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Paper:

The Global Shortest Path Visualization Approach with Obstructions

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The avoidance obstacle path planning problem is stated in an obstacle environment. The minimum Steiner tree theory is the basis of the global shortest path. It is one of the classic NP-hard problem in nonlinear combinatorial optimization. A visualization experiment approach has been used to find Steiner point and system's shortest path is called Steiner minimum tree. However, obstacles must be considered in some problems. An Obstacle Avoiding Steiner Minimal Tree (OASMT) connects some points and avoids running through any obstacle when constructing a tree with a minimal total length. We used a geometry experiment approach (GEA) to solve OASMT by using the visualization experiment device discussed below. A GEA for some systems with obstacles is used to receive approximate optimizing results. We proved the validity of the GEA for the OASMT by solving problems in which the global shortest path is obtained successfully by using the GEA.

Keywords: NP hard problem, geometry-experiment approach (GEA), steiner minimal tree, obstacle-avoiding Steiner minimal tree (OASMT)

1. Introduction

The avoidance obstacle path planning problem is stated as follows: in an obstacle environment, based on an evaluation criterion, such as the shortest path length, the shortest movement, the minimal energy consumption, is used to plan an optimal or sub-optimal collision free path from the start to the destination. This is universally applied in such fields as robotics, very large-scale integration (VLSI) design, and geographic information systems (GIS). The global shortest path is a classic nonlinear combinatorial optimization problem that has been extensively applied in engineering practice. The minimum Steiner tree theory is the basis of the global shortest path and the global shortest path algorithm for the minimum Steiner tree is polynomial hard (NP hard) problem [1] that has been widely applied in fields such as VLSI design, transportation route planning, and vehicle scheduling [2–5].

In the early, it is the main research objects without obstacle in systems which has two types of main methods for solving the shortest path problem – precise algorithms and heuristic algorithms. The first precise algorithm for an SMT problem was proposed by Z. A. Melzak in 1961. An algorithm in opposition to what the Melzak algorithm was put forward by P. Winter [6]. The Geo-Steiner put forward by Warmeetal who realized the algorithm put forward previously by P. Winter. The Geo-Steiner algorithm is currently the most precise algorithm for solving SMT problem [7]. SMT problem algorithms are mostly heuristic [8–10]. The Stein Lib Test data Library has been set up by K. Thorsten [a]. Many methods other than precise and heuristic algorithms exist, one of the most important being the geometry-experiment approach (GEA). The GEA uses physical chemistry characteristics of a surfactant and experiment device [10–13]. Minimum surfactant surface tensions come into being the shortest path in two-dimensional system. A transparency visualization scheme, i.e., a Steiner minimum tree, for an objective can be formed steadily and rapidly.

A fundamental problem in routing is finding a rectilinear Steiner minimal tree (RSMT). Because design often contains rectilinear obstacles, such as macro cells, IP blocks, and pre-routed nets, obstacle-avoiding RSMT (OARSMT) construction becomes a very technical problem. We use a simple, stable experimental approach for solving this problem. We previously used a partitioning method and an ant colony optimization method to construct an obstacle-avoiding Steiner minimal tree (OASMT) [14]. Experimental results show that our algorithm achieves the best wire length results in most test cases and that work time is very short even for larger cases in which both the number of terminals and the number of obstacles exceeds 100. Obstacles are included in systems in many practical problems, so by considering an obstacle, OASMT construction becomes very important.

In Section 2 of this paper, we define SMT and OASMT problems and introduce some results known about them. In Section 3, we present the theoretical basis of the visualization experiment approach and how to use a visualization experiment device. In Section 4, we show how the GEA method is used to get the OASMT, together with some pictures of experiments. In Section 5, we present conclusions.

2. SMT and OASMT Problems

We will introduce the SMT and OASMT problems and some known results in the sections that follow.

2.1. MST Problem Definition

For any connected graph $G = (V, E)$ if we traverse all vertices in graph G from any one vertex of graph G. All vertices and edges of graph G traversed are called a spanning tree of graph G. In all spanning tree sums of all edge weights, the smallest value is called the minimum spanning tree (MST). The MST is unique. The Prim and Kruskal algorithms are the two most classic algorithms with which to construct a MST.

The following mathematical description describes the MST:

If for any given set $X = \{P_1, P_2, \ldots, P_n\}$ we can construct a minimum network containing only all of the points of X, then this is called a MST of set X.

2.2. SMT Problem Definition and Properties

For point set $X = \{A_1, A_2, \ldots, A_n\}$ on a plane, $L_s(X)$ represents the length of the MST. For given set X, there is point set $Y = \{P_1, P_2, \ldots, P_m\}$. Supposing that we can find a set that makes $L_s(X \cup Y_0) = \min L_s(X \cup Y)$, the MST generated by $X \cup Y$ is called the minimum Steiner tree of set $X(SMT(X))$. Points in set X are called fixed points and points in set Y are called virtual Steiner points.

The following properties of the SMT [15] are well known:

Property 1: Given n points on the plane, the maximum number of Steiner points is $n-2$.

Property 2: A Steiner point has a degree equal to 3.

Property 3: The edges emanating from a Steiner point have mutual angle equal to 120°.

Property 4: All Steiner points lie in the convex hull of the given points.

The most important thing for the SMT problem is to find the number and positions of Steiner points. Once these are found, the SMT is gotten by using the minimal Steiner tree algorithm.

2.3. Euclidean Minimum Steiner Tree (ESMT) Definition and Properties

The Euclidean minimum Steiner tree is used to find the minimum network problem of a fixed point set in Euclidean space Z. On descartes plane R_2, a pair of points is represented in $u = (u_x, u_y)$ and $v = (v_x, v_y)$, the distance between u and v, or the L_p distance, is represented as follows:

$$||uv|| = (|u_x - v_x|^p + |u_y - v_y|^p)^{\frac{1}{p}}, 1 \leq p \leq \infty$$

We believe that the Euclidean Steiner tree has an L_2 distance, i.e., $p = 2$. The ESMT has the following properties:

Property 1: The Steiner tree is a tree structure, namely, there is no loop in the Steiner tree.

Property 2: If the Steiner tree has n fixed points, then it has $n-2$ Steiner points.

Property 3: If the number of degrees in Steiner points must be 3, it must have and only have 3 lines connected to Steiner points and the angle between all three lines each other is 120°.

Property 4: The degrees of fixed point must be less than 3 and may be any one of 1, 2, or 3.

Property 5: Steiner points must be located in a convex polygon formed by the fixed points.

2.4. Obstacle-Avoiding Steiner Minimum Tree (OASMT) Problem

Let $T = \{t_1, t_2, \ldots, t_n\}$ be a given set of points and $O = \{o_1, o_2, \ldots, o_m\}$ be a set of obstacles. The obstacle-avoiding Steiner minimum tree (OASMT) problem is to find a tree with a minimal total length that connects all given points together but does not intersect any obstacle. Supposing that the set of vertexes of the OASMT is V, we have $T \subset V$. Let t be a point of V. t is called a regular point if $t \in T$ but otherwise it is called a Steiner point.

The OASMT problem has become increasingly important to modern nanometer IC design that must consider all types of obstacles. The OASMT problem is therefore being taken into consideration.

2.5. Steiner Rate

It has been proven that the minimum Steiner tree problem is a NP hard problem, so we cannot find a polynomial time solution to solve the minimum Steiner tree problem, solving this problem, the only way to more practical to seek effective approximate solution.

For point set P, the length of the MST and minimum Steiner tree is very close and the solution is easy. As a result, the optimal solution for the minimum Steiner tree uses the point set MST approximation to approximate a representation of P. Point set P of the MST with the minimum Steiner tree length than called Steiner, is called the Steiner rate, and expressed in Eq. (1) as follows:

$$\rho = \inf_P \frac{L_s(P)}{L_M(P)} \quad \text{(1)}$$

where $L_M(P)$ is the length of the MST of P and $L_S(P)$ represents the minimum Steiner tree length of P. In 1968, Gilbert and Pollack in the papers' minimum Steiner tree proposed Steiner than conjecture, its representation such as Eq. (2):

$$\frac{L_s(X)}{L_M(X)} \geq \frac{\sqrt{3}}{2} \quad \text{(2)}$$

where X is the set of fixed points. This conjecture is applicable for all set X. The correctness of the conjecture was proved in 1990 by Ding Zhu. The conjecture shows that the minimum Steiner tree in an ideal situation can be better than the corresponding MST length reduced about 13%.

3. Visualization Approach with Obstructions

We first introduce the theoretical basis of the visualization experiment approach, and then use this method to obtain the OASMT.

3.1. Theoretical Visualization Experiment Basis

The surface tension of a liquid is a physical effect. When the surface tensions of a liquid try to achieve a steady state, it always makes the surface of the liquid smooth and the area of the liquid smallest. In this situation, the energy of the surface area is minimal. The surface tension of the liquid is defined as the surface energy of each area here. Assuming that the surface tension of the liquid is represented by σ, σ is the ratio of the work required to increase the surface area and increased surface area (ΔA). Under natural conditions, the energy of the liquid always is minimal because of the surface tension of the liquid when the plane of the liquid is stable. Similarly, if the state of the liquid is stable, the surface area state will be a minimum to make surface energy minimal [16]. Due to the physical characteristics of the liquid, the SMT is gotten by the visualization experimental method for the shortest path.

Since the 19th century, the Plateau geometry general rule was proposed by a scientist J. A. F. Plateau from Belgium based on research on the shape of the Plateau bubble geometry. He proposed the following rules [17–19]:

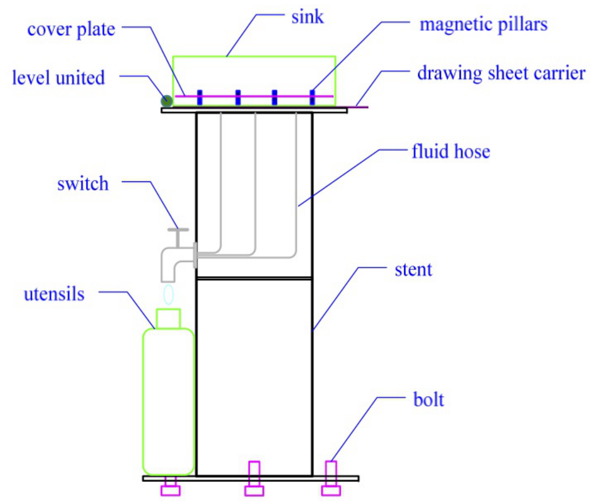
Rule 1: The surface of the bubble membrane attached to a wire frame or some other closed structure must be smooth.

Rule 2: Bubbles connect in one or two ways, one of which is three surfaces connecting along with one smooth curve, and the other is the six-plane form curve, connecting at a vertex.

Rule 3: Bubble membrane connects at the same curve or at the same vertex and between the two surfaces it is equal; the angle should be 120° when three surfaces connect at a vertex; the angle should be 120° when three surfaces connect at a vertex.

In this paper, based on the properties of liquid surface tension, we hold that a membrane has the smallest surface area when the membrane formed by the liquid in the system is in a stable state. We design two parallel plates that make a membrane surface with equal altitude. Then we can use the minimum surface area property to solve the minimum Steiner tree problem.

To solve the SMT problem, the GEA uses the property that the Plateau geometry general rule coincides with the principles of minimal Steiner tree theory.



(a) Schematic diagram

(b) Instrument image

Fig. 1. The shortest path experiment device.

GEA which uses Plateau geometry general rule coincides with the principles of the minimal Steiner tree theory to solve SMT problem.

In the following part, we will introduce our visualization experiment device.

3.2. Visualization Experiment Device

Using the coincidence between Plateau geometry general rule and the principles of the property of the minimal Steiner tree, we designed simple experiment equipment to get the Steiner points and SMT. See **Fig. 1** for the shortest path experiment device.

The shortest path of given points is obtained intuitively and simply through the visualization shortest path experiment device, according the physical properties of fluid.

Using GEA [12], the global shortest path can be found, and the approach has been applied in optimizing some power transmission grid system [20]. But it reads data through the instrument ledger coordinate system, the precision is not high; along with the increasing of given points, it takes more and more time to form membrane and the objective is not steady. For the system with a large number of points, a modified GEA algorithm was applied to get SMT [21–24].

3.3. Visualization Experiment Operation Steps

The visualization experiment method for solving the minimum Steiner tree problem takes the following steps:

Step 1: The formula of active agent liquid: first put 2000 mℓ of distilled water into the vessel and add 20 g detergent with few additives and 8 g glycerin and mix all the materials. After 3 to 24 hours, the liquid will mix fully. Then the membrane traces can be kept more than 30 minutes. The best solution can satisfy the requirement of experiment and debug visualization experiment device.

Step 2: To insert the planning drawings in the gap of plate on below, then the magnetic steel column is put to the given point position of the cover plate according to the drawings, and then we remove the cover plate in order to use later.

Step 3: The surfactant solution put into the tank slowly in order to avoid producing bubble. We stop until the plate is submerged completely by solution, then we discharge out the bubble in sink for pouring into the solution. The cover plate back is put into the liquid tank and makes the position of magnetic steel column and drawing on the selected node overlapping.

Step 4: To open switch at the bottom of experiment device, put out slowly the solution, the film of the minimum Steiner tree path will be formed between magnetic steel column and plate in the process of putting out the solution. After the thin film is stable, we read out and record the position of each point based on the coordinate system at the bottom of the sink. The point on coordinates includes the fixed point and the new Steiner points, then the pictures with a camera are made, finally we get the minimum Steiner tree film path graph.

Step 5: Based on the coordinates of each point, we calculates the film path length, i.e., the length of the minimum Steiner tree.

Visual experiment principle is under the action of surface tension, in order to make the lowest surface energy, the solution to minimum surface area in the formation of the membrane surface between the two plates; it will automatically find Steiner points. To avoid the complicated mathematical algorithm visualization experiment; through the visualization experiment device solving the minimum Steiner tree problem becomes easy. We use global shortest path visualization instrument in many experiments, to generate and analyze the shape of the fixed point set of the relationship between the Steiner tree and Steiner points.

Using GEA the global shortest path can be found, and the approach has been applied in optimizing some power transmission grid system, but it reads data through the instrument ledger coordinate system, and the precision is not high enough; along with the increasing of given points, it takes more and more time to form membrane and the objective is not steady, so the applicability of GEA are influenced simultaneously.

4. The Global Shortest Path Visualization with Obstructions

We analyzed the relationship between the shape of the fixed point set and steiner tree by a large number of experiments using global shortest path visualization instrument. When the fixed point set is convex, Melzak method is used to construct the minimum Steiner tree. For the existing obstacles Steiner tree problems, we also carried out some experiments and analyzed the relationship between the shape and location of obstacles with Steiner fictive points. Steiner tree has important theoretical significance and wide application. Since the minimum Steiner tree problem has been proved to be NP-hard problem, if not $P = NP$, Steiner tree problem does not exist polynomial-time algorithm. So, we need to find the suitable intelligent optimization algorithms to solve this problem.

In many practical problems, obstacles always exist in the systems. It is NP-hard problem. Thus, there exists no efficient optimal algorithm for finding an OASMT. Since GEA is very efficient for the system without obstacles, hence, GEA is used to obtain OASMT by adding obstacles in the experiments in this paper. In the experiments, the obstacles are replaced by plasticine. According to the shapes and sizes of the obstacles in the practical problems, the plasticine is cut to corresponding shape and size in proportion. Then, the plasticine was put into the position in the experiments.

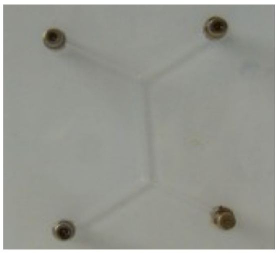
4.1. Experiment Using No Obstacles

We conducted a large number of experiments using the global shortest path visualization device. Experimental results showed that the minimum Steiner tree is full Steiner trees when the fixed point set is convex polygon. As shown in **Fig. 2**, the number of Steiner fictive points is fixed, i.e., the number of Steiner fictive points is the number of fixed points minus 2. This conclusion helps us construct a Steiner tree. We used the Melzak algorithm directly to solve the minimum Steiner tree problem when the fixed point set is convex polygons. It greatly reduced the difficulty in solving the minimum Steiner tree problem.

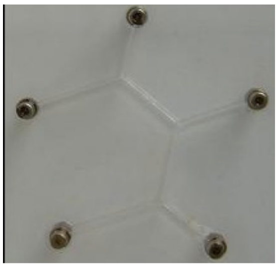
Experimental results showed that the minimum Steiner tree is not a full Steiner tree when the fixed point set is not a convex polygon. **Fig. 3** shows that the number of Steiner fictive points is not fixed.

4.2. Obstacles with Different Shapes

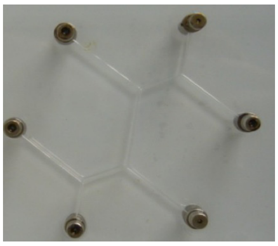
In practical problems, the shapes of obstacles differ. We chose several different shapes of obstacles when making experiments using the global shortest path visualization instrument. We assume that obstacles are located in the center of the fixed point. Experiment results are shown in **Fig. 4**, in which we found that the number of Steiner



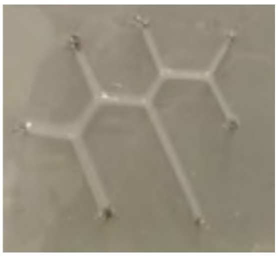
(a) Experiment using 4 points



(b) Experiment using 5 points



(c) Experiment using 6 points



(d) Experiment using 7 points

Fig. 2. Geometry-experiment pictures with a convex fixed point set.

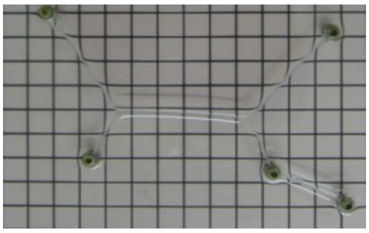
points differed: there are 2 Steiner points when there is no obstacle, there is no Steiner point when the obstacle is circular or quadrate, and there is only 1 Steiner point when the obstacle is triangular.

4.3. Experiments with Obstacles with Different Positions

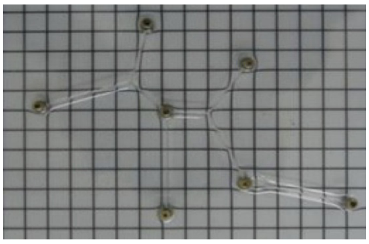
We considered the effect of the positions of circular obstacles on the SMT as shown in **Fig. 5**.

By comparing **Figs. 4** and **5**, we found that the number of Steiner points also differs when obstacles are located in different positions, as shown by **Fig. 5**.

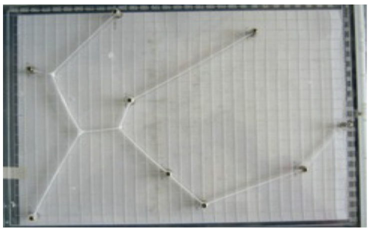
There are no Steiner points when the obstacle is in the middle and there is one Steiner point when the obstacle is at the boundary or near the center of the four fixed points.



(a) Experiment using 6 points



(b) Experiment using 7 points



(c) Experiment using 9 points

Fig. 3. Geometry-experiment pictures with no convex fixed point set.

5. Conclusions

We used the GEA based on physical visualization experiments to analyze our research route and explored the relationship between the construction of the Steiner minimal tree and the distributed shape of given points. We also examined the relationship between location and the number of Steiner points and distributed shapes of given points. We used the GEA to find Steiner points and the SMT with obstacles. We added obstacles with different shapes to the system and considered the obstacle's position. Experiments results showed that the number of Steiner points is related to obstacle shapes and positions. An OASMT matched with a visualization approach could be used both in path planning for engineering problems, such as logistics warehouse system locations, and for path planning for social services, such as transportation route planning. Applying the GEA to practical problems will be the next step in our work.

Acknowledgements

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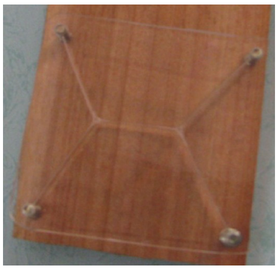
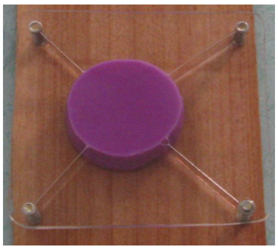
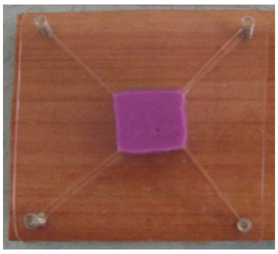


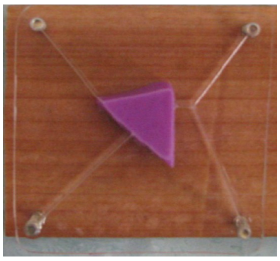
(a) 4 points without an obstacle



(b) 4 points with a circular obstacle

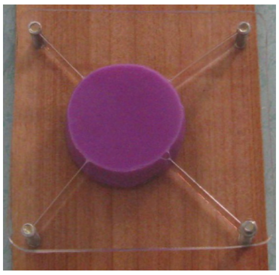


(c) 4 points with a quadrate obstacle

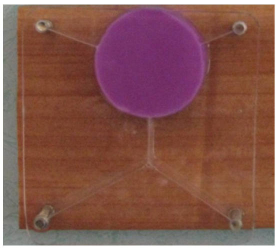


(d) 4 points with a triangular obstacle

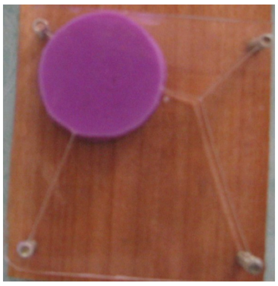
Fig. 4. Experiment using obstacles having different shapes.



(a) Obstacle in the middle



(b) Obstacle at the boundary



(c) Obstacle near the center of four fixed points

Fig. 5. Experiments using obstacles with different positions.

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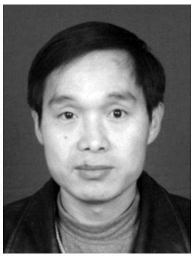

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Brief Biographical History:

1981 Received B.Sc. in Machine Design from Luoyang Institute of Technology
1987 Received M.Sc. in Mechanical Engineering from University of Science and Technology Beijing
1996 Received Ph.D. in Systems Science from Okayama University
2004- Full Professor, Institute of Systems Science and Engineering, and Henan Engineering Laboratory of Wind Power Systems, Henan University of Science and Technology

Main Works:

• system safety assessment methodology for process plants, system analysis and integration for system shortest path programming, and systematic behaviour of vertical axial wind turbine generation system

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