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Development of quadruped robot for flat terrain based on biological concepts

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Abstract

The paper tries to induce a quadruped which can walk with medium speed on flat terrain which is based on biological concepts. The design of quadruped is inspired by four legged animal for example dog where two joints of the leg enable to perform two basic motions-lifting and stepping. Forward kinematic model and inverse kinematic models are proposed which provides stable walk on flat terrain. The position and orientation of the robot feet are systematically adjusted. Detailed guideline is provided for leg mechanism through the study of various joints, links and degrees of freedom.

Keywords: Mobile robots; legged robots; quadruped robots; kinematic modeling; trajectory planning etc.

1. INTRODUCTION

Mobile robots are a major focus of current research. Basically there are two main types of mobile robots-wheeled robots and legged robots. Mobile robots are developed to be used in areas which are inaccessible or hazardous for human beings. Wheeled robots are much easier to design and construct. In today's economy, they are very much cheaper than their legged counterparts [1]. Legged robot mechanisms are often inspired by biological systems, which are very much successful moving through rough terrain. Wheeled robots are designed to work on smooth surfaces, roads or rails. Legged robots can navigate on any kind of surfaces which are inaccessible for robots with wheeled [2]. Legged robots can jump or step over the obstacles whereas wheels need to somehow travel over it or take a different path.

Another important part related to robot locomotion is stability. Locomotion techniques are divided into two categories -static stability and dynamic stability. Static stability means that the robot is stable, with no need of motion at every moment of time. The minimum number of ground contact points required for a statically stable robot is three. Robots that use static movement are always balanced; that is, their center of gravity is always within their ground contact base.Dynamic stability is where stability is achieved on movement. Dynamically stable robots are harder to control; they are more energy efficient and move faster than statically stable robots. Four legged robots are statically and dynamically stable. If the robot lifts one leg at a time, then there are three contact points to surface and the robot maintains stability while standing or moving. Moving one leg at a time makes robot slower and expensive on resources, but keeps it stable. This paper considers the walking pattern of robot with alternating pair of legs where at any time, the robot has two surface contact points creating a dynamically stable robot .Faster and efficient but less stable as compared to the first approach.

2. Leg Configuration

Leg configuration decides how the legs are situated on the body. This affects the stability of the robot and the workspace of the legs. To move a leg forward at least two degrees of freedom are necessary, one for lifting the leg and one for stepping or swinging the leg [1].

There are two main types of leg configurations, which are based on biological concepts. The first type is similar to cats, humans and birds, where the legs swing around a horizontal axis [2]. Legs are inline facing in the same direction and support the weight of the body by placing the feet under the body, near the vertical projection of the body's center of mass on the ground. The second type is more similar to insects where the legs swing around a more vertical axis. It has a sprawled stance where the legs stretch out from the body and the support is provided directly under the body, far from centre of gravity which makes them very stable [2]. This configuration is more common for multilimbed robots such as quadrupeds and hexapods.

In this paper, main concentration is given on the design of the quadruped involving two degrees of freedom where the robot is able for lifting and stepping only. Some assumptions are considered for deriving the kinematic model which are as follows:

a. The robot moves forward in a straight path on flat surface with alternating pair of legs.
b. The body is held at a constant height and parallel to the ground plane during locomotion.
c. The center of gravity of the body is assumed to be at the geometric center of the body.

This paper firstly introduces the formation of co-ordinate system linkage of quadruped robot. Then the forward and inverse kinematic equations of the quadruped robot are formulated. Finally using UG-NX, 3D model of the robot is prepared.

3. Direct Kinematics

The mechanical structure of the robot is mainly divided into two parts as body and legs. The body is a rigid rectangular box; the four legs are distributed symmetrically along the body and each leg has the same mechanical structure. The links are made up of a series of rigid linkages connected by rotating joints. There are two joints for each leg which are hip joint and knee joint [4].

The kinematic model of an open loop articulated chain can be divided into two problems-direct kinematic problem and inverse kinematic problem. The forward kinematic problem gives the position and orientation of the foot, in terms of joint variables. In contrast, the inverse problem gives the joint variables in terms of the position and orientation of the foot.

First the direct kinematic model is prepared and after that inverse kinematic model is done. In direct kinematics, co-ordinate frames are attached to the links. D-H algorithm is used for proper assignment of frames to the links. Single line diagram is drawn for simplification of the concept.

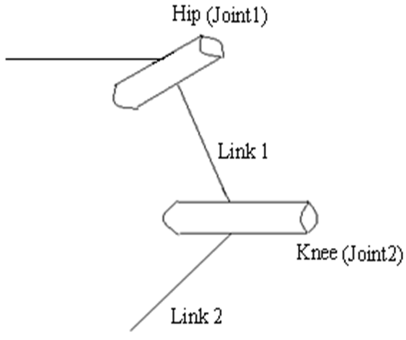

Figure 1: Single line diagram of each link

After single line diagram, frames are attached to each joint. The co-ordinate system diagram for each joint is given in Fig 2.

From the co-ordinate frame diagram, kinematic parameter table is prepared. From this table, the joint parameters and link parameters are obtained.

Table 1: Kinematic Parameters for One Leg

Axis	Type	Θ_k	d_k	a_k	α_k
1	Hip	Θ_1	0	a_1	0^0
2	Knee	Θ_2	0	a_2	0^0

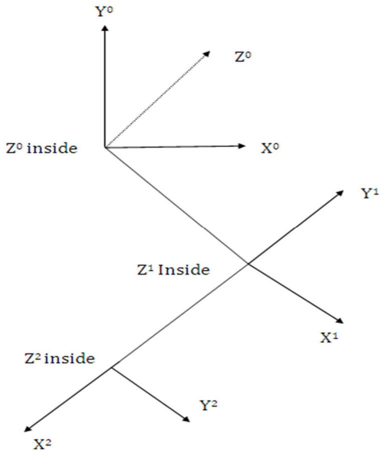

Figure 2: Co-ordinate system of each linkage

The links homogeneous transformation matrices have been presented as below.

$$ {}^0_1T = \begin{bmatrix} C_1 & -S_1 & 0 & a_1C_1 \\ S_1 & C_1 & 0 & a_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^1_2T = \begin{bmatrix} C_2 & -S_2 & 0 & a_2C_2 \\ S_2 & C_2 & 0 & a_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The resulting transformation matrix between foot tip reference frame {2} to the hip reference frame {0}.

$$ {}^0_2T = \begin{pmatrix} C_1C_2 - S_1S_2 & -C_1S_2 - C_2S_2 & 0 & a_1C_1 + a_2C_1C_2 - a_2S_1S_2 \\ C_1S_2 + C_2S_1 & C_1C_2 - S_1S_2 & 0 & a_1S_1 + a_1C_1S_2 + a_2C_2S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

As the four legs of the robot have same symmetry, we can calculate the forward and inverse kinematic model for one leg and then apply it to remaining 3 legs. Each leg has 2 degrees of freedom, hence total there are total 8 degrees of freedom for four legs.

4. Inverse Kinematics

The inverse kinematics consists in determining the joint variables in terms of the foot position and orientation. The inverse kinematic model finds out the rotation angle with which the robot can move [10]. The solution to the inverse kinematic problem is found out with the help of Tool Configuration Vector (TCV) [10].TCV (Tool configuration vector) is the compact representation of the foot tip position and foot orientation. The direction in which the foot is oriented or pointed is given by the approach vector or the last column of rotation matrix specifies the roll, but does not give any information about yaw and pitch.

The tool configuration vector is given by,

$$W(q) = \begin{bmatrix} \frac{w^1}{w^2} \end{bmatrix} = \begin{bmatrix} \frac{p}{(exp_{\pi}^{qn}\ )*r^3} \end{bmatrix}$$

Where,

w=Tool Configuration Vector

w^1=First three components of w, represents the foot position p.

w^2=Next three components of w, which represents foot orientation.

$$T_n = \begin{bmatrix} R_{11} & R_{12} & R_{13} & P_1 \\ R_{21} & R_{22} & R_{23} & P_2 \\ R_{31} & R_{32} & R_{33} & P_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Equating equation of T and T_n, we get

$p_1 = w_1 = a_1C_1 + a_2C_1C_2 - a_2S_1S_2$
(1)
$p_2 = w_2 = a_1S_1 + a_1C_1S_2 + a_2C_2S_1$
(2)
$p_3 = w_3 = 0$

Squaring and adding W1 and W2, we get θ2.

$$w_1^2 + w_2^2 = a_1C_1 + a_2C_1C_2 - a_2S_1S_2 + a_1S_1 + a_2C_1S_2 + a_2C_2S_1$$

After solving the equation,

We get knee angle as,

$$\theta_2 = \cos^{-1}\left(\frac{w_1^2 + w_2^2 - a_1^2 - a_2^2}{2a_1a_2}\right)$$

After finding out θ2, now we are going to calculate θ1.

$w_1 = a_1C_1 + a_2C_1C_2 - a_2S_1S_2$
$w_2 = a_1S_1 + a_1C_1S_2 + a_2C_2S_1$

Expand C1C2 and S1S2 using sum of sines and cosines; isolate C1, S1.Write in matrix form, collect all C1 terms and S1 terms and then find out θ1.

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$$w_1 = a_1C_1 + a_2C_1C_2 - a_2S_1S_2$$
$$= (a_1 + a_2C_2)C_1 - (a_2S_2)S_1 \quad (3)$$
$$w_2 = a_1S_1 + a_1C_1S_2 + a_2C_2S_1$$
$$= (a_2S_2)C_1 + (a_1 + a_2C_2)S_1 \quad (4)$$

The hip angle is given by,

$$\theta_1 = \tan^{-1}\left(\frac{(a_1+a_2*C_2)-(a_2S_2)w_1}{(a_1+a_2C_2)w_1+(a_2S_2)w_2}\right)$$

By using the values of θ1 and θ2, the hip and knee angles are determined, which gives the exact foot position while standing and walking.

5. Foot Trajectory Planning

One of the main objectives of any trajectory planning algorithm is to achieve a smooth motion of the foot. The robot is assumed to describe a continuous semicircular path which consists of movement of alternate pair of legs.The smooth motion has the important advantage of reducing the vibrations and wear of the mechanical system. Some assumptions are made for such kind of trajectory which is –

a. The body length of the robot should be 1m long and is at near about 0.8m from the ground.
b. The legs of the robot are placed at a distance of 0.6 m from each other and all the legs have the same symmetry.
c. The alternate pair of legs moves at a time i.e leg 1 and leg 3 move simultaneously. This is called as trotting. The distance between two legs i.e front and rear one is 0.6m and the distance covers in one stance is 0.3m.The speed of the robot is 2 m/sec.

Here 3D model of the robot has been developed in UG-NX, some of the design parameters are L1=L2=0.5m.

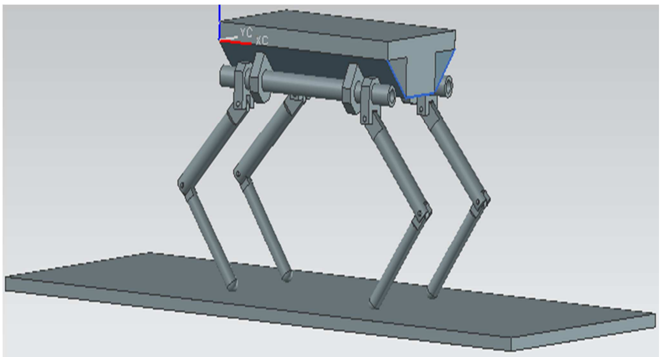
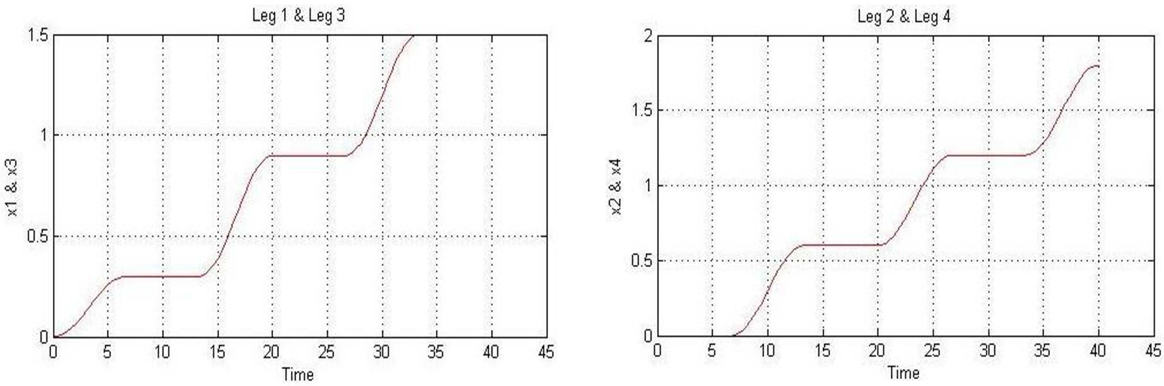


Figure 3: CAD model of quadruped robot

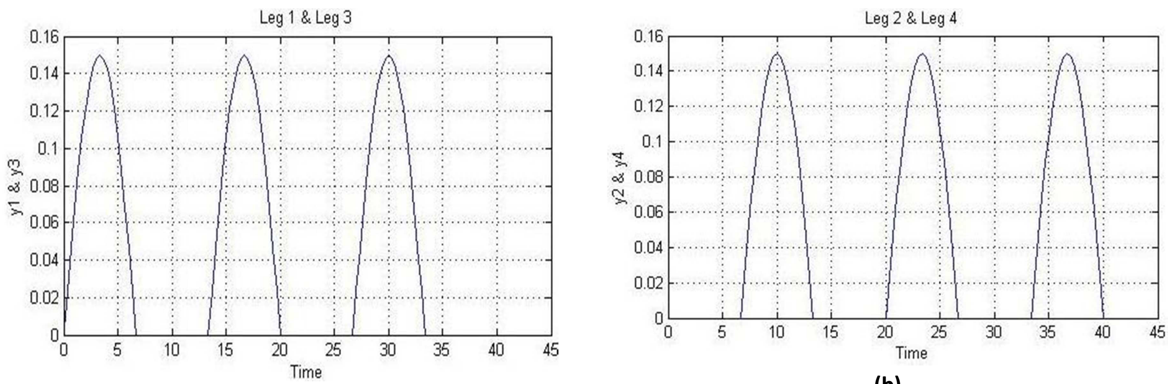
The trajectory of the robot's leg is set with the help of parametric equations and the values of angles find out from the inverse kinematics. One step should take 6.67 sec with uniform speed. Then graphs are drawn using Matlab2011.



(a) (b)

Figure 4: Movement in x- direction

The first and third leg moves first and after that second and fourth leg movement takes place. There is a time gap of 6.67sec in between the movement of fist step of 1st and 3rd leg and 2nd and 4th leg of second step.



(a) (b)

Figure 5: Movement in Y-direction

There is the verification of the forward kinematic model and inverse kinematic model with the help of robotic tool box. The robotic toolbox provides many functions that are useful in robotics such as kinematics, dynamics and trajectory planning. The toolbox is useful for simulation as well as in analyzing results from experiments with real robots. Robotics mathematics can be programmed in MATLAB and simultaneously results can be checked with MATLAB-2011a-Robotics toolbox.

6. Differential Motion And Statics

The direct and inverse kinematic model establishes the relationship between the manipulator's joint displacement and position and orientation of its end effector. These relationships permit the static control of the manipulator to place the end effector at specified location and make it traverse a specified path in space. However, for the manipulator not only the final location of the end-effector is of concern, but also the velocities at which the end-effector would move to reach the final location are an equally important concern.

This requires the co-ordination of the instantaneous end-effector velocity and joint velocities. One way to achieve this is to take the time derivative of kinematic equations of the manipulator. The transformation from the joint velocities to the end-effector velocity is described by a matrix, called the Jacobian. The Jacobian matrix which is dependent on manipulator configuration is a linear mapping from velocities in joint space to velocities in Cartesian space. The Jacobian is one of the most important tools for characterization of differential motions of the manipulator.

This mapping between differential changes is linear and can be expressed as

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$$Ve\ (t) = J\ (q)\ \dot{q} \tag{5}$$

Where,
Ve (t) =6*1 Cartesian velocity vector (End-effector velocity),
J (q) =6*n Manipulator Jacobian or Jacobian matrix,
$\dot{q}$=n*1 vector of n joint velocities.

$$Ve\ (t) = [J1\ (q)\ J2\ (q) \ldots\ldots\ldots Jn\ (q)]\dot{q} \tag{6}$$

In the above equation, J_i(q) is the ith column of the Jacobian matrix.

We can write the end-effector velocity as,

$$Ve\ (t) = \begin{bmatrix} v \\ w \end{bmatrix} \tag{7}$$

Equation (3) represents the forward differential motion model or differential kinematics model presented schematically in following figure which is similar to the forward kinematic model. Note that the J (q) is the function of the joint variables [11].The first three rows of Jacobian J(q) are associated with the linear velocity of the end effector v, while last three rows correspond to the angular velocity w of the end effector. Each joint of the manipulator generate some linear and/or some angular velocity of the manipulator. Column (i) of the Jacobian matrix J_i(q) is made up of three linear velocity components J_{vi} and three angular velocity components J_{wi} and can be expressed as,

$$J_i(q) = \begin{bmatrix} J_{vi} \\ J_{wi} \end{bmatrix} = \begin{bmatrix} J_{vxi} \\ J_{vyi} \\ J_{vzi} \\ J_{wxi} \\ J_{wyi} \\ J_{wzi} \end{bmatrix} \tag{8}$$

Where J_{vi} and J_{wi} represents the component k of linear velocity and angular velocity respectively, contributed by joint i with k=x, y, z or z and i=1, 2 …n. The contribution of joint i to column J_i is computed depending on whether joint I is prismatic or rotary.

Each column of Jacobian matrix is computed separately and all the columns are combined to form the total Jacobian matrix. Jacobian matrix for rotary joint is given by following equation,

$$J_i\ (q) = \begin{bmatrix} j_{vi} \\ j_{wi} \end{bmatrix} = \begin{bmatrix} P_{i-1} * {}^{i-1}_{n}P \\ P_{i-1} \end{bmatrix}) \tag{9}$$

The Jacobian matrix column J1 for joint 1, which is a rotary joint, is determined as follows,

The joint axis vector P0 (Pi-1 for i=1) is

$$P_0 = R_0 u \tag{10}$$

The transformation matrix and the rotation matrix are the identity matrix. Thus,

$$P_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{11}$$

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The end-effector position vector (for i=1 and n=2) is determined from following equation,

$$ {}^{i-1}_{n}P = {}^{0}_{n}TO_n - {}^{0}_{i-1}TO_n \qquad (12)$$

$$ {}^{0}_{2}P = {}^{0}_{2}T \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} - {}^{0}_{0}T \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} $$

$$ {}^{0}_{2}P = \begin{bmatrix} a_1C_1 + a_2C_2 - a_2S_1S_2 \\ a_1S_1 + a_1C_1S_2 + a_2C_2S_1 \\ 0 \\ 0 \end{bmatrix} \qquad (13)$$

The first column of Jacobian is calculated by substituting equation (11) & (13) in equation (9).

Thus,

$$ J_1 = \begin{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} * \begin{bmatrix} a_1C_1 + a_2C_2 - a_2S_1S_2 \\ a_1S_1 + a_1C_1S_2 + a_2C_2S_1 \\ 0 \end{bmatrix} \\ \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{bmatrix} $$

$$ = \begin{bmatrix} -a_1S_1 + a_1C_1S_2 + a_2C_2S_1 \\ a_1C_1 + a_2C_2 - a_2S_1S_2 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} $$

By following the similar steps for joint 2, we can get the Jacobian J2 as

$$ J_2 = \begin{bmatrix} -a_1C_1S_2 + a_2C_2S_1 \\ a_2C_2 - a_2S_1S_2 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} $$

$$ J = [J_1 \quad J_2] $$

$$ J = \begin{bmatrix} -a_1S_1 + a_1C_1S_2 + a_2C_2S_1 & -a_1C_1S_2 + a_2C_2S_1 \\ a_1C_1 + a_2C_2 - a_2S_1S_2 & a_2C_2 - a_2S_1S_2 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 1 \end{bmatrix} \qquad (14)$$

Equation (10) provides the linear and angular velocities of the end effector i.e foot of the robot.

That is,

$$ \begin{bmatrix} v_x \\ v_y \end{bmatrix} = J' \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} $$

Considering xy plane,

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \\ w_x \\ w_y \end{bmatrix}$$

From the above equation, we get the linear velocity of the foot position. By using Jacobian, we can find out the linear and angular velocity of the final foot position. With the help of Jacobian, we get the three linear velocity and three angular velocity components of the foot.

7. Conclusion

The kinematic analysis of quadruped robot is the basic of space planning, motion control and optimal design. Here the direct and inverse kinematic models for the robot are calculated. Direct kinematics gives exact position and orientation of robot feet and the inverse kinematics gives the angles of the joints of the legs. The results are verified with robotic toolbox of Matlab2011a. It provides the real time analysis of the joint variables, which lays foundation for following up motion control.

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A Brief Author Biography

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