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Dynamic Characters Analysis for Single Loop Six-bar Closed Chain Locomotive Robot

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Abstract: To simplify locomotive robot structure and reduce its volume, single loop polygonal closed chain is implemented as its body, which is composed by same cell and node so as to expand easily. The linkage and its retractile ability are being introduced as the walk mechanism can not only reduce the robot's volume and solve the strict transportation space but also satisfy the huge obstacle-surmounting requirement. The triangle robot is a single RPR-PRP six bar mechanism so the linkages length relationship condition when it rolls on typical landforms, such as flat, slope, stage and trench,can be analyzed and computed. Two properties, called move equation and roll condition, are introduced to help explain the move process. Then the system's dynamic equation is built by Lagrange's Equations of motion under the hypothesis of every linkage has same mass and shape. Finally, an example including the visual linkage dimension relationships of the robot is given and the conceptual prototype and its real walk pictures on the flat are presented. It is shown that the closed chain locomotive robot composed by the telescopic linkages could have good cross-country performance and obstacle climbing ability under the condition of smaller original volume.

Key words: Locomotive robot, polygon, six-bar closed chain mechanism, dynamic characters analysis

INTRODUCTION

Generally the mobile robot overall is open-chain mechanism, or in order to improve the operation stability and load performance of serial robot, partly is closed chain mechanism (Nakamura and Ghodoussi, 1989). Because closed chain mechanism's coupling motion between motion joints and bars, it makes the difficulty of motion analysis and control complexity greatly increased. But a mobile robot using completely closed-chain structure is not so much. Polygon (or polyhedron) is one of the simple geometric form, each edge (face) is equivalent. Inspired by this, transforming it into a closed chain mobile robot. Using its deforming theory as the mobile mechanism, not only has good expansibility but also can make the robot in the freedom of switching the movement in arbitrary state and makes the movement more flexible. When the robot meets unpredictable factors of inverted situation, it can still guarantee the robot work normally. This aroused some scholars' concern. Japan Tokyo industry university has developed a pentagon rolling robot (Yamawaki *et al.*, 2003), controlled the rolling of polygon by mutual coordination of the motors of 5 joints. Modular robot research team in Univ. Pennsylvania USA, proposed to use multiple reconfigurable robot modules to compose the closed chain polygon, using the dynamic deformation characteristics to realize the robot tumbling motion (Yakey *et al.*, 2001). Some scholars aim at the specialty of multiple degree of freedom of closed chain robot ,to research the motion path algorithm (Mellinger *et al.*, 2009). In the field of planetary exploration, by the limitation of carrying tools transport space, we hope the robot can compress its volume in the transport as far as possible. But for the general mobile robot system, the structure and shape of each unit is fixed, generally just the support arm, joint type manipulator can stretch through joint rotation and the overall volume compression is not so much. If the unit design of the robot is telescopic form, the proper combination can make the robot have more stretch space, Goddard space flight center of NASA and Langley Research center in 2000 in Autonomous Nanotechnology Swarms (ANTS) plan, presented a new type of robot that tetrahedron as the basic unit (TETWalker) and have successfully developed a tetrahedral robot (4-TET Robot) and cube robot (12-TET) prototype (Truszkowski *et al.*, 2006).

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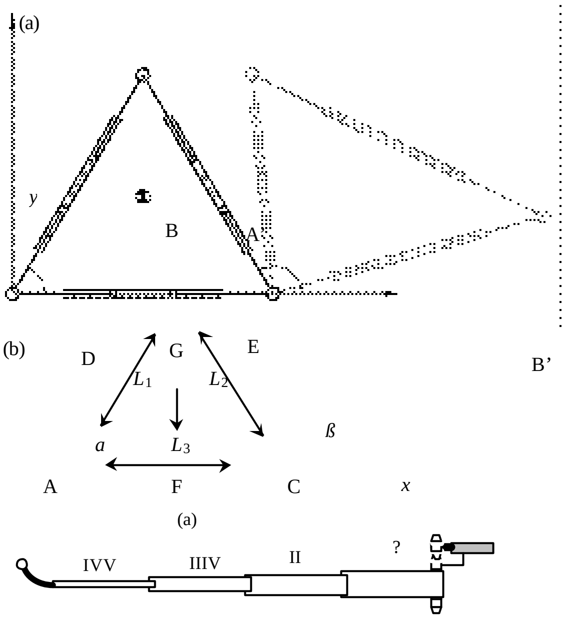

Fig. 1(a-b): Closed chain triangle rolling robot, (a) Robot figure and (b) Bar completely extended state

This article has a analysis of the kinematic and dynamic characteristics of the triangular overall closed chain mobile robot, for the convenience calculation and analysis of robot, each bar designs as the similar structure and quality characteristics. On this basis, we have a analysis and calculation of the tumble movement or obstacle crossing conditions in various typical terrain conditions. And at the same time, this article has a dynamics analysis by using the Lagrange equations. Finally gives a numerical analysis and the movement schematic illustration of robot concept physical prototype.

STRUCTURE DESIGN OF THE ROBOT GEOMETRIC DIMENSION RELATIONS

Robot structure figure as Fig. 1a, this rolling closed chain triangle robot is a RPR-PRP planar six bar mechanism which without fixed frame. The six bars are: AD, DB, BE, EC, CF, FA and the corresponding length are l_1-l_6, for arbitrary bar j, its length is a function of time, $l_j = l_j\ (t) = l_0+l_j'(t)$ and l_0 means the length when the bar is completely in the state of compression, $l_j'(t)$ means the adjustable length changes with time. Assumption:

- Point A as the origin of coordinates, coordinate system Axy is moving coordinate system, edge AC is the positive direction of x axis, the midpoint of the coordinates is (x, y), the ground as the absolute coordinate system, the coordinates of points for (O_x, O_y). Assume the origin of absolute coordinate system and A are coincident on the ground
- Each bar's length l_0 is same as the adjustable length, the Max adjustable length is d, the angle of AD bar and x axis is α, angle of BC bar and x axis is β
- Through moving the 2 bars with secondary connecting, if the shrinkage or expansion speed and the both trends are same, means $l_1'(t)= l_2'(t)$, $l_3'(t) = l_4'(t)$, $l_5'(t) = l_6'(t)$, so the 6 bars' length can be divided into three equivalent bar L_1, L_2, L_3 and meet the equality relation $L_1 = l_1+l_2$, $L_2 = l_3+l_4$, $L_3 = l_5+l_6$.

According to the geometry relationship of the triangle, can show the trigonometric function of α angle and β angle:

$$\begin{cases} L_1^2 = x_B^2 + y_B^2 \\ L_2^2 = (L_3 - x_B)^2 + y_B^2 \end{cases}$$

Get that:

$$\begin{cases} x_B = \left(L_1^2 + L_3^2 - L_2^2\right) \Big/ 2L_3 \\ y_B = \sqrt{4L_3^2 - \left(L_1^2 + L_3^2 - L_2^2\right)} \Big/ 2L_3 \end{cases} \tag{1}$$

The connecting bar's design is one of the key design for this robot, the difficulty is mainly from two side: First, ensure that the bar has a larger expansion ratio, such as TETWalker bar design is biologically inspired, designed as the spring tension pulley form, the expansion ratio has reached more than 5; Second, in the whole process of motion analysis, centroid and rotational inertia are the more complicated parameters, so it need to use proper structure design to analysis and calculate these two parameters.

Our connecting bar use the multiple-thread transmission structure and on the original conceptual basis of original development of rolling triangle robot, we have an improvement, the outer bar I is also designed with thread and at the same time, each joint designed with same structure, Fig. 2b, for the bar fully expansion state. When the bar is at the Min. compression state, multiple-thread transmission superimposed together, the nut on the thread sleeve is located on the right side of bar I. Bar expansion driving force is completed by the nut on the thread sleeve of motor driving, first step, nut moves right under the motor driving, when it moves to the endpoint, it is blocked by the limit stage; If the motor continue

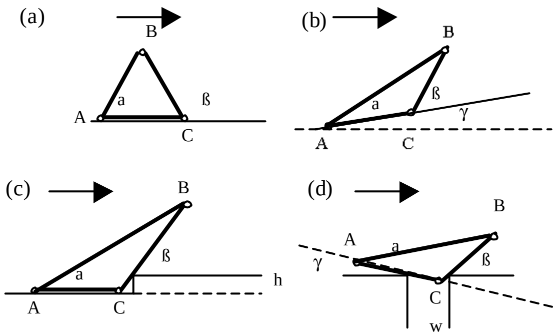

Fig. 2(a-d): Robot rolling under various topographic conditions, (a) flat land (b) slope tumble (c) climb the step (d)crossing trench

driving the outer thread sleeve rotating, loosen the internal thread bar (I-V) gradually, until the last thread bar is pulled out. This design is greatly improved the bar's expansion ratio.

Because the bars' mass and shapes are same, by moving the 2 bars with secondary connecting, with the same patch of the center of mass , same angle of patch and vertex and a couple of bars with symmetrically arranged, the bars are moving pairing in the process of extending and shorten, namely l_1, l_2 with the same adjusting speed,so the center of mass of the three equivalent bar L_1, L_2, L_3, is always in the midpoint of the two rotating secondary connecting lines.

The necessary conditions of robot moving, the abscissa exceed the critical point, the system centroid G (x_G, y_G) can be calculated through the centroid synthetic formula.

Plug in the system centroid synthetic formula:

$$x_G = \left(L_1^2 - L_2^2 + 3L_3^2\right) \Big/ 6L_3 \tag{2}$$

$$y_G = \frac{L_1}{6}\sqrt{1 - \left(L_1^2 + L_3^2 - L_2^2\right)^2 \Big/ 4L_1^2L_3^2} + \frac{L_3}{6}\sqrt{1 - \left(L_1^2 - L_2^2 - L_3^2\right)^2 \Big/ 4L_2^2L_3^2} \tag{3}$$

MOTION CHARACTERISTICS ANALYSIS

Assume that the initial state of the triangle is AC edge touch ground, robot motion direction for tumbling left to right, then robot will tumble around point C, AC length is no change when motion, AB and BC will adjust the length and make the centroid of robot move right. When the abscissa of the robot centroid is bigger than point B's, robot will clockwise tumble around point C under the action of gravity, then robot will adjust to triangle again and complete a waling gait. Common obstacle for the mobile robot: Slop, step, trench etc., as Fig. 2b-d, the principle of over these obstacles is still with a point for support and make the robot tumble.

Robot tumbling on the flat land condition is, system centroid abscissa is bigger than the tumbling support's, namely:

$$\left(L_1^2 - L_2^2 + 3L_3^2\right) \Big/ 6L_3 > L_3$$

And according to the relationship between the length of the three sides of triangle, the further evolution of the above equation is:

$$(L_2 + L_3)^2 > L_1{}^2 > L_2{}^2 + 3L_3{}^2 \tag{4}$$

Assume the bar stretch ratio is the ratio of bar longest and shortest, $n = (l_0+d)/l_0$, according to the critical condition of the robot tumbling, can get the corresponding critical value of the stretch ratio n = 1, means to make the robot tumble, must $d>l_0$.

Assume that robot is tumbling on the slope with the angle γ, as Fig. 2b, the ground as the absolute coordinate system and its vertex is A and A,C point is on the ground, similarly, robot centroid abscissa should be bigger than point C, then can make the robot forward and should fulfill below relationships:

$$\begin{bmatrix} {}^{O}x_G \\ {}^{O}y_G \\ \end{bmatrix} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_G \\ y_G \\ 1 \end{bmatrix} = \begin{bmatrix} x_G\cos\gamma - y_G\sin\gamma \\ x_G\sin\gamma + y_G\cos\gamma \\ 1 \end{bmatrix}$$

$${}^{O}x_G > {}^{G}x_C = L_3\cos\gamma$$

The slope range to make robot tumble successfully:

$$\gamma < \arctan\frac{x_G - L_3}{y_G} \tag{5}$$

Step height is h, in the process of rolling, the robot rotating around step vertex ,as the support point and when the centroid abscissa is bigger than the step vertex, robot can cross the step and the responding inequality relationship is as below:

$$\frac{L_1^2 - L_2^2 + 3L_3^2}{6L_3} > L_3 + h\cot\beta$$

Robot can cross the step height, should fulfill below relationship:

$$h < \frac{\left(L_1^2 - L_2^2 - 3L_3^2\right)\sin\beta}{6L_3\cos\beta} \tag{6}$$

A trench width is w, the initial position of robot is point C in the trench, AC bar ,BC bar support on the upper edge of both side, apparently if the robot shape is confirmed, point C's position has the relations with the supporting position of AC,BC. AC length L₃' is out of trench, the angle of AC and upper surface of the trench is γ,in the same way, if the robot successfully cross the trench, robot centroid should cross the upper position of right side of trench.

Now point A is not on the ground, centroid coordinate ($^o x_G$,$^o y_G$)in the absolute coordinates is:

$$\begin{bmatrix} ^O x_G \\ ^O y_G \end{bmatrix} = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & L_3'\sin\gamma \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_G \\ y_G \\ 1 \end{bmatrix}$$

$$= \begin{bmatrix} x_G\cos\gamma + y_G\sin\gamma \\ -x_G\sin\gamma + y_G\cos\gamma + L_3'\sin\gamma \\ 1 \end{bmatrix}$$

Robot successfully cross the trench should fulfill below inequality:

$$^O x_G > w + L_3'\cos\gamma$$

According to the trigonometric function, can get below inequality:

$$\frac{\sin(\beta-\gamma)}{L_3 - L'_3} = \frac{\sin\beta}{w}$$

Plugged L'_3 into inequality, can get trench width range:

$$w < \frac{(x_G\cos\gamma + y_G\sin\gamma - L_3)\sin\beta}{\sin\beta - \sin(\beta-\gamma)\cos\gamma} \tag{7}$$

DYNAMICS ANALYSIS

Common dynamic analysis method for Robot mainly: Newton-Euler equation, Lagrange equation etc., this article uses Lagrange equation and has a dynamic analysis(Zhang, 2000).

In order to reduce the complexity of the dynamic equation, in the same way, six bars are equivalent to three bars and have a calculation, three bars' adjusting speed and accelerated speed along its direction, separately is $\dot{L}_1, \dot{L}_2, \dot{L}_2$ and $\ddot{L}_1, \ddot{L}_2, \ddot{L}_3$, mass of the equivalent bar is m, bar's length displacement L_1, L_2, L_3 is generalized coordinates q_1, q_2, q_3.

Three equivalent bars corner can be expressed as:

$$\varphi_j = \varphi_j(q_1, q_2, q_3) \tag{8}$$

Any bar j of the three equivalent bars, the angular displacement and centroid coordinates equation relative to the origin of coordinates:

$$\begin{cases} x_{mj} = x_{mj}(q_1, q_2, q_3) \\ y_{mj} = y_{mj}(q_1, q_2, q_3) \end{cases} \tag{9}$$

Put the centroid coordinate equation and the time partial derivative into kinetic energy equation, can simplify the expression as:

$$E_K = \frac{1}{2}J_{11}\dot{q}_1^2 + \frac{1}{2}J_{22}\dot{q}_2^2 + \frac{1}{2}J_{33}\dot{q}_3^2 + J_{12}\dot{q}_1\dot{q}_2 + J_{13}\dot{q}_1\dot{q}_3 + J_{23}\dot{q}_2\dot{q}_3 \tag{10}$$

Can get the partial derivative, kinetic to generalized coordinates and kinetic to generalized coordinates first-order time derivative. Because the three generalized coordinates are independent each other, can confirm the generalized force base on the principle of virtual work, establish 3 independent equations.

The generalized force is the driving force on the driving bar, because the power of six motors are same, is P, it can be transformed into the relationship between power and displacement:

$$F_1 = \frac{2P}{\dot{q}_1}, F_2 = \frac{2P}{\dot{q}_2}, F_3 = \frac{2P}{\dot{q}_3} \tag{11}$$

System potential energy is:

$$E_P = 3mgy_G \tag{12}$$

The Eq. 10-12 into the Lagrange equation (Zhang, 2000) that the dynamical equations.

NUMERICAL ANALYSIS AND PROTOTYPE MOTION CASE

The initial length of each bar is 100 mm, bar expansion ratio is 3.5, then the initial length of equivalent bar is 200 mm, expansion ratio is 3.5. Firstly, according to

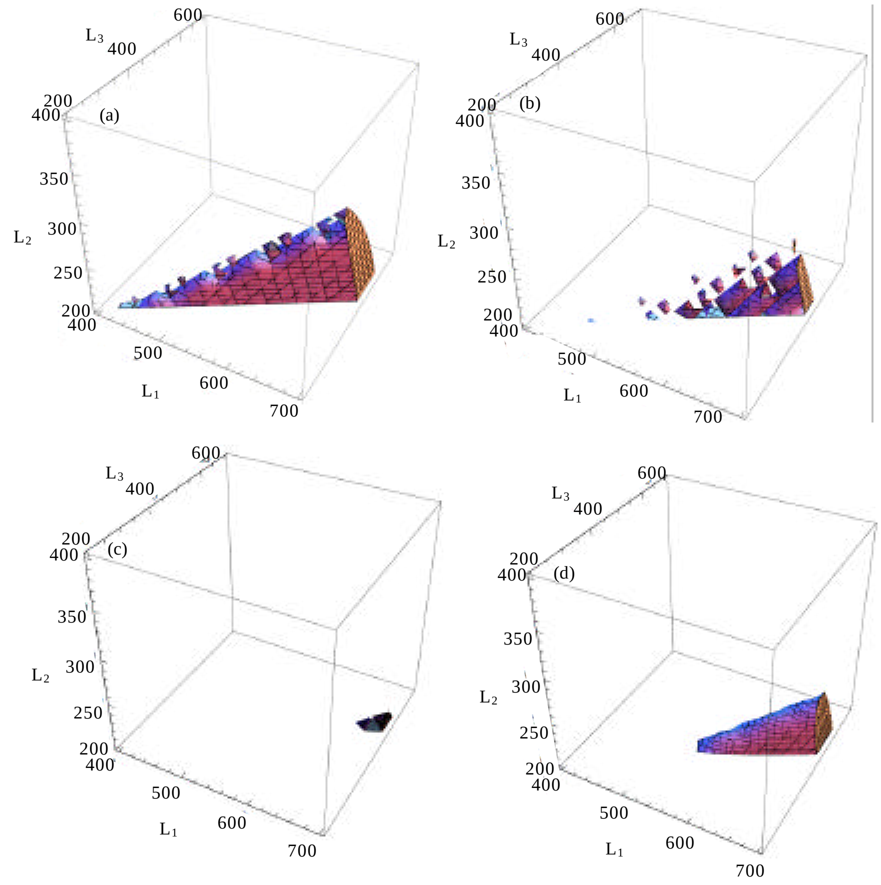

Fig. 3(a-d): Bar length distribution space when robot tumble in four topographic conditions

the robot bar length condition of tumbling in flat land, can draw the three equivalent bar size distribution space when robot tumble, as Fig. 3a.

When robot is walking on the slope, the slope angle is 30°, can get the 3 bars length distribution space when robot rolling on the slope, as Fig. 3b, in addition, theoretically, robot can roll on the greater angle of slope, but robot maybe decline on the slope, the actual angle can't be greater than the decline critical point. When robot crossing the step, set the step height is 50 mm, as Fig. 3c, is the current size distribution space, we can see, this hight has almost reached the limit. When crossing the trench, assume the angle of AC and trench upper surface of left side is 30°, trench width is 50 mm, the bar length distribution space is as Fig. 3d.

On this basis, making a simplified prototype of the robot, namely one of the pair bars is replaced by motor, another is two stage outer thread telescopic bar. Rolling gait coordination control is completed by manual operation. Fig. 4 is the video clips of robot prototype motion process, robot move from right to left, first, make sure the length of the bar on the ground is fixed, then adjust the other bars' length, make the robot center of gravity move left, when the robot rolled, readjust the bar length to initial state and a motion gait is completed.

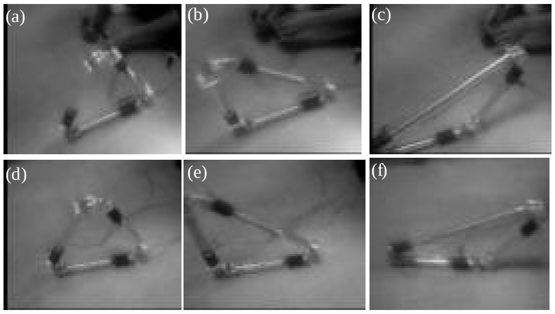

Fig. 4(a-f): Robot motion process on flat land, (a) t = 0s, (b) t = 3s, (c) t = 5s, (d) t = 14s, (e) t = 21s and (f) t = 23s

CONCLUSION

Based on the structure design of rolling closed chain triangle motile robot, has a analysis of its motion and dynamic characteristics and mainly study and analysis the bar length relationship and conditions of robot in various typical topographic conditions. Because bar motion of mutual restraint and mutual coupling, the path solution in actual place is still difficult and also brought the complexity of its dynamic analysis and motion control.

The triangular robot is using single loop six bar structure, there are few studies in mechanism and the polygonal can be extended, but the complexity will increase. So we need more and more efficient theories and methods to analysis and build the models of the new mobile robots.

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