Generalized Standard Foot Trajectory for a Quadruped Walking Vehicle

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Abstract

This article discusses a generalized method to produce standard foot trajectories for a quadruped walking vehicle having arbitrary reachable ranges and walking on uneven and inclined surfaces in random posture. The standard supporting foot trajectories are one of the most basic parameters for gait control, because the legs have to follow the trajectories as long as the irregular degree of terrain and posture conditions are maintained. The introduced method goes through the processes of (1) projection of the gait scheme on a horizontal plane, (2) definition of the effective searching areas, (3) selection of a crab-walking pattern between x *and* y *types, (4) generation of the stroke contour maps, and (5) selection of the longest stroke and its existing areas. The validity of the proposed method is verified by several computer simulations.*

1. Introduction

The quadruped walking vehicle will be one of the most practical locomotion machines to move about on uneven terrain and will be used in various industrial fields in the near future (Hirose 1984).

Based on this conviction, one of the authors (Hirose) has been continuously studying quadruped walking vehicles, primarily from the viewpoint of the mechanism (Hirose and Umetani 1980a; Hirose 1984), related sensors (Hirose, Yoshida and Taguchi 1987; Hirose, Yoshida and Toratani 1990; Hirose, Inoue and Yoneda 1990) and gait control (Hirose and Umetani 1980b; Hirose 1984; Hirose, Fukuda and Kikuchi 1986; Hirose, Kikuchi and Umetani 1986; Hirose and Kunieda 1986; Hirose and Yokoi 1988; Hirose et al. 1989). The experimental models constructed during the series of the studies, named TITAN III and TITAN IV, are shown in Figures 1 and 2.

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As to the gait control of the quadruped walking vehicle, the authors have mainly focused on statically stable walking and have clarified its hierarchical control structure and terrain-adaptive gait selection algorithm.

This article discusses ways of creating generalized standard foot trajectories for a quadruped walking vehicle having arbitrary reachable ranges and walking in a free body posture on a land of unspecified inclination and irregular surface.

The generalized standard foot trajectories stated in this study are defined to be the paths that are supposed to be cyclically followed by four feet at the supporting phase, based on the supposition that the terrain conditions and the walking vehicle's posture are continuously maintained. The generalized standard foot trajectories are one of the basic parameters for gait determination, for they are the object gait in convergence-to-standard free gait (Hirose, Fukuda and Kikuchi 1986), unless the vehicle is significantly affected by terrain disturbance.

The leg trajectories adapted in the gait scheme so far reported by the authors are shown in Figure 3. The gait scheme is based on the assumptions that (1) the walking vehicle always keeps its body horizontal; (2) the reachable range of each foot is of rectangular prism, and the four ranges take up symmetric positions; and (3) each trajectory symmetrically passes the center C_i of the plane that is the horizontal projection of the reachable area (hereinafter called the "horizontal reachable area").

The design to keep the body horizontal, assumed in (1), produces some desirable effects: such a design allows a walking vehicle in natural posture to carry material; it can introduce the gravitationally decoupled actuation (GDA) (Hirose and Umetani 1980a; Hirose 1984) by using the pantograph leg mechanism for better energy efficiency; and it can simplify the control of the leg motion. The body should be kept horizontal

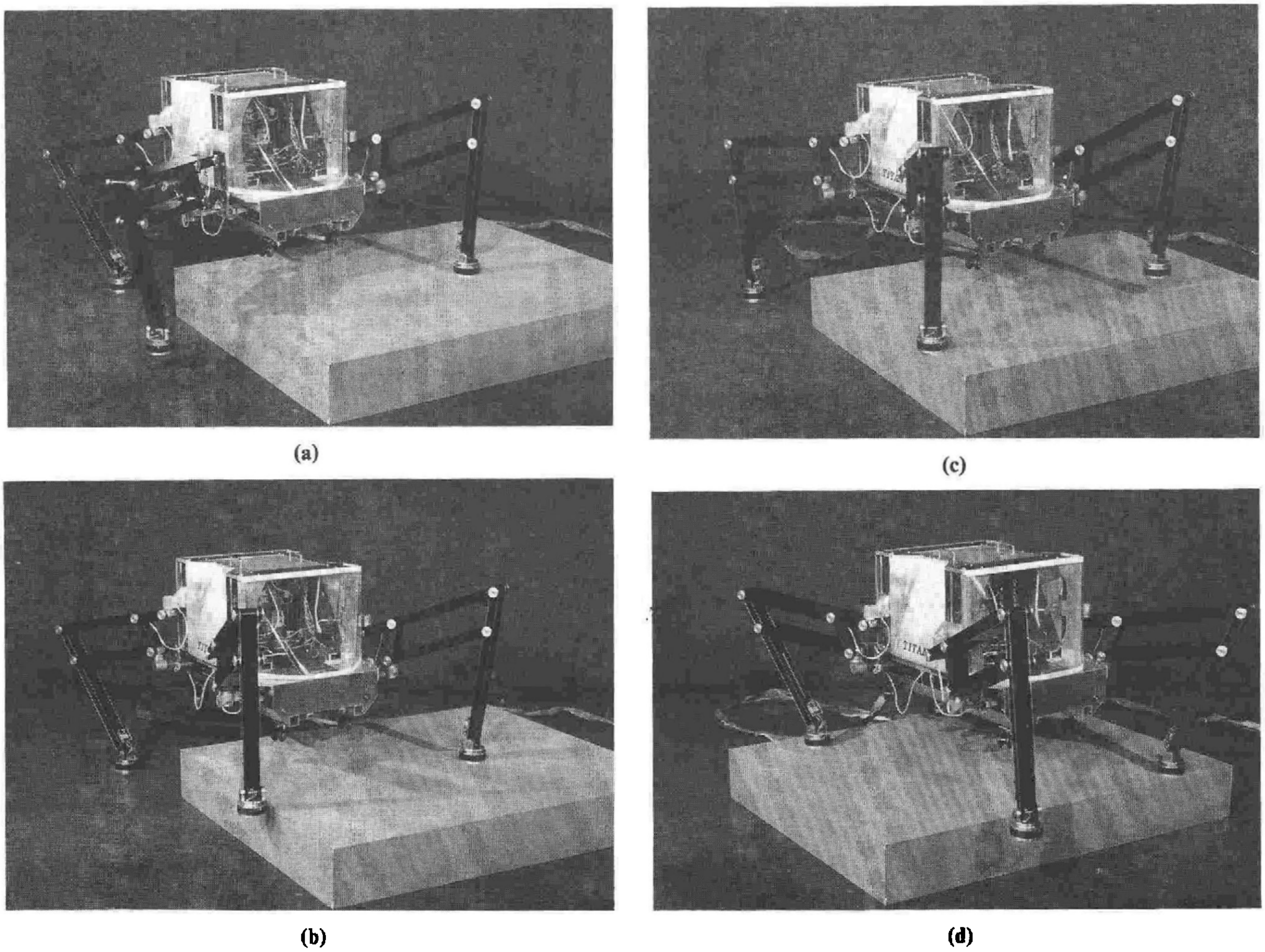

Fig. 1. The quadruped walking vehicle model TITAN III (Hirose et al. 1984). The vehicle is walking over a step with the crab walk angle $\alpha = 30°$. The vehicle automatically selects optimal gait while maintaining static stability and negotiating the irregular terrain by using whisker type proximity sensors around the feet.

as much as possible, because these merits are very significant. When the walking environment has inclination exceeding certain degree, however, the gait mentioned above can no longer adapt to the inclination. On this account, a quadruped walking vehicle that is expected to be applicable as a general "moving platform" in an extreme circumstance should prepare its gait for walking over a steep environment, such as stairways, by positively tilting its body.

The idea of regarding the reachable range to be a rectangular prism as stated in (2) was based on the prerequisite that the 3-D pantograph leg mechanism made a motion of three-axial Cartesian coordinates system. A walking vehicle in general, however, is supposed to have a variety of reachable ranges, depending on such factors as leg mechanism and interferences between legs and body or among legs. Therefore a future gait-determining method should be able to cope with various reachable ranges.

The condition of (3) was simply introduced for the purpose of maintaining the symmetry of the foot trajectories. When a generalized reachable range is assumed and body is allowed to incline, the reachable range with respect to the body coordinates will be asymmetric. Accordingly, it is insufficient to simply put the standard point C_i at the center of the horizontal reachable area.

To summarize the above, the studies so far presented did not shed light on methods to produce generalized standard foot trajectories capable of coping

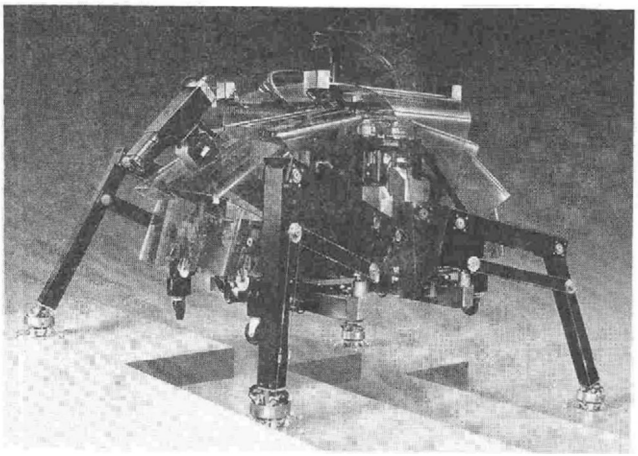

Fig. 2. TITAN IV, a model modified for demonstration at the Tsukuba Science Exposition in 1985. It walked about 40 km in total during the exposition period on the stage with stairs. Thereafter its performance was further improved so as to make dynamic stable walk (Hirose et al. 1989).

with free posture and arbitrary reachable ranges, in spite of the vital importance of establishing such methods for improving the land adaptability of a walking vehicle. Several important works have reported on the investigation of multi-legged walking vehicles (McGhee and Frank 1968; McGhee and Iswandhi 1979; Song and Waldron 1989). Nevertheless, systematic researches on gait control have not been made, nor has a method of producing generalized standard foot trajectories been determined. Accordingly, this article will at first discuss the creation of generalized standard trajectories (section 2), introduce a new concept named "diagonal triangle exchange" (DTE) (section 3), present a method for producing generalized standard trajectories in due order (section 4), and finally, demonstrate the validity of the method by simulations (section 5).

2. Preparation

Basic prerequisites and concepts are presented for developing generalized standard foot trajectories.

2.1. The Walking Vehicle and Its Coordinates

The object walking vehicle is assumed to have arbitrary reachable ranges for its four legs, as shown in Figure 4. Its body has the body coordinates $\Sigma(G_{xyz})$, and the walking environment has the absolute coordinates $\Sigma_0(Gx_0y_0z_0)$ in which z_0 is designed to agree with

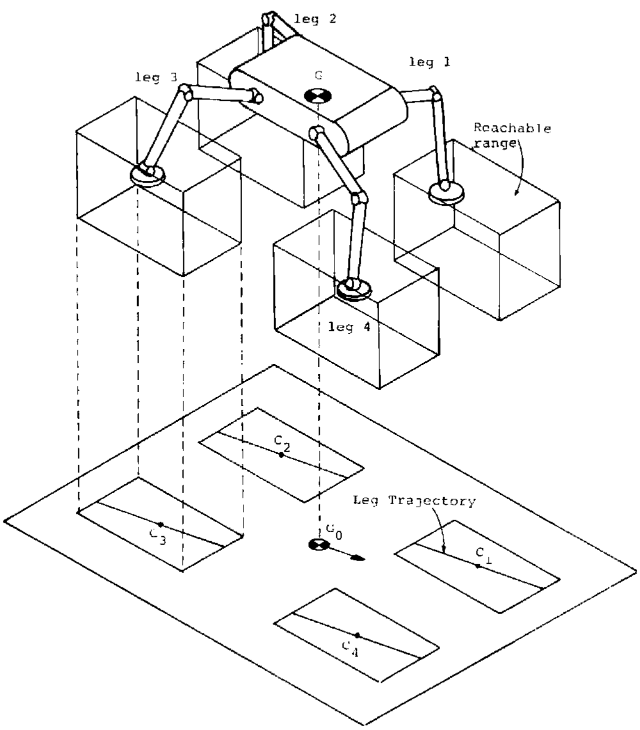

Fig. 3. Quadruped walking vehicle and its posture, assumed in authors' previous works.

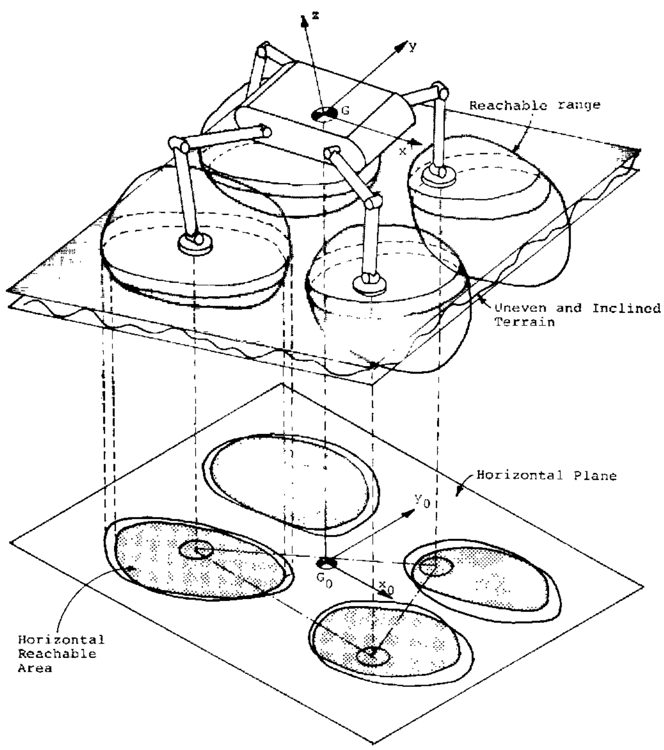

Fig. 4. Assumed model of the terrain, quadruped walking vehicle, and its motion. Projections on the horizontal plane are also shown.

the gravitational direction. Those coordinate systems are in the following relations: At first, the body coordinates Σ are in the state agreeing with the absolute coordinates Σ_0. Then they tilt around the x_0 axis of the absolute coordinates by a rolling angle Φ_r and subsequently tilt around the y_0 axis of the absolute coordinates by a pitching angle Φ_p. The body is in the posture after rotating as above (Hirose 1987). The coordinate transformation matrix **A** is

$$\mathbf{A} = \mathbf{E}^{j\phi}{}_p \mathbf{E}^{i\phi}{}_r \tag{1}$$

where

$$\mathbf{E}^{j\phi}{}_p = \begin{bmatrix} \cos\phi_p & 0 & \sin\phi_p \\ 0 & 1 & 0 \\ -\sin\phi_p & 0 & \cos\phi_p \end{bmatrix},$$

$$\mathbf{E}^{i\phi}{}_r = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_r & -\sin\phi_r \\ 0 & \sin\phi_r & \cos\phi_r \end{bmatrix}.$$

As the rotation is designed in such order, the positive projection of the x-axis of the body coordinates on the absolute coordinates x_0y_0 plane agrees with the x_0 axis of the absolute coordinates.

2.2. *Horizontal Reachable Areas*

Horizontal reachable areas should be introduced on the x_0y_0 plane first for locomotion on inclined and uneven surfaces. The idea is shown in Figure 4. The upper and lower limits of the walking surfaces are model-represented by two planes for the areas in the reachable ranges. The gap between the two planes corresponds to the amount of the surface irregularity. A stairway is represented by model planes consisting of two parallel planes passing the upper and lower edges of a step. Accordingly, whenever the vehicle walks on a slope, the supporting and landing points of each foot are always between the two planes. The horizontal reachable areas to be used for gait determination are defined to be the common part of reachable areas made by projecting the section of the reachable range sliced by the upper and lower planes on the absolute coordinates x_0y_0.

This method of setting the horizontal reachable area does not necessarily include all the practically possible areas. Nevertheless, it can select the important areas for gait determination, and the said areas are assured of selectable landing positions.

2.3. *Gait*

The walking vehicle is assumed to make a static walk in crawling gait. It is represented as $1 > \beta > 0.75$ of the duty factor (the ratios of time of each foot in the supporting phase against one cycle time) (McGhee and Frank 1968). It has already been discussed that some modification of the static gait plan could realize dynamic locomotion (Hirose et al. 1989). Therefore the investigation based on such a premise can be applied to gait determination of $1 > \beta \geq 0.5$ ranging from a crawling gait to a trotting gait.

The center of gravity of the body is assumed to move at a constant speed. The stroke length of the foot trajectory in the horizontal reachable ranges is set to be λ^*. The walking vehicle is considered to walk in a "crab gait" (Hirose, Fukuda and Kikuchi 1986), in which the walking direction makes a random crab-walking angle α against the mechanical front of the walking vehicle in the x_0y_0 plane.

2.4. *Static Stable Conditions and Their Analysis*

The static stable conditions of a quadruped walking vehicle are given by the positional relations of the supporting feet and the center of gravity in the gravitational field. More specifically, as shown in Figure 4, the projection point G_0 of the body's center of gravity G on the absolute coordinate x_0y_0 plane (horizontal plane) should always remain within the polygon formed by the supporting feet's (feet 1, 3, and 4 in Figure 4) projection points on the same x_0y_0 plane. For this purpose, to determine the gait of an arbitrary tilted posture on an inclined terrain, the body's center of gravity and the foot coordinates should first be transformed from the body coordinates to the absolute coordinates by means of equation (1) to obtain the "x_0y_0 gait" on the x_0y_0 plane. Subsequently, the "z_0 gait" on the z_0 axis should be obtained, taking account of the inclining degree of the terrain. They should be all returned to the body coordinates to compose the gait command.

2.5. *Evaluation Criterion*

The evaluation criterion at the gait determination is the maximization of the stroke length of each foot. As the crab walk is premised, the four feet are supposed to have an equal stroke length, which should be maximized. The longer the stroke, the relatively shorter the acceleration/deceleration time for leg swing. Thus the maximization of the stroke length of each foot may be regarded as the evaluation criterion for increasing the locomotion speed.

3. Introduction of the DTE Point

To create the generalized foot trajectories, the new concept of the diagonal triangle exchange (DTE) point is introduced. In the crawling gait, a walk is continued by repeating the successive exchange of the supporting foot triangle, with the body's center of gravity being kept within each triangle. The DTE point to be introduced here is the position of one set of feet composing the contact side with the adjacent supporting foot triangle at the time when the supporting foot triangles are switched without overlapping.

DTE is explained showing an actual case in Figures 5 and 6. This is a case of crawling gait at the crab-walking angle $\alpha = 0°$, duty factor $\beta = 0.80$. Figure 5 shows the walking manner of the half cycle of a crawling gait from time t_1 through t_5. The $t_1 \sim t_2$ is a three-leg supporting phase, with the first leg being free. The $t_2 \sim t_4$ is a four-leg supporting phase. The $t_4 \sim t_5$ is another three-leg supporting phase, with the third leg being free.

Figure 6 shows the same walking pattern observed from the body coordinates. The $t_1 \sim t_5$ of Figure 6 shows the positions of the foot-tips of Figure 5 at the same time. The $t_6 \sim t_8$ show the positions of the foot-tips corresponding to the remaining half cycle. The DTE point in this walk exists at the position of time t_3 in the first half of the cycle (shown in Figure 5) while

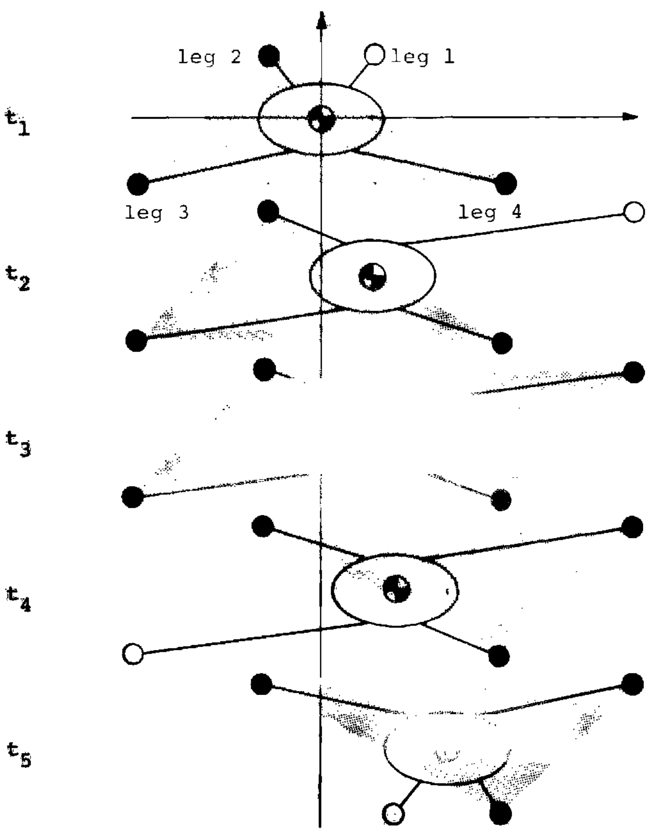

Fig. 5. Walking motion in the crawl gait ($\alpha = 0$, $\beta = 0.8$) observed from absolute coordinates.

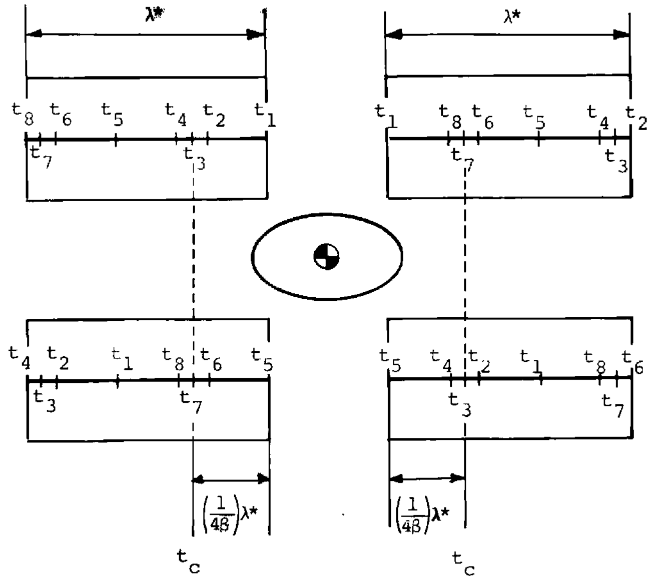

Fig. 6. Foot trajectory of the crawl gait ($\alpha = 0$, $\beta = 0.8$) observed from body coordinates.

feet 2 and 4 make the connecting side feet. In the later half of the cycle, the position of time t_7 is the DTE point, and feet 1 and 3 are the connecting side legs. The time at which these two diagonal triangles are exchanged is named the DTE time t_c in common. The foot positions in the stroke at the DTE time t_c are, as shown in Figure 6, $(1/4\beta)\lambda^*$ respectively from the rear edge of the stroke for the front legs and from the front edge of the stroke for the hind legs.

In standard foot trajectories, the first requirement is that the individual trajectories have the same length and direction. These are introduced from assuming a crab walk with crawl gait. At the same time, a second condition must also be satisfied: the body's center of gravity G should be located on the straight line linking the connecting side legs at the DTE point. This condition is introduced from the definition of the DTE point and the connecting side legs. Seeing the geometric relation between the center of gravity of the vehicle and the foot trajectories from the body coordinates, as shown in Figure 6, may aid in understanding this requirement. The concept of the DTE point is an important basis with which to introduce the generalized standard trajectories in view of providing the trajectories of the feet at the diagonal positions.

4. Introduction of Generalized Standard Foot Trajectories

The proposed introduction method involves (1) projecting the gait scheme on a horizontal plane, (2) setting effective searching areas, (3) setting the walking type, (4) producing stroke contours, (5) selecting the longest stroke, and (6) determining the foot trajectories. The procedure will be specifically presented based on a walking vehicle model having arbitrary reachable ranges, a crab-walking angle $\alpha = 6°$, and a duty factor $\beta = 0.75$.

4.1. Projection of the Gait Scheme on a Horizontal Plane

The horizontal reachable ranges, landing positions, and the position G_0 of the center of gravity projected on the x_0y_0 plane are obtained first as illustrated in Figure 4.

4.2. Setting Effective Searching Areas

The effective searching areas can be selected by the DTE point from the relations of the center of gravity G_0 with the horizontal reachable areas of individual feet. The areas are some domains of the horizontal reachable areas of the object foot. The domains should satisfy the condition in which a straight line passing the center of gravity G_0 from any point in the domains crosses the diagonally located horizontal reachable areas. The effective searching areas exemplified in Figure 7 are the shadowed areas in Figure 8*A*.

4.3. Setting the Walking Type

Possible patterns of the crab-walking gait are classified into types x, y or xy, based on the effective searching ranges and crab-walking angle α. (Hirose, Fukuda and Kikuchi 1986; Hirose, Kikuchi and Umetani 1986).

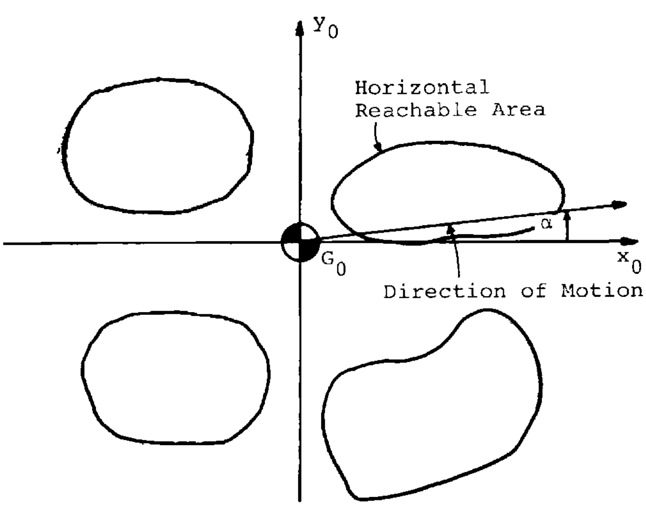

Fig. 7. Model reachable area on horizontal plane.

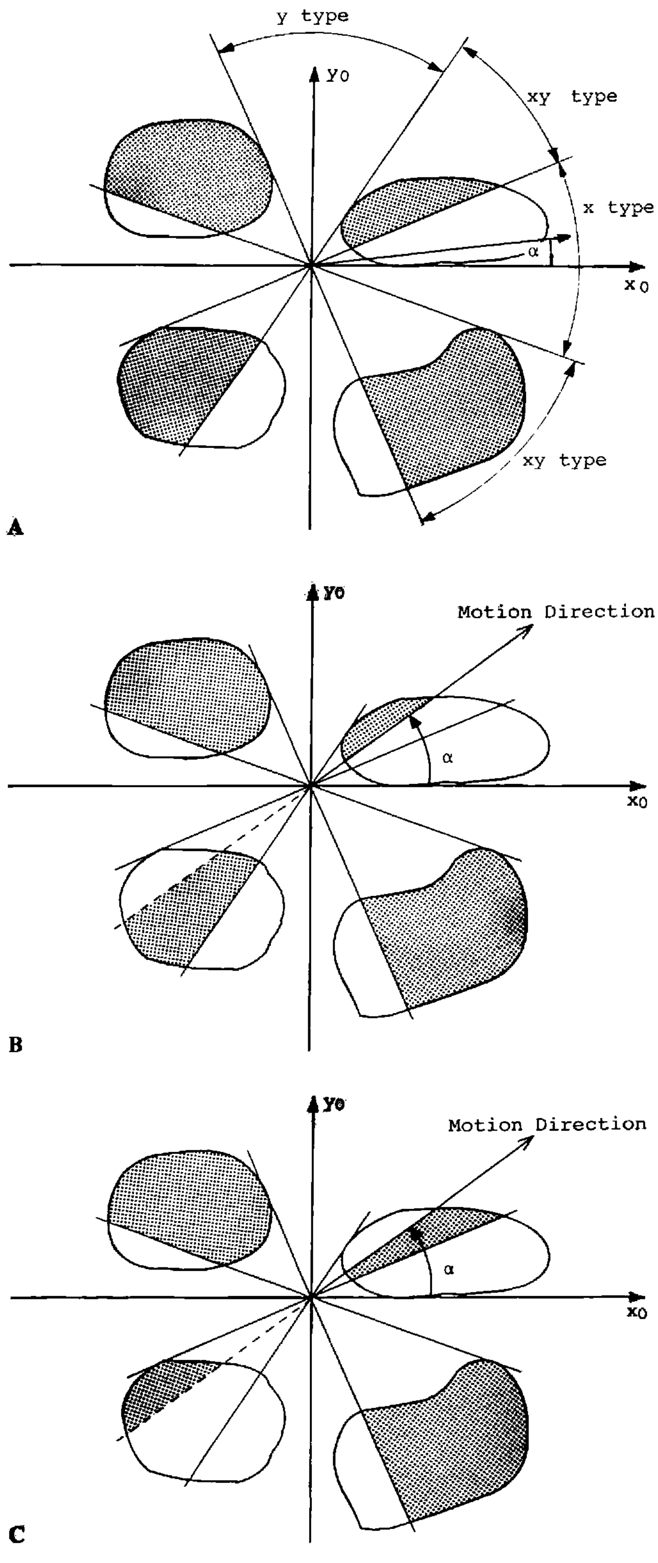

Fig. 8. Definition of effective searching area. A, *Effective searching area and crab walk to be selected as a function of crab angle.* B, *Effective searching area for x type crab walk.* C, *Effective searching area for y type crab walk.*

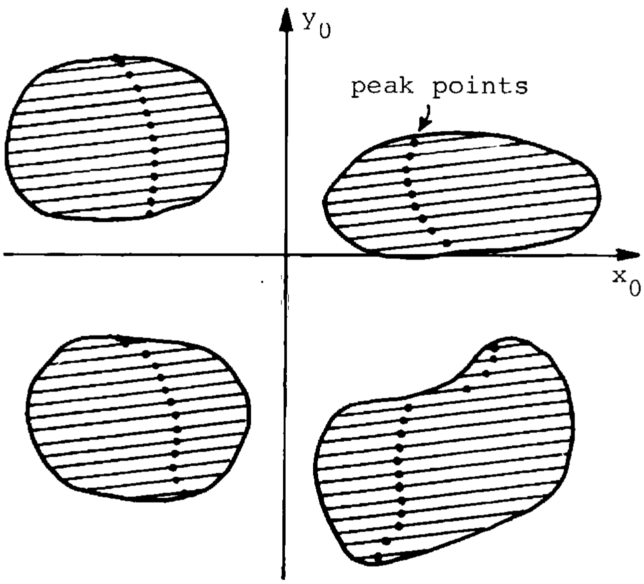

Fig. 9. Foot trajectories and corresponding diagonal triangle exchange points with the longest stroke.

The classified results are written in the peripheral parts of Figure 8*A*. The areas stated as the type *xy* indicate the moving direction that can choose both types *x*- and *y*-directed crab-walking gait. Selection of which type, *x* or *y*, in the type *xy* area depends on the possibility of generating longer stroke after "introducing the longest stroke," as stated later, at each crab-walking gait. When type *x* crab-walking gait is chosen in the type *xy* area, the effective searching areas are as shadowed in Figure 8*B*. When type *y* is selected, the effective searching areas are as shadowed in Figure 8*C*. In Hirose, Fukuda, and Kikuchi's (1986) study, the possible searching domain of the swing leg foothold within the reachable area was prescribed by three rules: domain-prescribing method I, which is only applied for the hind swing leg, is to guarantee the takeoff of another hind leg two steps later; domain-prescribing method II, which is also applied for the hind swing leg, is to guarantee the takeoff of the front leg in the next step; and domain-prescribing method III, which is applied for all swing legs, is to arrange the front and hind legs in symmetry to the direction of motion. The walking type–setting procedure introduced in this section is said to be a more generalized method of domain-prescribing method III.

4.4. Production of a Stroke Contour Graph

When possible DTE points exist at all points on the effective searching area of each foot, the longest possible stroke is introduced, and the contour graphs are formed based on the stroke length. The procedure is explained in Figure 9. Plural trajectories oriented toward the direction of crab-walking angle $\alpha = 6°$ within the horizontal foot–reachable areas are shown by solid lines in the figure. Let the length of the foot trajectory be represented by λ; the black marks are given as the points that divide the individual trajectories at the ratio of $(1/4\beta)\lambda : \lambda - (1/4\beta)$, from the rear end of the reachable range for the front legs and from the front end of the same for the hind legs. As the condition is assumed to be $\beta = 0.75$ in Figure 9, each marked point divides each trajectory at 1 : 2. The marks indicate the positions of the DTE point possible to make the strokes longest when the foot trajectories, shown by solid lines, are selected. The stroke length is restricted by the left boundary of the reachable areas when the DTE point is on the left side of the marks and by the right side boundary when it is on the right side.

If the DTE point is assumed to be selected in the whole areas of the effective searching areas by this approach, the stroke length possibly secured at the selected DTE point is obtained. Consequently, the stroke mountain is formed by erecting those stroke lengths at individual DTE points along the z_0-axis. Figure 10 shows such stroke mountains indicated by the stroke contour graphs.

4.5. Selection of the Longest Stroke

The longest stroke is to be chosen using the stroke mountains in the procedure as follows:

1. The effective searching areas are sliced by the plane of yoke angle θ, including the z_0-axis as

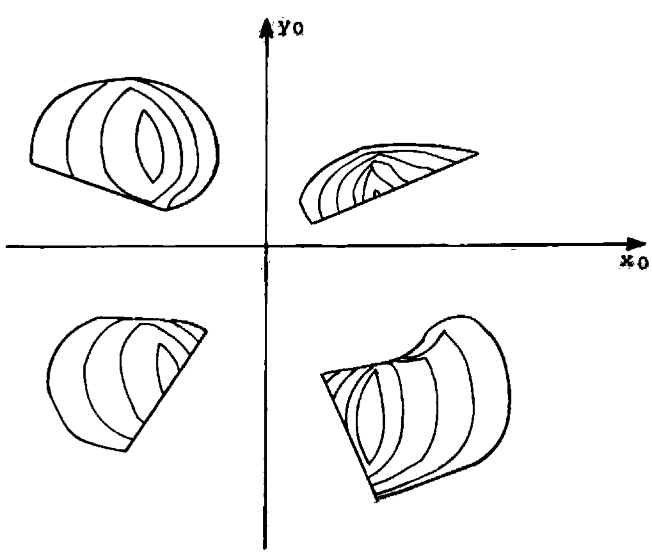

Fig. 10. Stroke contour map effective searching area.

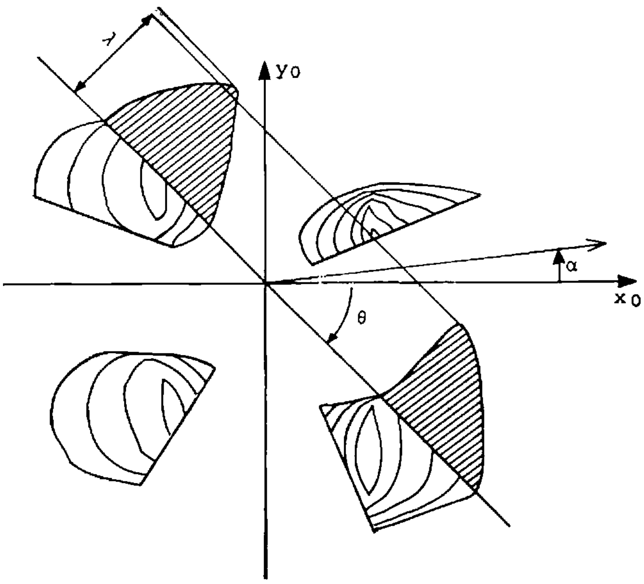

Fig. 11. Cross section of stroke contour along yoke angle θ.

shown in Figure 11. In Figure 11, the stroke mountains of feet 2 and 4 are sliced and the cross sections are represented by hatching.

2. All the feet should have the same stroke length. Thus peaks of both sections are compared, and the smaller peak with height λ^* in the figure is chosen as the practically feasible stroke candidate.
3. The effective searching areas of feet 2 and 4 are all chosen by changing the yoke angle θ of the section plane. The longest stroke thus selected is the practically feasible longest stroke between feet 2 and 4.
4. The longest stroke between feet 1 and 3 is obtained by the same manner.
5. The above-mentioned two strokes obtained in (3) and (4) are compared, and the smaller one is determined as the longest stroke λ^* in this walking type.

4.6. Determination of Foot Trajectories

The area in which DTE points higher than the determined longest stroke λ^* exist are sliced out of the stroke contour graph. The cutout areas are shown in Figure 12. In this situation, the foot trajectories exist as shown in Figure 13. In the example, the DTE point of feet 1 and 3 is only a point. When the yoke angle of the connecting side legs (shown by broken line in Figures 12 and 13) is revolved positively from the state, the stroke of foot 3 is elongated while the stroke of foot 1 is shortened. When it is revolved negatively, the stroke of foot 1 is elongated and that of foot 3 is shortened. Therefore the state of Figure 13 produces the longest foot trajectory.

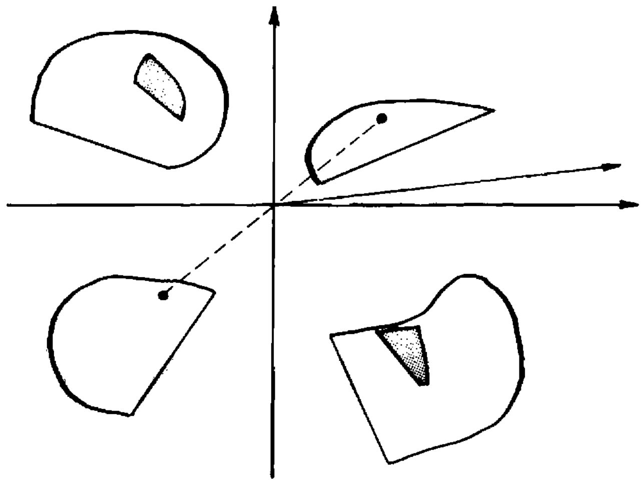

Fig. 12. Domains where the diagonal triangle exchange points have the longer stroke than the maximum stroke λ^*.

As regards feet 2 and 4, their foot trajectories may take up any positions within the selected areas if only the conditions of the DTE point are satisfied. Usually the trajectories are selected so as to satisfy the symmetric relation with respect to the trajectories of feet 1 and 3.

The preceding is the method for introducing the generalized standard foot trajectories.

5. Results of Simulation

The case exemplified in Figure 7 can be generalized so that foot trajectories can be produced by the same

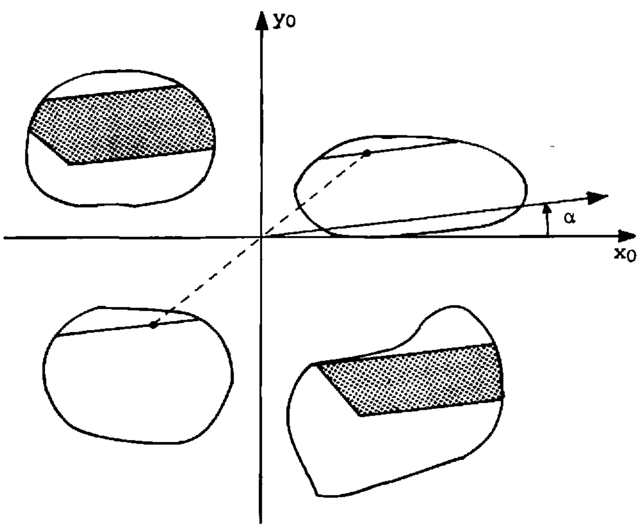

Fig. 13. Foot trajectory existing area.

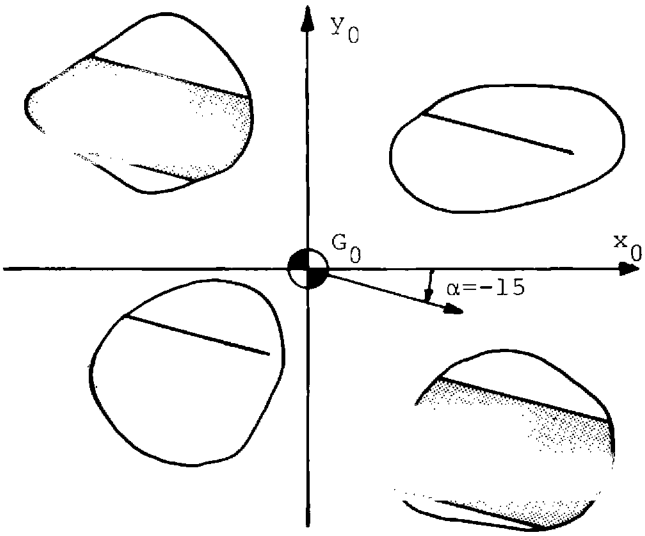

Fig. 14. Another example of selecting optimum foot trajectories. (crab angle $\alpha = -15°$).

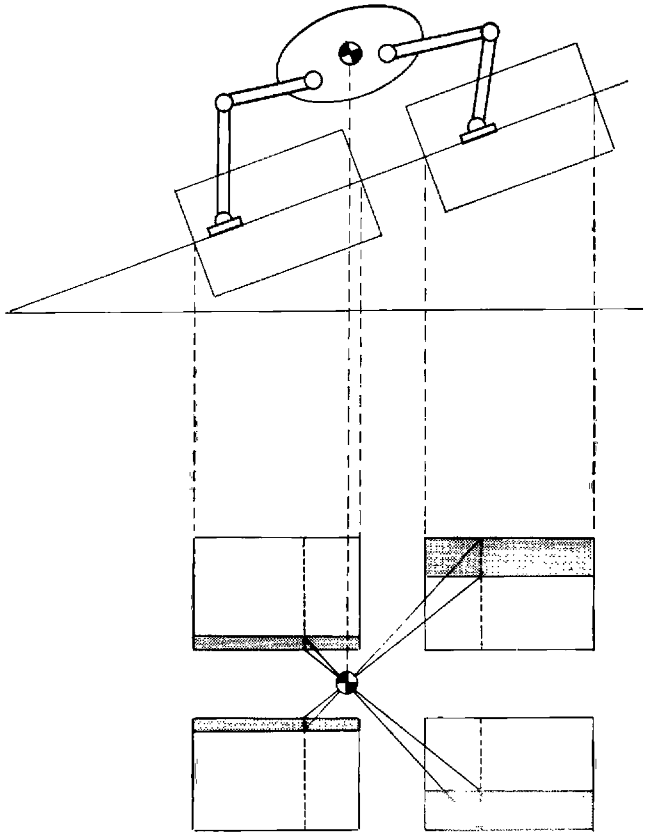

Fig. 15. Selection of the optimum foot trajectories in slope-climbing motion.

procedure for almost all the other cases. This section will additionally present two simple examples only. Figure 14 shows the foot trajectories of a walking vehicle having horizontal reachable areas and a crab-walking angle α different from the case of Figure 7.

In Figure 15, a walking vehicle having reachable ranges of a rectangular prism is climbing up a slope in a tilted posture at a crab-walking angle of $\alpha = 0°$. In this case, the trajectory-existing areas form a layout in which the uphill feet are open toward the y direction as shadowed while the downhill feet are closed. The foot arrangement forms a reversed trapezoid as shown in Figure 15. We have noticed in preliminary research the importance of this type of gait in slope walking and have named it a "reversed trapezoid gait" (Hirose and Kunieda 1986). Thus the technique proposed by this article proves to have general applicability to generating gaits in any situations, including special cases requiring reversed trapezoid gait.

6. Conclusions

This article has discussed a foot trajectory-generating method for a quadruped walking vehicle having arbitrary reachable ranges when it walks on uneven and inclined surfaces in a random posture. It has introduced a generalized trajectory-producing method to be carried out through (1) projection of the gait scheme on a horizontal plane, (2) setting of the effective searching areas, (3) selection of walking types, (4) generation of stroke contour maps, (5) selection of the longest stroke, and (6) determination of foot trajectories. The validity of the proposed method is verified by computer simulations.

The proposed method is considered to have general applicability and to be effectively usable for forming the gait control system of a quadruped walking vehicle designed in various types of leg mechanism. We intend in future studies to emphasize real-time characteristics and more simplified operations.

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