Gait Kinematic Modeling of a Hexapod Robot

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Planning tripod gait of an hexapod robot

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***Abstract*—Hexapod legged robot's missions, particularly in irregular and dangerous areas, require high stability and high precision. In this paper, we consider the rectangular architecture body of legged robots with six legs distributed symmetrically along two sides, each leg contains three degrees of freedom for greater mobility. The aim of this work is planning tripod gait trajectory, based on the computing of the kinematic model to determine the joint variables in the lifting and the propelling phases. For this, an appropriate coordinate frames are attached to the body and legs in order to obtain clear representation and efficient generation of the system equations. A simulation in Matlab software platform is developed to confirm the kinematic model and various trajectories to the tripod gait adopted by the hexapod robot in its locomotion.**

Keywords—Hexapod legged robot; tripod gait; inverse kinematic model; simulation in MATLAB.

I. INTRODUCTION

The legged hexapod robots are mechanical vehicles that use six legs to walk. This category is very interesting for several reasons. Indeed, they have greater mobility in irregular and accidentals terrains, which is particularly required in dangerous environments for human, like mine fields, space or planets, nuclear power station, or when it is essential to keep the terrain largely undisturbed for scientific tasks [1]. The hexapod robots possesses greater static stability while moving and while standing [2]. For these important reasons, the hexapod robots must respect some principal performances such as: stability, strong adaptability to the ground, and speed movement. However, the hexapod robots modeling becomes a complex tasks, due to the large number of legs with important degrees of freedom.

Indeed, to obtain successful design for legged robots, the designers must consider some of the most important design issues and constraints as: the mechanical structure of robot body, leg architecture, actuators and drive mechanism, control architecture, power supply and autonomy [1].

In this context, there are large research works devoted to the control of legged robots based on the structure design which contains body and leg architecture, kinematic model and gait planning. The first issue to respect in legged robots control is the mechanical structure of the robot's body. There are two basic architecture of the body platform according to the distribution of the legs around the body: rectangular and hexagonal [1].
The stability margin for rectangular architecture body of hexapod robots is considered in [3] with tripod gait. Also the most important task to obtain benefit locomotion control, is the gait planning. There are several types of gaits according to the locomotion mode -periodic or free gait-, stability, and speed.

Large research works consider tripod gait for its important advantage: the static and the dynamic stability in irregular areas. However, this gait presents complexity on the turning phase. A new turn gait is proposed in [4] with an elaboration of the kinematic model considering each leg as an isolated system. Indeed, leg configuration presents another important issue in robot gait control. For legged robots to be advantageous over a wheeled robots, minimum 3 degrees of freedom are needed per leg as mentioned in [5].

In this paper, in order to obtain successful control design we first describe the platform structure, which contains rectangular body architecture and six legs distributed along the two sides. Each leg possesses three degrees of freedom for efficient stability and motion. After the description of the hexapod robot, we define the tripod gait adopted by the robot in its locomotion. In section 2 we establish the inverse kinematic model for the lifting and the propelling phases. This will allow us to determine all the joint variables necessary for the control when the trajectories of the body and legs are specified. Finally, to confirm the kinematic model of the tripod gait, we develop program in Matlab to simulate the locomotion of the robot following different phases of the tripod gait.

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II. HEXAPOD ROBOT DESCRIPTION

It's important to know the architecture of the hexapod robots which influences all the performances with respect to given tasks. In this section we present a description of the robot's global structure, the details concerning the geometric aspect, and the joint used in the system.

A. *Body and leg configuration*

Figure 1 shows the global structure of the hexapod robot which contains rectangular body architecture and six legs distributed symmetrically along two sides, each side possesses three legs and each leg has three degrees of freedom. Therefore, this architecture presents longitudinal stability margin as described in [6].

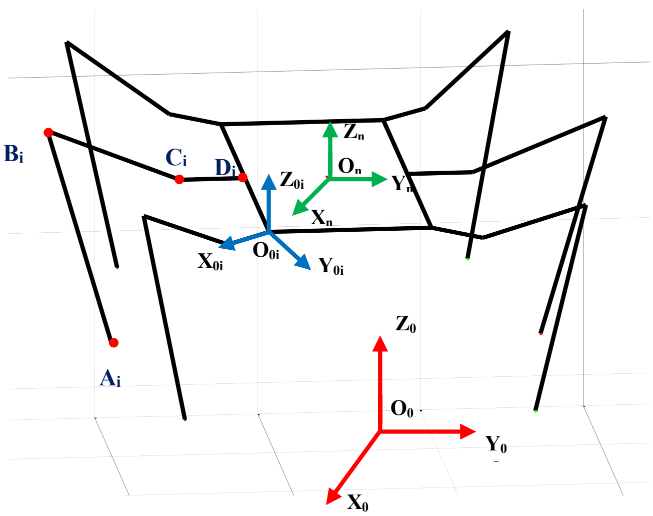

Fig. 1. Hexapod legged robot structure.

In order to establish efficient inverse kinematic model of the hexapod robot, we attach appropriate coordinate frames to the legs and the body as shown in the figure 1. However, these frames must be chosen carefully in order to obtain clear representation of the different gait phases of the robot. Also the appropriate description helps for a best shape of the equations system useful for the control process. Thus, different coordinate frames are attributed as follows:

R_n (O_n, X_n, Y_n, Z_n): body coordinate frame, whose origin is located in the center of mass of the body.

R_0 (O_0, X_0, Y_0, Z_0): global coordinate frame.

R_{0i} (O_{0i}, X_{0i}, Y_{0i}, Z_{0i}): legs coordinate frames placed successively on the centers of the joints with i=0…6 indicate the leg numbering.

Another most important issue to obtain successful design and coherent mobility of the hexapod legged robot is the leg architecture. In general a legged robot can move with two joints at each leg but for complex tasks especially in irregular and rougher terrains, more degrees of freedom on the legs are required to ensure better mobility and increase the ability to travel in a variety of gaits. For these reasons, we adopt leg's architecture with three degrees of freedom, two simple revolute joints and one actuator as shown in the figure 2.

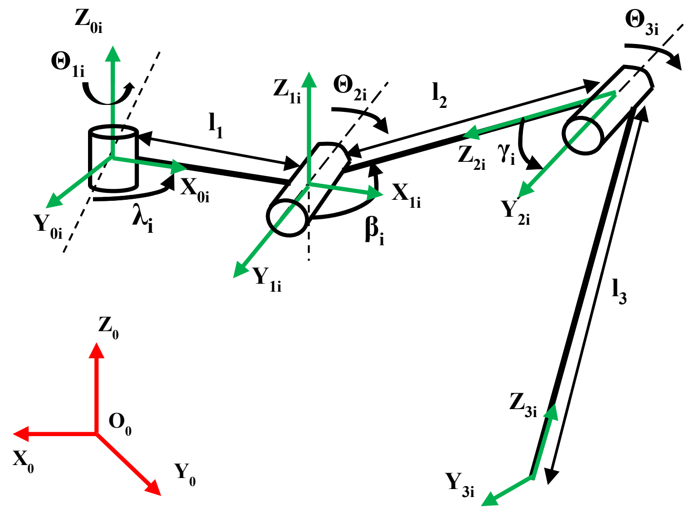

Fig. 2. Leg configuration.

In each connect joint we attach the coordinate frame R_{ji} which is defined as:

R_{ji} (O_{ji}, X_{ji}, Y_{ji}, Z_{ji}): legs coordinate frames placed successively on the centers of the revolute joint attached to the body with i=0…6 indicate the leg numbering, and j=1…3 indicate the joint connection numbering.

θ_i : joint variables.

β_i, λ_i, γ_i : the angles of inclination between the initial leg configuration and the configurations on the walking.

B. *Tripod gait planning*

Gait planning is a fundamental part of legged robots to obtain successful design, control motion and high speed. In this work we use the tripod gait because of its speed and static stability as defined in [7], the robot should have at least three legs on the ground at all times and robot's center of mass in inside the support polygon, which is realized in this tripod gait.

Tripod gait is periodic and it consists of two main phases: the lifting and the propelling. In the first phase, legs 1, 3 and 5 rise away from the ground and follow their specific trajectories, while legs 2, 4 and 6 are on the ground. The lifting of the group one of the legs (1, 3 and 5) is followed by the lifting of the second group; legs 2, 4 and 6 rise away from the ground and follow similar trajectories to the first ones. In the second phase, the six legs make ground contact to move the robot toward the body's trajectory.

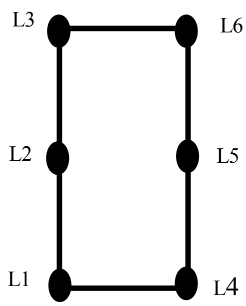

Fig. 3. Legs description.

Tripod gait algorithm:

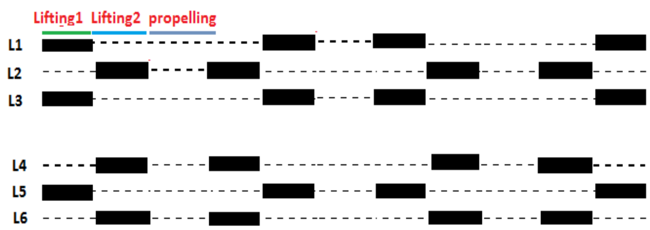

Fig. 4. Tripod gait algorithm.

III. Inverse Kinematic Model of Hexapod Legged Robot

In this section we develop an inverse kinematic transformation for the hexapod legged robot, which determines the required joint variables for a given gait. In the tripod gait of the hexapod robot we consider two phases of motion: lifting and propelling. In fact, the inverse kinematic model should be computed for the two phases.

A. Inverse kinematic analysis of the lifting

In order to establish the inverse kinematic model of the lifting and determine the joint variables $\boldsymbol{\theta_i}$, we assign carefully the coordinate frames to the body and legs as presented earlier in the figure 1 and 2.

To simplify the computing of the approach we express all terms in $\{R_0\}$ frame, then we use the rotations matrices for passing from $\{R_{i0}\}$ frame to $\{R_0\}$ frame as:

$$R^{0,1i} = \begin{bmatrix} \cos\alpha_{1i} & -\sin\alpha_{1i} & 0 \\ \sin\alpha_{1i} & \cos\alpha_{1i} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$R^{1,2i} = \begin{bmatrix} \cos\alpha_{2i} & 0 & \sin\alpha_{2i} \\ 0 & 1 & 0 \\ \sin\alpha_{2i} & 0 & \cos\alpha_{2i} \end{bmatrix} \quad (2)$$

$$R^{2,3i} = \begin{bmatrix} \cos\alpha_{3i} & 0 & \sin\alpha_{3i} \\ 0 & 1 & 0 \\ \sin\alpha_{3i} & 0 & \cos\alpha_{3i} \end{bmatrix} \quad (3)$$

With: $$\alpha_{1i} = \lambda_{1i} + \theta_{1i} \quad (4)$$

$$\alpha_{2i} = \beta_{2i} + \theta_{2i} \quad (5)$$

$$\alpha_{3i} = \gamma_{3i} + \theta_{3i} \quad (6)$$

$$\lambda_{1i} = [-\pi/4 \quad 0 \quad \pi/4 \quad \pi-(\pi/4) \quad \pi \quad \pi+(\pi/4)] \quad (7)$$

$$\beta_{1i} = [-(5\pi/8) \quad -(5\pi/8) \quad -(5\pi/8) \quad -(5\pi/8) \quad -(5\pi/8) \quad -(5\pi/8)] \quad (8)$$

$$\gamma_{1i} = [\pi/1.4 \quad \pi/1.4 \quad \pi/1.4 \quad \pi/1.4 \quad \pi/1.4 \quad \pi/1.4] \quad (9)$$

$$R^{0,2i} = R^{0,1i} \times R^{1,2i} \quad (10)$$

$$R^{0,2i} = \begin{bmatrix} \cos\alpha_{1i}\cos\alpha_{2i} & -\sin\alpha_{1i} & \cos\alpha_{1i}\sin\alpha_{2i} \\ \sin\alpha_{1i}\cos\alpha_{2i} & \cos\alpha_{1i} & \sin\alpha_{1i}\sin\alpha_{2i} \\ -\sin\alpha_{2i} & 0 & \cos\alpha_{2i} \end{bmatrix} \quad (11)$$

$$R^{0,3i} = R^{0,1i} \times R^{1,2i} \times R^{2,3i} \quad (12)$$

$$R^{0,3i} = \begin{bmatrix} C\alpha_{1i}C\alpha_{2i}C\alpha_{3i} - S\alpha_{2i}C\alpha_{1i}S\alpha_{3i} & -S\alpha_{1i} & C\alpha_{1i}C\alpha_{2i}S\alpha_{3i} - C\alpha_{1i}S\alpha_{2i}C\alpha_{3i} \\ S\alpha_{1i}C\alpha_{2i}C\alpha_{3i} - S\alpha_{1i}S\alpha_{2i}S\alpha_{3i} & S\alpha_{1i} & S\alpha_{1i}C\alpha_{2i}S\alpha_{3i} + S\alpha_{1i}S\alpha_{2i}C\alpha_{3i} \\ -S\alpha_{2i}C\alpha_{3i} - C\alpha_{2i}S\alpha_{3i} & 0 & -S\alpha_{2i}S\alpha_{3i} + C\alpha_{2i}C\alpha_{3i} \end{bmatrix} \quad (13)$$

With: C= cos and S= sin.

From the robot structure, we can write the vector expression:

$$O_0A_i^0 = O_0D_i^0 + D_iC_i^0 + C_iB_i^0 + B_iA_i^0 \quad (14)$$

And we try to establish the projection of this relationship in the fixed coordinate frame R_0 in order to determine the joint variables θi.

$$O_0A_i^0 = O_0D_i^0 + R^{0,0i}R^{0i,1i}D_iC_i^{1i} + R^{0,2i}C_iB_i^{2i} + R^{0,3i}B_iA_i^{3i} \quad (15)$$

$$O_0A_i^0 = O_0D_i^0 + R^{0,0i}R^{0i,1i}\begin{pmatrix} l1 \\ 0 \\ 0 \end{pmatrix} + R^{0,2i}\begin{pmatrix} 0 \\ 0 \\ -l3 \end{pmatrix} + R^{0,3i}\begin{pmatrix} 0 \\ 0 \\ -l2 \end{pmatrix} \quad (16)$$

Then according to the geometrical relationship and its projection in R_0 frame we obtain:

$$\theta_{1i} = a\tan(\frac{M_Y}{M_X}) - \lambda_{1i} \quad (17)$$

Where:

$$M_X = X_i - D_{1,i} = \cos\alpha_{1i}(l_1 - l_3\sin\alpha_{2i} - l_2\sin(\alpha_{2i}+\alpha_{3i})) \quad (18)$$

$$M_Y = Y_i - D_{2,i} = \sin\alpha_{1i}(l_1 - l_3\sin\alpha_{2i} - l_2\sin(\alpha_{2i}+\alpha_{3i})) \quad (19)$$

$$M_Z = Z_i - D_{3,i} = -l_3\cos\alpha_{2i} - l_2\cos(\alpha_{2i}+\alpha_{3i}) \quad (20)$$

$$O_0A_i^0 = \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} \qquad O_0D_i^0 = \begin{pmatrix} D_{1,i} \\ D_{2,i} \\ D_{3,i} \end{pmatrix} \quad (21)$$

And the second joint variable is expressed as follows:

$$\theta_{2i} = a\tan 2(a_i;b_i) \pm a\tan 2(\sqrt{a_i^2+b_i^2-c_i^2};c_i) - \beta_{2i} \quad (22)$$

Where:

$$a_i = -l_2\sin\alpha_{3i} \quad (23)$$
$$b_i = l_3 + l_2\cos\alpha_{3i} \quad (24)$$
$$c_i = D_{3,i} - Z_i \quad (25)$$

The expression of θ_{3i} is written as:

$$\theta_{3i} = \pm a\cos(M) - \gamma_{3i} \quad (26)$$

Where: $$M = \frac{xx^2+yy^2+zz^2-l_3^2-l_2^2}{2l_2l_3} \quad (27)$$

With:

$$xx = l_1\cos\alpha_{1i} - M_X \quad (28)$$

$$yy = l_1\sin\alpha_{1i} - M_Y \quad (29)$$

$$zz = -M_Z \quad (30)$$

B. Inverse kinematic analysis of the propelling

After the lifting, the six legs of the robot are on the ground. Then the impossibility of legs segments motion under the effect of the active joints cause reactions leading to the following kinematics of the robot structure: a ball joint in A, revolute joint in B along y axis which will be considered in this step as an active joint, and finally the CD segment is assumed to be fixed on the body.

In order to establish the inverse kinematic of the propelling and determine the joint variables, we write the geometrical vector from the robot structure, and we try to establish the projection of this relationship in the fixed coordinate frame R_0.

The vector expression is written as follows:

$$A_iB_i^{of} = A_iO_0^{of} + O_0O_n^{of} + O_nD_i^{of} + D_iC_i^{of} + C_iB_i^{of} \quad (31)$$

Where R_{of} (O_{of}, X_{of}, Y_{of}, Z_{of}) is the coordinate frame of the final configuration, and R_{oi} (O_{oi}, X_{oi}, Y_{oi}, Z_{oi}) is the coordinate frame of the initial configuration.

Then according to the projection of equation (31) in R_0 frame we obtain two relationships, the first present the joint variables for the propelling of the side one which contains the legs 1, 2 and 3 and the second relationship present the joint variables for the propelling of the side two, which contains the legs 4, 5 and 6 as follows:

$$\theta_{1i} = a\tan 2(a';b') + a\tan 2(\sqrt{a'^2+b'^2-c'^2};c') - \beta_i \quad (32)$$

i=(1…3)

$$\theta_{2i} = a\tan 2(a';b') - a\tan 2(\sqrt{a'^2+b'^2-c'^2};c') - \beta_i \quad (33)$$

i=(4…6)

Where:

$$a' = -2wx' + 2uz' \quad (34)$$
$$b' = 2ux' + 2wz' \quad (35)$$
$$c' = u^2 + w^2 + v^2 + x'^2 + z'^2 \quad (36)$$

$$AO_0^{0f} = \begin{pmatrix} -x_a \\ -y_a \\ -z_a \end{pmatrix} \quad O_0O_n^{0f} = \begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix} \quad O_nD^{0f} = \begin{pmatrix} x_d \\ y_d \\ z_d \end{pmatrix} \quad (37)$$

$$DC^{0f} = \begin{pmatrix} x_{dc} \\ y_{dc} \\ z_{dc} \end{pmatrix} \quad CB^{0f} = \begin{pmatrix} x_{cb}\cos\alpha + z_{cb}\sin\alpha \\ y_{cb} \\ -x_{cb}\sin\alpha + z_{cb}\cos\alpha \end{pmatrix} \quad (38)$$

$$u = -x_a + x_n + x_d + x_{dc} \quad (39)$$
$$v = -y_a + y_n + y_d + y_{dc} + y_{cb} \quad (40)$$
$$w = -z_a + z_n + z_d + z_{dc} \quad (41)$$

$$x' = x_{cb} \qquad z' = z_{cb} \quad (42)$$

IV. SIMULATION OF THE HEXAPOD ROBOT

The main purpose of the simulation of the hexapod robot is to validate the kinematic model and show the locomotion of the robot. In this section we plan several tripod gait trajectories, and we develop a program for the simulation of the hexapod robot following these trajectories using the software platform of Matlab.

For doing one step of the hexapod robot in the tripod gait we need three main phases: lifting of legs 1, 3 and 5, lifting of legs 2, 4 and 6, and finally the propelling of the body. In first, we specify the trajectories to follow by the legs 1, 3 and 5, as shown in the figure 5. Then, in the animation we observe a perfect following of these trajectories.

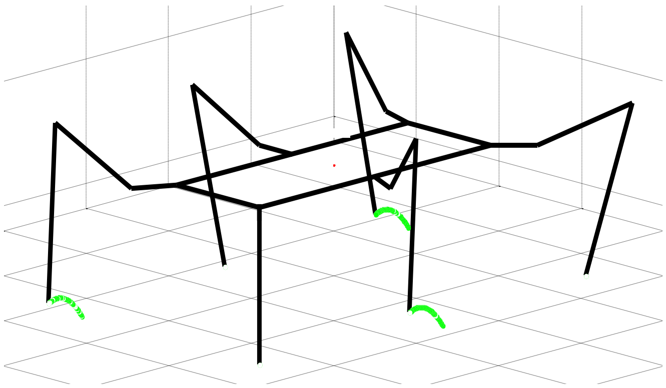

Fig. 5. Lifting of the legs 1, 3 and 5.

In the figure 6 we shown the lifting of the second group of legs: 2, 4 and 6 following the predefined trajectories. It can be see that the legs are mounted from the ground and move with respect the trajectories.

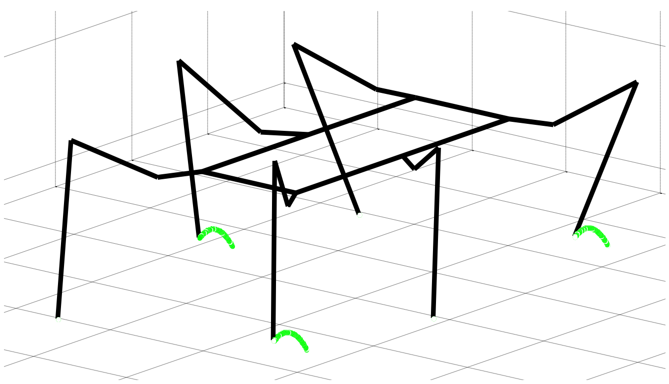

Fig. 6. Lifting of the legs 2, 4 and 6.

After the lifting of legs (1, 3 and 5), and the lifting of the second group of the legs (2, 4 and 6), the third step of the tripod gait is the propelling where the body moved forward as shown in the figure 6.

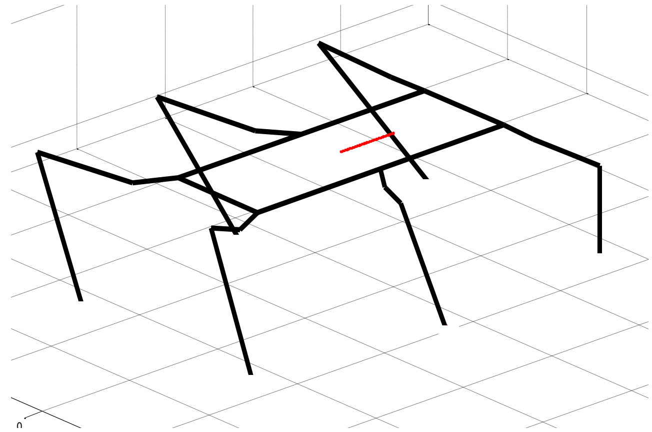

Fig. 7. Propelling of the robot.

To validate and illustrate the capacity and the adaptability of the hexapod robot to move within irregular terrains and obstacles in the propelling phase with several gaits, we plan complex trajectories such as the sinusoidal trajectory to follow by the body as shown in the figure 8.

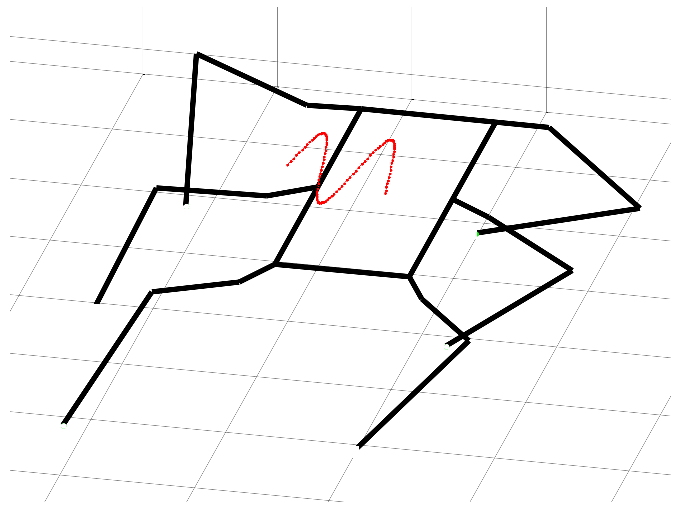

Fig. 8. Sinusoidal trajectory of the robot.

V. CONCLUSION

In this paper we have presented the structure of the legged robot with an efficient setting of the coordinate frames, we have proposed a particular approach to modeling a tripod gait for the hexapod robot . It's based on the gait planning, by specifying the trajectories of the legs and the robot's body in various phases of motion. So we have established the inverse kinematic model of the lifting and the propelling to determine the required joint variables for given trajectories. The simulation results shows clearly that the hexapod robot follow accurately the predefined trajectories in all phases of one step and more. Therefore, this approach of trajectory gait planning is more suitable for any gait and locomotion particularly in uneven terrains.

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