 legs are on the ground at some time instants (higher speeds)

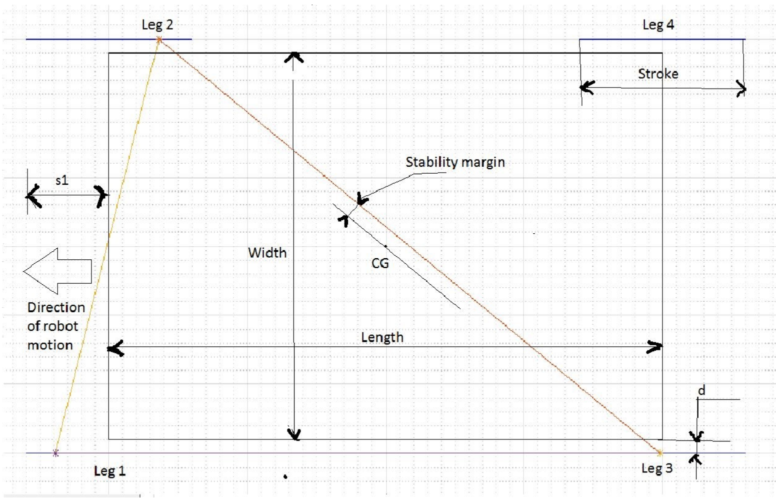
Due to the higher stability and ease of control of the static gait, we plan to implement it during the initial phase of the project.

The following parameters were used to define the Gait:

1. Φ1: Phase difference between Contralateral legs (Leg 1 and Leg 2,Leg 2 and Leg 4)
2. Φ2: Phase difference between Ipsilateral legs (Leg 1 and Leg 3,Leg 2 and Leg 4)
3. Stability margin(€): Least distance between side of the triangle and the centre of gravity
4. d – Offset distance between robot’s side edge and the leg

Gait System – Stability Triangle:

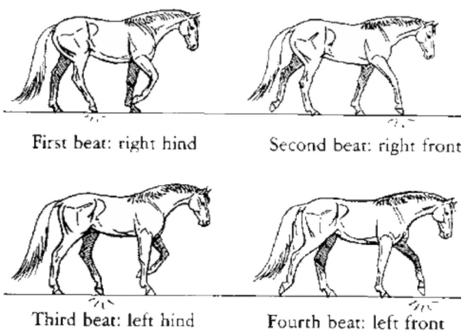
We designed the structure of robot ensuring the Centre of Gravity of the robot stays within the triangle formed when 3 legs are in contact with the ground and one leg is off the ground in flight phase.



Gait Pattern:

The legs are lifted off the ground in following pattern:

Left Front -> Right Hind -> Right Front -> Front Right



This resembles the walking gait of the horse.

The following values of phase difference was chosen for the stable movement of the robot:

$\Phi1 = +0.5$

$\Phi2 = +0.75$

Development of Walking Gait:

In order to obtain perfect gait for walking toe trajectories for various stroke lengths and different stride lengths were calculated and used for walking gait. As the center of gravity of the prototype robot did not coincide with geometric center the center of gravity did not fall inside the triangle formed by the three grounded legs. This led to instability and toppling of bot. In order to reduce the effect of asymmetry encountered, we reduced the stride height. To improve the walking speed of the prototype we increased the distance travelled per step, stoke length to maximum possible extent[6].

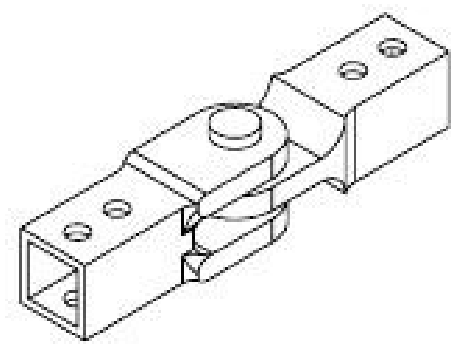
Development of Turning Gait:
Turning of robot would mean that pair of Ipsilateral legs (Leg 1 and Leg 3, Leg 2 and Leg 4) would be moving along the circumference of concentric circle. Turning would be caused by the differential speed of the inner and outer ipsilateral pair. Two approaches were tried for implementing the turning gait for the robot. First approach was to vary the time period legs so the legs on the outer curve have a higher speed keeping the stroke length constant. However this approach is not suitable for static stability as the difference in the time periods would cause changes in the phase difference and has a condition may arise where at least 3 legs are not in contact with the ground.
So the second approach of varying the stroke lengths of the legs was used. This was achieved by using different toe trajectories for ipsilateral leg pairs. To turn right, Legs 1 and Leg 3 used the stroke lengths of 16 cm while Leg 2 and Leg 4 used stroke lengths of 5cm[7].

Development of Stepping Gait :
The walking of the robot over a step can be broken down into two separate problems:
I. Stepping of the front legs onto a higher plane while climbing.
II. Stepping down from the step to level ground.
For stepping up the surface, the front two legs were provided a higher stride length so that the offset in the vertical direction can be achieved. The hind legs seemed to follow up once the front legs were on the step. Stepping down, however, was taken care by gravity but there was some tilting of the robot body. A more suitable approach would have been using dynamic walking by finding out the loads acting on the legs at each moment and therefore determining the actions in real-time.

Development of Climbing Gait (Inclined Plane) :
In order to decide the toe trajectories of four legs we need to know the long time average angle the base makes with the inclined plane (or with ground). As we would not be having any displaceable payload on robot we can use the toe trajectories same as the walking gait because a climbing up motion of robot can be seen from rotated perspective, and the motion can be seen as walking on plane ground with a component of gravity (g*cos(theta)) working in y-direction (vertical) and a component of gravity (g*sin(theta) working on x-direction (horizontal). Thus both motions are similar and can be gaited similarly.
While above part is theoretically correct, while practically testing it we found a different problem. The slippage of legs was significant due to reduced normal. We reduced the effect of slipping through reducing the stride height and reducing cycle time of the gait.

Design Modifications:
- Incorporated modifications in the joints so as to keep all revolute pairs in the same plane.
- Provided all the servo motors with bearing support to remove traverse loading of servo motors shaft thus preventing damages to motor
- Used light weight - high strength carbon fibre reinforced plastic (CFRP) to reduce the weight and moment of inertia of the leg improving agility of quadruped.
- Used Aluminium-7075 for the production of joints further reducing the moment of inertia of leg.

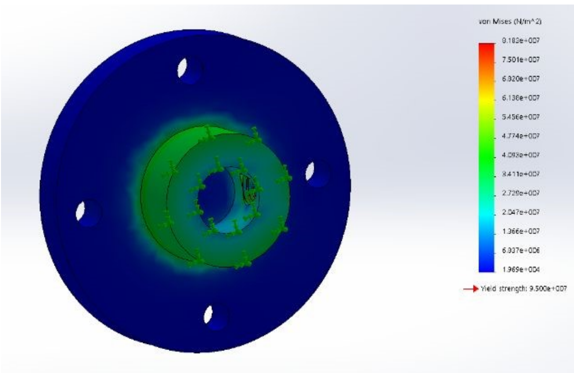
Initial CAD Model



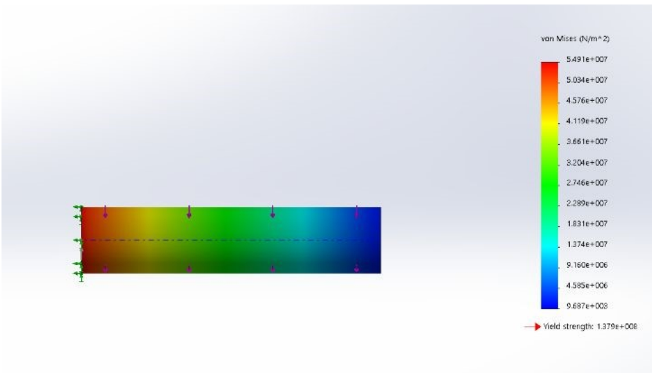
Joint Design

Materials used in Final Design:
As planned, we used CFRP (Carbon Fibre Reinforced Plastic Tubes) for the fabrication of legs. The internal and external diameter of the tubes used are 13 cm and 15 cm respectively. Simulation was done before using them to prevent any catastrophic failure. The joints were manufactured using Aluminium – 7075. This was done in order to maintain a high strength to weight ratio. The motor-mounts and motor-hub were included with the Dynamixel motors.
The chassis was manufactured using 20x20x1 mm aluminium (6063 series) channels to keep them lightweight and strong.

Results of the Simulation of Designed Parts:

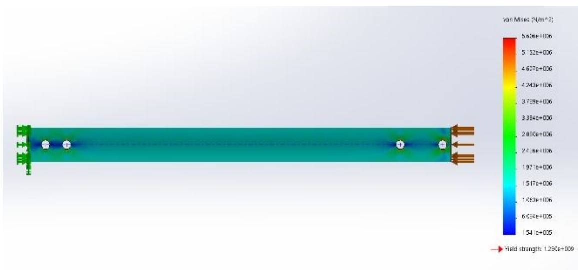


Motor Hub



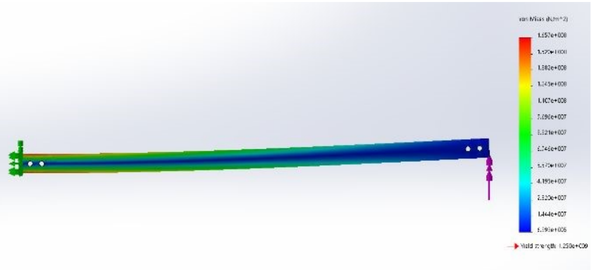
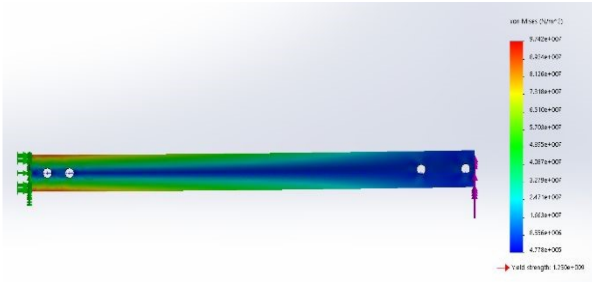
Motor Shaft

Results of Simulation of CFRP Tubes: (Axial Loading):



Coupler Crank

Results of Simulation of CFRP Tubes: (Transverse Loading):

Coupler Crank

Simulation Results:

As seen from results of the above simulation, the von-Mises stresses in all parts are below their yield limits. The simulation was performed with loads greater than those actually acting on the final robot, accounting for a factor of safety.

Similar analysis was done for various different parts of the leg and under various loading conditions. The link and joint designs were modified accordingly if the stresses developed were found to be high.

Dimensions of Final Model:

Length of crank 1 and crank 2 = 200 mm

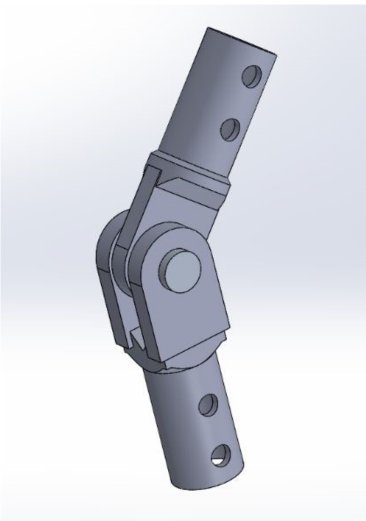
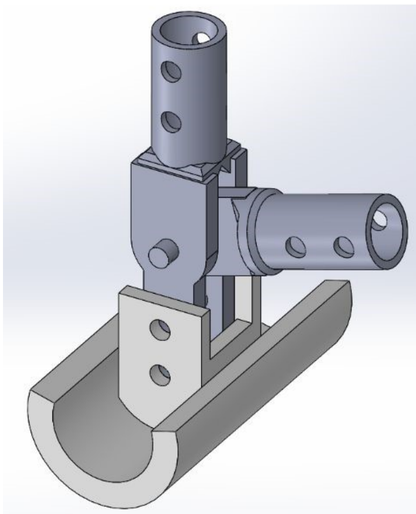
Length of coupler 1 and coupler 2 = 400 mm

Diameter of all linkages (leg) = 15 mm

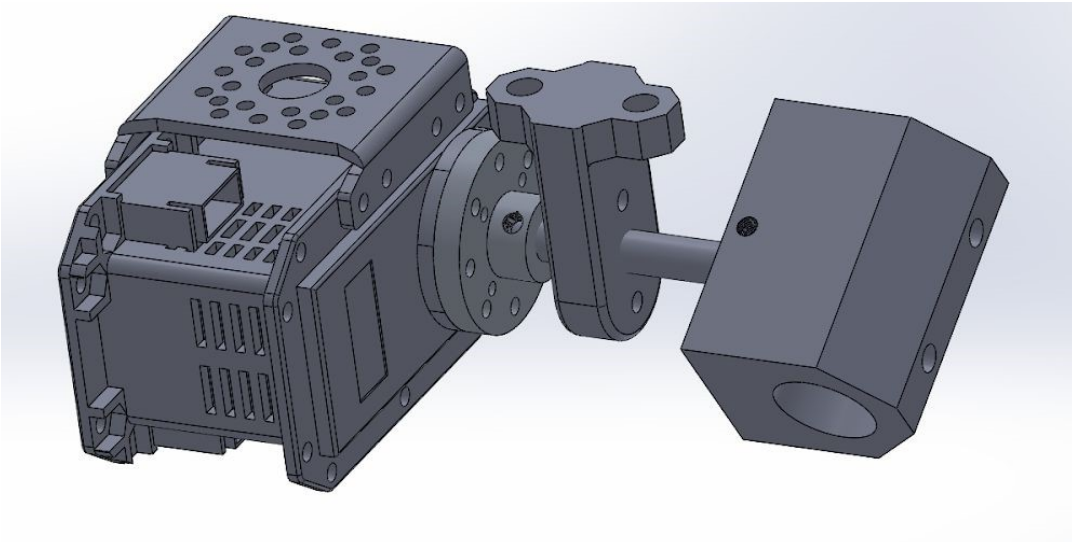
Distance between the pivot points A and B, i.e., between parallel axes of motors = 100 mm

Vertical distance from the toe to line AB during stroke = 100 mm to 230 mm

CAD model of Designed Parts:

Joint Assembly Bottom Joint Assembly



Dynamixel Hub and Bearing Housing Assembly

CAD model of Modified Leg:

Ongoing Work:

1. Fabricating the control system of the final robot
2. Implementation of walking, turning and stepping gait on the final model
3. Testing and Improvements of the final robot

Project Repository:

Shortened Url: https://goo.gl/cpL4vT

References:

[1] S. Kalouche, “Design for 3D Agility and Virtual Compliance Using Proprioceptive Force Control in Dynamic Legged Robots,” 2016.

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[5] A. Arbor, A. Abate, J. W. Hurst, and R. L. Hatton, “Robotics: Science and Systems Mechanical Antagonism in Legged Robots.”

[6] D. J. Blackman, J. V Nicholson, C. Ordonez, B. D. Miller, and J. E. Clark, “Gait Development On A Direct Drive, Quadrupedal Robot.”

[7] C. Gehring et al., Dynamic Trotting on Slopes for Quadrupedal Robots.