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Quadruped Free Gait Generation Based on the Primary/Secondary Gait

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SUMMARY

A free gait algorithm is proposed utilizing a new method of gait generation called *primary/secondary gait*. The primary gait is a fixed sequence of leg transfers with modified leg-end kinematic limits according to the obstacle presence, while the secondary gait is a flexible gait which is generated to adjust the leg-end position. The primary gait is generated considering the following four constraints: stability constraint, kinematic constraint, sequential constraint and neighboring constraints. Primary gait parameters are modified by the influence of the obstacle. Normally, the machine tends to move with the primary gait. When the primary gait cannot move the vehicle, the secondary gait is adopted to serve as a complement of the primary gait. With the proposed primary/secondary gait, it is expected to improve the efficiency of free gait generation while maintaining the mobility of the vehicle. Simulation results are given to demonstrate the efficiency of the proposed methodology.

KEYWORDS: Free gait; Walking machines; Primary/Secondary gait.

1 INTRODUCTION

Every walking machine moves according to a certain gait. There are two main types of gaits adopted in walking machines: periodic and non-periodic. In periodic gaits the feet are lifted and placed according to a fixed pattern. Walking machine's periodic gaits can be easily controlled and vehicles can move with optimal static stability margin.[1–3] However, the periodic gaits can only be used on a relatively flat terrain. On the other hand, non-periodic gaits are "free" in the sense that a pre-planned sequence of leg-end transfer is not required. For free gaits, the foot transfer is controlled by a set of rules which take the actual motion conditions into account and determine the next support pattern of the feet using certain criteria. The terrain adaptability of a walking machine could be increased by improving the gait generation.

There are several algorithms of free gait generation developed in the past. McGhee and Iswandhi[4] developed a partially heuristic algorithm for free gait planning. In their rule-based searching algorithm, the lifting and placing of legs are determined, so that the stability is maintained and the minimum kinematic margin over all legs is maximized. Hirose et al[5] proposed a so called "convergence to standard type free gait" in which the efficiency of gait generation was improved in two ways: first the standard pattern of regular gait was adopted for walking in relatively flat terrain; secondly the search was started from "search-initiating point". Pal and Jayarajan[6] used the heuristic graph search $A*$ algorithm to generate a straight line free gait for a quadruped. No rules/principles are used when selecting the transferring foot and its position. Free gait is generated through a graph search with a cost function. Salmi and Halme[7] developed a reasoning-based algorithm for a six-legged walking machine. In this algorithm, the machine state, described by a six dimensional time vector called Leg Phase State (LPS), is checked and predicted in every planning cycle. The leg with the smallest kinematic margin is lifted in the planning interval according to the stability requirement. The algorithm consumes a rather short computational time.

In this paper, we developed a free gait algorithm with a new mode of gait generation, called *primary/secondary gait*. The primary gait is a dominating gait that can be used for most of the walking conditions, while the secondary gait is used only when the vehicle cannot move with the primary gait. Four constraints were elaborated to narrow the searching scopes for gait parameters. With the proposed primary/secondary gait, the number of possible choices is greatly decreased and the efficiency of gait generation will then be improved.

2 MACHINE MODEL

As shown in Figure 1, the statically stable quadruped with legs numbered in an anti-clockwise manner is considered here. The machine moves in a straight line along the X direction, with the speed v_c,

$$v_c = k_v v, \quad k_v \in \langle -1, 1 \rangle, \tag{1}$$

where v is the nominal walking speed, k_v is a speed factor to be determined. A negative k_v implies a backward movement.

3 CONCEPTS INVOLVED IN THE ALGORITHM

3.1 Primary gait

The *primary gait* is a fixed sequence of leg transfers with modified leg-end kinematic limits according to the obstacle presence. The sequence selected for the primary gait should have a reasonable long static stability margin. It is well

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known[2,3,5,8,9] that wave gait has an optimal static stability margin. Results of gait analysis given in reference [8] are utilized for the proposed gait description. Three types of gait with high static stability, namely: *X* type, *Y* type and *O* type, are considered. The *X* and *Y* gait types shown in Figure 2 are suitable for the straight line motion in *X* and *Y* direction respectively, while the *O* gait type is suitable for circular motion. When walking machine moves forward in a straight line along *X* direction, the stability margin could be maximised by using the *X* type of gait.[9] Therefore we take this gait as the primary gait for gait planning.

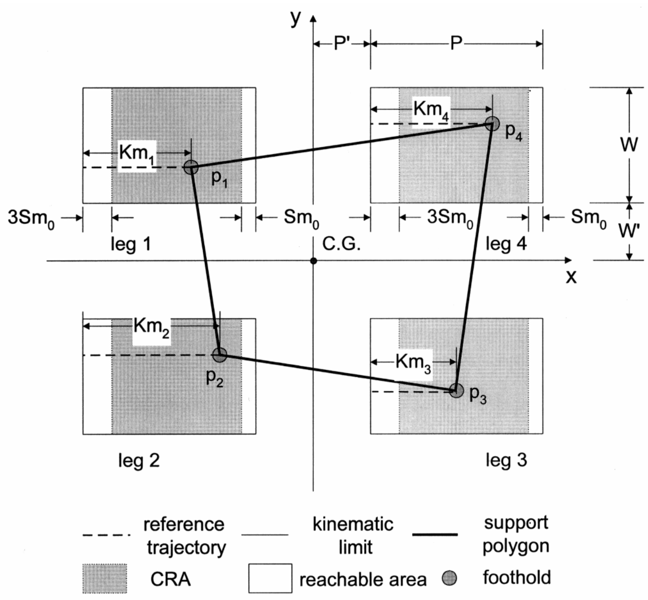

Fig. 1. Quadruped representation for gait analysis.

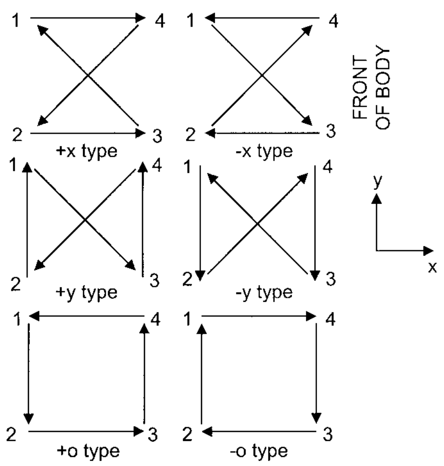

Fig. 2. Three types of leg sequences.

3.2 *Secondary gait*

The *secondary gait* is a flexible leg transfer sequence which is generated by searching with an aim to adjust the leg-end position when the primary gait fails to move the vehicle. As shown in Table I, the searching path is predefined for each leg. Two rules were applied to select the path:

(i) The path with minimum number of leg transfers is selected first. This will minimize the number of legs affected by the secondary gait.
(ii) If two or more paths have the same number of transferred legs, among these paths the one partly coincident to the primary gait is selected later than others. The reason lies in that this path is more likely failed in finding a solution since the leg transfer sequence has failed to move the vehicle in the primary gait.

The searching tree is generated based on these selected paths. Using the Depth-First strategy, the tree is searched to lift the leg with the shortest kinematic margin (Km_0) and to place it in its constrained reachable area (CRA). The goal state is that all the legs are in the CRA.

3.3 *Minimum stability margin* (Sm_0)

Every statically stable machine must maintain stability margin greater than zero to keep the static stability, the margin includes the possible errors in the data of displacement sensors and dynamic effects which are ignored in statically stable gaits synthesis. This stability margin is so called *minimum stability margin* (Sm_0). With the minimum stability margin, the stability criteria for a walking machine is:

$$Sm \geq Sm_0. \tag{2}$$

3.4 *Constrained reachable area (CRA)*

Every leg has a reachable area which results from its construction constraints. All the placement of legs and their

Table I. Searching path for the secondary gait

Transferred leg	Leg with Km_0	Searching path
1	2	[1–2], [1–3–2], [1–4–2], [1–4–3–2]
	3	[1–3], [1–4–3], [1–2–3]
	4	[1–4], [1–3–4], [1–2–4], [1–2–3–4]
2	1	[2–1], [2–4–1], [2–3–1], [2–3–4–1]
	3	[2–3], [2–4–3], [2–1–3], [2–1–4–3]
	4	[2–4], [2–1–4], [2–3–4]
3	1	[3–1], [3–4–1], [3–2–1]
	2	[3–2], [3–1–2], [3–4–2], [3–4–1–2]
	4	[3–4], [3–2–4], [3–1–4], [3–2–1–4]
4	1	[4–1], [4–3–1], [4–2–1], [4–3–2–1]
	2	[4–2], [4–1–2], [4–3–2]
	3	[4–3], [4–1–3], [4–2–3], [4–1–2–3]

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motion relative to the body must be within this area (the $P \times W$ rectangle in Figure 1). To guarantee the generation of primary gait, a new kind of leg-end placing area or *constrained reachable area* (CRA) is introduced. As shown in Figure 1, the CRA (shadowed area) is defined as a rectangular area on the intersection of the support plane and the leg-end kinematic working volume. In Figure 1, the distance from the outside of the CRA to the reachable area in the forward direction equals to Sm_0, while in the backward direction it is $3Sm_0$. They are the minimum values to avoid deadlock at the beginning of the motion.

3.5 *Initial state*

At the start of a walk an *initial state* is provided for the walking machine. The initital state here refers to the state that all legs are randomly placed on the ground within their CRA. For a machine in an initial state at least one leg could be selected to be first lifted with the primary gait. Another situation of the initial state appears at the moment when an adjustment with secondary gait is successfully finished.

4 CONSTRAINTS OF GAIT GENERATION

Specially considered constraints could effectively narrow ranges of gait parameters to be searched. Four constraints are considered when generating free gait in our algorithm: the stability constraint, kinematic constraint, sequential constraint and neighboring constraints. Of these constraints the former two constraints are essential for all static stable gait, while the latter two are suitable only for primary gait.

4.1 *Kinematic constraint*

The kinematic constraint affects the leg motion in two ways. When a leg in the air should be placed, the placing position must be within its reachable area. On the other hand, the supporting leg must be lifted before it reaches the limit of this constraint. Let $p_i(x_i, y_i)$, $(i \in \{1, 2, 3, 4\})$ be the i-th leg-end's position which is expressed in a planar frame with origin at the projection of the center of gravity of the vehicle (see Figure 1). Let S_p be such a subset of all possible values of p_i which consists only from the states which are in reachable area. To fulfill the demand of proper placing position it must be: $p_i \in Sp$. Since Sp varies with the shape of reachable area and is not related directly to the motion, it would be convenient to describe kinematic constraint using the meaning of *kinematic margin*. The kinematic margin of a supporting leg is the distance measured from the support point to the boundary of a preset kinematic limit opposite to the motion direction (see Figure 1). When the walking machine moves in straight line, such a constraint can be described as:

$$0 < Km_i \leq Km_{max}, \quad i \in \{1, 2, 3, 4\}, \tag{3}$$

where Km_{max} is the maximum value of the kinematic margin.

4.2 *Stability constraint*

It was stated that for statically stable machines the static stability margin Sm must be greater than the minimum stability margin Sm_0 (see equation (2)). Here Sm takes the meaning of the longitudinal stability margin. Let L_{ij} be the line joining a pair of footholds p_i and p_j, and $D(L_{ij})$ be the projection of the segment located between the center of gravity and line L_{ij} on the support plane and oriented along the motion direction. The stability margin can be determined by

$$\begin{aligned} Sm &= min\{|D(L_{12})|, |D(L_{34})|\}, \text{ if four legs in support} \\ &= min\{|D(L_{ij})|, |D(L_{ik})|\}, \text{ if three legs in support,} \quad (4) \end{aligned}$$

$(i, j, k \in \{1, 2, 3, 4\}, j, k \neq i$, and $j \neq k$,

the i-th leg is on opposite side of the body other than j-th, k-th legs.).

Assumption that the stability criteria can always be met when four legs are on the ground implies that both $|D(L_{12})|$ and $|D(L_{34})|$ are greater than Sm_0. Therefore we can consider only the case of three supporting legs, and further evaluate only the static stability margin corresponding to the pair of diagonally opposite legs. Let leg i and leg j be the pair of legs diagonally opposite when three legs are in support. The static stability margin is

$$Sm = |D(L_{ij})|. \tag{5}$$

In a straight line motion, $D(L_{ij})$ can be calculated by

$$D(L_{ij}) = \frac{y_i x_j - y_j x_i}{y_i - y_j}. \tag{6}$$

Taking into account the difference between the rear legs and fore-legs, the stability constraint could be evaluated by

$$\begin{aligned} &\frac{y_i x_j - y_j x_i}{y_i - y_j} > Sm_0, \text{ when a fore-leg to be lifted;} \\ &\frac{y_i x_j - y_j x_i}{y_i - y_j} < -Sm_0, \text{ when a rear leg to be lifted;} \end{aligned} \tag{7}$$

4.3 *Sequential constraint*

During locomotion, the vehicle center of gravity will cover some distance in each step. Suppose the minimum value of this distance for a single step m is d_m. If it takes n steps for a machine changing from leg i in the air to leg j being lifted, the minimum distance covered by the center of gravity in these n steps is

$$Cq_j(i) = \sum_{m=1}^{n} d_m. \tag{8}$$

For a step from the placement of a fore-leg to the lifting of its diagonally opposite one, $d_m = 2Sm_0$. In other cases, $d_m = \delta d$, where δd is a small value of moving distance of the vehicle.

When the primary sequence is adopted, it is clear that the position of any supporting leg should not exceed the reachable area until the moment of leg-lifting according to

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the gait sequence. This constraint is expressed in terms of kinematic margin as:

$$Km_j \geq Cq_j(i). \quad (9)$$

4.4 Neighboring constraints

Neighboring constraints are specially considered for rear legs. The constraints affect the gait of a rear leg in two aspects. Firstly a rear leg in the air must be placed on the ground in a time that the fore-leg in front of it will be able to transfer next. Otherwise, the stability constraint will never be satisfied for the lifting of the fore-leg, even if the rear leg in the air is placed at the foremost position. Such a constraint can be expressed as:

$$Km_j - v_c t_f \geq Km_j^*, j=3 \text{ or } 4, \quad (10)$$

where Km_j is the kinematic margin of front leg at the moment when the leg behind is starting to be lifted, t_f is the transfer time of the rear leg, while Km_j^* is the minimum value of kinematic margin corresponding to the foothold in the reference trajectory of the k-th leg. This foothold fulfills the minimum static stability margin when the diagonally opposite leg is placed at the foremost position (see the footholds on line III in Figure 3).

The second aspect that affects a rear leg is the position of the rear leg at the other side. When this rear leg, for instance Leg 2, is near to its kinematic limits ($Km_2 = 2Sm_0 + \epsilon$, ϵ is a small positive value), the rear leg in transfer (Leg 1) should be placed at such a position that this leg (Leg 2) could be lifted by primary gait in a shortest time. This constraint is expressed in terms of kinematic margin as:

$$|D(L_{ij})| \leq (Km_k - Sm_0), \ (i, k \in \{1, 2\} \text{ and } i \neq k, j = i+2). \quad (11)$$

This constraint is demonstrated in Figure 3 as line II is the boundary specified by $|D(L_{ij})| = (Km_k - Sm_0)$.

Substituting equations (6) into (11), we get:

$$\frac{y_i x_j - y_j x_i}{y_i - y_j} \leq (Km_k - Sm_0), \quad (12)$$

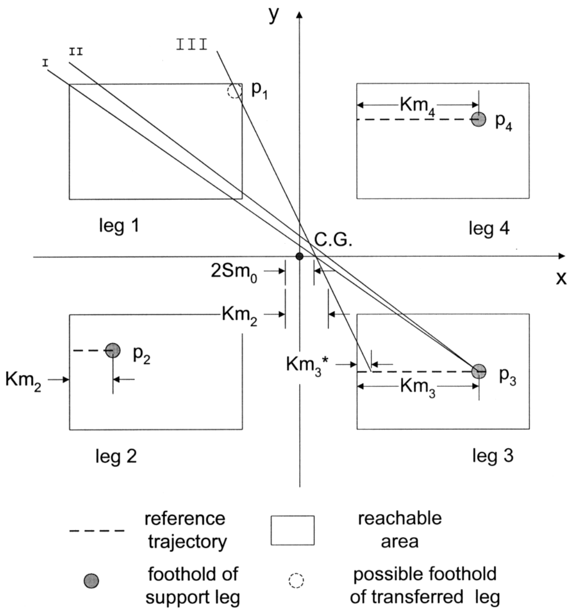

Fig. 3. The neighboring constraints.

in which x_i, y_i, x_j and y_j, are the coordinates of footholds p_i and p_j, respectively.

With all the above constraints, we can prove that a machine in the initial state can start to walk with the primary gait. The proof is given as follows:

Proof. For a machine initial state, the kinematic constraint can be naturally satisfied because all legs are within its own reachable area. When a fore-leg i has a kinematic margin $Km_i > 2Sm_0$, we can always find a landing position for its diagonally opposite leg j such that $|D(L_{ij})| > Sm_0$. A smaller $|D(L_{ij})|$ could also satisfy the constraint in equation (11). Therefore we can consider only the stability and sequential constraints. According to $D(L_{ij})$, two cases can be classified: $D(L_{ij}) > 0$ (Case 1) and $D(L_{ij}) \leq 0$ (Case 2).

At first, we calculate the maximum sequential constraint. It must be applied to the leg to be lifted three steps later. Using equation (8), we have:

$$Cq_j(i) = \sum_{m=1}^{3} d_m \leq 4Sm_0 + \delta d, \text{ when a rear leg } i \text{ is lifted} \quad (13)$$

and

$$Cq_j(i) = \sum_{m=1}^{3} d_m \leq 2Sm_0 + 2\delta d, \text{ when a fore-leg } i \text{ is lifted} \quad (14)$$

For Case 1, the machine will move backward by a distance Sm_0 at first and then lift a fore-leg i for which the stability constraint is satisfied. In such a state,

$$Km_j(t) = Km_j(t_0) + Sm_0, j \in \{1, 2, 3, 4\}, \quad (15)$$

where $Km_j(t)$ and $Km_j(t_0)$ are the kinematic margin of leg j before and after the movement adequately. It is known that $Km_j(t_0) > 3Sm_0$, so we obtain:

$$Km_j(t) > 4Sm_0. \quad (16)$$

Since $\delta d \approx 0$, the sequential constraint could be satisfied:

$$Km_j(t) > Cq_j(i). \quad (17)$$

The machine for Case 2 will move forward by a distance Sm_0 and lift a rear i-th for which the stability constraint is satisfied. Similar to Case 1, it can also be proved that the sequential constraint is satisfied for the rear leg to be lifted. Therefore, we can find in both cases the leg for which all constraints considered for the primary gait are satisfied. It is concluded that the machine in the initial state can start to walk with the primary gait.

5 PRIMARY GAIT GENERATION

The gait generation method includes a selection of gait model and the calculation of all gait parameters: the number (index) of the leg to be lifted, the placing position, the time when the leg is started to be lifted, and the time when it is placed. By default, the primary gait mode is adopted. Only when the constraints for primary gait mode are not satisfied, will the secondary gait mode be selected.

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5.1 Maximum transfer time (T_f)

The maximum transfer time T_f is the longest time for which a transferred leg can be in the air. T_f is determined based on four time limits associated to the four constraints described in Section 4.

(a) Kinematic time limit (T_k). The kinematic time limit T_k is the possible longest transfer time of a leg in the air under the kinematic constraint. It can be calculated from the temporal kinematic margin as:

$$T_k = min\{t_{ki}, t_{kj}\}, \tag{18}$$

where *i* and *j* denote the number of two supporting legs near the transfer leg. The temporal kinematic margin of a leg *i* can be evaluated as:

$$t_{ki} = Km_i/v_c. \tag{19}$$

(b) Stable state time limit (T_s). The stable state time limit T_s specifies the time slice when the current state of the machine is statically stable. This period can be calculated as follows:

$$T_s = (Sm - Sm_0)/v_c, \tag{20}$$

where Sm is the static stability margin at the time the leg is started to be lifted.

(c) Sequential time limit (T_q). The sequential time limit T_q represents the longest time of a leg in the air to guarantee the sequence in primary gait. Let leg *j* is in the air, the limit can be expressed as:

$$T_q = min\{t_{qi}\}, \tag{21}$$

where t_{qi} is the longest transfer time that satisfies the sequence constraint for leg i,

$$t_{qi} = (Km_i - Cq_i(j))/v_c, \quad i \neq j. \tag{22}$$

(d) Neighboring time limit (T_n). A neighboring time limit T_n is set for the rear legs (Legs 1 and 2) to guarantee the next lifting of the fore-legs as follows:

$$T_n = (Km_j - Km_j^*)/v_c, \tag{23}$$

where *j* is the number of the fore-leg located opposite to the rear leg considered.

Note that the limit for the fore-legs does not exist and can be virtually set to a very big value during calculation.

With all the above limits, the maximum transfer time T_f of the leg in the air can be obtained as

$$T_f = min\{T_k, T_s, T_q, T_n\}, \tag{24}$$

where T_k, T_s, T_q and T_n are given by equations (18), (20), (21) and (23) respectively.

5.2 Estimate obstacle influence

The influence of obstacle, if exists, is estimated in terms of the obstacle position. The distance of obstacle to the front boundary of the reachable area of a leg being considered is used to classify the obstacle influence:

(a) When the obstacle is very near ($0 < d_{ob} \leq P/4$, see Figure 4) or overlaps ($d_{ob} \leq 0$) the front boundary of the reachable area of the leg, it affects the placing position and transfer time. The influence is therefore defined as DIO (Double Influence of Obstacle)

(b) When the obstacle is far away from the front boundary of the leg's reachable area, but near ($0 < d_{ob} < P/3$) to that of the leg lifted next, the obstacle affects only the transfer time of the currently considered leg. This influence is now defined as SIO (Single Influence of Obstacle).

These two types of influence can be demonstrated by Figure 4. In Figure 4(a), the obstacle has an influence of DIO on Leg 3 and an influence of SIO on Leg 2. For the obstacle in Figure 4(b), it has a DIO influence on Leg 2 and a SIO on Leg 4.

When there is a density of obstacles in front of the vehicle, a procedure is adopted to find out the obstacles that affect the gait. At first, a list of obstacles near the vehicle is generated and maintained for each leg. All distances of obstacles to the reachable area of each leg are checked in every planning interval. Based on these distances the influences of obstacles are evaluated for the transfer leg. For each transferred leg, no more than one DIO and one SIO are selected for the determination of gait parameters. If there are two or more obstacles of SIO type, the obstacle which is nearest to the front boundary is selected. For the case of two or more DIO types, the one whose geometric center is

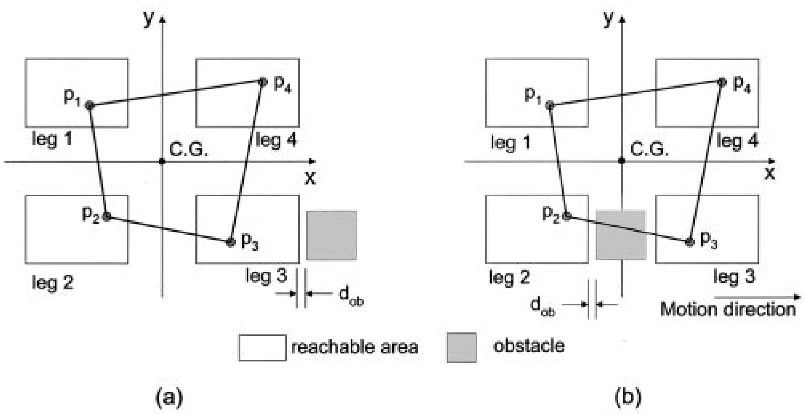

Fig. 4. Influence of obstacle on the gait: (a) the obstacle is of DIO type for Leg 3 and of SIO for Leg 2, (b) the obstacle is of DIO type for Leg 2 and of SIO for Leg 4.

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nearest to the front boundary of the reachable area of current transfer leg is selected.

5.3 Determination of gait parameters

(a) Transfer time. Possible transfer time must fulfull the condition: $t_f \in \langle T_{f0}, T_f \rangle$. The minimum transfer time T_{f0} is the time for leg transferred with the maximum speed. Final transfer time is determined by taking into account the actual conditions. When no obstacle exists, the leg transfer time can be set to the maximum transfer time, $t_f = T_f$. If there is an obstacle of SIO, the transfer time is set to the minimum transfer time, $t_f = T_{f0}$. Such a strategy would ensure that the next leg in primary gait will be lifted just at the moment when obstacle is around the front boundary of the leg's reachable area. Sequentially, the leg will have a big space in selecting foothold thus lowering the chance to deadlock.

The DIO affects the neighboring time limit, which must be re-evaluated in this case. The new value T'_n of this time limit will be obtained by considering the condition of minimum static stability margin:

$$\frac{y_i x_k - y_k(x_i - v_c T'_n)}{y_i - y_k} = Sm_0, \tag{25}$$

in which

- x_k, y_k: the coordinates of the k-th leg with respect to the maximum transfer time,
- x_i, y_i: the coordinates of diagonally opposite leg at the time when k-th leg is to be lifted,
- T'_n: the neighboring time limit for k-th leg.

With the evaluated T'_n using equation (25), the transfer time can be determined as:

$$t_f = min\{T_k, T_q, T_s, T'_n\}. \tag{26}$$

(b) Placing position. After evaluation of the actual obstacle position for the time equal to t_f, a range of possible leg-end positions could be obtained by equations (7) and (12). Within the reachable area the landing position is selected just at the safety margin of obstacle, if exists, so that a longer kinematic margin can be obtained. Here, the safety margin refers to a contour around the obstacle that enables the leg to be lifted without touching it.

6 IMPLEMENTATION OF THE FREE GAIT ALGORITHM

A free gait generation algorithm was developed based on the proposed assumptions of primary/secondary gait. In this algorithm, machine state and its walking environment are checked against all the constraints of the primary gait. If the constraints are satisfied, ranges of modified transfer time and placing position are generated. Primary gait parameters are then determined by taking into account the influence of obstacles. Otherwise, the secondary gait is adopted to adjust the leg position to resume the walking machine to the initial state.

6.1 Primary gait mode

The primary mode of a free gait is generated according to the following steps:

- (i) Determine the first leg to be lifted from the initial state of a machine by considering the constraints specified in equations (18), (20), (21) and (23). Check all legs against the four constraints to find the suitable leg(s) which can be transferred.
- (i.α) If there is more than one leg satisfying the constraints, the leg with the smallest kinematic margin is selected. When there are two legs with the same smallest kinematic margin, leg will be selected randomly.
- (i.β) If there is no leg satisfying the constraints then go to secondary gait.
- (ii) Calculate the maximum transfer time T_f for the leg to be lifted, by equation (24).
- (iii) Estimate the influence of obstacle, DIO or SIO.
- (iv) Determine the transfer time t_f and placing position.
- (iv.α) If there is not any obstacle influence, the transfer time is $t_f = T_f$. The leg is placed in position having maximum kinematic margin.
- (iv.β) If there is a SIO obstacle, the transfer time is set to the minimum value and the leg is to be placed at an anterior extreme position.
- (iv.γ) If there is a DIO obstacle, the transfer time is obtained by using equations (25) and (26). The placing position is then selected with respect to the obstacle position.
- (v) If t_f is less than zero then go to the secondary gait mode; otherwise go to step (vi).
- (vi) Update the value of leg positions and machine position and the walking time and select the next leg to be considered with the primary gait.

6.2 Secondary gait mode

The secondary gait is generated by the following steps:

- (i) Set the speed factor to zero to completely stop the vehicle.
- (ii) Check the machine state. If the placing positions of legs are within their CRAs, exit and go to primary gait control.
- (iii) Lift the leg that has been considered possible to transfer in the primary gait.
- (iv) Select the leg with the smallest kinematic margin as *reference* leg (see Table I: Leg with Km_0).
- (v) Applying the rules specified in Section 3.2, select the searching path according to the reference leg.
- (vi) Finish the search with the selected path.
- (vi.α) Select the next leg to be lifted next according to the selected path.
- (vi.β) Search within the CRA of current transfer leg, find a placing position such that the selected leg could be lifted after placing the transfer leg on the ground

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and an essential movement of C.G. If successful, continue. Otherwise, go to step (v).

(vi.γ) Check the current situation. If the transitions in the selected path are fully finished, go to step vii, otherwise go to step vi.α.

(vii) Check the stability margin for the reference leg. If it could be lifted, go to step (ii). Otherwise, go to step (iv).

An overall scheme of the algorithm is shown in Figure 5. In the scheme, t_w is the waiting time which is the time till the moment of next leg transfer.

7 SIMULATION RESULTS

Tests of the algorithm were performed using a gait simulator.[10] The walking machine was displayed together with the projection of center of gravity and with the kinematic limits. The support polygon was also shown. In each test, the machine starts to walk from the initial state. Several cases of different size and position of the obstacle were tested. One of the results of gait planning is demonstrated in moving sequences shown in Figures 6 and 7 in which the walking machine with a described free gait clears successfully a density of obstacles on a rough terrain. The simulation results illustrate that the walking machine could well move with the primary/secondary gait.

8 CONCLUDING REMARKS

A free gait algorithm has been developed using the *primary/ secondary gait* methodology. The primary gait specifies a dominating leg sequence when the walking machine moves forward. Ranges of transfer times and placing positions are evaluated by considering four constraints elaborated in the paper. Gait parameters are then determined based on these ranges and the influence of obstacles. When a walking machine cannot move by using the primary gait, secondary gait is generated to adjust leg position and enable the vehicle to keep on moving. Compared with the method in reference [5], the proposed method here has a higher flexibility in that it is not limited to a fixed supporting pattern. Instead of discretizing the reachable area, our method takes it as a whole and generates gait parameters on the ranges of transfer time and landing position thus consumes a shorter time than other methods for quadruped.[5,6] Simulation results show that the primary/secondary gait method is effective and efficient in the free gait generation. Currently the algorith is being developed and tested to coordinate with the different obstacles for circular motion of the machine body.

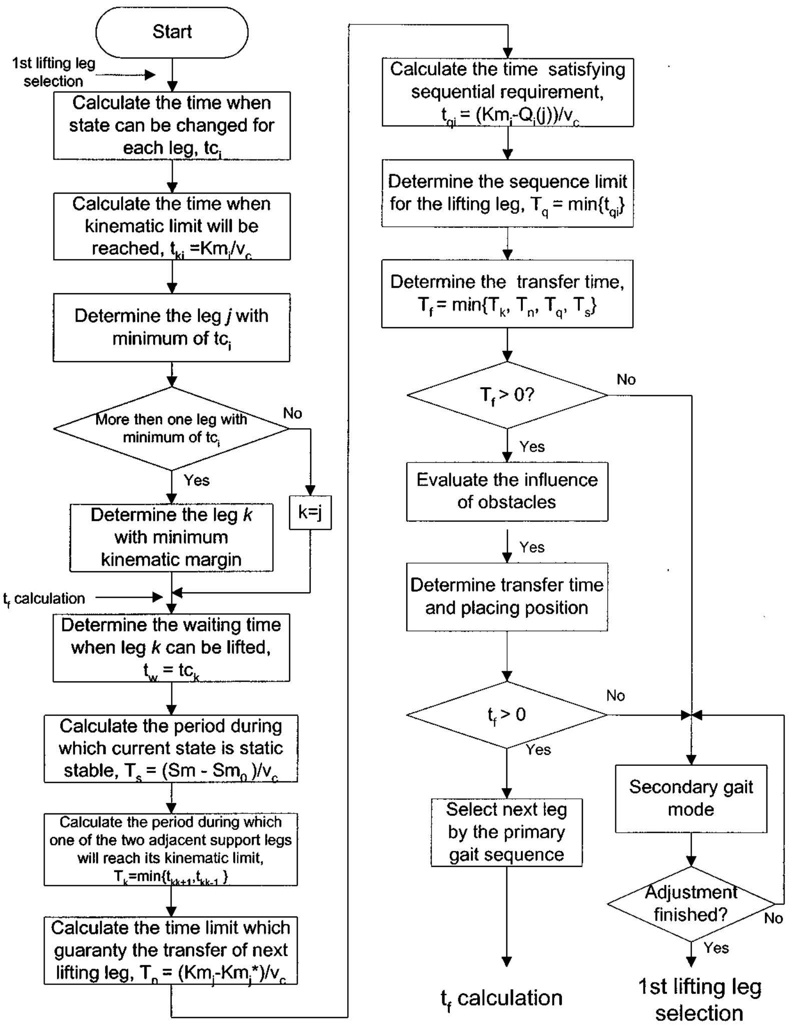

Fig. 5. A scheme of free gait generation with primary/secondary gait mode.

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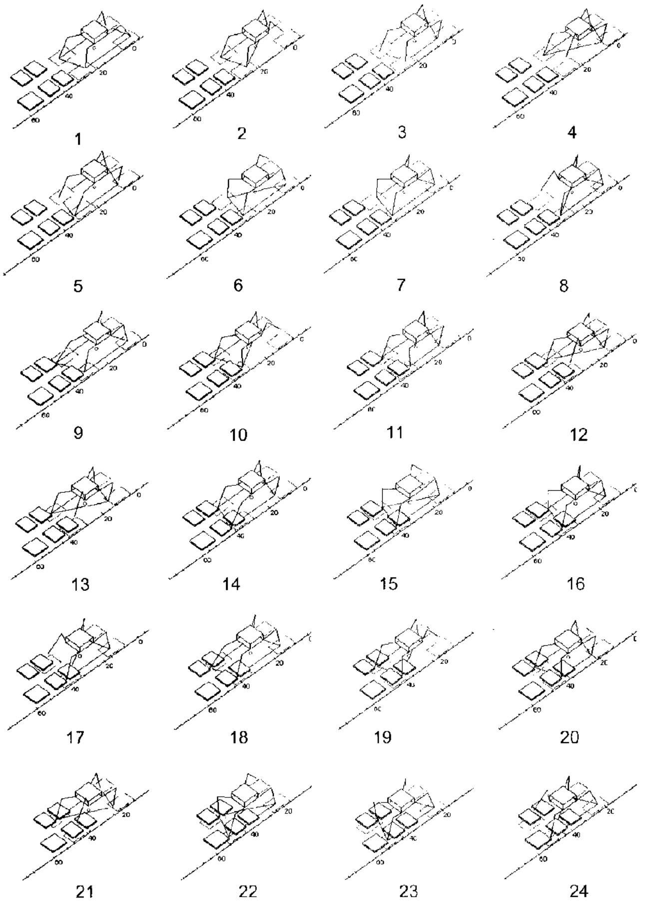

Fig. 6. Walking machine clears obstacles by free gait (to be continued in Figure 7). The number under each frame denotes the moving sequence.

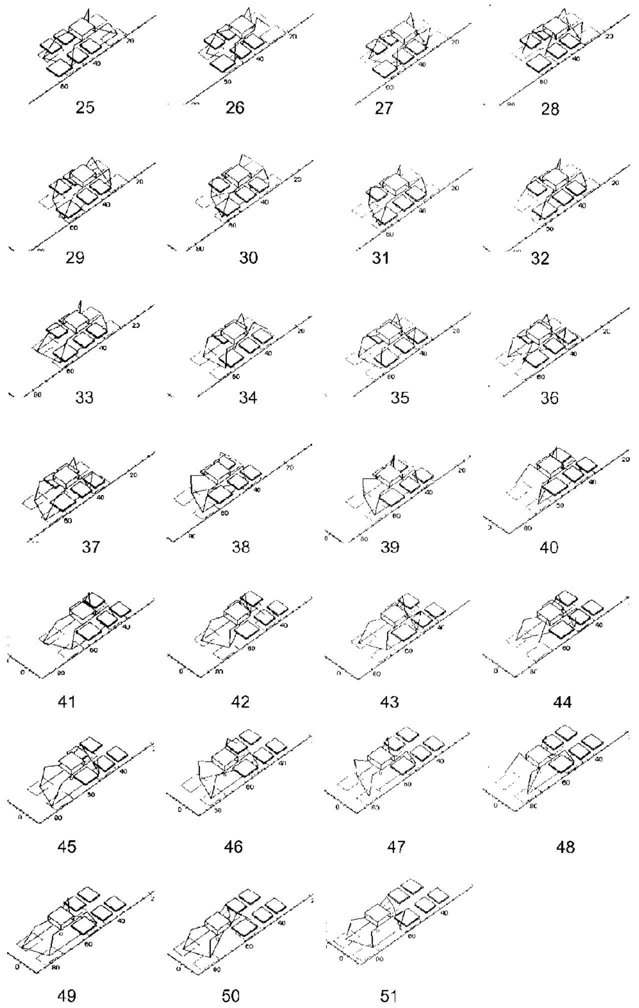

Fig. 7. Walking machine clears obstacles by free gait (continued from Figure 6). The number under each frame denotes the moving sequence.

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