Advanced Robotics, Vol. 15, No. 7, pp. 729–748 (2001)

Full paper

Terrain evaluation and its application to path planning for walking machines

SHAOPING BAI * and K. H. LOW

School of Mechanical and Production Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore

Received 6 November 2000; accepted 13 February 2001

Abstract—Motion planning of walking machines normally contains two aspects: gait planning and body trajectory planning. When generating an optimal body trajectory on natural terrain, the leg movement must be taken into account. Due to the large searching space resulting from the combination of leg movement and terrain conditions, it is quite time consuming to produce an optimal result of body trajectory planning. In this paper, an effective method of body trajectory planning is introduced by virtue of a terrain evaluation that links the terrain conditions with machine mobility. Based on the evaluation, a potential field is constructed for graph searching. Best first planning (BFP) is adopted to search the optimal path. The path generated with the proposed method could offer the best opportunity to place the machine feet moving with a certain gait over a rough terrain. The assumptions and shortages associated with the present work are also discussed.

Keywords: Path planning; walking machines; terrain evaluation; free gaits; machine mobility.

1. INTRODUCTION

The motion planning of legged locomotion systems normally contains two aspects: gait planning and body trajectory planning. In gait planning, leg sequences are specified so that the legged system can move forward with coordinated leg motion. Considerable research has been reported on gait planning [1–7]. For body trajectory planning, the task is to find a path that enables the machine to smoothly traverse a terrain. A well-planned path will not only shorten the travel distance, but also facilitate locomotion by eliminating any deadlock [6]. However, few research has been conducted on the methods of path generation for walking machines. As far as the authors are aware, path-generation related studies can only be found in the works of [4, 8]. In Lee and Song's [4] works, the locomotion of

*To whom correspondence should be addressed. E-mail: mspbai@ntu.edu.sg

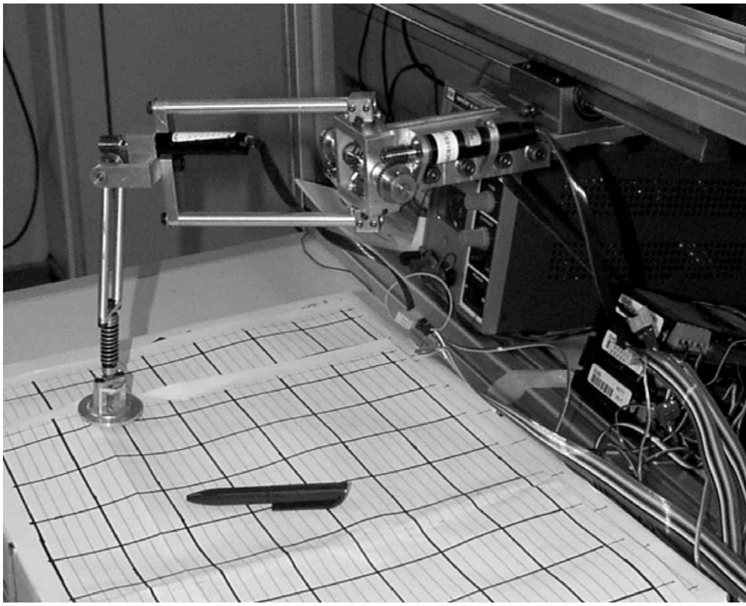

Figure 1. A leg of LAVA under testing.

a quadruped in an obstacle-strewn environment was studied and a path based on the Bezier curves was generated so that its shape can be easily adjusted to avoid obstacles. Since the Bezier curve is formed by some ‘control’ points which must be given manually, this method is actually a path smoothing process rather than path generation. In Chen’s works [8], an ordinal optimization method was introduced to the path generation of walking machines. The main idea of this method is to search for a path by considering a limited number of foothold samples. This method significantly reduces the computation time when compared with the best-path schemes. Nevertheless, the method is merely an off-line planning.

In this work, a method of path planning is developed that focuses on efficiently finding a path with a high possibility of foot placement. The work was conducted for a walking machine named LAVA (Legged Autonomous Vehicular Agent) that is currently being developed in the Robotics Research Center at NTU [9] (see Fig. 1 for the testing platform of a leg.) In our study, the functional structure of the motion planning system is divided into five hierarchical levels (see Fig. 2):

- *Task planning*: to produce the desired actions accomplishing specific tasks.
- *Path planning*: to generate a feasible route for the walking machine according to a specific task. It is required to provide the machine with a path that has a high possibility to place feet on the ground as well as a short traveling distance.
- *Gait planning*: to determine static stable gaits involving the sequence of lifting and placement of the gait as well as the position where the leg is placed. Minor modification on the body path can be performed to meet a certain gait pattern.

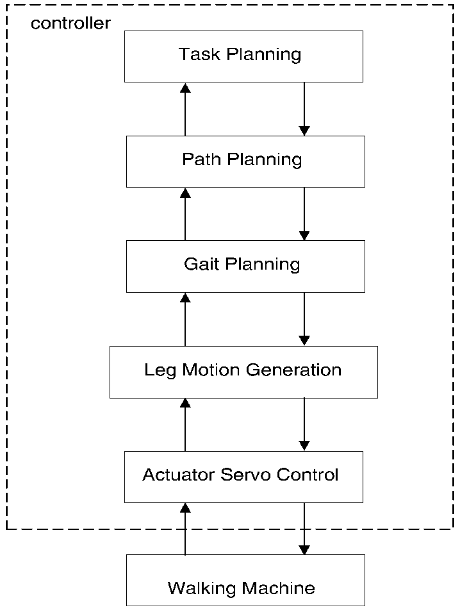

Figure 2. Hierarchical structure of the motion controller.

- *Generation of leg motion*: to handle the kinematics (and eventually dynamics) of the robot and to generate feasible physical parameters according to desired motion parameters given by the higher levels
- *Actuator servo control*: to produce a desired actuator displacement according to the physical parameters of motion generation level.

The main idea of our path planning consists of terrain evaluation and a potential-guided searching method. In terrain evaluation, the terrain information will be redefined for a new terrain representation relative to the machine. A potential field will then be generated using the evaluation results. The commonly known best first planning (BFP) [10] will also be adopted to search for an optimal path. Such a path is expected to provide the best opportunity for the machine to place its feet while moving with a certain gait over a rough terrain.

In this paper, the problem of path planning for walking machines is stated in Section 2. The principle of terrain evaluation is introduced in Section 3. In Section 4, a method of path planning is developed, which includes the construction of the potential field and the procedure of graph searching. The simulation results using the proposed methodology are presented in Section 5. Finally, discussions and conclusion are given in Section 6.

2. PROBLEM STATEMENT

The path planning in this work is mainly carried out for quadrupeds ($n = 4$). As shown in Fig. 3, it is modeled as a point of center of gravity (CG) surrounded by

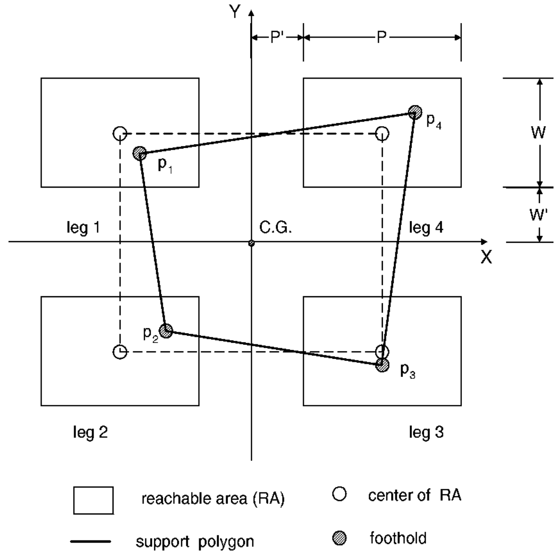

Figure 3. Reachable areas for path planning of a quadruped ($n = 4$). All legs are assumed to be identical.

four identical rectangles with dimensions of $P \times W$ units, which specify the leg's reachable area (RA). A two-dimensional terrain model in which inaccessible areas are randomly located (see Fig. 4) is applied to the planning. The inaccessible areas represent those physical obstacles such as a rock, hole, ditch, etc. The terrain to be traversed is divided into square cells of 1 unit in length. Each cell is identified with a pair of integers (i, j). Depending on the properties of terrain, a cell is either permitted or forbidden for foot placement. The terrain considered in each stage of path planning is about three to four body lengths and it could be a segment of the whole map.

The main task of the current path planning is to find a path that enables the machine to smoothly traverse a terrain. It is well known that there is a wide range of methods of path generation, such as dynamic programming [11], artificial potential method [12], and also methods based on harmonic function, penalty function, heuristic planning, etc. [13, 14]. Some methods have successfully been applied to wheeled vehicles. An example is the free space method in which a path is generated in the virtual free space [15] where no obstacle exists. However, these methods cannot be directly applied to path generation of walking machines. There are two main problems of such a direct application. One is that one may not find a possible path due to the complexity of the terrain even if there exists one in the terrain. Take a terrain with a long ditch as shown in Fig. 4 as an example. In spite of the assumption that this ditch can be crossed over by a machine, a continuous path from S to G cannot be produced by the free space method since the free space is not connected. Another problem is that the path found may not be optimal for legged robots since the mobility of walking machines is higher than wheeled robots on the same scale.

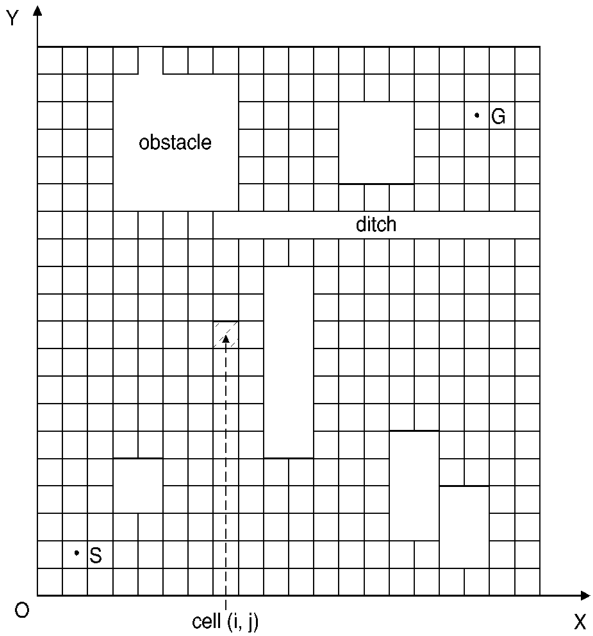

Figure 4. Terrain model for path planning. Each cell is identified with a pair of integers (i, j). Rectangular blocks are inaccessible areas. Letters S and G stand for the starting and goal position, respectively.

A walking machine can cross over some small obstacles instead of avoiding them by all of its body parts.

The above-stated problems suggest that the issue of leg motion should be considered in the path planning of walking machines. However, the task will be very time consuming for cases that combine terrain conditions and leg motion (lifting and placement). For an n-legged machine traversing a terrain discretized into cells, if the number of cells within the RA of a single leg is equal to k, the maximum number of choices for leg placement in each step (leg transfer and placement) is:

$$N = \sum_{j=0}^{n-3} k^j C_n^j, \tag{1}$$

where C_n^j is the combination of n taken j at a time and j is the number of legs lifted at the same time. Supposing a segment of path takes m steps to travel, the total number of choices may be N^m. For example, there are 1.34×10^{16} choices for a quadruped to walk in 10 steps ($m = 10$) if there are 10 cells within a RA ($k = 10$). Such a big number of choices imply intensive computation. Therefore it is difficult to find an optimal path in an efficient way. This could be a reason why the body trajectory of TITAN over a rough terrain was manually designed [2]. With an ordinal optimization method [8], a feasible path can be found in less computation time if compared with the best-path schemes. Nevertheless, the gait sequence is fixed with respect the path generated. This made the machine less flexible when there is a disturbance in the path and therefore its application in on-line planning is limited.

In this paper, a new approach of path planning for the walking machine is proposed. We do not deal with path planning directly with the leg movement (lifting and placement) of a specific gait. Instead, we try to find a path by evaluating the terrain conditions with respect to features of leg movement. The evaluating results represent the possibility to place a leg on the ground. By searching for points with a high possibility for foot placement, a feasible path will be found. With such an approach, the intensive computation resulting from the direct consideration of leg motion could be avoided.

3. TERRAIN EVALUATION

The following assumptions are made in terrain evaluation:

- The heights of obstacles are low so that the legs of walking machine can step over them. Therefore, the height constraint of obstacles to the legs is not an issue of concern here.
- The machine is in the phase of translating motion. The task of body rotation shall be fulfilled in the gait planning (see [2, 3, 16] for details of gait planning.)
- Movements like wall climbing and stair walking are not considered in the present work.

It is also noted that the static stability of a walking machine is indeed a major concern of gait planning. It is not involved in the present terrain evaluation.

In the following subsections, a formula of terrain evaluation is derived through three phases: cell availability, area availability and terrain accessibility. The cell availability measures to what extent a single cell can become a foothold. It reflects the terrain property. The area availability deals with the possibility of placing a foot on a certain area. This measure still reflects the general terrain property. The terrain accessibility synthesizes the area availability over the reachable areas of all legs to get a specific indicator of terrain conditions relative to a certain machine.

3.1. Cell availability A_c

Since the footholds of a walking machine are a set of discretized cells, foothold selection is directly dependent on the property of a single cell. The evaluation of a single cell is the basis for terrain evaluation. We introduce the measure of *cell availability* to evaluate the extent to which a cell is available to become a foothold.

As shown in Fig. 5 (also Fig. 4), cell (i, j) is a desired foothold in the discretized terrain model. Each cell in the terrain is either permitted or forbidden for foot

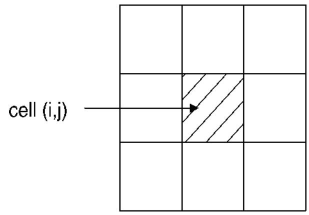

Figure 5. A single cell and its neighbors in a terrain.

placement. This property of a cell $p(i, j)$ is denoted with a function $f(i, j)$ as:

$$f(i,j) = \begin{cases} 1 & \text{if the cell is permitted} \\ 0 & \text{if the cell is forbidden.} \end{cases} \tag{2}$$

In terms of leg motion, a permitted cell can become a foothold. On the other hand, although a forbidden cell cannot be selected as a foothold, an alternative to this cell can be found from surrounding cells with little influence on the gait. In this aspect, a forbidden cell can be *partly* available to the foothold selection in gait planning. If the availability of a permitted cell is defined as 1, the availability of a forbidden cell can be evaluated by a fraction of the permitted cells in all cells around. Let A_c represent the *availability* of a cell to become a foothold, the value of A_c is:

$$A_c(p) = \begin{cases} 1 & \text{if } f(i,j) = 1 \\ N_p/N_t & \text{if } f(i,j) = 0, \end{cases} \tag{3}$$

where N_t is the total number of cells in a region containing the cell $p = p(i, j)$ in the considered terrain **C** (the set of all cells), and N_p is the total number of permitted cells among these N_t cells. Considering the boundary condition (marginal cells of the terrain map) of this region, (3) is then modified to:

$$A_c(p) = \begin{cases} 1 & \text{if } f(i,j) = 1 \\ \frac{\sum_{i=i_L}^{i_H} \sum_{j=j_L}^{j_H} f(i,j)}{(i_H - i_L)(j_H - j_L)} & \text{if } f(i,j) = 0, \end{cases} \tag{4}$$

where i_H, i_L, j_H and j_L denote the upper and lower boundary for i and j, respectively. These boundaries are determined according to the cell position based on Table 1, where i_{max} and i_{min} stand, respectively, for the upper and lower limit of the index of cells in a certain area. Three calculation examples of cell availability are given in Fig. 6. The cell availability is equal to 1 for the case shown in Fig. 6a, and equal to 2/3 in both Fig. 6b and 6c.

3.2. Area availability (A_a)

The motion of legs of a walking machine is within a certain area, the RA. The possibility of a walking machine finding a foothold for a leg is dependent on the

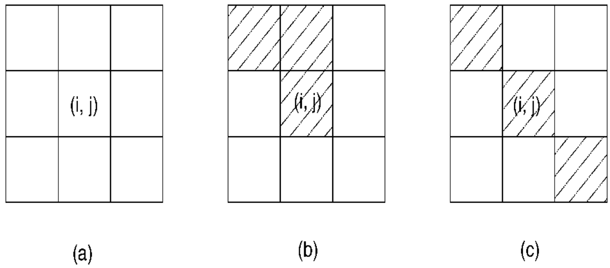

Figure 6. Calculation examples of cell availability: (a) $A_c(i, j) = 1$, (b) and (c) $A_c(i, j) = 2/3$. Shadowed cells are forbidden for foot placement.

Table 1.
Determination of index boundaries

	$i = i_{min}$	$i_{min} < i < i_{max}$	$i = i_{max}$
i_L	i	$i - 1$	$i - 1$
i_H	$i + 1$	$i + 1$	i

combination of cells in this area. We use *area availability* to describe the possibility of foot placement in a certain area. It is defined as the sum of the availability of all cells in this area.

Let us assume that an area contains $M \times N$ cells and all of them are reachable to the leg considered. Since the maximum accessibility of this area is equal to $M \times N$, the area availability A_a can be normalized as:

$$A_a = \frac{1}{NM} \sum_{i=1}^{N} \sum_{j=1}^{M} A_c(p), \qquad p = p(i, j). \tag{5}$$

Obviously, $A_a = 1$ implies an area containing all permitted cells, while $A_a = 0$ is an area of all forbidden cells. The value of area availability obtained by (5) contains not only information of the number of permitted cells but also that of their distribution in the considered area.

For the two areas of Fig. 6b and 6c in which $M = N = 3$, the values for A_a are equal to 0.82 and 0.85, respectively. Two more examples with $A_a = 0.91$ and $A_a = 0.98$ are given in Fig. 7 ($M = 7$, $N = 5$). As observed from these examples, the areas with equal numbers of available footholds but with differences in their distribution can be distinguished by the area availability.

3.3. Terrain accessibility for machine traversing (A_t)

A cell of a terrain could be accessed by the CG if footholds can be found from cells around for all legs. Terrain accessibility, describing the probability of a machine to access a certain terrain, is introduced by considering the product of the availability over all the RAs of the machine. For an *n*-legged machine, the terrain accessibility

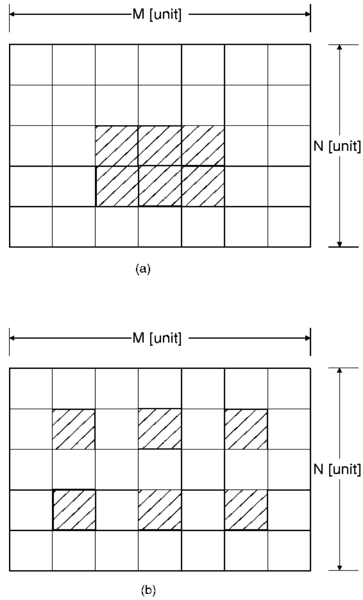

Figure 7. Evaluation examples for area availability. The area availability is 0.91 in (a) and 0.98 in (b), respectively. Note that M and N are numbers of cells in the two directions of the RA.

of cell $p(i, j)$ is:

$$A_{\mathrm{t}}(p) = \prod_{q=1}^{n} A_{\mathrm{a}q}, \quad p = p(i, j), \tag{6}$$

where q is the index of legs. According to (5), the availability of a RA to leg q is obtained as:

$$A_{\mathrm{a}q} = \frac{1}{PW} \sum_{i_q = i_{0q}}^{i_{fq}} \sum_{j_q = j_{0q}}^{j_{fq}} A_{\mathrm{c}}(p_q), \quad p_q = p(i_q, j_q), \tag{7}$$

where (i_{0q}, j_{0q}) and (i_{fq}, j_{fq}) denote the boundaries which are varied with leg indices. With (6) and (7), the terrain accessibility of a walking machine can now derived as:

$$A_{\mathrm{t}}(p) = \frac{1}{(PW)^n} \prod_{q=1}^{n} \left(\sum_{i_q = i_{0q}}^{i_{fq}} \sum_{j_q = j_{0q}}^{j_{fq}} A_{\mathrm{c}}(p_q) \right), \quad p = p(i, j), \quad p_q = p(i_q, j_q). \tag{8}$$

Equation (8) evaluates the terrain condition for the motion planning with respect to machine mobility, i.e. the capability of terrain traversing. Taking the terrain in Fig. 8 as an example (refer to Fig. 3). Let us consider $n = 4$, $P = 7$ and $W = 5$ (solid-line rectangles), the calculated value A_{t} at cell p is $0.91^4 = 0.68$. The value of A_{t} will decrease to $0.72^4 = 0.26$ if $P = 4$ and $W = 3$ as depicted by

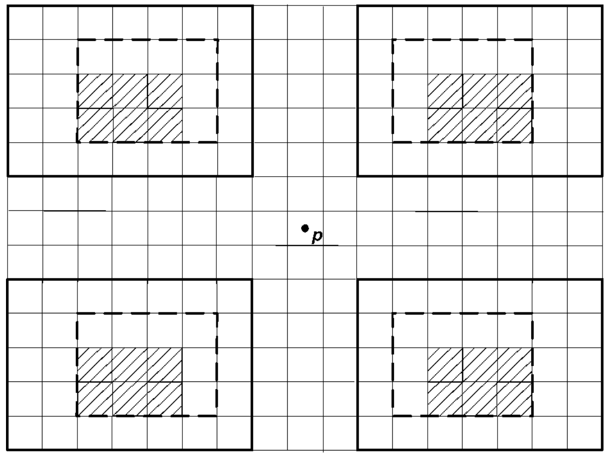

Figure 8. An evaluation example for terrain accessibility.

dash rectangular areas. The difference in the values indicates the contribution of the terrain overcoming capability of the machine in the evaluation.

4. PATH PLANNING INVOLVING POTENTIAL FIELDS

The terrain evaluation introduced in Section 3 is a useful tool for the path planning of walking machines. In this section, a method of path planning will be developed by applying terrain evaluation to the concept of potential fields [12, 13]. The method utilizes the strategy of a potential field with graph searching.

4.1. Potential field approach

The potential field method is a successful heuristic approach which takes the form of functions that are defined as *potential fields*. In this method, the walking machine is represented as a point in configuration space. The moving path of the machine is under the influence of the potential fields. Normally, there are two potentials defined in the field. One potential is defined as the *attractive potential* which pulls the robot toward the goal and the other as the *repulsive potential* which pushes the robot away from the obstacles [13].

The potential field method can be efficient in that it has been developed as an on-line collision avoidance approach [12]. The drawback is that the search can get trapped into local minima of the potential function other than the goal configuration. The drawback can be compensated by combination with graph searching graph searching algorithms. Therefore, the method developed in this work utilizes the strategy of a potential field with graph searching.

4.2. *Construction of the potential field with* A_t

The potential fields are constructed with the accessibility given by (8). The potential function is defined over the terrain as the sum of the attractive potential pulling the machine toward the goal configuration and the repulsive potential pushing the machine away from a forbidden area.

To facilitate the construction of the potential field, the terrain accessibility is converted to the *complexity of terrain* as given by:

$$\overline{A}_{\mathrm{t}}(p) = 1 - A_{\mathrm{t}}(p), \quad p = p(i, j). \tag{9}$$

The repulsive potential is proportional to the terrain complexity:

$$E_{\mathrm{r}}(p) = K_{\mathrm{r}}\overline{A}_{\mathrm{t}}(p), \tag{10}$$

while the attractive potential is proportional to the distance to the goal:

$$E_{\mathrm{a}}(p) = \frac{K_{\mathrm{a}}\|p - p_{\mathrm{g}}\|}{\|p_{\mathrm{s}} - p_{\mathrm{g}}\|}, \tag{11}$$

where subscripts s and g denote the starting and goal point, respectively. Note that K_{r} and K_{a} in (10) and (11) are two positive scaling factors.

The potential of a certain point within the terrain can now be:

$$E(p) = E_{\mathrm{r}}(p) + E_{\mathrm{a}}(p), \quad p = p(i, j). \tag{12}$$

In the potential field given by (12), the simpler the terrain and the closer a point to the goal, the lower the potential of the point. A path should therefore be generated with points of lower potentials. In (10) and (11), the two factors K_{r} and K_{a} actually represent the weight of each potential in the path planning. If K_{r} is greater than K_{a}, the terrain complexity plays an important role in the planning. Otherwise, the distance takes the predominant role if K_{a} is bigger.

4.3. *Path planning and modification*

4.3.1. Path planning. With the potential field, an optimal path can be generated by tracing points with the minimum potential. There are several techniques of potential-guided path planning, such as the depth-first mode, best-first mode, etc. BFP [10] is adopted here as this method is fast and reliable in a two-dimensional searching space [13]. This method guarantees to return a feasible path whenever there exists one in the terrain.

In the method of path searching, two lists are used: one list CLOSE is for visited nodes (cells) and another list OPEN for unexplored nodes (cells) located in the neighborhood of visited nodes. Nodes in OPEN are sorted by increasing values of the potential function. The procedure of BFP is summarized as follows:

Step 1 Install starting cell p_{s} in CLOSE list; insert p_{s} into OPEN; mark p_{s} visited.

Step 2 If OPEN is empty, exit with failure; otherwise, the node with maximum potential is removed from OPEN, denote it as cell p.

Step 3 For every neighbor p_n of p, if $\overline{A}_t(p_n)$ [refer to (9)] is less than a user defined limit $\overline{A}_{max}$ and p_n is not explored, put p_n into CLOSE with a pointer towards p.

Step 4 If the goal point p_g is reached, return the constructed path by tracing the pointers in CLOSE and exit.

Step 5 If neighbors of p are not fully explored, go to Step 3, otherwise go to Step 2.

4.3.2. Path modification. Once the path is generated by the BFP method, it can be modified to shorten the travel distance of the machine. As a matter of fact, the turning points in the primary path are identified according to the direction change in the motion. For any turning point, if the complexities $\overline{A}_t$ of nodes on the line joining its two next turning points are all equal to zero, this turning point can be deleted from the path. By connecting the undeleted turning points, a path which is optimal in travel distance is finally generated. The scheme of the simulation for the body trajectory generation is depicted in Fig. 9.

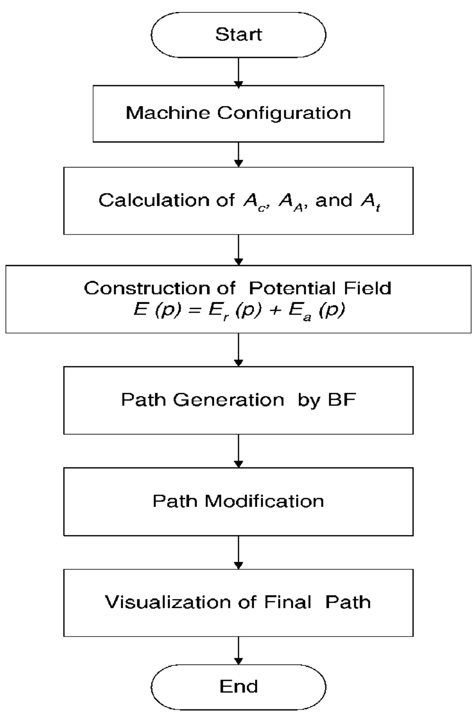

Figure 9. Scheme of path planning by accessibility evaluation.

5. SIMULATION RESULTS

The proposed path planning method has been implemented in ANSI C and *Maple V* [17]. The whole searching process was completed by C and the result was visibly displayed in *Maple*. In the simulation, the dimension of the RA (Fig. 3) is assumed as $P = 5$, $W = 4$, $P' = 4$ and $W' = 3$ units, respectively. The two scaling factors of potentials are $K_r = K_a = 10$. The identical K_r and K_a implies that the two potentials play an equal role in the planning.

5.1. Path planning with fixed $\overline{A}_{max}$

The path planning was simulated by setting the limit of $\overline{A}_t$ to $\overline{A}_{max} = 0.5$. Such a value implies an identical accessibility and complexity of terrain. The simulation

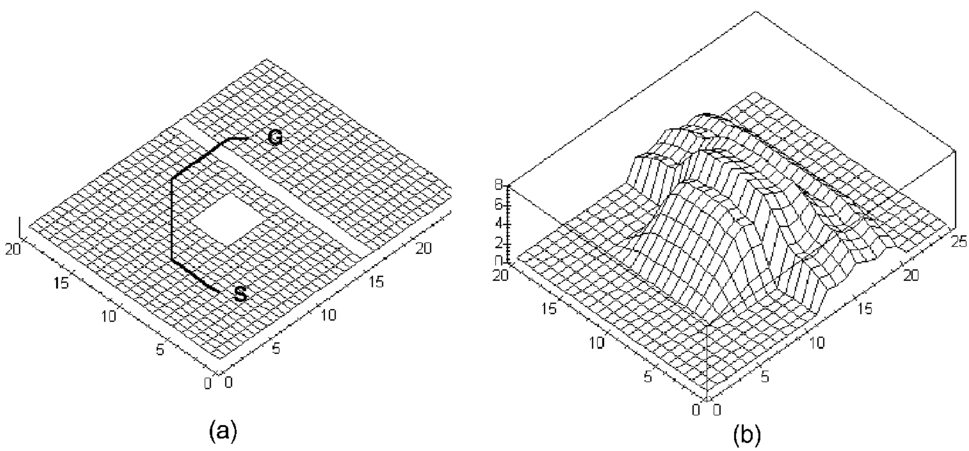

Figure 10. Path planning with $\overline{A}_{max} = 0.5$ for terrain with a simple obstacle and a ditch. The terrain model and generated path are shown together in (a), while the potential field model is shown in (b) for reference.

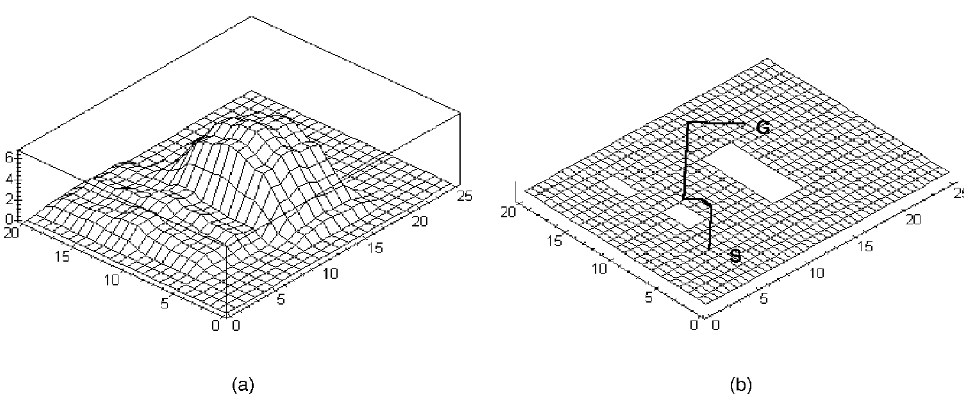

Figure 11. Path planning with $\overline{A}_{max} = 0.5$ for a terrain with multiple obstacles. The potential field model is shown in (a), while the terrain model and generated path are shown together in (b) for clarity.

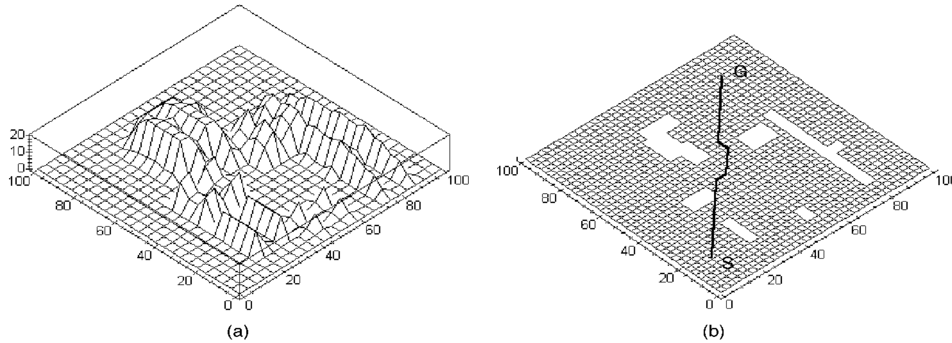

Figure 12. Path planning with $\overline{A}_{\max} = 0.5$ for a complex terrain with multiple obstacles. The potential field model is shown in (a), while the terrain model and generated path are shown together in (b) for clarity.

results of path planning are shown in Figs 10–12. In Fig. 10, only a single obstacle and a narrow ditch are considered and an appropriate result is obtained. In Figs 11 and 12, terrains with multiple obstacles are considered. The simulation demonstrates that a path can be found in any case. It is seen from these results that the method is able to handle the complex terrains.

A careful observation of Fig. 12b shows that there is an intersection of the path with an obstacle. The intersection shows that the machine can cross over the obstacle without avoiding it. Such a feature is clearly shown by Fig. 10 in which the path goes through the ditch. It distinguishes the path planning for the walking machine from that for the wheeled robots. From the simulations, it is seen that the proposed method could effectively generate a path with respect to the property of walking machines.

5.2. *Path planning with variable* $\overline{\mathrm{A}}_{max}$

The influence of the complexity limit $\overline{A}_{\max}$ on the path generated by terrain accessibility was tested by simulation. Paths with different $\overline{A}_{\max}$ have been generated for the terrain shown in Fig. 12. The results shown in Fig. 13 correspond to different values of $\overline{A}_{\max}$ varying in the range of [0, 1]. It is seen that the lower $\overline{A}_{\max}$ implies a path further away from large obstacles. On the other hand, the travel distance increase while $\overline{A}_{\max}$ is smaller. By setting a suitable limit $\overline{A}_{\max}$, the proposed method can produce an optimal path which satisfies different requirements of the traversing capability. This method is therefore very flexible in dealing with machines of different motion capabilities.

It is interesting to note that the result in Fig. 13d is similar to that generated by the free space method [15]. It implies that the method becomes the free space method when the complexity limit $\overline{A}_{\max}$ is defined as zero. It is logical since an area with a zero complexity is a free space. In view of this, the presented method can also be used in a wide range of applications.

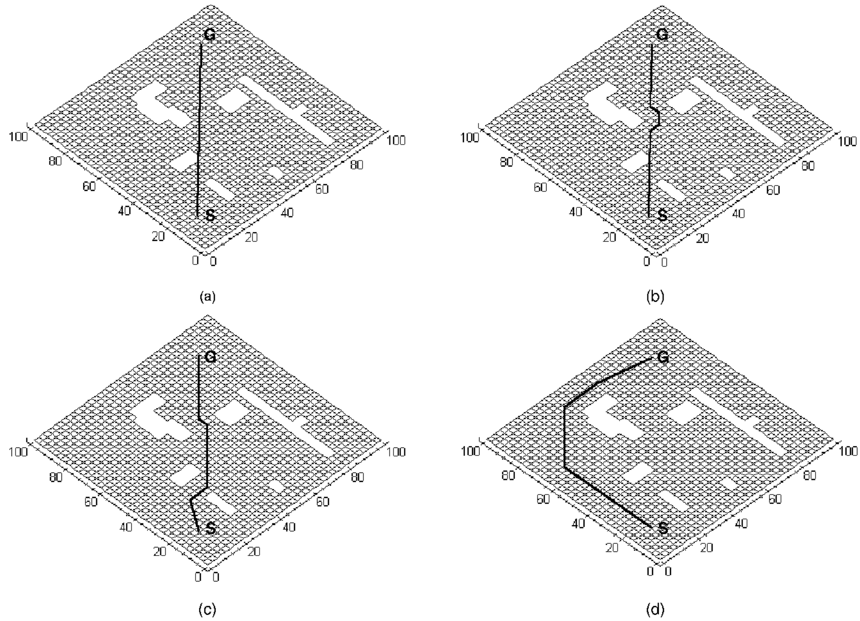

Figure 13. Influence of $\overline{A}_{\max}$ on the path generation: (a) $\overline{A}_{\max} = 1.0$ and travel distance $\widehat{GS} = 98$, (b) $\overline{A}_{\max} = 0.75$ and $\widehat{GS} = 100$, (c) $\overline{A}_{\max} = 0.25$ and $\widehat{GS} = 103$, and (d) $\overline{A}_{\max} = 0.0$ and $\widehat{GS} = 130$.

5.3. Path implementation with gait generation

After considering the path generation with the presented body trajectory planning method, a simulation was carried out to test the machine traversing capability along a planned path with free gaits. The solid line is the body trajectory obtained with the proposed method (see Fig. 13b). The path is smoothed as the dash line shown in Fig. 14a so that less turns are needed. Following this trajectory, the quadruped successfully traversed a rough terrain using the primary free gait [16], as illustrated in Fig. 14b.

5.4. Terrain influence on path generation

The terrain conditions, such as the obstacle size, density, distribution, etc, have a great influence on the path planning results. There is a limitation of terrains to which the path planning method fails. In this work, the limitation is evaluated with respect to the *area density of obstacles* (ADO), which is the percentage of the total area of obstacles in the whole terrain.

Let us first evaluate the simple case when there is only one obstacle located in a certain RA. Assume the obstacle be w_{ob} units in the x direction and be long enough to cover the RA in the y direction (refer to Fig. 3). The area accessibility of a leg to one RA can be obtained from (7) as:

$$A_{\text{a}} = \frac{(P - w_{\text{ob}})W + 2W/3}{WP} = 1 - \frac{1}{P}(w_{\text{ob}} - 2/3), \quad (w_{\text{ob}} \leqslant P). \qquad (13)$$

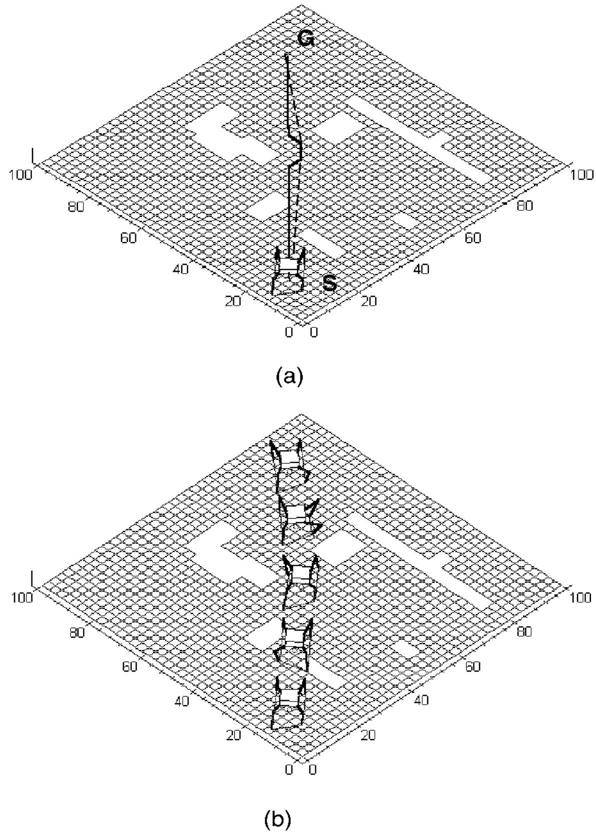

Figure 14. An example of path planning ($\overline{A}_{\max} = 0.5$) together with gait generation: (a) planned path (thick solid line) and initial configuration, (b) snapshots of machine walking, with the free gait, following the planned path in (a).

In such a case, the terrain complexity $\overline{A}_{\rm t}$ is $1 - A_{\rm a}$. Then consider the case when two obstacles are located separately in the reachable areas of two legs. The terrain complexity $\overline{A}_{\rm t}$ in this case becomes $1 - A_{\rm a}^2$. Accordingly, the complexity for the case of three and four obstacles which separately locate in the three or four RAs is $1 - A_{\rm a}^3$ and $1 - A_{\rm a}^4$. The relationship between the complexity and the obstacle size is plotted in Fig. 15. It is seen that the complexity increases with the number of obstacles. On the other hand, the dimension of the obstacles that can be crossed by the walking machine decreases with increasing numbers of obstacles.

Based on these simple cases, the evaluation continues further to the case of randomly located inaccessible areas. The inaccessible areas will be distributed randomly over the whole terrain. Table 2 presents the result of paths generated with respect to the terrain. It provides some guidance for the use of the path planning method. For example, it is quite likely that the planning would fail in finding a feasible path if the ADO exceeds 50%. The result also helps to determine a suitable value of $\overline{A}_{\max}$ with respect to the terrain condition. For instance, if the ADO is about

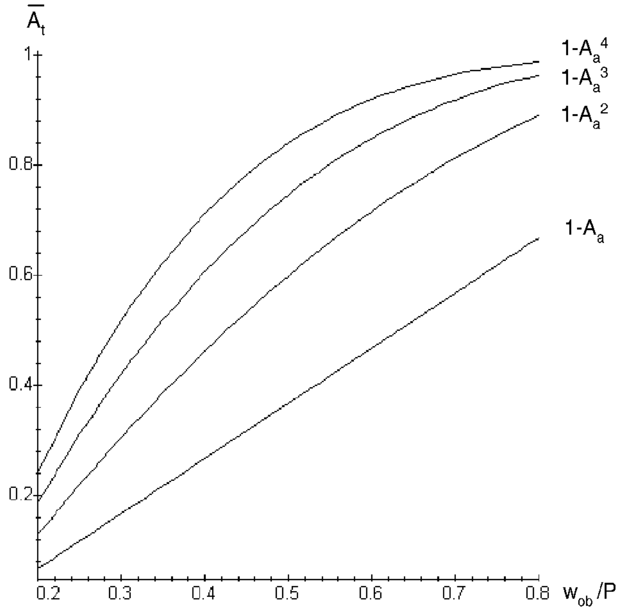

Figure 15. Relationship between complexity and obstacle size.

Table 2.
Outcome of path planning with different ADOs

$\overline{A}_{\mathrm{max}}$	ADO				
	20%	30%	40%	50%	60%
0.5	F	F	F	F	F
0.6	S	F	F	F	F
0.7	S	F	F	F	F
0.8	S	S	F	F	F
0.9	S	S	S	F	F

S, success; F, fail.

30%, $\overline{A}_{\mathrm{max}}$ should be set to 0.8 in order to find the highest number of accessible paths.

6. DISCUSSION AND CONCLUSIONS

The problem of path planning for walking machines has been studied. A method of path planning is proposed based on terrain evaluation. In terrain evaluation, the terrain information of all cells in the discritized model is reconstructed to get a specific indicator of the terrain condition relative to the mobility of a certain machine. The results of terrain evaluation are directly used in building a potential field for legged locomotion. The field is searched by the best-first searching method to generate an optimal path. In addition to the short traveling distance, the path is featured with a high possibility of foot placement. Therefore, the machine following such a path will be flexible in gait selection.

The validity of the proposed method has been tested by simulations. In the simulations, optimal paths were generated in terms of travel distance. In fact, the method becomes a free space method if the maximum terrain complexity is set to zero. This implies that the method can be used in a wide range of applications. With the advanced terrain mapping technologies [18, 19], it is believed that the method developed has a high potential to be put into practical use.

The significance of the proposed method lies in the terrain evaluation. Using terrain evaluation, the searching space of path generation is converted from five-dimensional (two walking directions, leg section, foothold selection, step number) to only three-dimensional (two walking directions and terrain potential). Sequentially, the computational cost is greatly reduced.

In addition, the terrain evaluation method is also useful to determine the influence of terrain on the legged locomotion. The terrain complexity is a general indicator of the terrain information such as obstacle numbers, their sizes and distributions. The limitation of legged locomotion with respect to the terrain complexity has also been analyzed. The analysis result provides some guidance for the use of the path planning method.

In the current stage of the proposed method, several limitations result from our assumptions. The first one is that only translating motion is considered for terrain evaluation. It is logical to include the rotating motion in the evaluation. In the current work, the determination of orientation is a task in the gait layer. Although the simulations demonstrate that the proposed path planning method can produce expected results, there is still a need to explore the effect of orientation consideration on path planning. Secondly, the terrain evaluation in a three-dimensional model will produce more reasonable results than that obtained in the two-dimensional model. However, due to the complexity of legged locomotion, the above limitations have not been overcome in this work. Needless to say, they will be focus of our future efforts.

Acknowledgements

The authors would like to thank the reviewers for their constructive comments and many suggestions to improve the quality of the manuscript. The authors thank Dr. Habo. T. Zielinska for her suggestions and support in motion planning. This work is conducted with the support of the Robotics Research Center, NTU, Singapore.

REFERENCES

1. S. Bai, K. H. Low, G. Seet and T. Zielinska, A new free gait generation for quadrupeds based on primary/secondary gait, in: *Proc. IEEE Int. Conf. on Robotics and Automation*, Detroit, MI, pp. 1371–1376 (1999).

2. S. Hirose, Y. Fukuda and H. Kikuchi, The gait control system of a quadruped walking vehicle, *Adv. Robotics* **1** (4), 289–323 (1986).
3. V. R. Kumar and K. J. Waldron, Adaptive gait control for a walking robot, *J. Robotic Syst.* **6** (1), 49–76 (1989).
4. J. K. Lee and S. M. Song, Path planning and gait of walking machine in an obstacle-strewn environment, *J. Robotic Syst.* **8** (6), 801–827 (1991).
5. W. Lee and D. E. Orin, Omnidirectional supervisory control of a multileggd vehicle using periodic gaits, *IEEE J. Robotics Automat.* **4** (6), 635–642 (1988).
6. R. B. McGhee and G. I. Iswandhi, Adaptive locomotion of a multilegged robot over rough terrain, *IEEE Trans. Syst. Man Cybernet.* **9** (4), 176–182 (1979).
7. S. M. Song and K. J. Waldron, *Machines that Walk: The Adaptive Suspension Vehicle*. MIT Press, Cambridge, MA (1989).
8. C.-H. Chen, V. Kumar and Y.-C. Luo, Motion planning of walking robots using ordinal optimization, *IEEE Robotics Automat. Mag.* **5** (2), 22–32 (1998).
9. J. Heng, T. Zielinska, S. Bai and D. Zhou, Developmental work on a legged machine dedicated for pick and place tasks, in: *Proc. 3rd Int. Conf. on Industrial Automation*, Montreal, pp. 11.12–11.19 (1999).
10. E. Rich and K. Knight, *Artificial Intelligence*. McGraw-Hill, New York (1991).
11. D. J. White, *Dynamic Programming*. Kluwer, Edinburgh (1969).
12. O. Khatib, Real-time obstacle avoidance for manipulator and mobile robots, *Int. J. Robotics Res.* **5**, 90–98 (1986).
13. J. C. Latombe, *Robot Motion Planning*. Kluwer, Boston, MA (1991).
14. A. Morecki and J. Knapczyk, *Basics of Robotics: Theory and Components of Manipulators and Robots*. Springer Verlag, New York (1999).
15. R. A. Brooks, Solving the find-path problem by good representation of free space, *IEEE Trans. Syst. Man Cybernet.* **13** (3), 190–197 (1983).
16. S. Bai, K. H. Low and T. Zielinska, Quadruped free gait generation for straight-line and circular trajectories, *Adv. Robotics* **5** (13), 513–538 (1999).
17. M. B. Monagan, *Maple V Programming Guide*. Springer, New York (1998).
18. M. Hebert, C. Caillas, E. Krotkov and T. Kanade, Terrain mapping for a roving planetary explorer, in: *Proc. IEEE Int. Conf. on Robotics and Automation,* Scottsdale, AZ, USA, pp. 997–1002 (1989).
19. E. Krotkov and R. Hoffman, Terrain mapping for a walking planetary rover, *IEEE Trans. Robotics Automat.* **10** (6), 728–739 (1994).

ABOUT THE AUTHORS

Shaoping Bai received his BS degree in Precision Instrument Engineering from Harbin Institute of Technology, Harbin, China, in 1988, and the MSc degree in Mechanical Engineering from Tsing Hua University, Beijing, China, in 1993. Currently, he is a Research Associate at the School of Mechanical and Production Engineering, Nanyang Technological University, Singapore. His research interests include walking machines, parallel manipulators, mechanism design and simulation.

K. H. Low obtained his MSc and PhD degrees in Mechanical Engineering from the University of Waterloo in 1983 and 1986, respectively. After spending 2 years as a Postdoctoral Fellow at the University of Waterloo, he joined the School of Mechanical and Production Engineering, Nanyang Technological University. His teaching and research interests include robotics, vibrations, and machine and mechanism design. He is the author of about 60 journal papers in the areas of structural dynamics and vibrations, robotics, and power transmission systems.