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LEG TRAJECTORY PLANNING FOR A HEXAPOD ROBOT

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In this paper, we present a kinematic description and a simulation for leg trajectory planning of a six-legged robot with 3dof legs. First, the kinematic model of the leg is described. A leg trajectory planning procedure for tripod gait of the robot is proposed, and the desired motion of the leg joint angles is obtained from the assigned desired motion of the leg tip in Cartesian space. Simulation results are presented to evaluate the performance of the proposed model.

1. Introduction

Legged vehicles have a number of potential advantages over wheeled or tracked vehicles for locomotion over rough terrain. This is a result of the abilities of legs to use discrete foot-terrain interactions and to adapt to the terrain, which permit the vehicle body to move smoothly over the surface while legs absorb or avoid terrain irregularities. Six legged locomotion is the most popular legged locomotion concept because of the ability of static stable walking. The hexapods are often inspired by the nature as Lauron [1] and Genghis [2]. Most of the existing hexapods are laboratory prototypes [3, 4, 5], but there are also a few legged robots built for specific applications, such as SILO06 [6], a six-legged robot built for demining. Since all aspects of walking are governed by linkage geometry and physical limitations of the leg, a major topic in a legged vehicle development, is the kinematic design of the leg mechanism, as well as of the overall vehicle geometry. Kinematic models of a six-legged robot were presented, for example, in [7] and [8]. On the other hand, the walking performances of the hexapod are related to the motion of the leg tip. Much work has been also addressed to the leg trajectory generation and motion analysis for hexapods [9, 10, 11], for different gaits and speeds of the robot body. A specific feature of the trajectory planning procedure is that the desired trajectories of the feet belong to the Cartesian space, while they must be mapped into the joint space of the legs to accomplish the movement.

In this paper, we present a kinematic description and a simulation model for leg trajectory planning of a six-legged robot with 3dof legs. Kinematic model of the robot is developed and the forward and inverse kinematic problems are resolved. For a tripod gait of the robot, a leg trajectory planning procedure is proposed and a desired motion of the leg joint angles is obtained from the assigned desired motion of the leg tip in cartesian space. Simulation results are presented to evaluate the performance of the proposed model. The organization of the paper is as follows: In Section 2, a kinematic model of the leg is developed. In Section 3, a leg trajectory generation algorithm for a hexapod is presented. We provide simulation results in Section 5. Conclusions are presented in Section 6.

2. Kinematic model

In this paper, we consider a walking robot with six identical legs equally distributed along both sides of the robot body in three opposite pairs as shown in Figure 1.

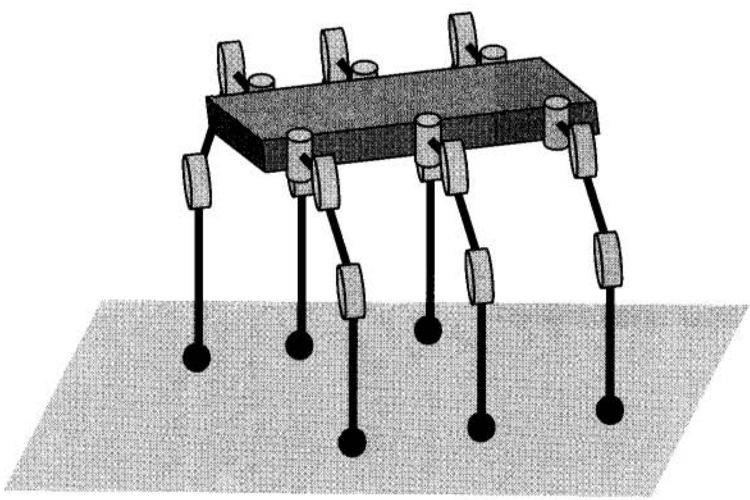

Figure1. The hexapod geometry

Each leg consists of three links and three revolute joints (Figure 2). The first two joints (thoracic and hip), denoted by θ_1 and θ_2, respectively, are orthogonal to each other, and the third (knee), denoted by θ_3 is parallel with the second. The

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Denavit-Hartenberg convention [12], is used for the description of the leg kinematics.

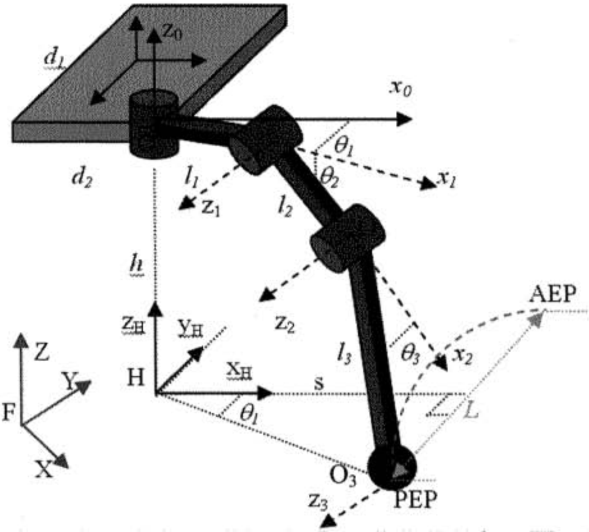

Figure 2. Link frame attachment to the 3 degrees-of-freedom leg

The link parameters of each leg are shown in Table 1, where θ_i, (i = *1,2,3*), are the joint variables, and l_i , (i = *1,2,3*), are the lengths of the links.

Table 1. Link parameters for a 3-link leg (Denavit- Hartenberg convention)

link	l_i	α_i	d_i	θ_i
1	l_1	$\pi/2$	0	θ_1
2	l_2	0	0	θ_2
3	l_3	0	0	θ_3

The corresponding homogeneous transformation matrices which define the relative position and orientation between the adjacent frames, (the frame i with respect to the frame i-*1*) are

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$$A_1=\begin{bmatrix}\cos\theta_1 & 0 & -\sin\theta_1 & l_1\cos\theta_1\\ \sin\theta_1 & 0 & \cos\theta_1 & l_1\sin\theta_1\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\qquad A_2=\begin{bmatrix}\cos\theta_2 & -\sin\theta_2 & 0 & l_2\cos\theta_2\\ \sin\theta_2 & \cos\theta_2 & 0 & l_2\sin\theta_2\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{1}$$

$$A_3=\begin{bmatrix}\cos\theta_3 & -\sin\theta_3 & 0 & l_3\cos\theta_3\\ \sin\theta_3 & \cos\theta_3 & 0 & l_3\sin\theta_3\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\qquad A_H=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & h\\ 0 & 0 & 0 & 1\end{bmatrix}$$

where A_H is the transformation matrix of the coordinate system $O_0x_0y_0z_0$ with respect to the coordinate system $Hx_Hy_Hz_H$ attached to robot body (Figure 2). Using expressions (1), the coordinates of the foot 0_3 with respect to the frame $Hx_Hy_Hz_H$ are

$$\begin{aligned} {}^H x_{0_3} &= \cos\theta_1(l_1 + l_2\cos\theta_2 + l_3\cos(\theta_2+\theta_3))\\ {}^H y_{0_3} &= \sin\theta_1(l_1 + l_2\cos\theta_2 + l_3\cos(\theta_2+\theta_3))\\ {}^H z_{0_3} &= h + l_2\sin\theta_2 + l_3\sin(\theta_2+\theta_3)\end{aligned} \tag{2}$$

In order to solve the inverse kinematics problem, i.e., the problem of finding the joint variables in terms of the foot position, we solve Eqs. (2) in closed-form for θ_i, $(i = 1,2,3)$

$$\theta_1 = a\tan\frac{{}^H y_{0_3}}{{}^H x_{0_3}};\qquad \theta_2 = a\sin\frac{b_1b_4 - b_2b_3}{b_1^2+b_2^2};\qquad \theta_3 = -a\cos\frac{b_3^2+b_4^2-l_2^2-l_3^2}{2l_2l_3} \tag{3}$$

where

$$b_1 = l_2 + l_3\cos\theta_3;\qquad b_2 = l_3\sin\theta_3;\qquad b_3 = \frac{{}^H x_{O_3} + l_3\cos\theta_1}{\cos\theta_1};\qquad b_4 = {}^H z_{O_3} - l_3$$

3. Trajectory Generation

The robot is assumed to have a desired horizontal movement at a constant height h and constant forward speed, and follows a straight-line trajectory. The motion planning of the legs is accomplished by prescribing desired Cartesian trajectories of the leg tips. Afterwards, using the inverse kinematics solution (3), the corresponding desired joint trajectories in the join angle space are obtained. The desired motion of the foot is expressed as time function of the coordinates of point O_3 in coordinate system $Hx_Hy_Hz_H$ attached to robot body, (Figure 2). In this paper, a tripod gait is used, as shown in Fig. 3. The white area indicates a transfer phase, and the dark area indicates a support phase. During walking, the legs move cyclically and the motion of the leg is partitioned into two phases: support phase when the leg is used to support the robot, and transfer phase, when the leg is moved from one foothold to the next.

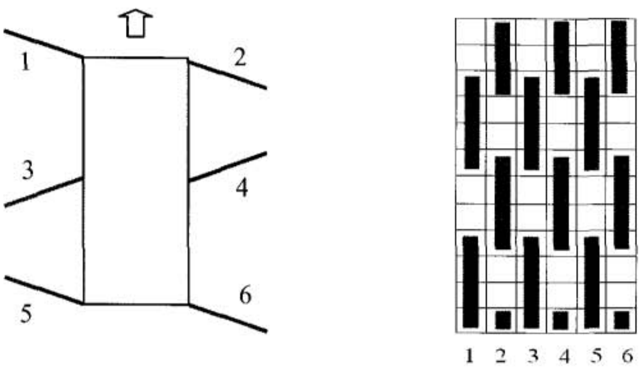

Figure 3. Gait diagram of tripod gait

During the support phase, the desired y_d trajectory of the leg tip is determined by using the constant speed along the Hy_H axis, which is the speed of the robot body v_{rob} with inverse sign. The component z_d is equal to zero. The desired Cartesian coordinates of the leg tip are given by

$$p_{0_3 d}(t) = \begin{bmatrix} l_1 + l_2 & -v_{rob}t & 0 \end{bmatrix}^T \quad (4)$$

During the transfer phase, the motion of the leg tip is expressed as a function of the coordinates of the leg tip in the y_Hz_H plane. For each cycle, the desired (y_d, z_d) trajectories of the leg tip are computed through a cubic polynomial $f_d(t)$ for y_d and sinusoidal function for z_d (with assigned maximum foot clearance c), respectively. The component z_d is over the ground. The desired trajectory of the leg tip in Cartesian space is generated by

$$p_{0_3 d}(t) = \begin{bmatrix} l_1 + l_2 & f_d(t) & c\sin^2(\pi \frac{t}{t_f}) \end{bmatrix}^T \quad (5)$$

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Using the inverse kinematic solution obtained in the previous section, a set of joint variables θ_i, ($i = 1,2,3$) for each leg, that achieves the desired position of the leg tip is obtained.

4. Simulation Results

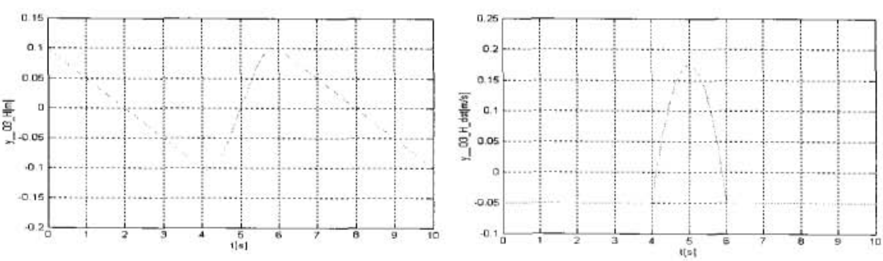
Using Matlab, our model was simulated with leg parameters given in Table 2.

Table 2. Length of the links of each leg

link	1	2	3
length	0.07[m]	0.285[m]	0.31[m]

For the simulation, the desired walking height h was defined in terms of the length of the third link, i.e., $h = l_3 = cte$. The robot forward speed was set to be $0.05m/s$. The foot positions for generating a tripod gait are given in Figure 3. The stroke L was set to be $0.2m$ (the distance between Posterior Extreme Position PEP and AEP). The foot distance from the body was $s = l_1 + l_2 = 0.355m$. The leg cycle time T was chosen to be $6s$. The support (t_s) and the flight (t_f) times were set to be $4s$ and $2s$, respectively, (duty factor $\beta = 2/3$).

Figure 4a and Figure 4b plot the desired time evolution of the y-horizontal displacement and the y-velocity component, respectively, of the leg tip with respect to frame $Hx_Hy_Hz_H$..



(a) (b)

Figure 4. a) Desired horizontal y-displacement of the leg tip (point O_3) with respect to frame $Hx_Hy_Hz_H$; b) Desired y-component of the velocity of the leg tip (point O_3) with respect to frame $Hx_Hy_Hz_H$

Figure 5a and Figure 5b plot the desired time evolution of the z-vertical displacement and the z-component of the leg tip velocity, respectively, with respect to frame $Hx_Hy_Hz_H$.

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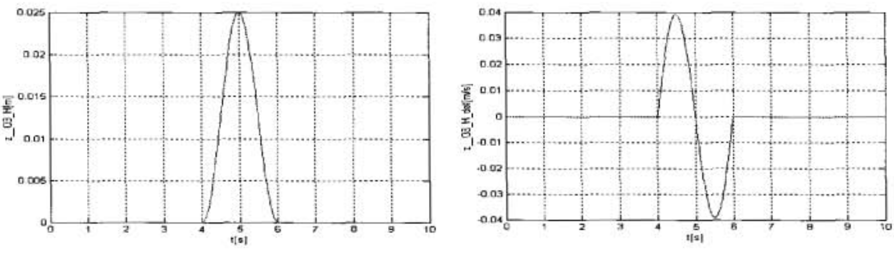
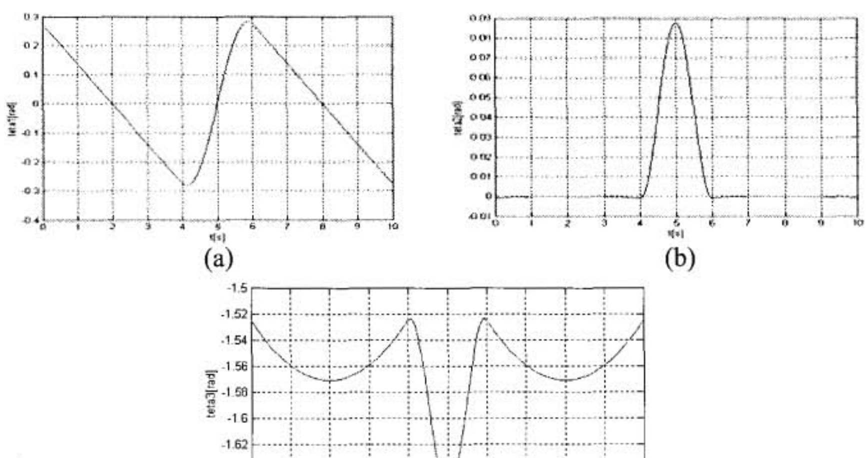


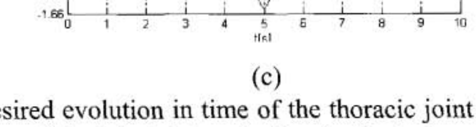
(a) (b)

Figure 5. a) Desired vertical z-displacement of the leg tip (point O_3) with respect to frame $Hx_Hy_Hz_H$; b) Desired z-component of the velocity of the leg tip (point O_3) with respect to frame $Hx_Hy_Hz_H$

The desired evolution of the joint angles θ_1, θ_2, and θ_3 obtained by means of the inverse kinematic solution is presented in Figure 6a, Figure 6b and Figure 6c, respectively.



(a) (b)



(c)

Figure 6. a) Desired evolution in time of the thoracic joint angle θ_1; b) Desired evolution in time of the hip joint angle θ_2; c) Desired evolution in time of the knee joint angle θ_3

The results of the simulation verify the validity of the proposed leg trajectory planning procedure.

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5. Conclusion

In this paper, a leg trajectory planning procedure for tripod gait of the robot was proposed, and the desired motion of the leg joint angles was obtained from the assigned desired motion of the leg tip in Cartesian space. Simulation results were presented to evaluate the performance of the proposed model.

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