Design, Analysis and Fabrication of Quadruped Robot with Four bar Chain Leg Mechanism

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Abstract

The paper presents design, analysis and fabrication of a 1.71 Kg. quadruped robot which incorporates four bar chain leg mechanism as its locomotion element. The main objectives of this paper are mechanical design, gait analysis and fabrication of quadruped robot. Quadruped robot designed and fabricated here involves 8 degrees of freedom which are controlled by servomotors and it walks on flat terrain using symmetrical gaits viz. trot and pace. Its locomotion is controlled by controlling angular rotation of servomotors.

Keywords: *Four bar chain leg mechanism, Mechanical design, Gait analysis, Fabrication, Trot, Pace.*

1. Introduction

Mobile robots are able to use their skills and do their tasks effectively wherever applied. On the other hand robot manipulators which are bolted at their shoulder to the base have limited range of motion that depends on where these are bolted down. Thus mobile robots are superior to robot manipulators.

In mobile robots, mobility can be achieved by incorporating a mechanism. Depending upon the two broad categories viz. legged mechanisms and wheeled mechanisms, mobile robots incorporating them are classified as legged robots and wheeled robots respectively. It is well known that legged robots are superior to wheeled robots [1] and thus are in the focus of this research work. For locomotion of legged robots a legged mechanism is required. Very few legged mechanisms have been developed till date [2]. Simple insect leg design, pantograph leg design which has been used in RIMHO robot [3], 2 and 3 degree of freedom leg design which has been used in SCOUT I & II robots [4] etc. are few of the mechanisms used for locomotion of robots in past.

In legged robots, quadruped robots are simple to construct. Also, controlling their locomotion is easier than biped and hexapod robots [1]. Thus in this paper quadruped structure is preferred over other legged structures. Generally, quadruped robot is composed of a torso frame which forms base to hold actuation system, control system and power pack [4]. It has four legs as a locomotion element [4]. For locomotion of quadruped robot, movement of these legs with respect to torso frame is to be controlled. The leg of a quadruped robot is actually a mechanism. In this paper, four bar chain mechanism in modified form has been used as legged mechanism for the quadruped robot.

The work in this paper mainly focuses on mechanical design, trot and pace gait locomotion analysis, fabrication and experimentation of quadruped robot. Conclusions derived from this research work are pointed out at the end.

2. Mechanical Design of Quadruped Robot

In this paper, mechanical design of quadruped robot includes robot specifications and structure, kinematic modeling, trajectory planning, joint torques calculations and CAD model development of quadruped robot.

2.1 Robot specifications

Before starting design of any machine it is necessary to decide its specifications. Here also performance and physical specifications of quadruped robot are decided. Performance specifications describe task related specifications and physical specifications describe robot’s dimensions and weight. In this research work, quadruped robot is able to walk with trot and pace gaits over flat terrain. Maximum targeted speed is 20 mm/s. 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.

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2.2 Robot structure

Basic structure of quadruped robot consists mainly of torso frame and legs which are attached to it. Each leg consists of two or more links connected to each other by revolute joints. Also each leg is attached to torso frame by revolute joint. The leg of robot which is actually a mechanism is shown in figure 1 below.

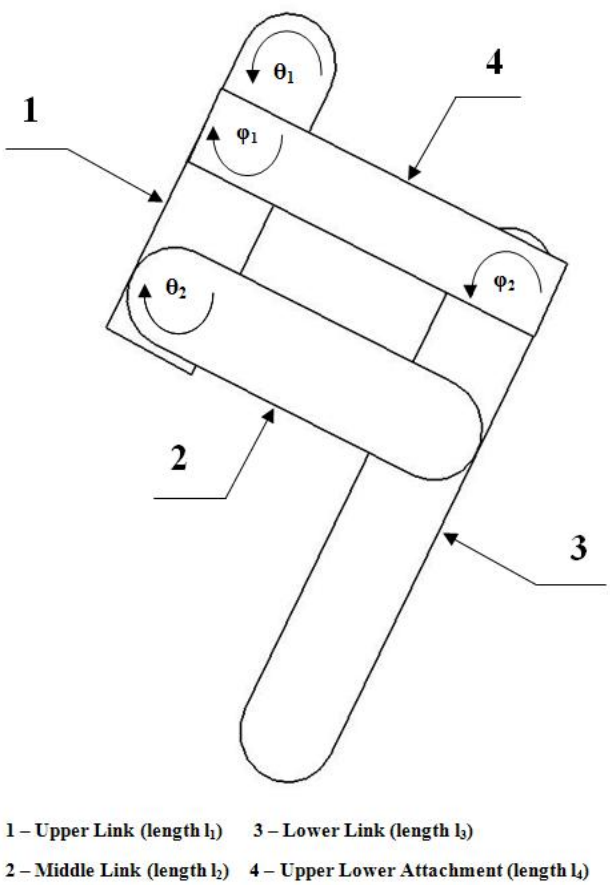

Fig. 1 Robot Leg Mechanism

As shown in figure 1 above, out of five revolute joints two joints are active joints whose motion is to be controlled. These two joints are Hip flexion/extension (θ_1) and Knee flexion/extension (θ_2). Each of these joints is controlled by single servomotor. Φ_1 and ϕ_2 are passive joints and thus are not required to be considered here.

2.3 Kinematic modeling

Kinematic modeling of quadruped robot is divided into two sections viz. direct kinematics and inverse kinematics. Direct kinematics gives position and orientation of endpoint of robot leg with respect to its base at torso frame given its joint angles [5]. Inverse kinematics gives joint angles given the position and orientation of endpoint of robot leg with respect to its base [5].

1. Direct kinematics

In this paper, a generalized arm matrix for the robot leg is derived using direct kinematics procedure. By substituting joint angle values in the arm matrix for a leg, position and orientation of that leg with respect to torso frame can be found out. Derived generalized arm matrix is

$$T = \begin{bmatrix} Cos\theta_1 & -Sin\theta_1 & 0 & (l_3 + l_5) * Cos\theta_1 + l_4 * Cos(\theta_1 + \theta_2) \\ Sin\theta_1 & Cos\theta_1 & 0 & (l_3 + l_5) * Sin\theta_1 + l_4 * Sin(\theta_1 + \theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where, l_2, l_3 and l_4 are link lengths as shown in figure 1. Using armed matrix mentioned in Eq (1), Soft Home Position (SHP) of robot leg is calculated for joint angles $\theta_1 = 74.5°$ and $\theta_2 = 90°$ and geometrical constraints $\phi_1 = \theta_2$ and $\phi_2 = -\theta_2$. In SHP, distances of endpoint of robot leg from its base in X-direction and Y-direction are 35.3 mm and -209.3 mm respectively. SHP is verified by sketching in UG NX 7.5.

2. Inverse kinematics

Input to inverse kinematics is the position and orientation of robot leg in the form of Tool Configuration vector (TCV) [5]. Solving equations obtained by equating arm matrix and TCV for robot leg, formulae to calculate active joint angles are obtained. These formulae are

$$\theta_2 = Cos^{-1}\left[\frac{W_1^{\,2} + W_2^{\,2} - (l_3 + l_5)^2 - l_4^{\,2}}{2 * (l_3 + l_5) * l_4}\right] \quad (2)$$

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$$\theta_1 = \tan^{-1}\frac{\mathrm{Sin}\theta_1}{\mathrm{Cos}\theta_1} = \tan^{-1}\frac{S\theta_1}{C\theta_1} \qquad (3)$$

Where,

$$S\theta_1 = \left| \frac{\begin{matrix} (l_3+l_5)+l_4 * C\theta_2 & W_1 \\ l_4 * S\theta_2 & W_2 \end{matrix}}{\begin{matrix} (l_3+l_5)+l_4 * C\theta_2 & -l_4 * S\theta_2 \\ l_4 * S\theta_2 & (l_3+l_5)+l_4 * C\theta_2 \end{matrix}} \right|$$

$$C\theta_1 = \left| \frac{\begin{matrix} W_1 & -l_4 * S\theta_2 \\ W_2 & (l_3+l_5)+l_4 * C\theta_2 \end{matrix}}{\begin{matrix} (l_3+l_5)+l_4 * C\theta_2 & -l_4 * S\theta_2 \\ l_4 * S\theta_2 & (l_3+l_5)+l_4 * C\theta_2 \end{matrix}} \right|$$

W_1 and W_2 are first two rows from TCV.

3. Trajectory planning

In robotics, trajectory means the way from one location to another location along which robot moves in a controlled manner. In trajectory, along with the path, at what time of interval 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 paper, 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 236 mm apart. Torso frame of quadruped robot is maintained at 209 mm from the ground. Semi-elliptical trajectory is shown in figure 2 below.

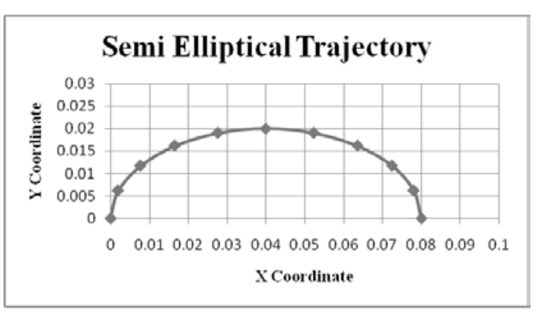

Fig. 2 Semi-elliptical Trajectory

4. Calculation of joint angles

Hip flexion/extension and knee flexion/extension joint angles throughout locomotion are calculated using eq. (2) and (3). Plot of Time (tn) vs. joint angles for legs 1 & 3 and legs 2 & 4 are shown in figures 3 & 4 below respectively.

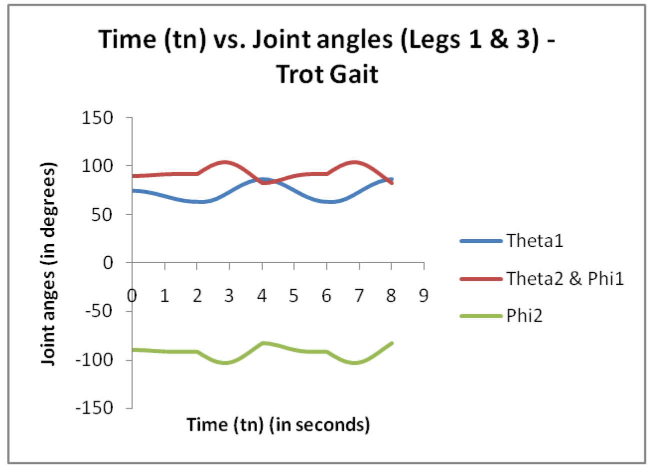

Fig. 3 Plot of Time (tn) vs. Joint angles for legs 1 & 3 in trot gait

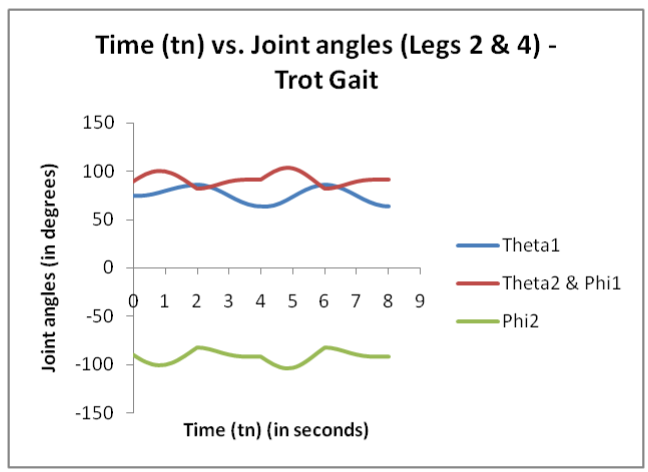

Fig. 4 Plot of Time (tn) vs. Joint angles for legs 2 & 4 in trot gait

Results of joint angle calculation are verified by sketching a line diagram of robot leg in UG NX 7.5. Line diagram drawn is for robot leg 2 at time (tn) = 2 seconds. Line diagram is shown in figure 5 below.

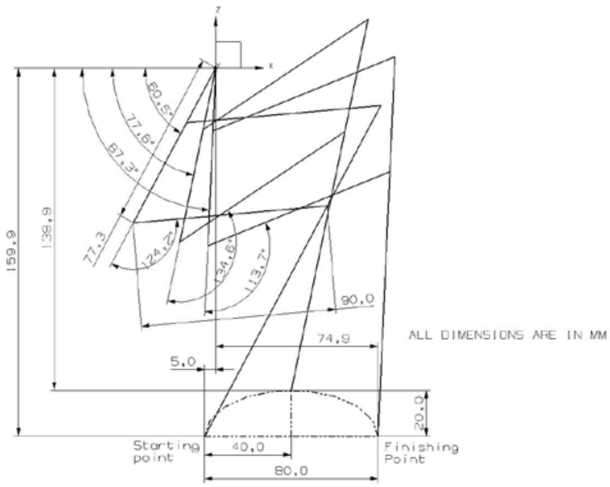

Fig. 5 Line Diagram for Robot Leg

2.4 Joint Torques Calculation

To select actuation system for the quadruped robot it is necessary to estimate the joint torques that is required for locomotion. In this research work, joint torques have been calculated when quadruped robot is stationary and when it performs locomotion using trot and pace gaits. For calculations, basic principles in mechanics and robotics have been used. To maintain soft home position while standing, quadruped robot is required to maintain 1.86 kg-cm and 1.75 kg-cm torques in clockwise direction at hip flexion/extension joints of front and rear legs respectively. And it requires maintaining 3.1 kg-cm and 2.91 kg-cm torques in counterclockwise direction at knee flexion/extension joints of front and rear legs respectively. Joint torques in legs 1 & 3 and legs 2 & 4 calculated for trot gait locomotion are shown in figure 6 & 7 respectively below.

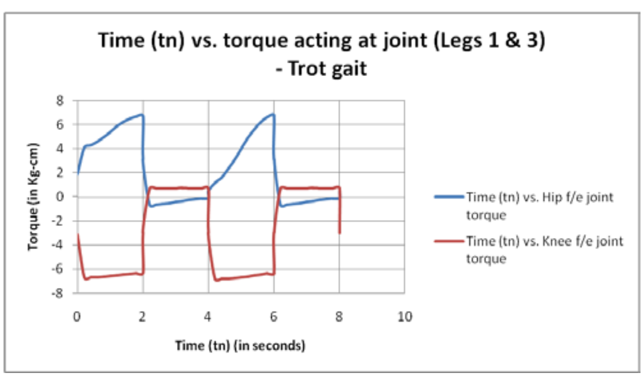

Fig. 6 Plot of Time (tn) vs. Torques at joints of legs 1 & 3 using trot gait throughout locomotion

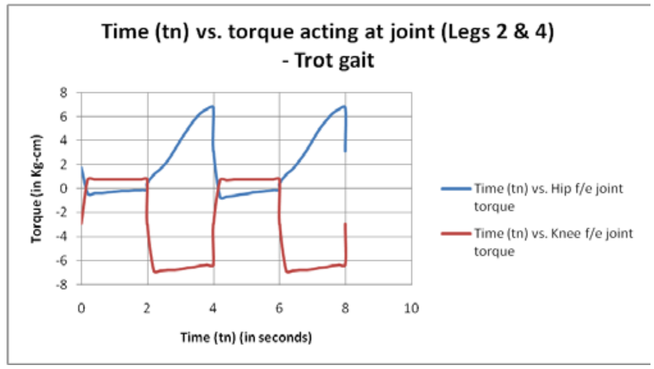

Fig. 7 Plot of Time (tn) vs. Torques at joints of legs 2 & 4 using trot gait throughout locomotion

2.5 Development of CAD model of Quadruped Robot

Before the work proceeds from design stage to fabrication stage it is necessary develop a CAD model of quadruped robot. In this research work, CAD model of quadruped robot has been developed on UG NX 7.5 Siemens software platform. Development of CAD model helps in fixing dimensions of quadruped robot and calculation of mass properties of quadruped robot. CAD model is shown in figure 8 below.

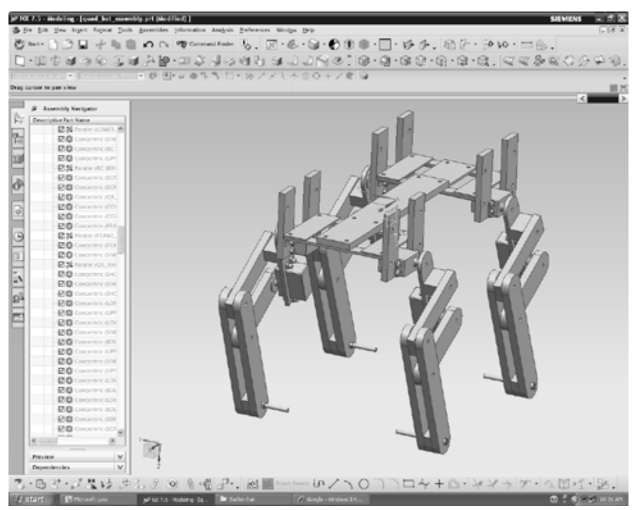

Fig. 8 CAD model of quadruped robot

3. Gait Analysis of Quadruped Robot

For smooth and steady locomotion of quadruped robot, a sequence of leg and body motion must be generated. This sequence is termed as a gait [6]. In this research work, quadruped robot walks using two symmetric gaits viz. Trot and Pace. Supportive feet in trot and pace gait locomotion [6] are shown in figure 9 below. Table 1 below shows symbols used for legs in gait representation in figure 9.

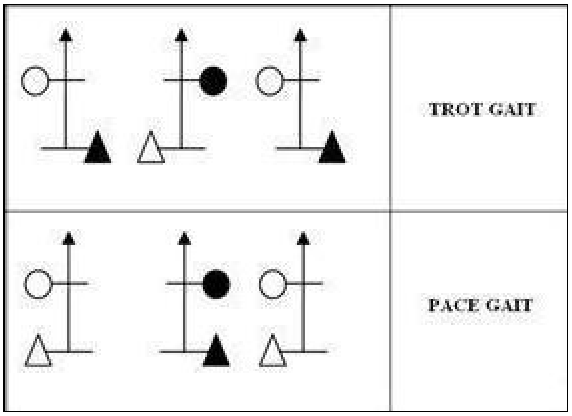

Fig. 9 Supportive feet under trot and pace gaits [6]

Table 1: Symbols used for legs in gait representation [6]

Leg	Symbol
Left-Front (LF)	○
Right-Front (RF)	●
Left-Rear (LR)	△
Right-Rear (RR)	▲

In this research work, trot and pace gait locomotion of quadruped robot is analyzed for parameters viz. stride, mean speed of foot, duty factor, cycle time etc. Following are the results of gait analysis.

1. Stride frequency:

Quadruped robot takes 4 seconds to cover single stride of 80 mm. Thus stride frequency is

$$f = \frac{1}{4} \qquad (4)$$

2. Mean speed of foot:

It is the product of stride length and stride frequency [6]. Stride length is 80 mm. Mean speed of foot is

$$u = \lambda * f = 80 * {}^{1}\!/_{4} = 20 \text{ mm/s} \qquad (5)$$

Stride frequency should by maximum for given stride to obtain maximum mean speed of foot.

3. Duty factor and relative phase:

Both trot and pace gaits have duty factor 0.5. In trot gait, Left-Front and Right-Rear legs have 0 relative phases. Other two legs have 0.5 relative phases. In pace gait, Left-Front and Left-Rear legs have 0 relative phases. Other two legs have 0.5 relative phases.

4. Fabrication of Quadruped Robot

After development of CAD model, dimensions of robot hardware components and overall dimensions of quadruped robot are fixed. Robot hardware components viz. torso frame and legs are fabricated from PVC foam sheet (Sunboard) material.

4.1 Quadruped Robot Assembly

Quadruped robot is assembled from robot hardware components, actuators (servomotors in the given case), control system (controller board and servo shield in the given case) and batteries. Assembled quadruped robot is shown in figure 10 below.

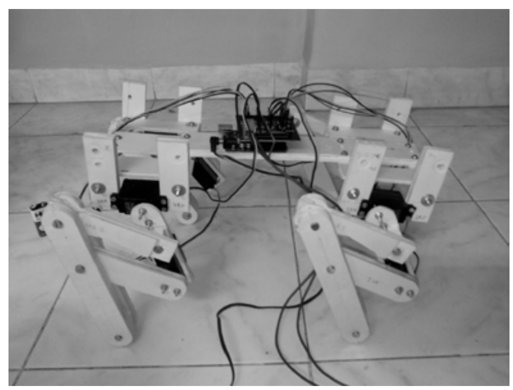

Fig. 10 Assembled quadruped robot

Properties of quadruped robot assembly:

1. Total weight of quadruped robot assembly = 1.71 Kg.
2. Overall height = 291 mm , Overall length = 352 mm, Overall width = 280 mm.

4.2 Hardware and software used

Hardware includes control system consisting of controller board and servo shield, servomotors and power sources. In this research work, Arduino controller board controls the 8 servomotors. Servo shield facilitates mounting J connectors of servomotors over Arduino controller board. Futaba S3305 servomotors are used to actuate the legs. At 4.8 Volts, one such servomotor has stall torque of 7.1 kg-cm. And at 6 Volts, it has 8.9 kg-cm stall torque. Servomotor with maximum stall torque little higher than requirement is selected due to losses during its operation. Each of this Futaba S3305 servomotor weighs 47 grams. Power sources include 1.5 Volts batteries and 9 Volts batteries. 4 1.5 Volts batteries power servomotors and 9 Volts battery powers Arduino controller board. Regulated DC power supply also required sometimes because of higher current usage of servomotors.

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 and pace gait locomotion separately. It is then fed to controller board for use.

5. Experimentation

Experiments on locomotion of quadruped robot using trot and pace gaits over flat terrain are performed. The results of experiment are tabulated below. Table 2 below shows joints angles in right hand side legs (when quadruped robot is observed from behind in direction of motion). On comparing the values from experiments and theoretical calculation of inverse kinematics, little difference is found between them. This difference exists because of restriction to servomotor revolution due to its mounting arrangement on quadruped robot.

Table 2: Results of experiments

X distance (in mm)	**Y distance (in mm)**	**Hip flexion/extension joint angle (in degrees)**	**Knee flexion/extension joint angle (in degrees)**
2	-230	69	73
-33	-218	57	82
-33	-225	59	75
-62.5	-235	55	68

Also stride completed by legs in one cycle and time required for it is observed. Mean speed of foot is then calculated as follows.

Stride length (λ) = 80 mm
Total time taken for one stride = 2.31 seconds

Again we have, Stride frequency is the number of strides taken in unit time. Therefore, stride frequency,

$$f = 1/2.31 \tag{6}$$

And Mean speed of foot,

$$u = \lambda * f = 80 * 1/2.31 = 34.63 \text{ mm/s} \tag{7}$$

The mean speed of foot obtained from experiment (34.63 mm/s) is greater than what is obtained from theoretical calculations of gait analysis (20 mm/s).

6. Conclusions

Quadruped robot which is a legged robot requires a legged mechanism for locomotion. Four bar chain leg mechanism developed in this research work requires actuation only at two joints out of five joints. Also total load acting on robot gets divided among these joints in the legs.

Kinematic model is the connecting link between Cartesian coordinate system and joint coordinate system.

Quadruped robot designed and fabricated in this research work is able to navigate using trot and pace gaits over flat terrain and attains maximum mean speed of foot of 34.63 mm/s

Quadruped robot serves as a platform for implementation in real world applications.

References

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