'95 대한전기학회 하계학술대회 논문집(1995. 7. 20~22)

능률적이고 안정된 로보트 경로계획 알고리즘 개발에 관한 연구

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An Efficient and Robust Robot Path Planning Algorithm

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***Abstract* - This paper presents an efficient and robust robot path planning technique that can always find a path, if one exists, in a densely cluttered, unknown and unstructured obstacle environment. The terrain in which the robot is expected to navigate is represented as a tesselated grid of square cells. The generated path is resolution complete and also resolution optimal once the terrain is fully explored by the robot or all the information about the terrain is given. The technique enables the accurate wave propagation to the diagonally adjacent cells and facilitates the implementations of various essential features for a real-time path planner such as partial updates and parallel computations.**

I. Introduction

The path planning is one of the key issues for the successful development of the autonomous mobile robots. As such, developments of robust and efficient mobile robot path planning techniques have drawn keen attentions from many researchers in robotics community, making significant progress in this field.

In the roadmap approach, which sometimes is also referred to as a geometric approach or an edge detection approach, the robot environment is represented into a configuration space, or a C-space in short. The visibility graph method [1], [2] and the free space method based on generalized cylinders [3], Voronoi diagrams [4], or convex regions [5], [6] have been proposed. These methods have some difficulties in finding corner points with the obstacles having curvilinear boundaries, also in finding all the pairs of visible corner points, and in backtracking from a dead end in a densely cluttered obstacle environment.

The potential field approach represents the robot as a point, something like a marble, in the configuration space and makes it role toward the goal with the artificial potential or force produced by the goal and the c-obstacles [7]. This approach relies on heuristics, essentially a steepest descent optimization, and as such suffers from potential trapping into local minima.

The cell decomposition approach, or more precisely an "approximate" cell decomposition approach [8], the terrain is decomposed into an array of square elements called cells. Jarvis and Byrne [9] proposed a path planning technique based on a grid representation using the distance transform. The computational time of the distance transform increases as the obstacles become more cluttered. In case of the distance transform, the chamfer algorithm gives better approximation of $\sqrt{2}$ than the 4- or 8-neighbor algorithms used in [9], but it creates complications in creating the partial update algorithm for reducing the computational time.

Other interesting path planning techniques based on rule-based systems, certainty factors, fuzzy logic or neural network have also been proposed by several researchers [10], [11], which can be used in conjunction with the other algorithmic techniques in developing intelligent robots that can execute task level commands.

In this paper, we present an adaptive and efficient path planning technique that is based on the cell decomposition and the wavefront propagation approaches. Our approach is similar to that of the Lengyel's approach [12]. However, in our approach, a virtual wave from a cell can also propagate to its four point adjacent cells with a distance value of $\sqrt{2}$ as well as four side adjacent cells with a distance value of 1. This improvement will reduce the worst case path length from about $\sqrt{2}$ times of that of the straight line distance to 1.08. An algorithm called CREEP (Concentric Ripple Edge Evaluation and Progression) has been developed.

II. Virtual Wave Generation and Propagation

The terrain in which the robot is expected to navigate is represented as a 2D grid of square cells. A disc type planar robot is assumed. The size of a cell is such that it can circumscribe the robot to guarantee the robot passage through any unobstructed cell. The robot is assumed to have sensory capability such that it can recognize the obstacles and their locations within a given limited range as it navigates. Each cell location is represented with its center point. The cell at the *i*th row and *j*th column in the grid is denoted as $c_{i,j}$. Then given a cell $c_{i,j}$, the set of *side adjacent cells*, denoted as $A_{i,j}^s$, has cells $c_{i-1,j}$, $c_{i,j-1}$, $c_{i+1,j}$ and $c_{i,j+1}$ as its elements, and the set of *point adjacent cells*, denoted as $A_{i,j}^p$, has cells $c_{i-1,j-1}$, $c_{i+1,j-1}$, $c_{i+1,j+1}$ and $c_{i-1,j+1}$ as its elements respectively.

A virtual wave is assumed to be emanated from the goal cell, denoted as c_g, and propagates along the terrain surface from cell to cell. The wave strength value for the goal cell, denoted as w_g, should be assigned to c_g initially. The w_g should be sufficiently large such that the wave can reach any cell in the terrain after all possible attenuations in going through arbitrary numbers and shapes of the obstacles. We assume the normalized and binary traversabilities, i.e., the traversabilities for all the unobstructed cells are assumed to be 1 and for all the obstructed cells to be 0.

For an arbitrary cell $c_{i,j}$, $c_{i,j}$ can receive its wave strength (WS) value from any one of its 8 adjacent cells that already have their WS values. However, a wave can not propagate between the point adjacent cells that are both side adjacent to a common obstacle cell. Let $A_{i,j}'$ be the set of all such indirectly obstructed cells to $c_{i,j}$. Then given an arbitrary cell $c_{i,j}$, where $c_{i,j} \neq c_g$ and $c_{i,j} \notin W$, the *wave strength* (WS) value of $c_{i,j}$, denoted as $w_{i,j}$, can be received from one of its adjacent cell $c_{k,l} \in (A_{i,j} \cup W)$ such as

$$w_{i,j} = \max \left[((w_{k,l} - 1) \ \forall\ c_{k,l} \in A_{i,j}^{s}),\ ((w_{k,l} - \sqrt{2}) \ \forall\ c_{k,l} \in A_{i,j}^{p} - A_{i,j}') \right]$$

where W is the set of all the cells that already have received their WS values. The cell $c_{k,l}$ that satisfies the above condition and gives the $w_{i,j}$ value to $c_{i,j}$ is said to be the *parent cell* to $c_{i,j}$ and denoted as $p_{i,j}$.

Given a cell $c_{i,j}$ and its WS value $w_{i,j}$, the *ripple number* $r_{i,j}$ is associated with $c_{i,j}$ and assumes an integer value $k \geq 1$ if the following condition is satisfied:

$$w_g - k - 1 < w_{i,j} \leq w_g - k$$

Then the set of all the cells whose WS values satisfy the above inequality relation become the elements of a *ripple set*, or a *ripple* for short, R(k), and $R(0) = \{c_g\}$. To compute the WS value for any cell in R(k), the ripple sets R(k-1) and R(k-2) should be complete and fixed, and all the cells in those two ripples should already be assigned with their WS values. These sequential WS value and ripple number assignment operations are defined as the *expansion* of the cells and will appear elsewhere.

Fig. 1 shows the upper left corner parts of a terrain represented as a grid for illustration. The c_g is arbitrarily assigned as $c_{4,4}$ and w_g as 50.0. Fig. 1a shows the wave propagating only to 4 side adjacent cells each time based on the breadth first search order, which will be referred to as a 4-neighbor propagation. Fig. 1b shows the wave that propagates 4 diagonally adjacent cells, i.e., point adjacent cells, as well as to 4 side adjacent cells also based on the breadth first search order. The wave strength attenuation for the diagonal propagation is approximated with 1.4, which seems sufficient for illustration with the small grid size. For 256 x 256 grid, 1.414 may be used. The number in the parenthesis in each cell shows the search level or depth of that cell in the adjacency graph. As discussed before, the diagonal propagation is excessively penalized in the 4-neighbor propagation. In Fig. 1c, accurate wave propagation with the CREEP algorithm is shown. The number in the parenthesis in each cell shows the ripple number of that cell. Unlike the wave propagation with the breadth first search shown in Fig. 1b, no wave backpropagation occurs since the wavefront propagation speed is regulated with the ripples. For example, Two wavefronts meet at $c_{5,12}$. However, $w_{5,12}$ value becomes 35.0 with $c_{4,12}$ as $p_{5,12}$ and since it is still less than $w_{6,12}$, no wave backpropagation is necessary. Similar situation occurs at $c_{4,9}$ and $c_{5,9}$. Once the robot cell c_r receives its WS value from its parent, then the path is the sequence of the parent cells starting from c_r towards the goal cell c_g.

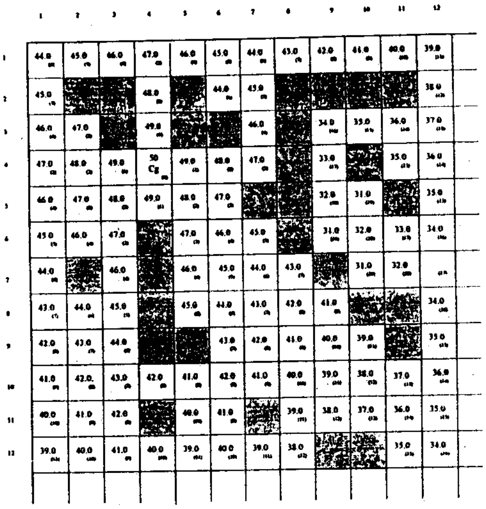

Fig. 1a. 4-Neighbor Propagation with the Breadth First Search

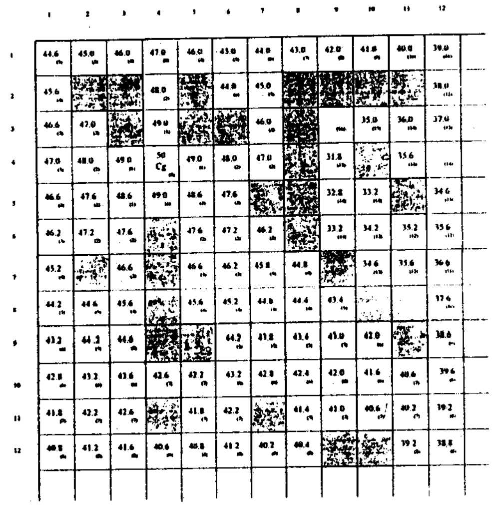

Fig. 1b. Accurate Diagonal Propagation with the Breadth First Search

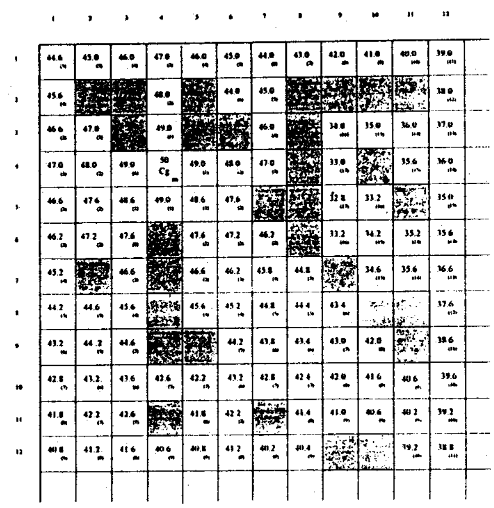

Fig. 1c. Accurate Diagonal Propagation with the CREEP Algorithm

III. Algorithm Development and Test Results

Based on the approach explained in the previous sections, the navigation algorithm CREEP has been developed and programmed in C Language to test the algorithm in various obstacle environments. Examples of the simulation runs are shown in Fig. 2. The program is still evolving stage and the CREEP Algorithm has not been fully implemented. However, the preliminary simulation results clearly show the potential and the robustness of the CREEP Algorithm working under arbitrarily shaped and cluttered obstacle environment.

IV. Concluding Remarks and Future Research

A reliable and adaptive technique that can plan a path for an autonomous mobile robot in an arbitrarily cluttered and complicate obstacle environment has been presented. Unlike the similar cell decomposition and wave propagation approaches proposed in the past, the technique can generate more accurate path by letting the wave to propagate directly to the point adjacent cells with a proper wave strength attenuation. The concentric ripple approach also enables an efficient partial update and provides a framework for the accommodation of other essential features for path planning, such as the parallel computation for the WS value and the implementation of the variable traversabilities for the terrain. Furthermore, if is desirable for the robot to maintain some distance from the obstacles, as in the case of potential field approach, we can simply assign the cells around the obstacles some low traversabilities. Since the goal cell is the only location emanating the virtual wave, our technique will not suffer from the local minima problems.

Further research is needed especially in the implementation of the continuous traversability and the dynamic grid resolution based on the distance from the robot to enable the robot to plan its immediate path in more details and to pass through the partially occupied obstacle cells.

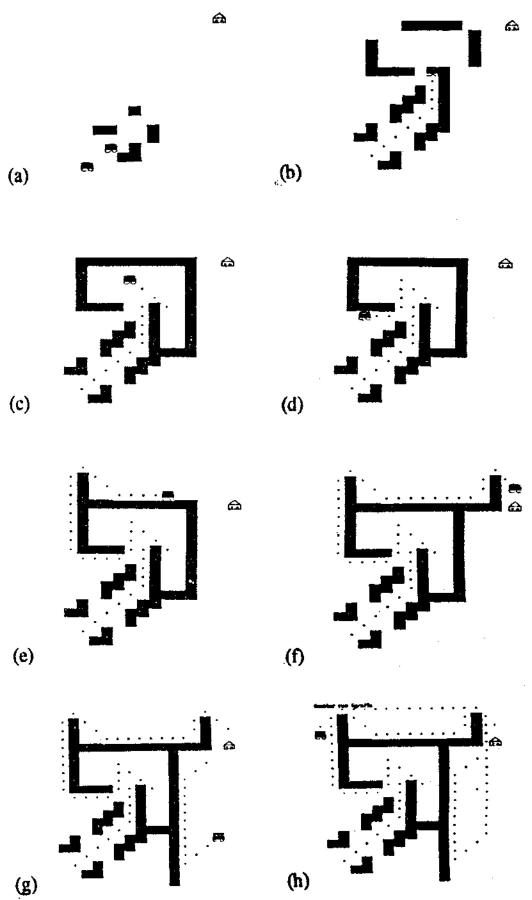

Fig. 2. A Mobile Robot Navigation Example based on CREEP Algorithm

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