Kinematics Analysis and Motion Simulation of a Quadruped Walking Robot with Parallel Leg Mechanism

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Abstract: Compared with the serial mechanism, the parallel mechanism has many advantages. Using the parallel mechanism as the basic leg mechanism of a walking robot, not only the payload-weight ratio can be improved, but also the robot walking stability and security performance can be enhanced. By combining the kinematics features of 3-UPU parallel mechanism with the structural features of the quadruped walking robot, the inverse kinematics of a quadruped walking robot with parallel leg mechanism is analyzed, and a unified formula is obtained. According to the design parameters, a numerical example and simulation results are provided. This research sets a theoretical basis for future investigation on the quadruped walking robot with parallel leg mechanism.

Keywords: Walking robot, parallel leg mechanism, inverse kinematics, kinematics simulation.

INTRODUCTION

With the increasing aging population and surge in the number of physically disabled patients, the research into life assistive walking robot has become an emerging filed of study in the robot research area. At present, the research of life assistive walking robot has focused on biped humanoid robots [1-5], whose leg mechanisms mostly adopt serial mechanism. The downsides of serial mechanism are the high load inertia, long drive chain, large error accumulation, poor control precision and bad stability. The study of parallel mechanism can be traced back to the thirties of last century. Parallel mechanism is mainly used in the industrial areas in the early years, such as body painting robot, tire testing robot, pilot simulation training institutions. Compared with the serial mechanism, the parallel mechanism has greater stiffness, more steady structure and higher load capacity at the same weight or volume because the upper platform of parallel mechanism is supported by a number of linkages simultaneously. The parallel mechanism has the virtues of small accumulation error, simple inverse kinematics and easy to place motor on the base, allowing it to be easily implemented in real-time control. From the point of view of kinematics, the forward kinematics of serial mechanism is easy, but the inverse kinematics is hard. However, parallel mechanism is the exact opposite. The parallel mechanism which is completely symmetrical has better isotropy. Its disadvantages are mainly smaller working space and higher precision requirement for the process and assembly of its kinematic pairs when used for a robot [6].

Parallel leg mechanism can be applied to quadruped walking robot to overcome the disadvantages of serial leg

mechanism. Many researchers had developed the walking robot with parallel leg mechanism [7]. In 1992, Tokyo Institute of Technology firstly applied the parallel leg mechanism with 6-DOF (degrees of freedom) to the walking robot, and developed Para-walker serial robots [8]. Since 2001, Takanishi laboratory of Waseda University of Japan had developed a series of biped robots with parallel leg mechanism [9]. Kinki University and Japan RRIC Institute developed a biped walking robot Kupm with parallel leg mechanism which could work in dangerous situations [10]. So far, no literature on the application of parallel leg mechanism to quadruped walking robot has been found. In 2009, the Yanshan University firstly applied parallel leg mechanism to the walking robot, and presented a reconfigurable quadruped/biped walking robot with 3-UPU parallel leg mechanism [11]. The research on application of parallel leg mechanisms in quadruped/biped reconfigurable walking robot will open up a new research area of parallel robots and expand the application of parallel robots.

Aiming at the crawl gait on normal roads [12], this paper describes the modeling, the inverse kinematics and motion simulation of the quadruped walking robot. This work sets a basis for further investigation on the forward kinematics, dynamics and control of walking posture for the quadruped walking robot with parallel leg mechanism.

QUADRUPED WALKING ROBOT WITH PARALLEL LEG MECHANISM

In general, a quadruped walking robot should at least achieve three-dimensional movement, so the leg mechanism should meet the requirements of DOF during quadruped walking and be able to adjust the stability of the robot.

The basic leg mechanism of the quadruped walking robot presented in this paper is a 3-UPU parallel mechanism which

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is proposed by Tsai [13]. As shown in Fig. (**1**), the 3-UPU parallel mechanism consists of a moving platform, a fixed platform and three serial branches that connect the two platforms. Each serial branch adopts the same UPU structure, that is, one linear drive, one U joint connecting the lower platform, and one U joint connecting the upper platform. The lower platform is defined as fixed platform, its circumference radius is r. The upper platform is defined as moving platform, its circumference radius is R. The fixed coordinate system $OXYZ$ is established at the center of lower platform. The junctions between each branch and upper platform are marked as $A_i (i=1,2,3)$ and the junctions between each branch and lower platform are marked as $B_i (i=1,2,3)$. At the first branch, the branch coordinate system $o_1 x_1 y_1 z_1$ is established, whose origin is B_1. $\$_{ij} (i=1, 2, 3; j=1, 2,\ldots, 5)$ are the five screw motions of each branch of 3-UPU and $\$_{i1} // \$_{i5}$ $\$_{i2} // \$_{i4}$ are its assembly features.
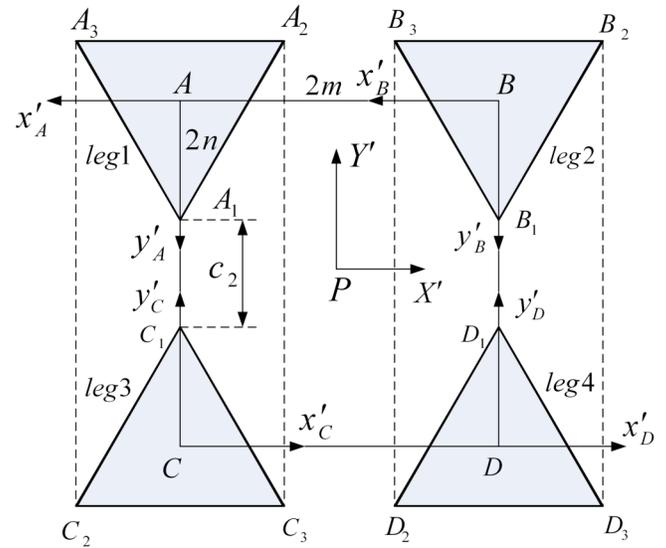
Fig. (2). One layout of the upper platform of parallel leg mechanism.
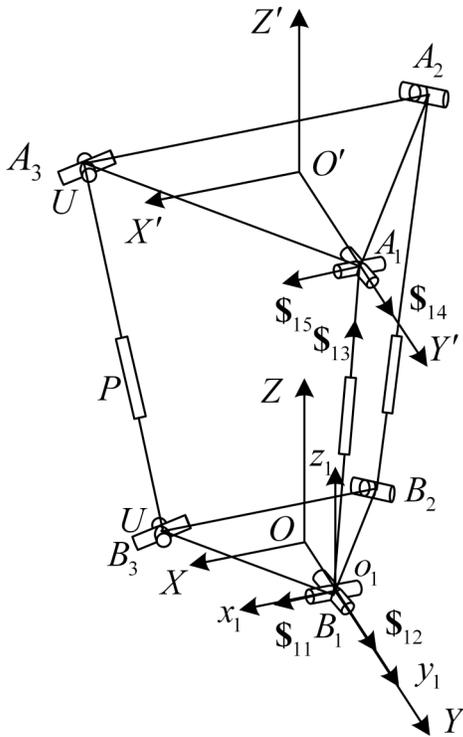
Fig. (1). The 3-UPU parallel mechanism.

The quadruped walking robot consists of one body and four identical parallel leg mechanisms, and the upper platform of each parallel leg mechanism is fixed to the body. When the lower platform of parallel leg mechanism contacts with the ground, it is defined as standing leg; when the lower platform does not contact with the ground, the parallel leg mechanism is defined as swing leg. In the walking process, the robot realizes the overall movement by lifting up and putting down the four leg mechanism in turn according to certain gait order. Fig. (**2**) is the layout of the upper platforms of each leg mechanism. A, B, C and D are the four points which respectively connect the body with the leg 1, leg 2, leg 3 and leg 4. The three-dimensional model of the robot is shown in Fig. (**3**).
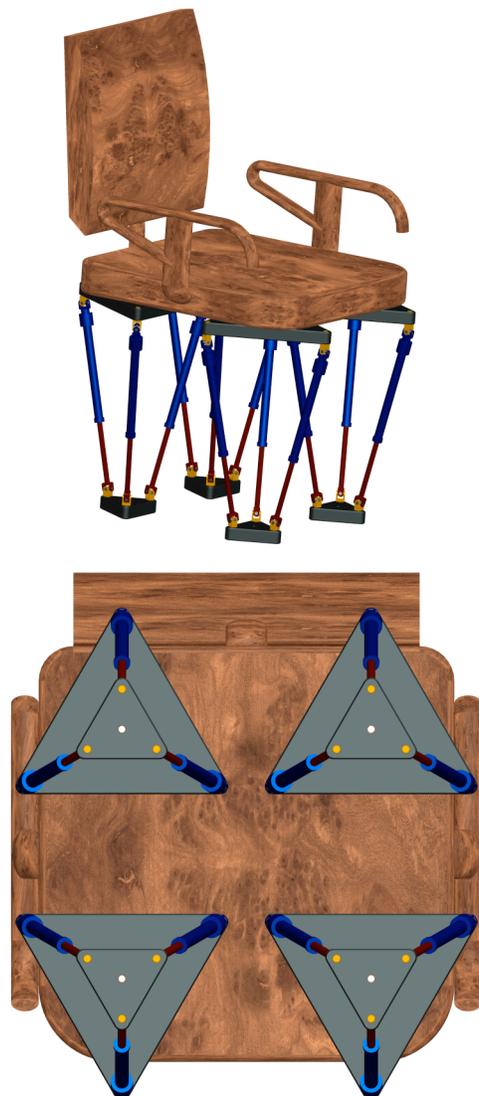
Fig. (3). Three-dimensional model of the robot.

Because the 3-UPU basic leg mechanism is a translational parallel mechanism, the posture of lower platform of every leg mechanism is the same with the corresponding upper platform. When the upper platform of leg mechanism is fixed to the chair of robot, the chair can be considered as the upper platform of parallel leg mechanism, the ground as the lower platform, and the standing legs as the movement branch between the upper and lower platforms. Then, the robot can be equivalent to a new parallel mechanism. Reference [14] analyzed the degree of freedom of the quadruped walking robot, and concluded the robot constituted by the standing legs has 3 translational DOF without rotational DOF. Although the swinging leg also has 3 translational DOF, it does not influence the DOF of robot body. Therefore, the leg mechanism DOF of the robot can meet the requirement of DOF during quadruped walking and can adjust the static stability of the robot.

THE GAIT ANALYSIS OF QUADRUPED WALKING ROBOT

It is difficult to analyze the whole kinematics of the quadruped walking robot with parallel leg mechanism because it is a multi-branched, time-varying topological and redundantly driven system. Therefore, the kinematics of the multi-legged walking robot is more complex than that of the average wheeled mobile robot. To control the swing leg and body posture during walking, the inverse kinematics is needed to analyze. The literatures [15, 16] on the inverse kinematics of the walking robot with serial leg mechanism provided a reference for the overall kinematics of the quadruped walking robot with parallel leg mechanism.

Real-time computation of walking robot needs to calculate the inverse kinematics, which is easy to achieve for parallel mechanisms. The quadruped walking robot in walking can be seen as a new parallel mechanism formed by several legs supporting a seat, where the body and ground are regarded as the upper and lower platforms, respectively.

The quadruped walking robot has three standing legs and a swing leg when in the crawl gait. Therefore, the quadruped walking robot can be considered as a parallel mechanism with 9 branches and a 3-UPU swing leg mechanism.

Fig. (**4**) shows the diagram of quadruped walking robot when the leg 4 (*DH*) lifting. The fixed coordinate system *OXYZ* is established on the ground, marked with {*O*}. The body coordinate system *PX'Y'Z'* is established at the center of the robot body, marked with {*P*}. Assume that $AB = 2m$, $AC = 2n$, the center of the body in the fixed coordinate system is expressed as $[P]=[P_X \quad P_Y \quad P_Z]^T$. Four points *A, B, C, D* on the leg mechanisms connected with the body are expressed as $[P'_i]=[P'_{iX} \quad P'_{iY} \quad P'_{iZ}]^T$ (*i=A, B, C, D*) in the body coordinate system. We can establish the leg coordinate systems $x'_A A y'_A \quad x'_B B y'_B \quad x'_C C y'_C \quad x'_D D y'_D$, whose origins are *A, B, C, D* respectively (Fig. **2**), marked as {C_i}.

Assume that the foot center point of the leg mechanism in the fixed coordinate system is expressed as $[Z_j] = [Z_{jx} \quad Z_{jy} \quad Z_{jz}]$ (*j = E, F, G, H*), we can establish the feet

coordinate systems $x'_E E y'_E \quad x'_F F y'_F \quad x'_G G y'_G \quad x'_H H y'_H$ at the center of each foot, marked as $\{Z_j\}$, *j= E, F, G, J*. The connection points between the various branches of the leg mechanism and the upper platform are written as I_{ik} (*i = A, B, C, D; k = 1, 2, 3*) in the fixed coordinate system, and expressed as I'_{ik} in the body coordinate system, and marked as I''_{ik} in the leg mechanism coordinate system. The connection points between the various branches of the leg mechanism and lower platform are marked as Z_{jk} (*j = E, F, G, H; k =1, 2, 3*) in the fixed coordinate system, written as Z'_{jk} in the body coordinate system, and marked as Z''_{jk} in leg mechanism coordinate system.
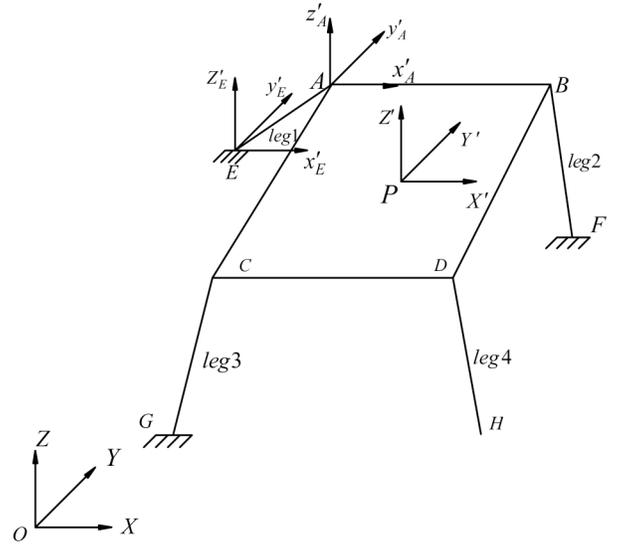
Fig. (4). The quadruped walking robot in crawl gait.

According to the geometric relationship of the equilateral triangle shown in Fig. (**2**), we can obtain the following equations:

$$I''_{i1} = \begin{bmatrix} 0 & R & 0 \end{bmatrix}^T$$

$$I''_{i2} = \begin{bmatrix} -\dfrac{\sqrt{3}}{2}R & -\dfrac{1}{2}R & 0 \end{bmatrix}^T \qquad (1)$$

$$I''_{i3} = \begin{bmatrix} \dfrac{\sqrt{3}}{2}R & -\dfrac{1}{2}R & 0 \end{bmatrix}^T$$

$$(i = A, B, C, D; k = 1, 2, 3)$$

$$Z''_{j1} = \begin{bmatrix} 0 & r & 0 \end{bmatrix}^T$$

$$Z''_{j2} = \begin{bmatrix} -\dfrac{\sqrt{3}}{2}r & -\dfrac{1}{2}r & 0 \end{bmatrix}^T$$

$$Z''_{j3} = \begin{bmatrix} \dfrac{\sqrt{3}}{2}r & -\dfrac{1}{2}r & 0 \end{bmatrix}^T \qquad (2)$$

$$(j = E, F, G, H; k = 1, 2, 3)$$

The transformation relation between the leg mechanism coordinate system {C_i} and the body coordinate system {*P*} is given as follows:

$$[I'_{ik}] = \begin{bmatrix} {}^P_{C_i}T_i \end{bmatrix}[I''_{ik}] \quad (i = A, B, C, D; k = 1, 2, 3) \tag{3}$$

$$\begin{bmatrix} {}^P_{C_i}T_i \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} {}^P_{C_i}R_i \end{bmatrix} & [P'_i] \\ 0 \;\; 0 \;\; 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} {}^P_{C_i}R_i \end{bmatrix} = \begin{bmatrix} \cos\alpha_i & -\sin\alpha_i & 0 \\ \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

In the above equation, α_i is the rotation angle of the leg coordinate system relative to the body coordinate system. Thus, the coordinates $[I'_{ik}]$ of the connected point between each branch of leg and the upper platform in the body coordinate system can be obtained.

Suppose the body's position in the fixed coordinate system during walking is shown in Fig. (**4**), the transformation relation between the body coordinate system $\{P\}$ and the fixed coordinate $\{O\}$ can be obtained as follows:

$$[I_{ik}] = \begin{bmatrix} {}^O_PT \end{bmatrix}[I'_{ik}] (i = A, B, C, D; k = 1, 2, 3) \tag{5}$$

$$\begin{bmatrix} {}^O_PT \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} {}^O_PR \end{bmatrix} & [P] \\ 0 \;\; 0 \;\; 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} {}^O_PR \end{bmatrix} = \begin{bmatrix} n_1 & o_1 & a_1 \\ n_2 & o_2 & a_2 \\ n_3 & o_3 & a_3 \end{bmatrix} \tag{6}$$

In the above equation, n_k, o_k, a_k $(k=1,2,3)$ are the direction cosine of the body coordinate system in the fixed coordinate system. So, the connection points between the various branches of the leg mechanism and the upper platform in the fixed coordinate system can be expressed as follows:

$$[I_{ik}] = \begin{bmatrix} {}^O_PT \end{bmatrix}[I'_{ik}] = \begin{bmatrix} {}^O_PT \end{bmatrix}\begin{bmatrix} {}^P_{C_i}T_i \end{bmatrix}[I''_{ik}] \tag{7}$$

where, $i = A, B, C, D; k = 1, 2, 3$.

For the different layouts of the upper platform, the transformation matrix of the foot coordinate system on the leg mechanism relative to the fixed coordinate system is different. The main feature of basic 3-UPU leg mechanism is that the relative motion between the upper and lower platforms is always a translation. The rotation transformation matrix between foot coordinate system $\{Z_i\}$ and the body coordinate system $\{P\}$ is the same as that between the corresponding leg mechanism coordinate system $\{C_i\}$ and the body coordinate system $\{P\}$, and can be obtained as follows:

$$[{}^P_{Z_E}R_E] = [{}^P_{Z_F}R_F] = [{}^P_{C_A}R_A] = [{}^P_{C_B}R_B]$$
$$[{}^P_{Z_G}R_G] = [{}^P_{Z_H}R_H] = [{}^P_{C_C}R_C] = [{}^P_{C_D}R_D] \tag{8}$$

The coordinates of the connection points between the various branches of leg and the lower platform in the fixed coordinate system can be expressed as:

$$[Z_{jk}] = \begin{bmatrix} {}^O_{Z_j}T_j \end{bmatrix}[Z''_{jk}] \quad (j = E, F, G, H; k = 1, 2, 3) \tag{9}$$

$$\begin{bmatrix} {}^O_{Z_j}T_j \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} {}^O_{Z_j}R_j \end{bmatrix} & [Z_j] \\ 0 \;\; 0 \;\; 0 & 1 \end{bmatrix} \quad (j = E, F, G, H) \tag{10}$$

$$[{}^O_{Z_j}R_j] = [{}^O_PR][{}^P_{Z_j}R_j] \quad (j = E, F, G, H) \tag{11}$$

From the above analysis, the coordinates of the connected points between the two platforms and the all branches in the fixed coordinate system can be obtained. Therefore, the inverse kinematics solution of the quadruped walking robot can be expressed as follows:

$$\left| I_{ik} - Z_{jk} \right| = L_{ijk} \tag{12}$$

In this formula, $i = A, B, C, D; j = E, F, G, H; k = 1, 2, 3$, L_{ijk} is the length of branch k in the leg mechanism, i and j indicate the centers of the upper platform and the lower platforms. From equations (3), (7) and (9), the inverse kinematics of quadruped walking robot can be expressed in the following equations:

$$L^2_{ij1} = \left\{ \begin{matrix} P_X - Z_{jX} + a_1 P'_{iz} + n_1 P'_{iX} + o_1 P'_{iY} + \\ (R-r)[o_1 \cos(\alpha_i) - n_1 \sin(\alpha_i)] \end{matrix} \right\}^2$$
$$+ \left\{ \begin{matrix} P_Y - Z_{jY} + a_2 P'_{iz} + n_2 P'_{iX} + o_2 P'_{iY} + \\ (R-r)[o_2 \cos(\alpha_i) - n_2 \sin(\alpha_i)] \end{matrix} \right\}^2$$
$$+ \left\{ \begin{matrix} P_Z - Z_{jZ} + a_3 P'_{iz} + n_3 P'_{iX} + o_3 P'_{iY} + \\ (R-r)[o_3 \cos(\alpha_i) - n_3 \sin(\alpha_i)] \end{matrix} \right\} \tag{13}$$

$$L^2_{ij2} = \left\{ \begin{matrix} P_X - Z_{jX} + a_1 P'_{iZ} + n_1 P'_{iX} + o_1 P'_{iY} - \\ (R-r)[o_1 \cos(\alpha_i - \tfrac{\pi}{3}) - n_1 \sin(\alpha_i - \tfrac{\pi}{3})] \end{matrix} \right\}^2$$
$$+ \left\{ \begin{matrix} P_Y - Z_{jY} + a_2 P'_{iZ} + n_2 P'_{iX} + o_2 P'_{iY} - \\ (R-r)[o_2 \cos(\alpha_i - \tfrac{\pi}{3}) - n_2 \sin(\alpha_i - \tfrac{\pi}{3})] \end{matrix} \right\}^2 \tag{14}$$
$$+ \left\{ \begin{matrix} P_Z - Z_{jZ} + a_3 P'_{iZ} + n_3 P'_{iX} + o_3 P'_{iY} - \\ (R-r)[o_3 \cos(\alpha_i - \tfrac{\pi}{3}) - n_3 \sin(\alpha_i - \tfrac{\pi}{3})] \end{matrix} \right\}$$

$$L^2_{ij3} = \left\{ \begin{matrix} P_X - Z_{jX} + a_1 P'_{iZ} + n_1 P'_{iX} + o_1 P'_{iY} - \\ (R-r)[o_1 \cos(\alpha_i + \tfrac{\pi}{3}) - n_1 \sin(\alpha_i + \tfrac{\pi}{3})] \end{matrix} \right\}^2$$
$$+ \left\{ \begin{matrix} P_Y - Z_{jY} + a_2 P'_{iZ} + n_2 P'_{iX} + o_2 P'_{iY} - \\ (R-r)[o_2 \cos(\alpha_i + \tfrac{\pi}{3}) - n_2 \sin(\alpha_i + \tfrac{\pi}{3})] \end{matrix} \right\}^2 \tag{15}$$
$$+ \left\{ \begin{matrix} P_Z - Z_{jZ} + a_3 P'_{iZ} + n_3 P'_{iX} + o_3 P'_{iY} - \\ (R-r)[o_3 \cos(\alpha_i + \tfrac{\pi}{3}) - n_3 \sin(\alpha_i + \tfrac{\pi}{3})] \end{matrix} \right\}$$

In the above equations, $i = A, B, C, D; j = E, F, G, H; k = 1, 2, 3, \begin{bmatrix} Z_{jX} & Z_{jY} & Z_{jZ} \end{bmatrix}$ is the position of foot center in the fixed coordinate system during the walking, and when the leg mechanism is the swing leg, it indicates the point on foot trajectory curve; $\begin{bmatrix} P'_{iX} & P'_{iY} & P'_{iZ} \end{bmatrix}^T$ is the position of the points *A, B, C, D* in the body coordinate system; $[n_k, o_k, a_k]$ is the direction cosine of the body coordinate system in the fixed coordinate system; α_i is the rotation angle of *i*-th leg coordinate system relative to body coordinate system. Formulas (13)-(15) are the inverse position solution of quadruped walking robot during walking, which expresses the length relationship of the four legs with a unified mathematical form.

From DOF point of view, the body of the walking robot has 3 DOF, while the walking robot has a total of 9 driving motors. Any three of them can be selected as main motors, and the remaining are redundant motors. The three-dimensional movement of the quadruped walking robot can be obtained by controlling three main motors when they are selected. Consider from the aspect of robot control, the problem comes down to the redundant problem of robot during walking. We need strictly to control the input of each joint based on the equation (12) to achieve three-dimensional movement of body.

The leg mechanism proposed in this paper consists of 3-UPU parallel mechanism with 3 DOF and has identical structure form. When the leg mechanism acts as standing leg, if the motor is added to the three branches of the 3-UPU parallel mechanism, the movement of the upper platform of standing leg mechanism can be achieved. Since the upper platform in leg mechanism and the body are permanent connection, it is essential to achieve three-dimensional movement of body by adding active drive to 3-UPU parallel mechanism acting as a standing leg. Since the three active driving joints may be selected in any a standing leg, the kinematics problem of quadruped walking robot comes down to that of 3-UPU parallel mechanism. The relationship of speed and acceleration during walking can be attained by the first order and second order influence coefficient matrix of 3-UPU standing leg mechanism.

For the swing leg, whose upper platform is permanently connected with the body, when the lower platform has completed three-dimensional movement in accordance with given foot track, the upper platform are also moving with body. From equation (12), the driving variable of the swing leg can be obtained. The foot walking track of the swing leg is the superposition of body trajectory and foot trajectory. The speed and acceleration of the swing leg can also be obtained by the first order and second order influence coefficient method.

NUMERICAL EXAMPLE

According to the actual designed size of the robot, set the circumference radius of the upper platform of the 3-UPU parallel mechanism as 161.7 mm (edge length 280 mm) and the circumference radius of the lower platform as 57.7 mm (edge length 100 mm), the seat size as *m* = 200 mm, *n* = 200 mm, the platform layout is shown in Fig. (**2**), then:

$$\alpha_A = \alpha_B = \alpha_E = \alpha_F = 180° \qquad (16)$$
$$\alpha_C = \alpha_D = \alpha_G = \alpha_H = 0°$$

$$[P'_A] = \begin{bmatrix} -m & n & 0 \end{bmatrix}^T$$
$$[P'_B] = \begin{bmatrix} m & n & 0 \end{bmatrix}^T$$
$$[P'_C] = \begin{bmatrix} -m & -n & 0 \end{bmatrix}^T \qquad (17)$$
$$[P'_D] = \begin{bmatrix} m & -n & 0 \end{bmatrix}^T$$

Assume that the quadruped walking robot moves forward along the *Y* direction as shown in Fig. (**4**), namely:

$$\begin{bmatrix} {}^O_P R \end{bmatrix} = \begin{bmatrix} n_1 & o_1 & a_1 \\ n_2 & o_2 & a_2 \\ n_3 & o_3 & a_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (18)$$

From equations (13)-(15), the inverse kinematics expressions of the robot in walking can be obtained as follows:

$$L_{AE1} = \sqrt{(P_X - E_X - 116.7)^2 + (P_Y - E_Y + 137.8)^2 + (P_Z - E_Z)^2}$$

$$L_{AE2} = \sqrt{(P_X - E_X - 187.8)^2 + (P_Y - E_Y + 303.3)^2 + (P_Z - E_Z)^2}$$

$$L_{AE3} = \sqrt{(P_X - E_X - 295.6)^2 + (P_Y - E_Y + 159)^2 + (P_Z - E_Z)^2}$$

$$L_{BF1} = \sqrt{(P_X - F_X + 283.3)^2 + (P_Y - F_Y + 137.8)^2 + (P_Z - F_Z)^2}$$

$$L_{BF2} = \sqrt{(P_X - F_X + 212.2)^2 + (P_Y - F_Y + 303.3)^2 + (P_Z - F_Z)^2}$$

$$L_{BF3} = \sqrt{(P_X - F_X + 104.4)^2 + (P_Y - F_Y + 159)^2 + (P_Z - F_Z)^2}$$

$$L_{CG1} = \sqrt{(P_X - G_X - 200)^2 + (P_Y - G_Y - 96)^2 + (P_Z - G_Z)^2}$$

$$L_{CG2} = \sqrt{(P_X - G_X - 290.1)^2 + (P_Y - G_Y - 252)^2 + (P_Z - G_Z)^2}$$

$$L_{CG3} = \sqrt{(P_X - G_X - 109.9)^2 + (P_Y - G_Y - 252)^2 + (P_Z - G_Z)^2}$$

$$L_{DH1} = \sqrt{(P_X - H_X + 200)^2 + (P_Y - H_Y - 96)^2 + (P_Z - H_Z)^2}$$

$$L_{DH2} = \sqrt{(P_X - H_X + 109.9)^2 + (P_Y - H_Y - 252)^2 + (P_Z - H_Z)^2}$$
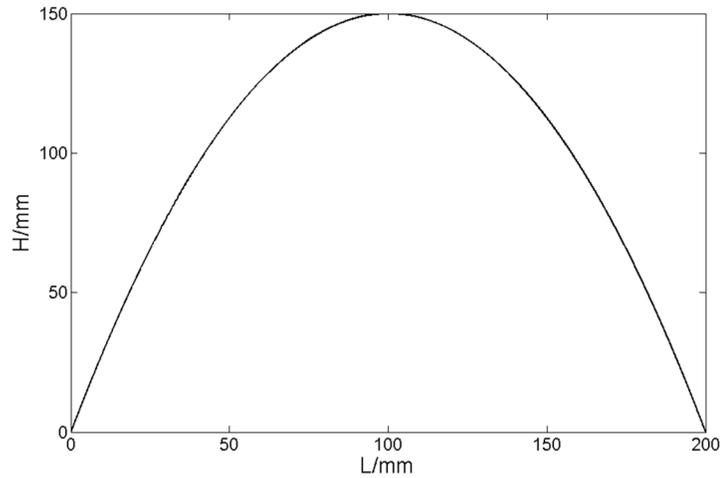
Fig. (5). Foot parabola trajectory.
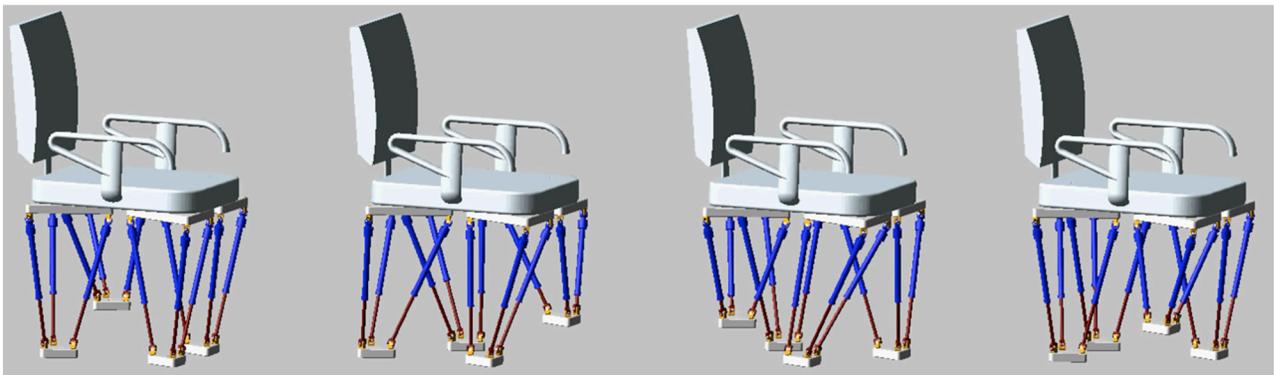
Fig. (6). The quadruped walking robot in crawl gait.

$$L_{DH3} = \sqrt{\begin{aligned}&(P_X - H_X + 290.1)^2 + \\ &(P_Y - H_Y - 252)^2 + (P_Z - H_Z)^2\end{aligned}}$$

From the above equation, the change in bar length of every branch of the robot leg mechanism during walking can be calculated. The velocity and acceleration of the quadruped walking robot can also be solved by the derivative of the above equations.

MOTION SIMULATION

Using ADAMS simulation software, the modeling, kinematics and dynamics simulation of parallel mechanism do not need cumbersome analysis, derivation and calculation, therefore, the position solution and the movement characteristics of the walking robot can be obtained by simulation. Also, the simulation can solve the problem of motion visualization, visualize the working process of the mechanism, and provide an effective way for the design and analysis of walking robot. Here we will adopt Pro/E and ADAMS interface software Mechanism/Pro, and import the well-established three-dimensional model into ADAMS.

When establishing the three-dimensional model, according to the actual designed size of the robot, set the circumference radius of the upper platform of the 3-UPU parallel mechanism as 161.7 mm (edge length 280 mm) and the circumference radius of lower platform as 57.7 mm (edge
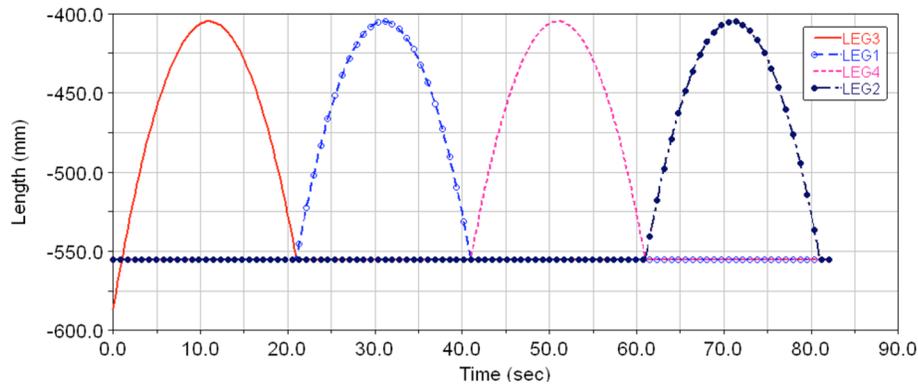
Fig. (7). Foot trajectory.

length 100 mm), the seat size as m = 200 mm, n = 200 mm, the robot body's initial position as (0 0 400). Set the foot walking path of the quadruped walking robot as the parabola trajectory as shown in Fig. (**5**). Take H = 150 mm, L = 200 mm, the parabolic expression is $z = -0.015x^2 + 3x$.

The quadruped walking robot moves according to the classic 3-1-4-2 crawling gait as shown in Fig. (**6**). Maintain a 0.75 duty cycle, and continuously adjust the position of the center of gravity [17], set the step distance as 200 mm, add the movement of general point to the foot center of the robot model in ADAMS.

Take points as splines from the curve shown in Fig. (**5**), and add it as a foot path of the quadruped walking robot.

When the robot completes a motion simulation, the measured four foot trajectories of leg mechanism are shown in Fig. (**7**). Also, the change of link length of each leg in the movement is shown in Fig. (**8**).

The foot trajectory obtained by simulation during walking is shown in Fig. (**7**), corresponding to the trajectory given as shown in Fig. (**5**). It can be seen that when giving parabolic trajectory, the foot height of the leg mechanism changes smoothly in the walking process of the "up - forward - down". Fig. (**7**) shows that the center track of the foot is the superposition of the body trajectory and foot trajectory when leg mechanism acts as the swing leg.
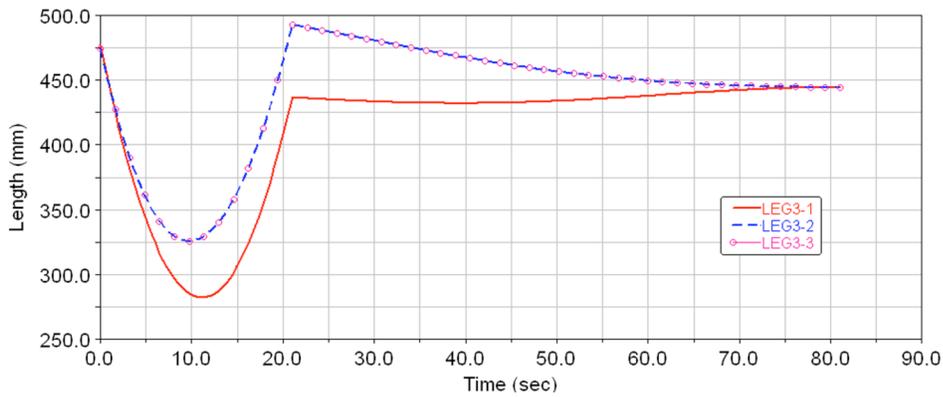
(a) The curve of branch length of leg 3.
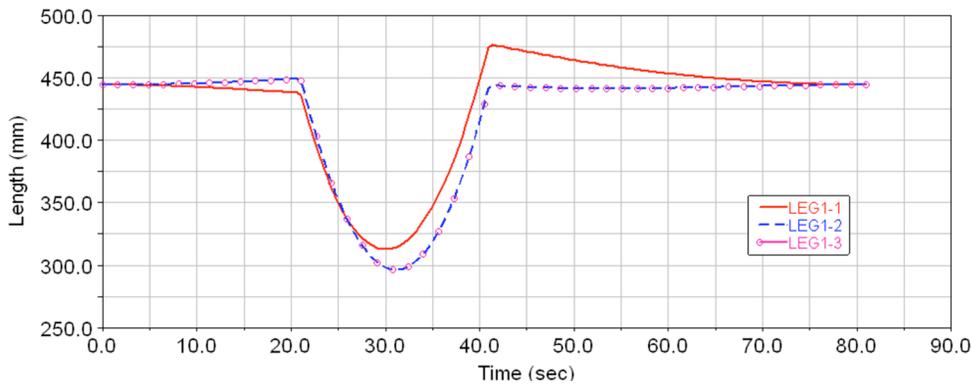
(b) The curve of branch length of leg 1.
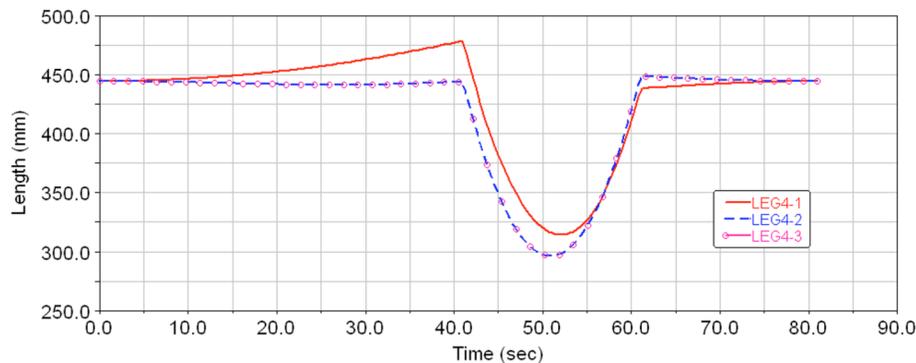
(c) The curve of branch length of leg 4.

(Fig. 8) Contd…..
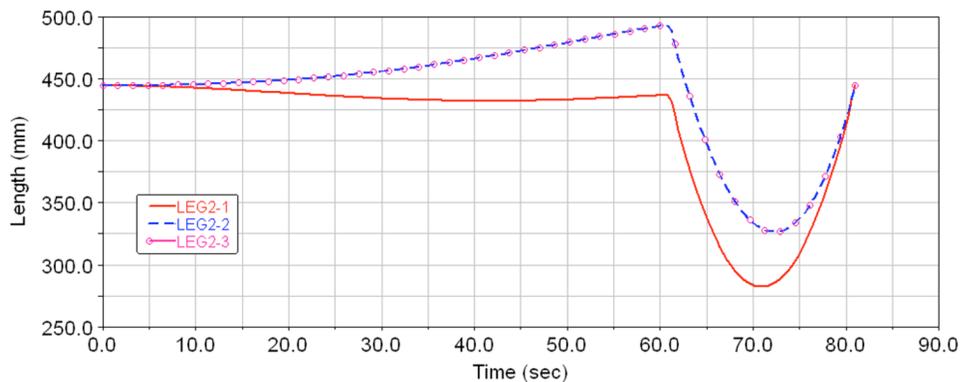
(d) The curve of branch length of leg 2.

Fig. (8). The length change of every branch of the swing leg.

Fig. (**8**) shows the length change of every branch when each leg mechanism acts as the swing leg. Change in link length of every branch is within the permitted range. The length changes of the second and third branches of the leg mechanism are consistent throughout the walking process, which is consistent with the actual walking process of the robot. Moreover, the change curve of the link length has some similarities when each leg mechanism acts as the swing leg, which is because of their same structures.

CONCLUSION

(1)   The paper analyzes the model and derives the inverse kinemics of a quadruped walking robot with parallel leg mechanism in general crawl gait.

(2)   Combined with the movement characteristics of 3-UPU parallel mechanism and the structural features of the quadruped walking robot, the paper relates the kinematics of the whole quadruped walking robot to the kinematics of basic leg mechanism.

(3)   Based on the unified expression of the inverse kinematics, combined with the design parameters, the numerical examples and the simulation results are given, which provides the foundation for the forward displacement, dynamics and the posture control of the quadruped walking robot.

(4)   This research sets a theoretical basis for further investigation on the quadruped/biped reconfigurable walking robot with parallel leg mechanism. It is significant to expand research field and the application of parallel robots.

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