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Adaptive gait planning for multi-legged robots with an adjustment of center-of-gravity

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SUMMARY
Adaptive gait planning is an important aspect in the development of control systems for multi-legged robots traversing on rough terrain. The problem of adaptive gait generation can be viewed as one of finding a sequence of suitable foothold on rough terrain so that legged systems maintain static stability and motion continuity. Due to the limit of static stability, deadlock situation may occur in the process of searching for a suitable foothold, if terrain contains a large number of forbidden zones. In this paper, an improved method for adaptive gait planning is presented by active compensation of stability margin, through center of gravity (CG) adjustment in the longitudinal axis and/or body translation in the lateral direction. An algorithm for the proposed method is developed and embedded in a computer program. Simulation results show that the method provides legged machines with a much larger terrain adaptivity and better deadlock-avoidance ability.

KEYWORDS: Multi-legged robots; Gait planning; Motion planning; CG adjustment.

1. INTRODUCTION

There is a growing need for multi-legged vehicles to traverse rough terrain in applications such as agriculture, underwater[1] as well as planetary and volcanic exploration.[2] In these demand applications, the superior terrain adaptivity is a critical requirement.[3]

The terrain adaptivity of a legged system depends directly on the *gait planning*. The problem of gait planning in a multi-legged system can be generally formulated as how to coordinate the motion of legs and body to make the machine traverse over a particular terrain with static stability manner. An *adaptive gait* should be able to coordinate the locomotion of legged systems to negotiate the terrain containing forbidden zones. Specifically, the task of an adaptive gait planning in control includes a determination of optimal schedule for lifting and placing of legs of walking robots and a finding of suitable footholds as supporting points for the transfer leg(s) over the whole trajectory.[4,5] To achieve an effective adaptive gait, some limits, namely, terrain condition, geometry (or kinematic) constraint and static stability, must be taken into account in planning.[6] The geometry constraint requires all legs keeping their foot tips in the respective *reachable area*, while static stability constraint refers to that the projection of the body center of gravity (CG) must be located inside the boundary of *support polygon* composed by the tips of supporting legs.[4] In other words, the *stability margin* must be greater than zero during locomotion.

A considerable amount of prior work has been devoted to the study of the adaptive gait over past decades. Representative of these works is a *free gait* algorithm which was first recognized and formalized by Kugushev and Jaroshevskij,[4] and subsequently improved and developed for a hexapod robot by McGhee and Iswandhi.[5] The general strategy of free gait is to find a sequence of support patterns such that there is an overlap of the *existence segment* of each support state with that of the proceeding support state. To reduce the complexity of the problem, the algorithm developed by McGhee and Iswandhi determines the support pattern sequence only one cycle forward rather than over the whole trajectory. Such an approach may lead to a situation of deadlock if terrain contains a large number of forbidden zones. For four-legged robots, due to fewer choices about selecting their steps, free gait algorithm may become more susceptible to deadlock situation. Hirose[7] presented a hierarchical algorithm to overcome the deadlock problem of quadruped robots. In his algorithm, new support points are selected through the three reflexes from sensors. The selection tends to restrict the search area of new footholds. More recently, some improved free gait algorithms based on all possible leg-ends and body transfer,[8,9] and a graphic search over the whole trajectory[10] are also presented for obstacle-avoidance.

Careful examination of the methodology of these algorithms for free gait shows that the trade-off between stability and adaptability is critical for successful generation of a free gait. A deadlock situation will occur if a contradiction appears in stability and adaptability. It is clear that the likelihood of deadlock will decrease if the value of stability margin is compensated.

Two ways can be utilized to compensate stability margin. One is to adjust the CG position relative to the platform[11–13] and another is to move the vehicle body in the lateral and/or longitudinal direction acordingly.[14,15] Ding and Scharf[11] applied the former method to study deadlock avoidance for a quadruped, in which the CG is shifted forward and backward in the longitudinal direction by moving an arm. Messuri and Klein,[14] under the assumption of a sufficiently slow body speed, used the second approach in precision-footing control mode, developing a body regulation scheme

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to aid the operator in maneuvering the hexapod vehicle (ASV).

This paper focuses on improving adaptive gait behaviors through compensating the stability margin, using a combination of CG adjustment in the longitudinal axis and body regulation in the lateral axis. An algorithm is developed for a quadruped simulation prototype. The significant feature of this algorithm is that it can provide the machine with a much greater adaptivity over rough terrain at a reasonable walking speed. The paper is organized as follows. The scheme of stability margin compensation for a quadruped prototype is described in Section 2. In Section 3 the motion of non-periodic gait is described and then the adaptive gait planning is formulated. The method to improve adaptive gait behaviors through stability margin compensation is addressed in Section 4 together with the strategy of CG adjustment. An adaptive gait planning algorithm is presented in Section 5 and simulation results are given in Section 6 to illustrate the benefit of the proposed method. Finally, a summary and conclusions are made in Section 7.

2. COMPENSATION DEVICE

A quadruped robot, referred to as NTU-Q1, is being developed at the Nanyang Technological University to facilitate the study of adaptive locomotion of legged systems. Figure 1 shows a computer simulation prototype of NTU-Q1. When completed, it will be a self-contained walking robot intended for material handling on irregular terrain environment. Each of its four legs has three independent rotary joints arranged in an arthropod configuration. The two terrain scanners located at the front are used to provide terrain data for the prediction of suitable foothold position. To achieve superior terrain adaptivity, a device for the compensation of stability margin has also been incorporated into the design of this machine.

The scheme of stability margin compensation adopted by NTU-Q1 involves the CG adjustment relative to body frame along the longitudinal axis and body frame translation in the lateral axis. Such an arrangement allows the machine to enhance the minimum value of stability margin, while it is independent of the machine's locomotion in the longitudinal direction. A movable weight which may consist of the batteries and control parts is used as balancing mass to adjust the CG position in the longitudinal axis. On the other hand, the arthropod configuration of each leg enables the body frame to translate laterally in a sufficiently large range, thus affecting the adjustment of the CG position in this direction.

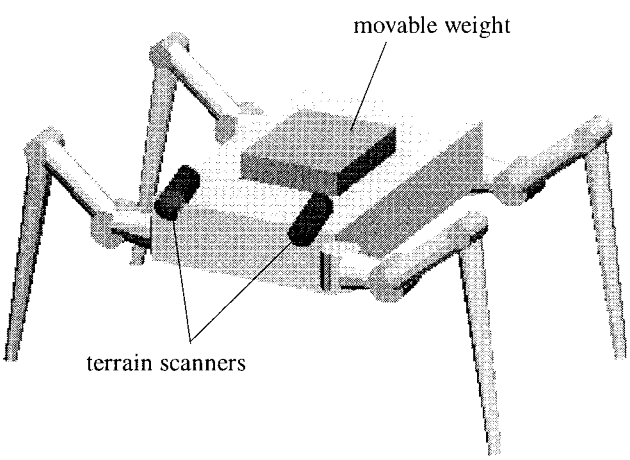

Fig. 1. Computer model of NTU-Q1.

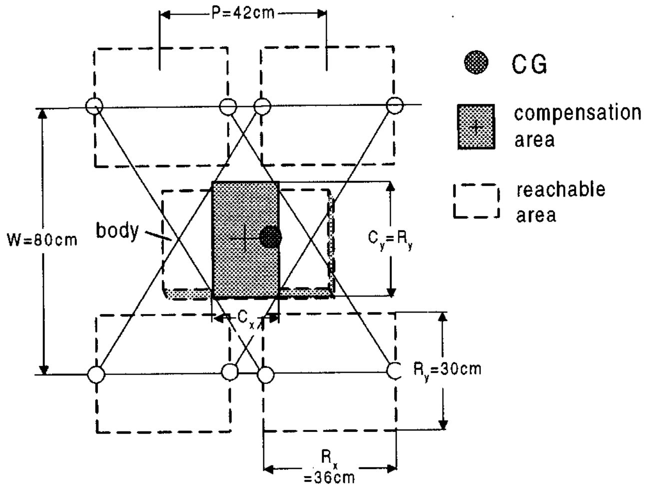

Fig. 2. Compensation area of NTU-Q1.

As shown in Fig. 2, *compensation area* is a region in which the CG can be adjusted through the motion of movable weight in the longitudinal axis and the motion of body frame along lateral axis. Clearly, the compensation area will be a rectangle if the body is not allowed to rotate. The length in the lateral direction depends on the position of support legs in the lateral stroke, while the length in the longitudinal direction is determined by the maximum distance covered by the movable weight. The size of compensation area may affect the extent of stability margin compensation. A reasonable size of the compensation area is needed to maintain the machine's static stability on the support pattern permitted by the reach of support legs. For NTU-Q1, the desired size of compensation area is $C_x = 20.2$ cm in the longitudinal direction and $C_y = 30$ cm in the lateral direction (see Fig. 2). Some preliminary simulations have shown that such an adjusting region is adequate to keep the machine's static stability. Figure 3 shows several examples of how the CG position can be adjusted within the compensation area to maintain the static stability.

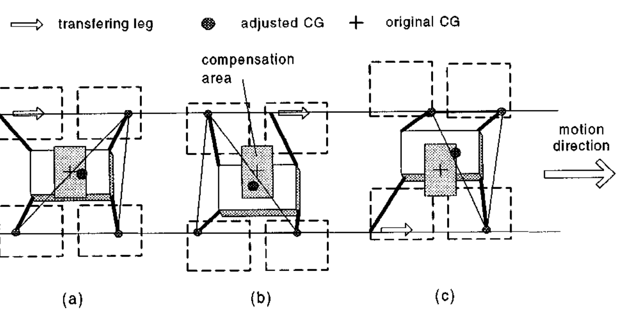

Fig. 3. Top view of CG adjustment in some support patterns. (a) longitudinal direction, (b) lateral direction, (c) longitudinal and lateral direction.

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3. PROBLEM STATEMENT

An entire gait consists of a finite number of support states. Thus an adaptive gait planning for the complete trajectory can be divided as the gait planning in a support state. At this point, the problem of adaptive gait planning can be viewed as the coordination of the motion of legs and body with static stability within a support state and state shifting.

3.1 Description of motion

The *support state* of a *K*-legged locomotion system is actually a state description of the legs touching or lifting from the ground. For the purpose of discussion, the support state can be classified into two types:

(i) F-state, if all the legs are the supporting leg,

(ii) T-state, if there is at least one swing leg.

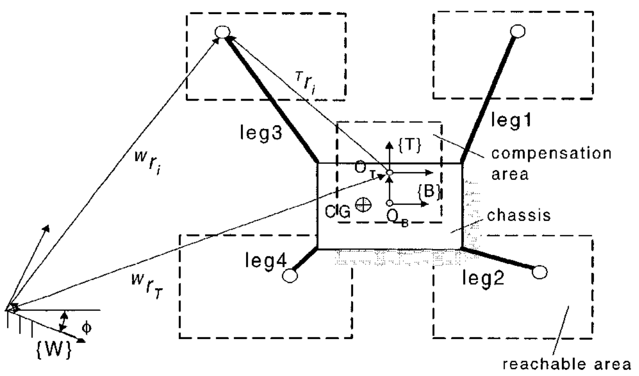

Fig. 4. Kinematic coordinate systems.

The shifting of support state from one to another is caused by the occurring of at least one event. A gait *event* is the placement or lift of the leg. For adaptive gait, the sequence of support state is irregular, which closely depends on the given terrain condition. To take the sequence of support states into account, an integer number n is used for each support state according to the time order. If the location of a support state in the series formed by all support states is n, then this support state will be denoted as S(n). Thus F-state is denoted as SF(n), and T-state as ST(n).

The time length occupied by a support state is called the *state period*. A state period associated with S(n) can be denoted as $\Delta t(n)$. The moment of shifting from S(n-1) to S(n) is denoted as $t^-(n)$, likewise, the moment from S(n) to S($n+1$) as $t^+(n)$, both of which are measured from the initial time. We can get the following equations,

$$\Delta t(n) = t^+(n) - t^-(n)$$

$$t^-(n) = \sum_{k=1}^{n-1} \Delta t(k) \tag{1}$$

$$t^+(n-1) = t^-(n).$$

During the period of support state, the body of the machine may move or rest. A *body's motion state*[16] is defined as 1 if the body has moved, and as 0 if the body has not moved. Evidently, if more body motion states are 1 in a complete gait, then the machine will reach relatively higher speed or

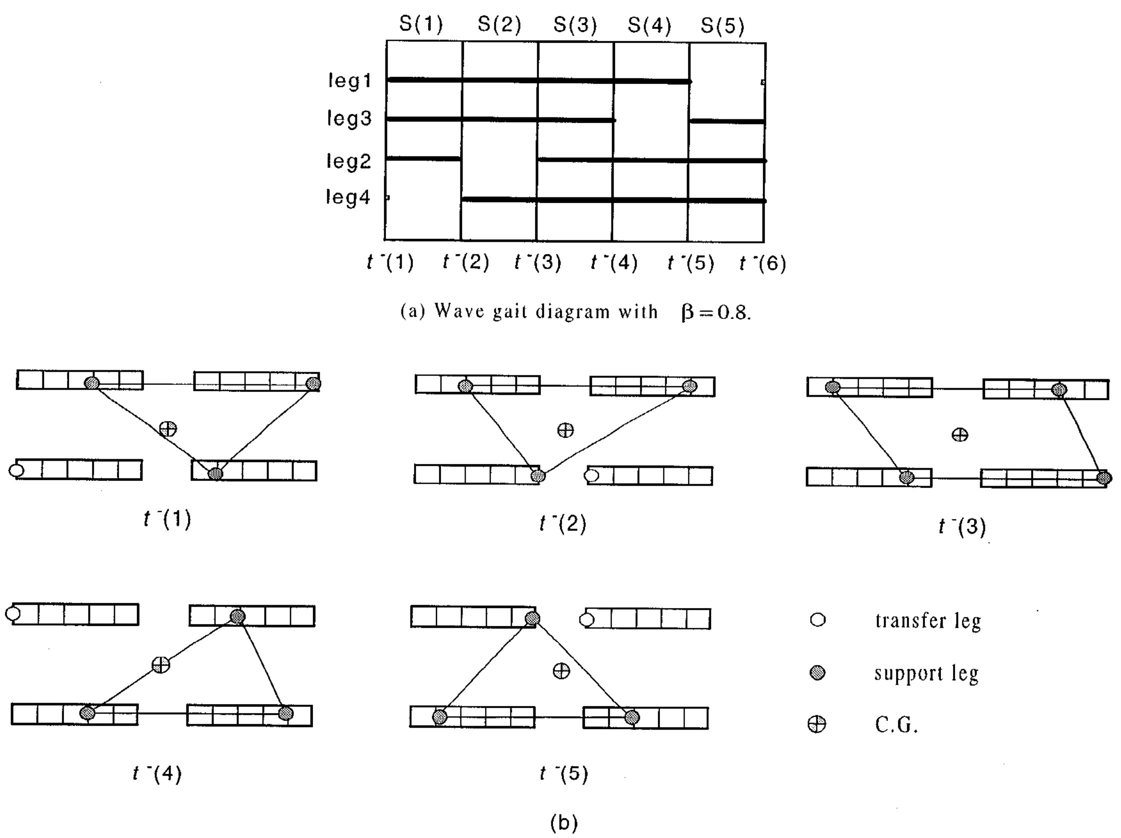

Fig. 5. Initial foot conditions in one cycle of a wave gait.

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the motion of the machine will be "smoother".

The *locomotion state* is a description of machine's motion that involves both body state and support state. According to the motion of legs and body, locomotion state of a machine in any time is possibly one of four cases, (ST, 0), (ST, 1), (SF, 1), and (SF, 0). The locomotion state (SF, 0) means legs and body rest. Such a locomotion state generally possesses the best static stability because all feet are supporting legs. The locomotion state can be utilized in some cases to adjust the position of CG for the subsequent motion, which leads to *a transitional state*, denoted by S([n]). This is a locomotion state that the legs and body rest but the movable weight may move.

The determination of the type of a locomotion state relates to the support state's *foot condition*, i.e. the position of the supporting feet with respect to the body-frame. Foot condition is also represented through the *kinematic margins* of the feet. Note that the *kinematic margin*[11] is the length of a vector opposite motion direction from the current support point to the intersection point with a reachable area boundary.

In this work, $KM_i(n)$ is used to denote the kinematic margin of leg i in S(n). It is also useful in gait planning to identify the order of magnitudes of all leg kinematic margins. If there are k support legs at certain moment of S(n), $K(i, n)$ denotes the i-th kinematic margin from the minimum value, thereby having $K(1, n) \leq K(2, n) \leq \ldots \leq K(k, n)$. Note that $K(i, n)$ is generally a function of time. If a body motion state is 1 in a support state, the foot condition in different instance during this support state will be different. The foot condition at the moment of the beginning of a support state is called *initial foot condition*. Unless otherwise specified, $KM_i(n)$ or $K(i, n)$ is measured in the initial foot condtiion of S(n).

The motion speed of the body and swing leg, in practice, may vary within a state period. We use the *average body speed*, $V_b(n)$, and *average swing speed*, $V_s(n)$, to describe the velocities of the body and transfer leg. Note that $V_b(n)$, is measured with respect to the global-frame while $V_s(n)$ is measured with respect to the body-frame. Without ambiguity, $V_b(n)$ and $V_s(n)$ will also be called *body speed* and *swing speed* in later sections for abbreviation. Let us define β-factor and α-factor, denoted by $\beta(n)$ and $\alpha(n)$ as follows:

$$\beta(n) = \frac{V_s(n)}{V_s(n) + V_b(n)} \quad \text{and} \quad \alpha(n) = \frac{V_b(n)}{V_s(n) + V_b(n)}. \tag{2}$$

Note that $\beta(n)$ may vary from state to state around a specified β for adapting the terrain. For a given β-factor, swing speed will be fixed, but body speed may change owing to different $\beta(n)$. It is assumed that the backward motion of body is prohibited. The following relations about $\beta(n)$ and $\alpha(n)$ will always hold in a support state

$$1 \geq \beta(n) > 0, \; 1 > \alpha(n) \geq 0, \; \text{and} \; \alpha(n) + \beta(n) = 1. \tag{3}$$

In fact, if the sequence of support states is periodic, β-factor in quantity will be equal to the duty factor defined in a periodic gait.[16,17]

3.2 *Formulation of problem*

The following assumptions are adopted in this work.[18,19]

- The machine keeps its body level at a constant height during locomotion.
- All legs possess the same rectangular reachable area.
- No backward motion of body is allowed.
- No rotation of body is allowed during locomotion.
- Terrain is smooth except in forbidden zones.

Based on these assumptions, the machine-terrain system can be modeled as a two-dimensional system as shown in Fig. 4 (see Appendix for the definition of symbols).

Three frame-systems, namely, global-frame {W}, body-frame {B} and trace-frame {T} are used to describe the machine's motion. The global frame is fixed to the ground and used to define the motion of the body-frame and/or the trace frame. The body frame is attached to the body chassis and used to facilitate the depiction of leg motion relative to the body. Since the CG position is adjustable with respect to the body chassis through moving the movable weight, the origin of the body frame (O_B) is not fixed at the CG but at the geometry center of the chassis. The trace-frame, the origin of which (O_T) is fixed at the center of the compensation area, is used to describe the CG adjustment relative to the compensation area. It should be noted that without CG adjustment, the three points, namely CG, origin of body frame and origin of the trace-frame will coincide together. Clearly, the position of O_B on {T} represents the adjustment of the body chassis along the lateral axis, and the position of CG on {B} represents the adjustment of CG caused by the motion of the movable weight along the longitudinal axis. Note that {B} has no rotation relative to {T}.

The coordinate of the foot tip of leg i in {W} can be expressed in {B} as

$$\begin{bmatrix} {}^{W}x_i(n) \\ {}^{W}y_i(n) \end{bmatrix} = \begin{bmatrix} {}^{W}x_T(n) \\ {}^{W}y_T(n) \end{bmatrix} + {}^{W}_{T}A(\phi) \begin{bmatrix} {}^{B}x_i(n) \\ {}^{B}y_i(n) - {}^{T}y_B(n) \end{bmatrix}, \tag{4}$$

where ${}^{W}_{T}A(\phi) = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}$ is a rotational matrix from {T} to {W}.

The kinematic margin of each leg can be obtained by

$$KM_i(n) = \begin{cases} {}^{B}x_i(n) - \left(\frac{k}{2} - i\right)\frac{P_x}{2} + \frac{R_x}{2}, & \text{if } i \text{ is odd} \\ {}^{B}x_i(n) - \left(\frac{k}{2} - i + 1\right)\frac{P_x}{2} + \frac{R_x}{2}, & \text{if } i \text{ is even} \end{cases} \tag{5}$$

where k is the number of legs, while P_x and R_x are respectively the pitch and stroke in the longitudinal direction.

By now the problem of the adaptive gait planning in S(n) has been defined:

For a given terrain condition and a desired β, if a machine state at $t = t^-(n)$ is known, the task of the gait planning is to determine the parameters of the machine state at $t = t^-(n+1)$ for a statically stable motion.

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4. AN IMPROVED ADAPTIVE GAIT PLANNING

4.1 Rules of selection of locomotion state

We assume that the support state S(n) always begins from a condition with full supporting legs. At this instant, a decision will be made on which leg should be the transfer leg and which type of the support state (T-state or F-state) should be used for the next step. Accordingly, some rules should be made to govern machines' locomotion so as to ensure the following requirements:

(i) Support states must be statically stable.
(ii) Geometry limit for all legs cannot be violated.
(iii) The lifting or placing of a leg should result in the minimum value of the kinematic margin of all supporting legs maximum.[5,17]
(iv) To keep $\beta(n)$ equal to the desired β-factor, if possible.

Based on the above requirements, the following rules are set up for the selection of the transfer leg and the support state:

Rule 1: *the leg with the minimum kinematic margin will always first be selected as the transfer leg.*

Rule 2: *a leg cannot be selected as a transfer leg twice successively.*

Rule 3: *if two or more legs are with the minimum kinematic margin, the leg which, when lifted, results in the largest stability margin should be selected as a transfer leg.*

Rule 4: *if the transfer leg is still not determined, then the sequence of the swing legs, 1-4-2-3, should be used, which possesses the largest stability margin in the periodic gait.*[20]

After the transfer leg has been determined, it is necessary to consider whether this chosen leg is lifted immediately, which result in a T-state, or this leg is lifted after a period, which result in an F-state. The method of the generation of a support state type is given by **Rules 5–8**.

Rule 5: *if the support state tends to be statically unstable when the transfer leg selected is lifted, then an F-state should be used.*

Actually either such an F-state produced from Rule 5 is a transitional state or it is followed by a transitional state. During the period of this transitional state, the CG of the machine will be adjusted to a suitable position so as to guarantee the selected swing leg can be lifted. If without stability compensation, the case occurring in Rule 5 will result in a deadlock situation.

Rule 6: *without violating Rule 5, if the minimal kinematic margin of support legs is equal to zero, then a T-state should be used.*

For the case of the minimum kinematic margin greater than zero, both T-state and F-state may be used for the machine locomotion. However, for the purpose of the "smoother" motion of the machine, it is often necessary to keep $\beta(n)$ of the desired β-factor by virtue of the characteristics of different types of support state. The following rules can be used for this purpose.

Rule 7: *an F-state must be followed by a T-state, i.e., two successive F-states are prohibited.*

Rule 8: *without violating Rule 7, if* $K(2,n) > \dfrac{[R_x - K(1,n)]\alpha(n)}{\beta(n)}$ *and* $K(1,n) > 0$, *then an F-state should be used, otherwise a T-state should be used.*

Although the above rules are presented for adaptive gait planning, when applied to analyze the periodic gaits they should also lead to the same sequence of support state as that from known periodic gaits. This feature can be used to check the correctness of these rules. Consider a wave gait with a duty factor $\beta = 0.8$. Its gait diagram is shown in Fig. 5(a), in which a total of 5 support states are included in a cycle. The initial foot condition of each support state is shown in Fig. 5(b). Clearly, according to Rules 1 and 6, S(1), S(2), S(4) and S(5) are T-states, with the transfer legs leg 4, leg 2, leg 3 and leg 1, respectively. According to Rules 1 and 8 S(3) is an F-state with leg-3 as the possible transfer leg. These results are agreeable to those obtained from the wave gait formulation.

4.2 Foothold selection

A suitable foothold for the transfer leg in a T-state should be one that the transfer leg can reach it in a statically stable manner while not violate the geometry, kinematics and static stability limits of the machine. Obviously, such a foothold is not unique. The underlying logic for foothold selection here is to find a region in which all feasible footholds satisfy the above constraints. After the region is determined, the suitable foothold (support point) will be selected from this region according to appropriate optimal rules.

4.2.1 Geometry constraint. Geometry constraint requires that all foot tips of the machine must be placed within respective reachable area. To determine the foothold region satisfying the geometry constraint, the maximum distance covered by the transfer leg should be computed. With the aid of body motion the maximum distance the swing leg can cover should be

$$C_g(n) = R_x - K(1, n) + K(2, n). \tag{6}$$

Equation (6) implies that any a foothold within $C_g(n)$ if selected as a support point will ensure the transfer leg satisfy the geometry limit.

4.2.2 Kinematic constraint. When a legged system walks with a desired β-factor specified in advance, the following cases may appear: (i) The swing leg reaches the boundary of its reachable area, but the support legs do not. (ii) The support leg with kinematic margin $K(2, n)$ reaches the boundary of its reachable area, while the transfer leg does not. The first case may reduce the distance the body can cover in a support state, while the second case may result in a deadlock situation. To avoid these cases, the maximum distance the swing leg can cover in S(n) should satisfy the following kinematic constraint

$$C_k(n) = \min\{[R_x - K(1, n)]/\beta(n),\ K(2,n)/[1 - \beta(n)]\}. \tag{7}$$

Obviously, $C_k(n) \le C_g(n)$. The value of $C_k(n)$ will get its maximum value, $C_g(n)$, if $\beta(n)$ is appropriately adjusted in

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the form

$$\beta(n)=\beta_m(n)=\frac{R_x-K(1,n)}{R_x-K(1,n)+K(2,n)}. \quad (8)$$

At this point both the support legs and swing leg will reach their reachable area boundary simultaneously.

4.2.3 Stability constraint. Static stability requires the projection of the CG of a machine locating inside the support polygon or the static stability margin of the machine positive at any time. From Rule 5, at the beginning of a T-state the stability margin should be greater than zero, or a transitional state will be used. Furthermore, since the backward motion of a machine is forbidden, only the front stability margin need to be considered in the foothold selection. The front stability margin in the period of a support state is monotone function, and the minimum and maximum values occur respectively at the end and beginning of that support state.[19] It implies that if the maximum front stability margin during S(n) is $SM_l(n)$, then under the consideration of stability constraint without CG adjustment, the maximum distance the body can translate in S(n) will be $SM_l(n)$. Assume the front boundary of the support pattern of S(n) is composed by the foot tips of leg-i and leg-j, we have

$$SM_l(n)=\frac{{}^Bx_j(n)-{}^Bx_i(n)}{{}^By_j(n)-{}^By_i(n)}[{}^By_G(n)-{}^By_i(n)]+{}^Bx_i(n)-{}^Bx_G(n). \quad (9)$$

Denote $C_s(n)$ as the maximum distance that transfer leg can cover under the condition of the stability constraint. Similar to that presented in subsection 4.2.2, $C_s(n)$ can be determined by

$$C_s(n)=\min\{[R_x-K(1,n)]/\beta(n),\ SM_l(n)/[1-\beta(n)]\}. \quad (10)$$

Comparing Equations (7) and (10), the maximum distance, $C(n)$, that the transfer leg can cover under kinematic constraint and stability constraint should be a minimum of $C_s(n)$ and $C_k(n)$,

$$C(n)=\min\{[R_x-K(1,n)]/\beta(n),\ \min[(SM_l(n),\ K(2,n))/(1-\beta(n)]\}. \quad (11)$$

Likewise, the value of $\beta_m(n)$ can be obtained by

$$\beta_m(n)=\frac{R_x-K(1,n)}{R_x-K(1,n)+\min[SM_l(n),K(2,n)]}.$$

Without the compensation of stability margin, $SM_l(n)$ will passively depend on the support polygon. It is possible that $SM_l(n)$ becomes very small in some support states if terrain is very rough. For this case, $C(n)$ may decrease even become zero, consequently the swing leg may find no-place to rest. Thus the terrain adaptivity of the transfer leg will be lowered, and the deadlock case may occur. If there is a compensation of stability margin, $SM_l(n)$ will be independent from the support polygon because the coordinate $[{}^Bx_G(n),\ {}^By_G(n)]$ in Eq. (9) is adjustable. The value of $SM_l(n)$ can be enhanced through adjusting the CG position within the compensation area. Further, if the compensation mechanism is constructed appropriately, it is possible that there is at least one point within the compensation area which results in

$$SM_l(n)\geq K(2,n). \quad (13)$$

It means that $C(n)$ will be equal to $C_k(n)$ under the consideration of the CG adjustment. Thus the selection of the foothold will be independent from the stability constraint. It is the task of CG adjustment to find a point satisfying Eq. (13) within the compensation area. Therefore in planning, the support point can be selected in term of $C(n)=C_k(n)$, while static stability is satisfied through actively adjusting the CG position.

4.2.4 Foothold determination. The term $C(n)$ defines a range in which any feasible foothold can be selected as a support point for the next support state S($n+1$). Such a defined range is also called *foot range*. It is clear that a foot range closely associates with the given support state and its initial foot condition. If the compensation mechanism is constructed appropriately so that Eq. (13) is true, the foot range will be determined only by kinematic constraint ($C_k(n)$). From Eqs. (11) and (12), we have: $C(n)=R_x-K(1,n)+D(n)$, if $\beta(n)=\beta_m(n)$; $C(n)=D(n)/(1-\beta(n))$, if $\beta(n)>\beta_m(n)$; $C(n)=[R_x-K(1,n)]/\beta(n)$, *if* $\beta(n)<\beta_m(n)$.

After foot range is determined, a suitable foothold can be selected from the foot range. In general, we select the suitable foothold based on such a rule:

Rule 9: *the feasible foothold with the maximum distance from the original support point will always be selected as the next support point for the transfer leg.*

It implies that (i) if the forbidden zone is totally within the foot range, then the foothold with a distance of $C(n)$ will be selected as the support point, (ii) if the forbidden zone crosses the front boundary of the foot range, then the foothold nearest to the forbidden zone will be selected as the support point. This rule tends to make the swing leg get the maximal ability of obstacle avoidance.

4.3 Locomotion control

Once the support point is selected based on the foot range, the real distance covered by the body can be finally determined. Assume that the coordinate of the new support point $[{}^Wx_i^*(n),\ {}^Wy_i^*(n)]$ is positioned through the machine's sensory system. The distance from the current support point to new one, $c(n)$, is

$$c(n)=\sqrt{[{}^Wy_i^*(n)-{}^Wy_i(n)]^2+[{}^Wx_i^*(n)-{}^Wx_i(n)]^2}. \quad (14)$$

Thus the state-period of S(n) will be

$$\Delta t(n)=c(n)/(V_s(n)+V_b(n))=c(n)\beta(n)/V_s(n). \quad (15)$$

The real distance the body translates, $d(n)$, is

$$d(n)=\Delta t(n)V_d(n)=c(n)\alpha(n)\text{ or }c(n)(1-\beta(n)). \quad (16)$$

By virtue of Eq. (16), the origin of the trace-frame at $t^-(n+1)$ can be obtained by

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$$\begin{bmatrix} {}^W x_T(n+1) \\ {}^W y_T(n+1) \end{bmatrix} = \begin{bmatrix} {}^W x_T(n) \\ {}^W y_T(n) \end{bmatrix} + d(n) \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix}. \qquad (17)$$

The foot tip coordinate with respect to {T} and the kinematic margins of all legs at the instance of $t^-(n+1)$ are also obtained by

$$\begin{aligned} &{}^T x_i(n+1) = {}^T x_i(n) - d(n), \\ &{}^T y_i(n+1) = {}^T y_i(n), \text{ if leg } i \text{ is support leg in S}(n). \qquad (18a) \\ &K_i(n+1) = K_i(n) - d(n), \end{aligned}$$

$$\begin{bmatrix} {}^T x_i(n+1) \\ {}^T y_i(n+1) \end{bmatrix} = {}^W_T A(\phi)^{-1} \begin{bmatrix} {}^W x_i(n+1) - {}^W x_T(n+1) \\ {}^W y_i(n+1) - {}^W x_T(n+1) \end{bmatrix},$$

$$K_i(n+1) = K(1,n) + c(n)\beta(n),$$

$$\text{if leg } i \text{ is transfer leg in S}(n). \qquad (18b)$$

Likewise, for an F-state, we have the following relations

$$\begin{cases} {}^T x_i(n+1) = {}^T x_i(n) - d_F(n), \\ {}^T y_i(n+1) = {}^T y_i(n), \\ K_i(n+1) = K_i(n) - d_F(n), \end{cases} \qquad (18c)$$

where $d_F = K(1, n)$ is the distance that body translates in F-state.

4.4 *Strategy of CG adjustment*

In the selection of the foothold, we don't consider the static stability constraint of the machine because the CG is adjustable in the compensation region. The selection of the foothold is only based on the kinematic or geometrical limit. Thus a larger foot range, also a larger obstacle-crossing ability can be obtained. In this section, the strategy of how to adjust the CG position to ensure static stability for the new foothold is studied. Generally, two phases need to be considered in keeping the static stability of the machine. Firstly, during the period of $S(n_0)$, the CG should be adjusted to an appropriate position resulting in the stability margin greater than zero. Secondly, during the shifting of two successive support states such as $ST(n) \to ST(n+1)$ or $SF(n) \to ST(n+1)$, the adjusted CG position should also keep the stability margin at $t^-(n+1)$ greater than zero.

The static stability of S(n) is closely associated with its support pattern. To clearly address the strategy of CG adjustment, we represent the support pattern at the beginning of S(n) as $P^-(n)$ and the support pattern at the end of S(n) as $P^+(n)$. Here the symbols of $P^-(n)$ and $P^+(n)$ also represent the point set covered by the support patterns when observed from the body frame. Furthermore, denote the location of the CG projection on the trace frame at the instance $t^-(n)$ as $g^-(n)$, at $t^+(n)$ as $g^+(n)$, and assume the support state at $t^-(n)$ is stable. In addition, we denote the intersection of support patterns $P^+(n)$ and $P^-(n+1)$ as A, the intersection between $P^+(n)$ and the compensation region (denoted by $\Re$) as B, and the intersection between $P^-(n+1)$ and $\Re$ as C. We have the following relationship

$$\begin{aligned} &A = P^+(n) \cap P^-(n+1), \\ &B = P^+(n) \cap \Re, \qquad (19) \\ &C = P^-(n+1) \cap \Re. \end{aligned}$$

It is clear that (1) if $g^+(n) \in B$, then support state S(n) is

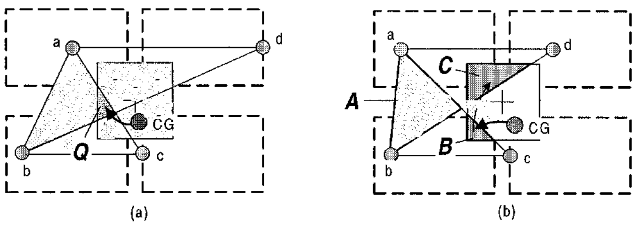

Fig. 6. Schematic diagram of the strategy for CG adjustment where a-b-c is the support pattern at $t^+(n)$, and a-b-d is the support pattern at $t^-(n+1)$; (a) $Q \neq 0$, (b) $Q = 0$.

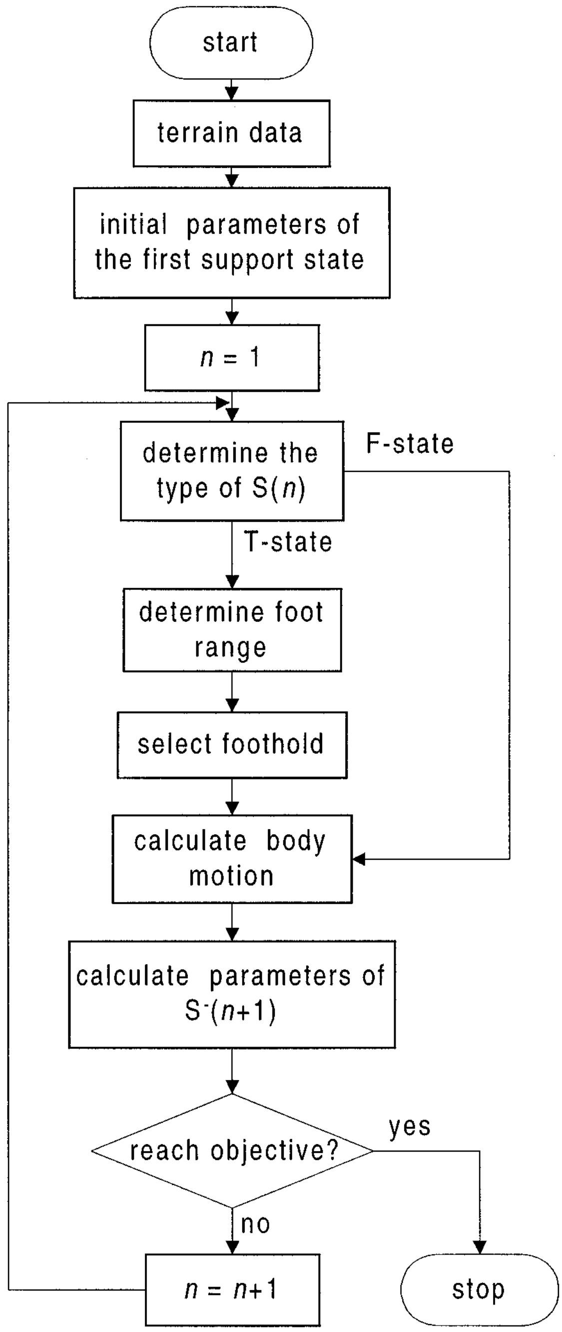

Fig. 7. Flowchart of determining support points of transfer leg.

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stable at $t^+(n)$, (ii) if $g^+(n) \in C$, then $S(n+1)$ at instance $t^-(n+1)$ is stable, and (iii) if $g^+(n) \in A$, then the shifting from $S(n)$ to $S(n+1)$ is stable. Therefore to guarantee static stability of both $S(n)$ and the shifting from $S(n)$ to $S(n+1)$, the CG location at $t^+(n)$ should satisfy

$$g^+(n) \in Q = A \cap B \cap C = P^+(n) \cap P^-(n+1) \cap \Re \quad (20)$$

where Q is the intersection area among A, B and C. For a stable $S(n)$ at $t^-(n)$, if $g^-(n) \in Q$ and let $g^+(n) = g^-(n)$, then CG can satisfy the stability requirement during the period of $S(n)$ without any adjustment. However, if $g^-(n) \notin Q$, the CG location must be adjusted to $g^+(n)$, a new position satisfying Eq. (20).

It should be noted that, in the terrain containing a large number of forbidden zones, it is possible that $Q = 0$. In that case, it is necessary to insert a *transitional state* $S([n])$. Since $S([n])$ is with full support legs, the support pattern $P([n])$ covers $P^+(n)$, $P^-(n+1)$ and $\Re$. Thus we can get

$$\begin{aligned} g^+(n) &= g^-([n]) \\ &= P^-([n]) \cap P^+(n) \cap \Re = P^+(n) \cap \Re, \\ g^+([n]) &= g^-(n+1) \\ &= P^+([n]) \cap P^-(n+1) \cap \Re = P^-(n+1) \cap \Re. \end{aligned} \quad (21)$$

It means that if $Q = 0$, CG will first move to a position within B, $g^+(n)$. Consequently, it moves to the final position

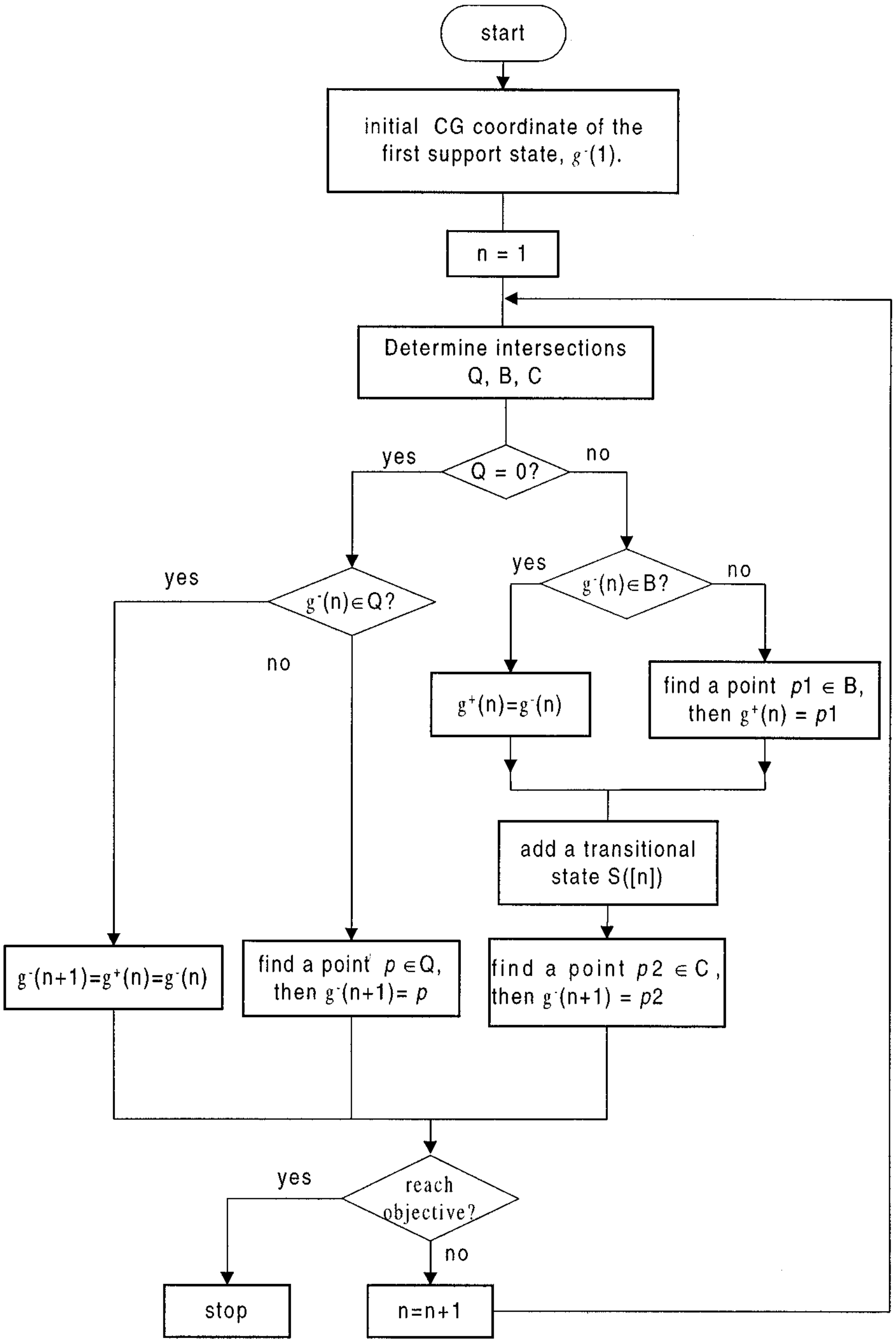

Fig. 8. Flowchart of CG adjustment.

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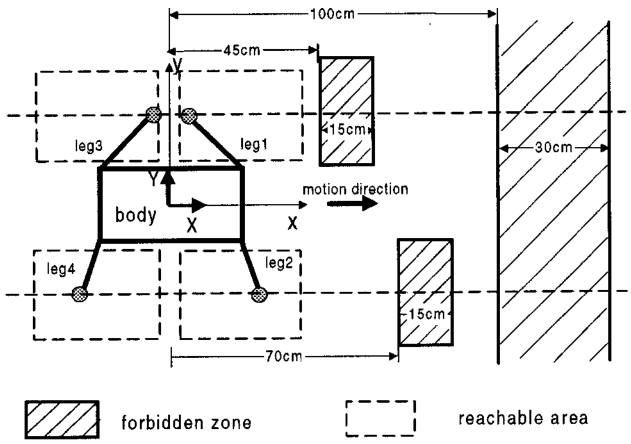

Fig. 9. Simulation model of NTU-Q1 and typical rough terrain.

within C, $g^+([n])$, through the transitional state S($[n]$). Note that $C \neq 0$ and $B \neq 0$ due to the limitation of the foot range on the body motion and the selection of the new supporting point.

The strategy of the CG adjustment has been summarized by virtue of Figure 6.

5. RECURSIVE ALGORITHM

We have verified that the machine is capable of moving from $S^-(n)$ to $S^-(n+1)$ with statically stable manner if CG adjustment is used. The locomotion during $S(n)$ only depends on its initial foot condition and the local terrain condition. It means that if information of $S^-(1)$ is known we can plan the locomotion of all later support states using a recursive way until the machine reaches the objective location.

Figures 7 and 8 show the flowchart of the proposed recursive algorithm. The feature of this recursive algorithm is that the determination of supporting point (Fig. 7) is free from the consideration of static stability. Static stability of the machine is realized through a CG adjustment strategy (Fig. 8). Combination of both foothold selection and CG position adjustment will produce a complete gait. The gait can be generated off-line or on-line. In the case of off-line, a separate computer is used to calculate the coordinates of the foothold based on terrain data and then the CG adjustment position according to the obtained foothold coordinates. The on-board computer then combines these results together to generate a complete gait. This case requires terrain data known in advance. In the case of on-line, the on-board computer implemented CG adjusting strategy immediately after each step. The machine moves forward into $S(n+1)$ by virtue of the location of the foothold and the CG coordinate obtained in $S(n)$. In that case, only required is terrain data in the next step.

6. SIMULATION RESULTS

A gait generation algorithm has been proposed and implemented by virtue of Maple V.[21] The animation is conducted by using UNIX system and displayed on a SUN-station through a commercial software package DADS, which also performs dynamic and kinematic analysis of the prototype. The computer model of NTU-Q1 as shown in Fig. 1 is used and only locomotion with zero crab angle is considered during the simulation. The program allows the user to set up the terrain data, to select desired β-factor and/or to vary initial foot condition according to the requirement, testing the terrain adaptivity of the prototype. From the initial position, the machine walks over the rough terrain until the given objective location is reached.

As an example, Figure 9 shows a schematic representation for the system including the machine and a typical rough terrain, in which the shadow area presents the forbidden zone. Note that the movable mass within the body is not shown in this figure. The initial foot condition in this example is, $KM_1(1)=0.0$, $KM_2(1)=24.0$ cm, $KM_3(1)=36.0$ cm and $KM_4(1)=12.0$ cm and the maximum distance from the initial point to the objective location covered by the body frame is 270 cm. Figure 10(a)–(j) shows ten representative phases of this simulation experiment with a swing speed of the transfer leg, $V_s=25$ cm/s, and the desired β-factor, $\beta=0.8$. Here, the transfer leg is indicated with an arrow near that leg. In this example, the negative stability margin or deadlock situation would occur in Fig. 10(e)–(j) if without compensation of stability margin. These cases can also be monitored at corresponding time of these phases in Fig. 11, which shows the comparison of stability margins with and without compensation. The trajectories of the CG adjustment relative to the trace-frame in the longitudinal and lateral direction are shown in Fig. 12. The foot tip trajectories of the four legs are plotted in Fig. 13. Comparing Figs. 10 through 13, it can be found that, after compensation of stability margin, the presented algorithm tends to extend the transfer leg to its maximum reach at each T-state. This means that the machine may obtain a bigger terrain adaptivity.

The above simulation includes 58 support states in total. Of them there is one transitional state which occurs at the interval of $\Delta t=27.0$ s ~ 29.6 s. This transitional state is aimed to help the machine to shift the CG into new support polygon so that the leg reaching its kinematic limit can be lifted in the next step. However, it is often undesired having transitional state because it causes the discontinuity of the body motion. Transitional state can be removed if a bigger β-factor value is used.

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Several different terrain conditions have been investigated with the proposed algorithm. As long as the maximum width of the forbidden zone is less than the stroke of machines' reachable area, no deadlock cases have been found even though the machine traverses on a continuous forbidden zone such as ditch. For very rough terrain condition, the algorithm will automatically adjust the value of $\beta(n)$ around the given β for the continuity of body motion. If the terrain becomes perfect, the algorithm will produce a periodic gait for locomotion of the machine. Therefore the algorithm can provide machine with a reasonable walking speed over rough terrain. These features of the algorithm are highly desirable in some applications.

7. CONCLUSIONS

This paper has presented an alternative method for improving the terrain adaptivity of a multi-legged machine traveling over rough terrain. It is achieved through a 2D CG adjustment, compensating the stability margin according to terrain condition. An algorithm for the gait planning under the above consideration has also been developed and the

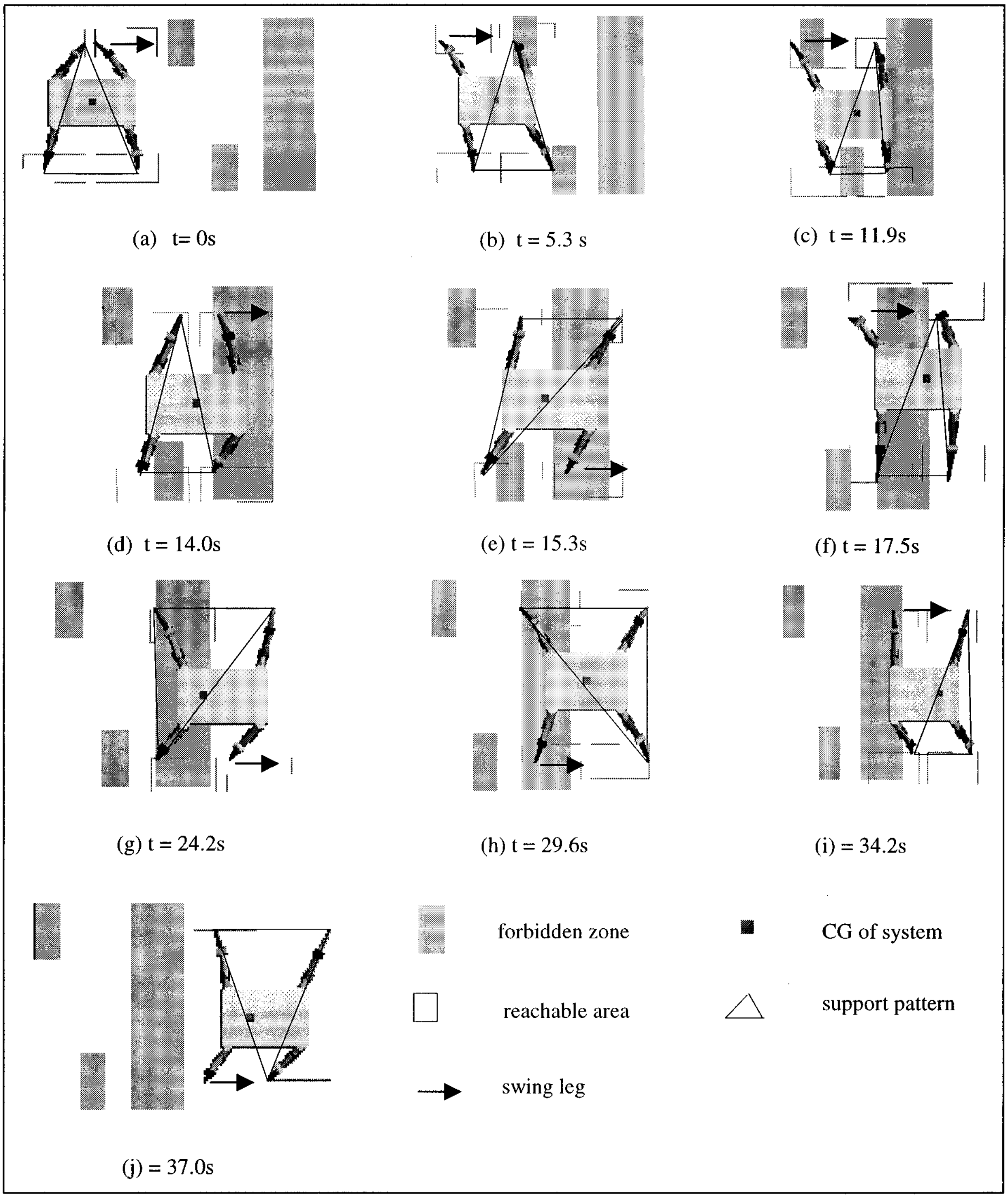

Fig. 10. Walking phases of NTU-Q1 over a typical rough terrain.

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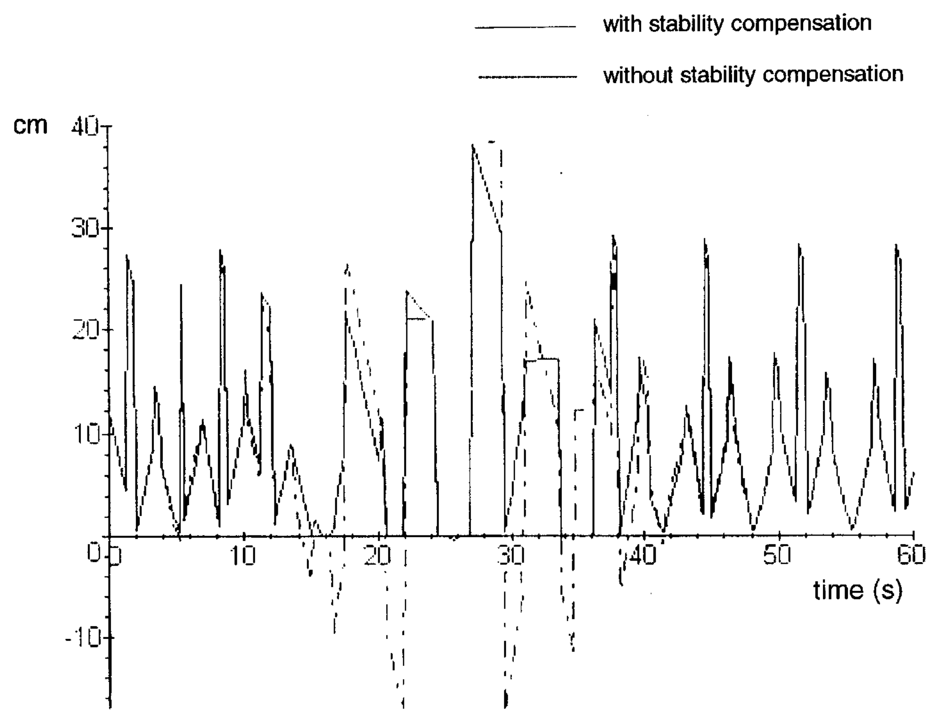

Fig. 11. Comparison of the stability margins with and without compensation (at $\beta = 0.8$).

simulation program to realize the algorithm has been written. This algorithm determines footholds based on the current support pattern rather than over the whole trajectory. With the stability compensation, the determined footholds are capable of maintaining the machine static stability during the current support state as well as the shifting from the current support state to the proceeding one. In this way, the possible deadlock situations could be avoided unless the forbidden zone is larger than its reachable area. Some simulation work has been implemented to test the validity of the proposed algorithm.

The concept of stability margin compensation has been applied to the design of the quadruped robot NTU-Q1. Since the above algorithm provides a way to control stability margin actively, it is believed that NTU-Q1 will possess a larger degree of freedom to accommodate rough terrain during locomotion. As the simulation result has shown, it is also possible that the machine may be able to achieve a larger adaptivity on rough terrain at a reasonable higher body speed.

It should be pointed out that the trajectory of the CG adjustment is not unique. Although a feasible CG trajectory has been given in this paper, apparently, it may not be the optimal one. Further research is therefore necessary in finding the strategy to achieve the optimal trajectory of the CG adjustment based on the given criteria such as minimum adjusting distance and smoothness.

As a final remark, although only a quadruped robot and a 2D terrain are considered in the article, the proposed method can also be extended to other multi-legged systems such as six-legged robots, and the terrain containing 3D obstacle.

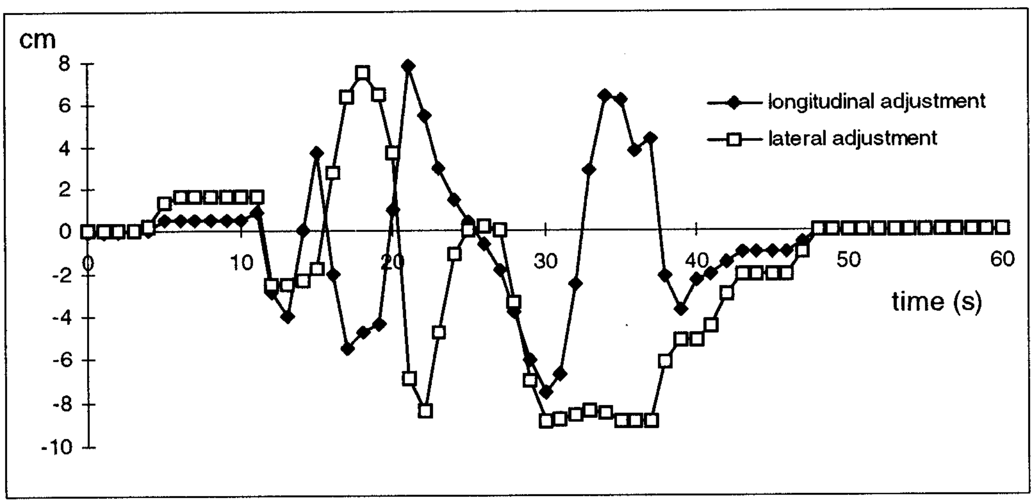

Fig. 12. CG trajectory in longitudinal and lateral directions with respect to {T}.

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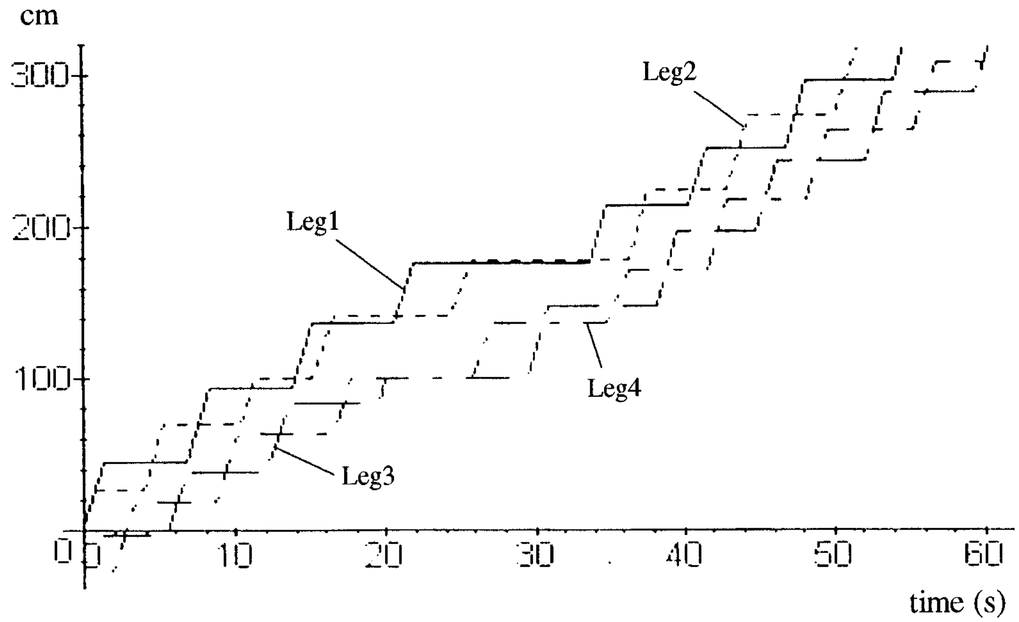

Fig. 13. Foot tip trajectory of four legs with β=0.8.

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APPENDIX: NOMENCLATURE

A: intersection area of $P^+(n)$ and $P^-(n)$.
B: intersection area of $P^+(n)$ and $\Re$.
{B} body frame.
C: intersection area of $P^-(n+1)$ and $\Re$.
$C(n)$: maximum distance covered by swing leg in S(n) under geometry, kinematic, and stability constraints.
$C_s(n)$: maximum distance covered by swing leg in S(n) under stability constraint.
$C_k(n)$: maximum distance covered by swing leg in S(n) under kinematic constraint.
$C_g(n)$: maximum distance covered by swing leg in S(n) under geometry constraint.
C_x: the length of compensation area in longitudinal axis.
C_y the length of compensation area in lateral axis.
$c(n)$ the distance from the current support point to selected foothold.

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$d_F(n)$ maximum distance that body can translates in F-state.
$d(n)$ real distance body can translate in T-state.
F: F-state, one kind of support state, in which all legs are supporting legs.
$g(n)$: CG position in S(n).
$g^+(n)$: CG position at $t^+(n)$
$g^-(n)$: CG position at $t^-(n)$.
$g_x(n)$: x coordinate of CG respect to trace frame at $t^-(n)$.
$g_y(n)$: y coordinate of CG respect to trace frame at $t^-(n)$.
$KM_i(n)$: kinematic margin of leg i in S(n).
$K(i, n)$: the i-th kinematic margin in the orders from small to big in S(n).
${}^W_TA(\phi)$ rotational matrix from {T} to {W}.
P pitch of legs.
P_x longitudinal pitch.
$P(n)$: support pattern of S(n).
$P^+(n)$: the area covered by support pattern when observed at $t^+(n)$ from body frame.
$P^-(n)$: the area covered by support pattern when observed at $t^-(n)$ from body frame.
Q: the intersection area among A, B, and C.
R_x: longitudinal stroke.
R_y: lateral stroke.
$\Re$: the area covered by compensation region.
$SM_l(n)$: minimum front stability margin of S(n).
S(n): the n-th support state.
T: T-state, one kind of support state, in which there are at least one transfer leg.
{T}: trace frame.
$t^-(n)$: the time moment of shifting from S($n-1$) to S(n).
$t^+(n)$: the time moment of shifting from S(n) to S($n+1$).
$\Delta t(n)$: state period of S(n).
${}^Bx_i(n)$: x coordinate of foot tip of leg i with respect to body frame in S(n).
${}^By_i(n)$: y coordinate of foot tip of leg i with respect to body frame in S(n).
${}^Bx_G(n)$: x coordinate of the CG with respect to body frame in S(n).
${}^By_G(n)$: y coordinate of the CG with respect to body frame in S(n).
${}^Wx_i(n)$: x coordinate of foot tip of leg i with respect to global frame in S(n).
${}^Wy_i(n)$: y coordinate of foot tip of leg i with respect to global frame in S(n).
${}^Wx_T(n)$: x coordinate of the origin of the trace-frame with respect to global frame in S(n).
${}^Wy_T(n)$: y coordinate of the origin of the trace-frame with respect to global frame in S(n).
$V_S(n)$: average swing speed.
$V_b(n)$: average body speed.
W distance between two side central lines of lateral stroke.
{W}: global frame.
[n]: index of transitional state.
ϕ: direction angle of {T} relative to {W}.
$\alpha(n)$: α-factor in S(n).
$\beta(n)$: β-factor in S(n).
β: desired β-factor.
$\beta_m(n)$: β-factor associated with the maximum $C_k(n)$.