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Line Segment Selection Method for Fast Path Planning

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Abstract: Path planning is required for a vehicle with the mission which includes the avoidance of certain areas. There are various kinds of algorithms for path planning. Typical algorithms are Voronoi diagram, visibility graph, potential field and trajectory optimization. These algorithms often need post-processing technique to satisfy the vehicles' constraints such as turning angle and minimum moving distance. The proposed method does not need post-processing steps and always provides the fast and stable solution. It also gives a unique solution, while rapidly exploring random tree algorithms do not guarantee same solution. We use the local search and the global search at the same time in order to get a more appropriate path. We validate the proposed method by simulations and the results show that the method is fast and effective for path planning.

Keywords: Avoidance area, global search, fast path planning, line segment selection.

1. INTRODUCTION

A path planning is to determine the path which is required for a vehicle to complete its mission and avoid obstacles. The path planning methods are widely used in the areas of robot, unmanned vehicles, and so on.

A path can be represented by a trajectory but it can also be simplified by constructing waypoints. Waypoints are defined as a set of the reference points for a vehicle to head for. These waypoints are virtual points which a vehicle does not pass actually and are used as reference points for a vehicle to turn.

There are various kinds of algorithms for path planning. The conventional algroithms are Voronoi diagram [1,2], visibility graph [3,4] potential field [5], trajectory optimization [6,7] and rapidly exploring random tree(RRT) [8-10], etc. The algorithms such as Voronoi diagram, visibility graph and potential field can generate an optimal path relatively fast. However, these methods have some disadvantages in that it is hard to consider the constraints of a vehicle in advance and they need a post-processing technique. RRT has advantages to plan a path very rapidly and to consider the complex constraints. But, the same path is not guaranteed due to a random search. Trajectory optimization method can theoretically generate a path to consider the various constraints, but it usually takes more time than other methods. Its solution sometimes provides the local minimum or does not give a solution.

It is a difficult problem to satisfy the both rapid and stable path planning. This paper presents the path planning ideas and procedures to generate waypoints rapidly and stably. We use the local search method and the global search at the same time in order to get a proper path.

The rest of the paper is structured as follows. Section 2 describes a concept of candidate points and line segments. Local search procedures using line segment are introduced in Section 3. Global search procedures are introduced in Section 4. We demonstrate the proposed ideas using simulations and compare with Voronoi diagram in Section 5, and we finally conclude this paper in Section 6.

2. CANDIDATE POINTS AND LINE SEGMENTS

2.1. Constructing candidate points and line segments

A determined point in Fig. 1 is a waypoint which is sequentially determined by the proposed method and it starts from a starting point. The determined point is a kind of pivot point to construct waypoint candidates one of which will be a determined point later. Candidate line segments are defined as line segments between a determined point and candidate points and a basis line segment is defined as a line segment pointing to a target.

Candidate points are constructed considering the vehicles' constraints such as a minimum distance and an angle between the waypoints. We set candidate points to be on the circle with a radius of minimum distance and its origin is at a determined point. Candidate points are placed symmetrically along a basis line segment. As an example in Fig. 1, we see two candiate points on both sides which are separated by a basis line segment. These candidate points can be increased depending on vehicles' constraints or a

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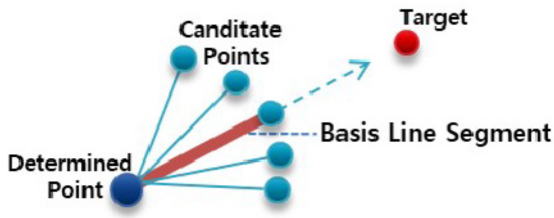

Fig. 1. Candidate points and line segments.

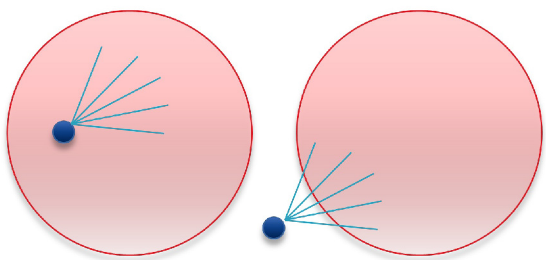

Fig. 2. Candidate points within the avoidance area.

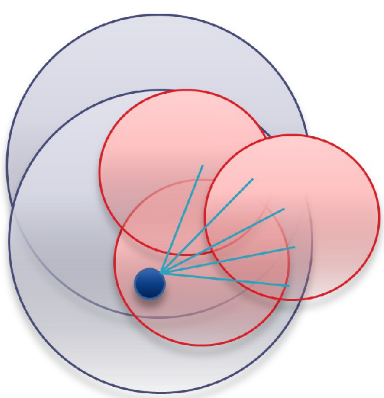

Fig. 3. Candidate points within multiple avoidance areas.

computing power. The more candidate points we consider, the more accurate path we can get.

2.2. Line segment evaluation

Line segment evaluation is based on calculating a distance between a candidate line segment and an avoidance area. It is important because waypoints are determined according to the evaluation results.

We can simply evaluate line segments by checking whether there is a collision with the avoidance area or not, but the more elaborate evaluation method is required to deal with the case in which all the candidate line segments collide with the avoidance area such as in Fig. 2. It is also possible that there are collisions with multiple avoidance areas such as in Fig. 3.

We evaluate the candidate line segments using a minimum distance between the center of the avoidance area

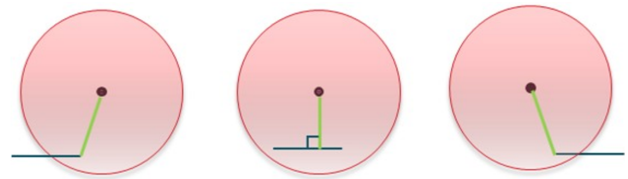

Fig. 4. A minimum distance between the center of the avoidance area and a candidate line segment.

Fig. 5. Minimum distance which is longer than the radius.

and a candidate line segment such as in Fig. 4.

Evaluation is better as this minimum distance gets longer. Once this minimum distance gets longer than the radius of the avoidance area such as in Fig. 5, evaluation does not depend on the minimum distance any more. Evaluation values can be expressed as a function of a minimum distance(d) and the radius(r) of the avoidance area. A variable x is defined as $\frac{d}{r}$. Then, evaluation value is represented as a function $f(x)$. A function $g(x)$ can be defined, when a minimum distance is smaller than the radius of the avoidance area. When a minimum distance is longer than the radius, evaluation value is saturated to a constant, α. Finally, $f(x)$ can be shown in (1).

$$f(x) = \begin{cases} g(x), & 0 \leq x \leq 1, \\ \alpha, & x > 1. \end{cases} \tag{1}$$

A marginal distance(ε) can be added in calculating evaluation value as a safety factor such as in Fig. 6. The role of marginal distance is to prevent a vehicle from approaching too closely to avoidance areas. Especially if there is not marginal distance under turning angle restriction, it causes a problem for a vehicle to pass through the avoidance areas. As marginal distance increases, a vehicle avoids avoidance area by a wide margin and the probability of passing through the avoidance area decreases even if there is strict turning angle restriction. In Fig. 6, the radius of the avoidance area becomes $r+\varepsilon$. The definition of a variable x is also changed as $\frac{d}{r+\varepsilon}$. $h(x)$ denotes an evaluation function in a marginal area. Evaluation function, $f(x)$ can be expressed as in (2).

$$f(x) = \begin{cases} g(x), & 0 \leq x < \dfrac{r}{r+\varepsilon}, \\ h(x), & \dfrac{r}{r+\varepsilon} \leq x < 1, \\ \alpha, & x \geq 1. \end{cases} \tag{2}$$

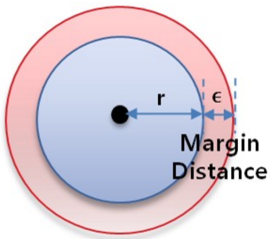

Fig. 6. Avoidance area with a marginal distance.

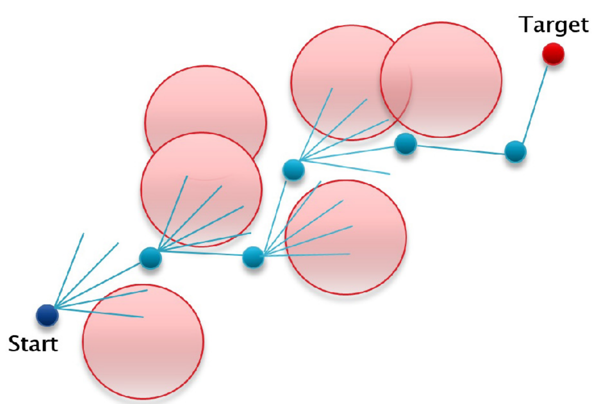

Fig. 7. A basic idea to generate waypoints.

3. LOCAL SEARCH USING LINE SEGMENT SELECTION

3.1. Basic idea

A basic idea to generate waypoints is introduced in Fig. 7. Waypoints are generated from a starting point sequentially by evading the avoidance area to reach a target.

3.2. Procedures to generate waypoints

The procedures to generate waypoints are as follows. Candidate points are constructed at a determined point. The determined point is a starting point at first and is sequentially changed as evaluation steps go on. Line segment evaluation is conducted at the determined point to choose a next waypoint, namely the next determined point. After line segment evaluation, we choose the candidate point which is an endpoint of the best evaluated line segment. When multiple candidate line segments have the same evaluation value, the candidate line segment closest to a basis line segment is chosen. Once a candidate point is selected as a determined point, another candidate points are generated from a newly generated determined point and line segment evaluation is conducted up to a target point. Table 1 summarizes the precedures for generating waypoints.

Table 1. Procedures for waypoint generation.

Step 1	Construct candidate points at a starting point.
Step 2	i) Choose the best candidate point after evaluating the candidate line segments. ii) When multiple candidate line segments have the same evaluation value, choose the candidate point closest to a basis line segment.
Step 3	Repeat Step 2 at a recent determined point up to a target point.

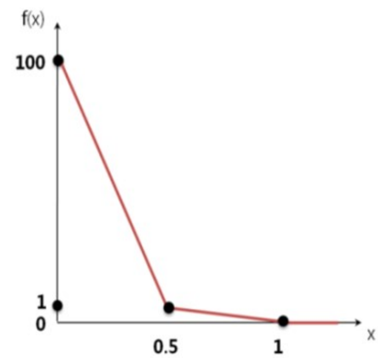

Fig. 8. Evaluation function ($r = 0.25$, $\varepsilon = 0.25$).

3.3. Illustration using the experiments

We illustrate the line segment selection method using the experiments. Eighty-one candidate line segments are constructed and the angle difference between the adjacent line segments is 1 degree. The length of a candidate line segment is 1. The radius of the avoidance area(r) is 0.25 and a marginal distance(ε) is 0.25. Equation (3) and Fig. 8 represent evaluation function according to x. We set a candidate line segment to be evaluated better as evalution function $f(x)$ is smaller. Evaluation value is 100 at the center of a radius and becomes 1 at x of 0.5. Evaluation value is 0 when x is greater than 1.

Fig. 9 shows the results for 4 different starting and target points with 100 avoidance areas.

$$f(x) = \begin{cases} -198x + 100, & 0 \leq x < 0.5, \\ -2x + 2, & 0.5 \leq x < 1, \\ 0, & x \geq 1. \end{cases} \tag{3}$$

Next experiment is for the case where a radius of the avoidance area is greater than the length of a candidate line segment. The radius of the avoidance area(r) is 1.5 and a marginal distance(ε) is 0.375($= 0.25r$). The other avoidance area has r and ε as 1.2 and 0.3 respectively. The number of candidate line segments is 81 and the length of a candidate line segment is 1. Equation (4) and Fig. 10 represent evaluation function according to x. Evaluation value is 100 at the center of a radius and becomes 1 at x of 0.8.

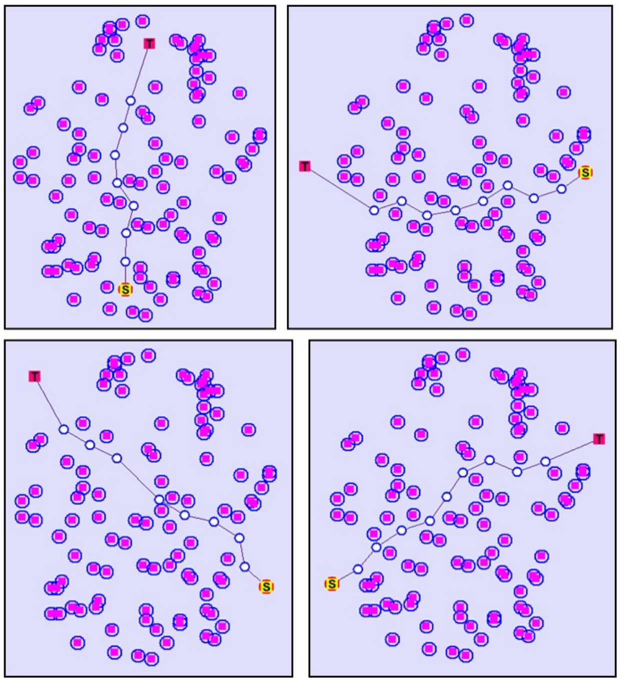

Fig. 9. Results of waypoint generation(S means a starting point and T means a target point).

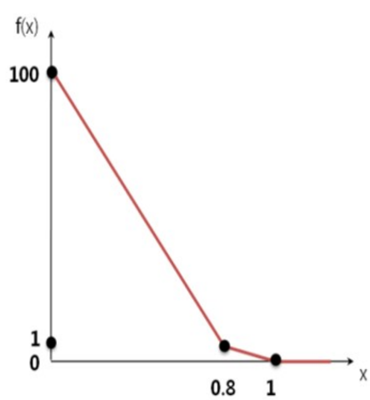

Fig. 10. Evaluation function ($r = 1.5$, $\varepsilon = 0.375$).

$$f(x) = \begin{cases} -123.75x + 100, & 0 \le x < 0.8, \\ -5x + 5, & 0.8 \le x < 1, \\ 0, & x \ge 1. \end{cases} \quad (4)$$

In Fig. 11, waypoints are generated for 6 avoidance areas (3 avoidance areas with r of 1.5 and 3 avoidance areas with r of 1.2). We notice that this method shows a good performance for various avoidance areas.

We conducted trial and error to get the parameters of (3) and (4) to get good results. We set maximum evaluation value as 100 when the vehicle goes through the center of avoidance area. We set evaluation value as 1 when the vehicle goes through the border of avoidance area. Concerning marginal distance, turning angle restriction and the proportion of the radius of avoidance area to the length

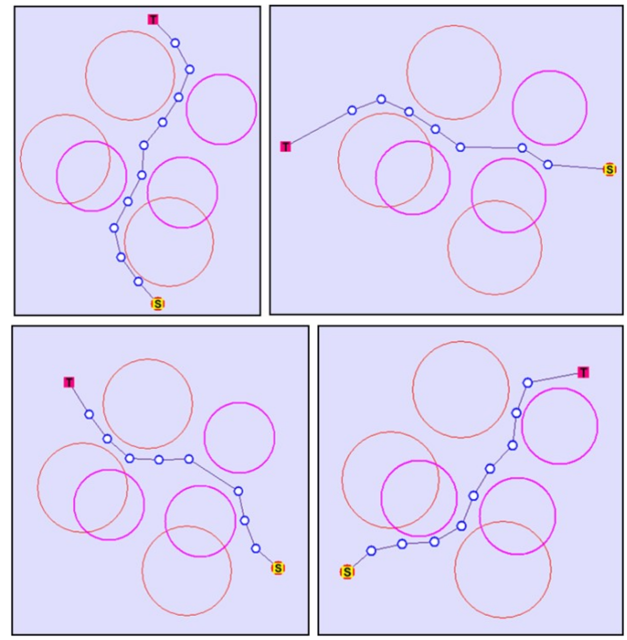

Fig. 11. Results of waypoint generation for the avoidance areas with two different radii.

of line segment are important factors. If there is no turning angle restriction, we do not need marginal distance. If there is turning angle restriction and the proportion of the radius of avoidance area to the length of line segment is increased, we need longer marginal distance. For example, we set the marginal distance (0.375) in (4) longer than the marginal distance (0.25) in (3), because the proportion of the radius of avoidance area to the length of line segment in (4) is longer than that in (3). When the candidate line segment is affected by multiple avoidance areas, we add all the evaluation values from each avoidance area.

4. GLOBAL SEARCH USING LINE SEGMENT SELECTION

4.1. Necessity

The key idea of waypoint generation using the line segment selection method in Section 3 is to select the best candidate among the candidate points which are separated by line segment distance from the determined point. Therefore, this method has a limitation of local search. The left figure of Fig. 12 shows an example that waypoints are generated through the crowded avoidance areas. In terms of a total distance of a path, it may be a good path. But in terms of getting away from avoidance areas, the result shown in the right figure of Fig. 12 is much better than that of the left figure.

In this section, we describe a global search method using line segment selection to overcome the limitation of the local search that is shown in Fig. 12.

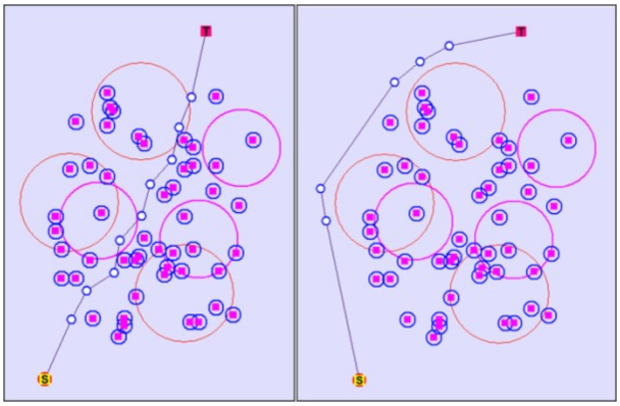

Fig. 12. Necessity of global search.

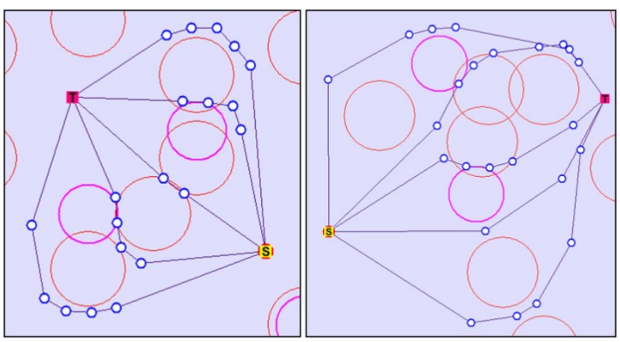

Fig. 13. Example of various path generation.

4.2. Basic idea of global search

The first idea of global search is to generate diverse paths by variation of line segment selection method. Fig. 13 shows an example of the generation of 5 different paths. The second idea is to select the best path among the various paths considering avoidance areas and path distance. In other words, after generating various paths using local search variation, we can select the best path.

4.3. Basis line segment variation

By basis line segment variation, we diversify searching regions. The basis line segment in the line segment selection method in section 3 always aims at a target such as in Fig. 14. However, we can get a different path by making the basis line segment aim at a different direction other than a target such as in Fig. 15.

We set the direction of a basis line segment to be changed as a waypoint advances to a target. Fig. 16 shows the concept of basis line segments with varying directions along waypoints.

In a first row of Fig. 16, a basis line segment at a starting point aims at 90 deg up and gradually changes its direction toward a target as a generated waypoint advances to a target. However, in a thrid row in Fig. 16, all the basis line segments are aiming at a target.

$\omega_i(n)$ is defined as the direction of a basis line segment

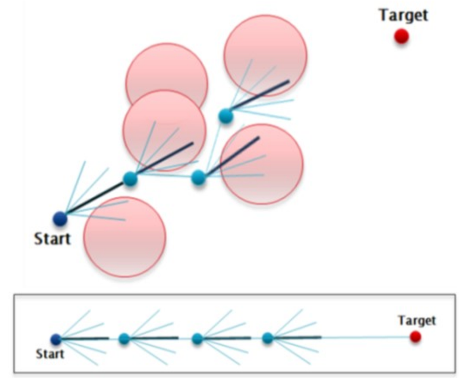

Fig. 14. Basis line segments aiming at a target point.

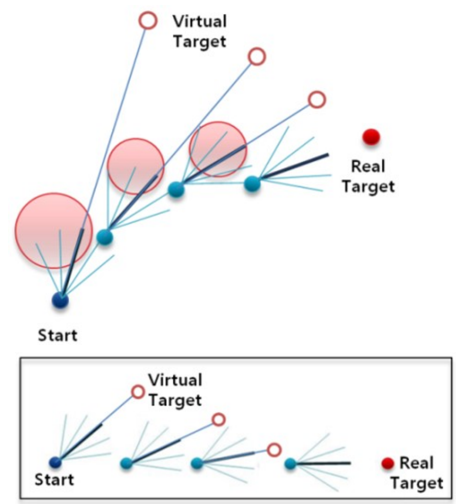

Fig. 15. Basis line segments aiming at a different direction other than a target.

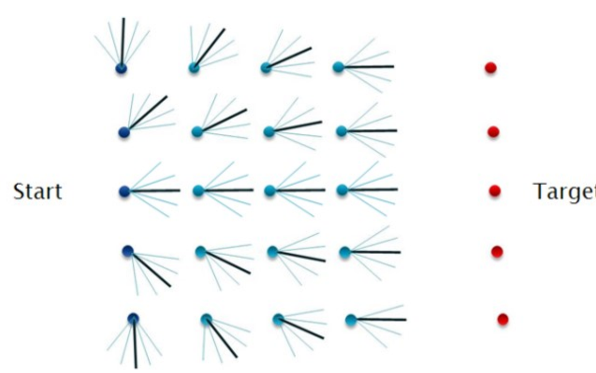

Fig. 16. Variation of basis line segment direction relative to distance to a target.

at the nth waypoint of the ith path. i and n denote a path index and a waypoint index, in respect. $\theta_i(n)$ is defined as the direction which points to a target at the nth waypoint of the ith path. δ_i is defined as a constant which controls the degree of varying basis line segment direction and it is

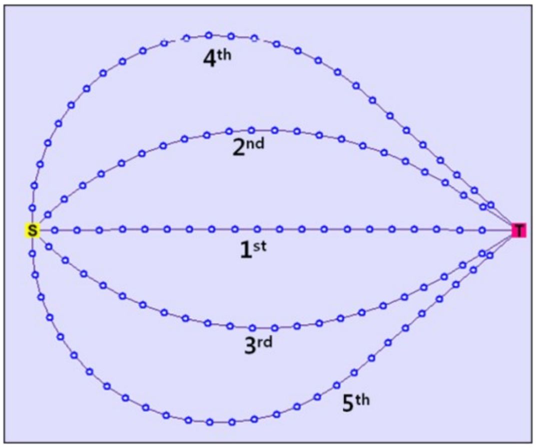

Fig. 17. Waypoints generation using basis line segments variation.

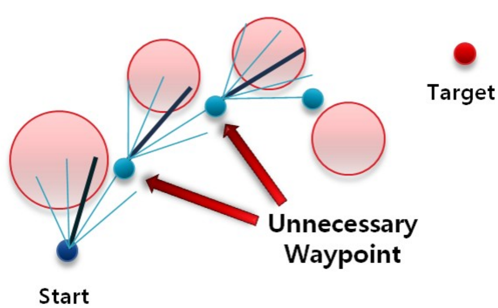

Fig. 18. An example of unnecessary waypoints.

also a property to determine the ith path. Then, $\omega_i(n)$ can be described as a function of i and n such as (5).

Fig. 17 shows 5 different paths using basis line segment variation using (5) when δ_i is 0, -2.25, 2.25, -4.5 and 4.5 as i increases from 1 to 5. Basis line segments aim at a target after the 20th index since n is 20.

$$\omega_i(n) = \begin{cases} \theta_i(n) + (20-n)\,\delta_i, & n < 20, \\ \theta_i(n)+, & n \geq 20. \end{cases} \tag{5}$$

4.4. The method to delete unnecessary waypoints

It is possible that basis line segment variation causes unnecessary waypoints, because waypoints can be generated regardless of avoidance areas. For example, in Fig. 18, the 2nd and the 3rd waypoints are unnecessary because a path connected from a starting point to the 4th waypoint is more reasonable in terms of the travel distance.

In Fig. 19, we have 3 waypoints. We can decide whether a middle waypoint is unnecessary by conducting another line segment evaluation, which is not conducted by constructing candidate points. A double line segment evaluation is carried out using 3 waypoints and a direct line segment evaluation is done just using the 1^{st} and the 3^{rd} waypoints. If a direct line segment evaluation shows a better result, a middle waypoint is unnecessary and it is deleted.

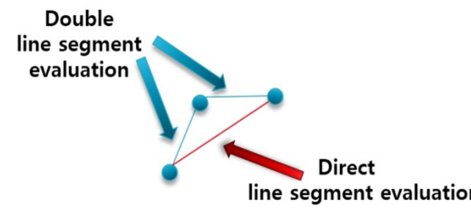

Fig. 19. Double and direct line segment evaluation.

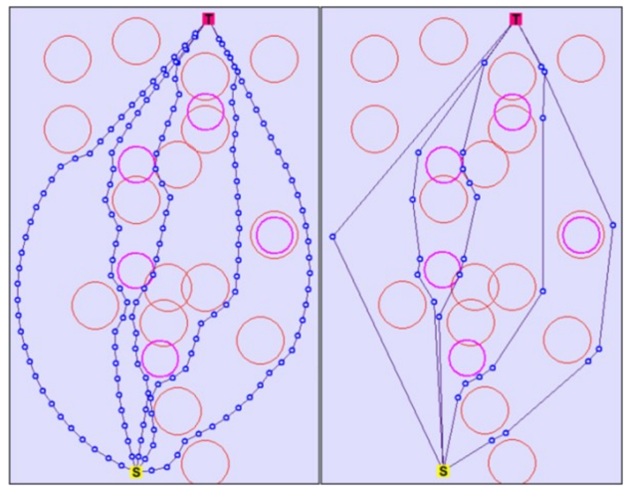

Fig. 20. Results before and after deleting unnecessary waypoints.

Table 2. Procedures for generation of each path.

Step 1	Construct candidate points at a starting point using basis line segment variation.
Step 2	i) Choose the best candidate point after evaluating the candidate line segments. ii) When multiple candidate line segments have the same evaluation value, choose the candidate point closest to a basis line segment.
Step 3	Repeat Step 2 at a recent determined point and delete unnecessary waypoints up to a target point.

The left figure of Fig. 20 shows the original result with all the waypoints. In the right figure, unnecessary waypoints are deleted.

4.5. Procedures to generate a final path

At first, multiple paths are created by varying a basis line segment according to the procedures in Table 2. Then, a final path is selected among multiple paths by comparing the evaluation result.

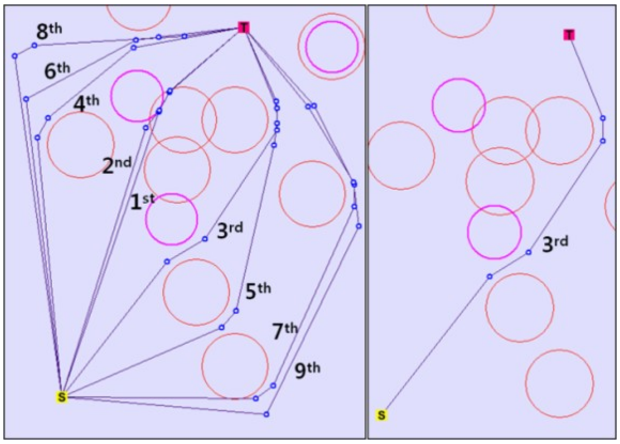

Fig. 21. An example of multiple paths and the best path.

4.6. Illustration using the experiments

An experiment with varying basis line segments is illustrated in this section. The properties of the avoidance area and the evaluation function are the same as section 3.3. The parameters to construct candidates line segments are the same as before except the fact that this experiment uses varying basis line segments. Nine different paths are generated internally and only one of them is chosen as the best path. The first criterion to select the best path is how well a path gets away from the avoidance areas. If multiple paths have the same results, the second criterion is the total distance of a path. The path with the shortest distance is chosen as the best path.

The direction of a basis line segment is defined in (6). δ_i is 0, -1, 1, -2, 2, -3, 3, -4, 4 for 9 paths.

$$\omega_i(n) = \begin{cases} \theta_i(n) + (25-n)\,\delta_i, & n < 25, \\ \theta_i(n)+, & n \geq 25. \end{cases} \tag{6}$$

Fig. 21 shows 9 paths generated using basis line segments variation according to (6). We have same evaluation results regarding the avoidance areas for the 3rd, the 4th, the 5th, the 6th, the 8th and the 9th paths. The 3rd path is selected as the best since it is the shortest distance.

5. PERFORMANCE ANALYSIS

5.1. Simulation results

We validate the proposed method using a simulation. In Fig. 22, the avoidance areas with a radius 1.5, 1.2 and 0.25 are randomly generated in a square of 20×20. A hundred starting points are located along the line which is 1 down from the bottom of the square. At the same time, 100 target points are located along the line which is 1 above from the top of the square. The total number of simulations is 10,000 because we have combination of 100 starting points and 100 target points.

Fig. 23 illustrates some of simulation results. We can see that the paths do not pass the avoidance areas. Table 3 shows that there is no collision for 10,000 simulations. The results also indicate that 3,126 cases do not need varying basis line segment for obtaining the best path. The path of global search is chosen as the best for 6,874 cases.

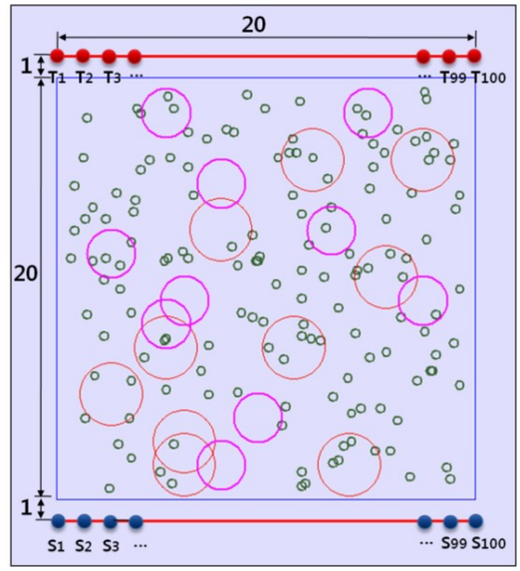

Fig. 22. Simulation environments.

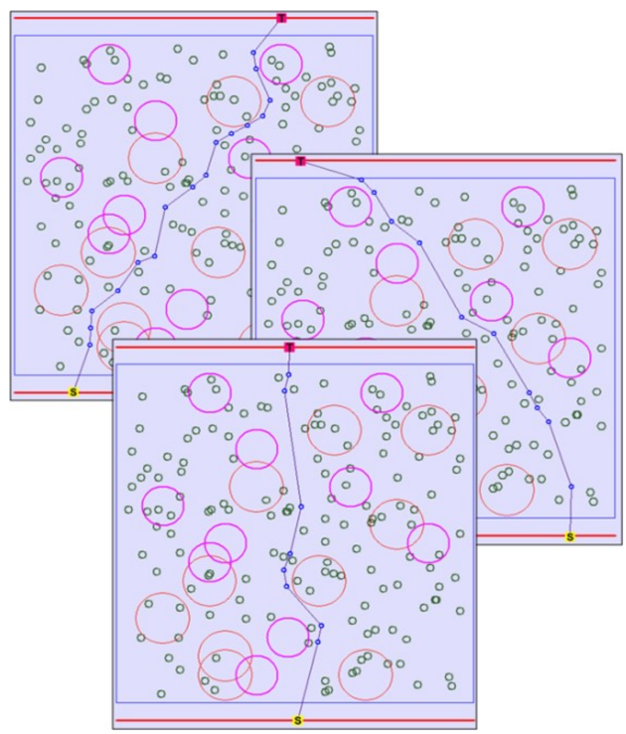

Fig. 23. Illustrations of simulation results.

When we compare the total distance of the best path selected by the proposed method with the direct (namely, shortest) distance from a starting point to a target point, the average value of the ratio is 1.1064. This result means that the selected paths, which is just 10.64% longer than

Table 3. Simulation results.

	Collision	No collision
Local Search	0	3,126
Global Search	0	6,874
# of simulations	0	10,000

the direct paths, can avoid all the avoidance areas.

The computation time is 2,190 seconds ($\approx$ 36 minutes) for 10,000 simulations. Therefore, 0.22 seconds is used for a simulation on average. Since 9 candidate paths are generated for a simulation, only the average time of 0.024 seconds is needed for a candidate path. We notice that line segment selection method can generate a path very rapidly. PC specifications for the simulation are Intel(R) Xeon(R) CPU X5460 @ 3.16GHz / 3.00 GB RAM.

5.2. The number of operations

The basic operation of the proposed method is line segment evaluation which is based on calculating a distance between a line segment and an avoidance area. A line segment consists of a determined point and a candidate point. To obtain one waypoint, we need $N_p \times N_a$ operations. N_p and N_a denote the number of candidate points and avoidance areas, respectively. The maximum number of waypoints in one path, M_w can be calculated using the distance of feasible boundary of starting and target points, so this is deterministic value. Then, to get one path we need $N_p \times N_a \times M_w$ operations. To overcome the limitation of the local search, we generated multiple paths and chose the best one. Then, to get the final path we need $N_p \times N_a \times M_w \times N_m$ operations. N_m denotes the number of multiple paths. We find out that the total number of operation is in direct proportion to the number of avoidance areas, so the total number is limited. This means that the algorithm originated from our method converges.

5.3. Comparison with Voronoi diagram

Voronoi diagram [1,2] is widely used technique in path planning. We compare the proposed method with voronoi diagram to show that the proposed method is more applicable than voronoi diagram. Fig. 24 illustrates an example of voronoi diagram and the path that is generated using the voronoi diagram.

From Fig. 25 to Fig. 27, we show the comparison examples of voronoi diagram with the proposed method according to the different circular avoidance areas. The path with blue line is generated by the proposed method. The path with red line is generated using voronoi diagram. The path generated using voronoi diagram do not change even if there are changes in circular avoidance areas.

From the Fig. 25, we know that the proposed method generates more efficient and shorter path than the path generated using voronoi diagram.

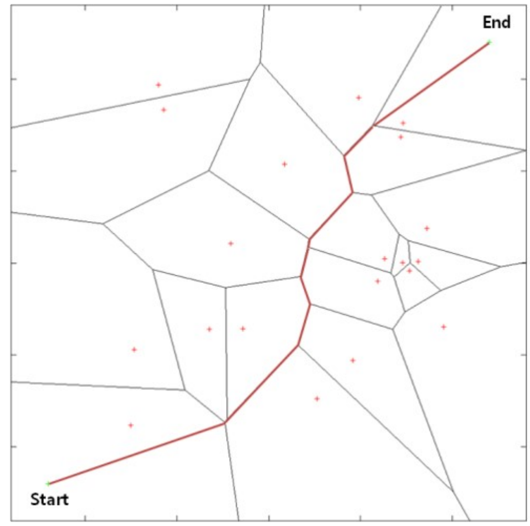

Fig. 24. Voronoi diagram.

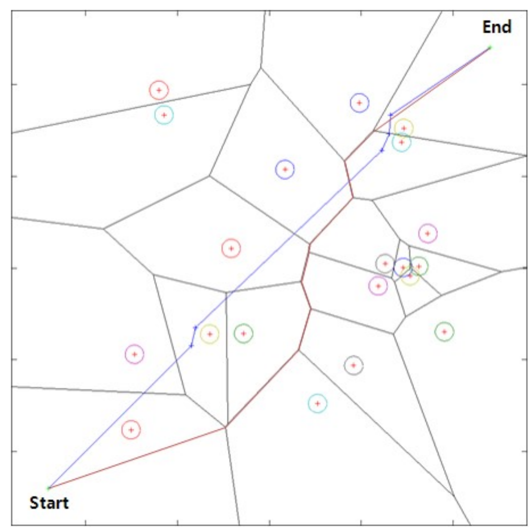

Fig. 25. Comparison example 1.

From the Fig. 26 and Fig. 27, it is likely that the path generated using voronoi diagram goes through the avoidance areas. But the proposed method generates the waypoints which consider the various sizes of circular avoidance areas.

5.4. Real world application

The proposed method can work on the real maps such as google map. The point in these map are defined by using coordinate system such as degree (longitude/ latitude), MGRS, and so on. But in the paper, the points are defined in the Cartesian coordinates. To apply real world problem, we need a conversion between two coordinate systems. By the specific conversion technique, we applied the proposed method to the unmanned aerial vehicle path planning project which we had conducted for several years.

We need a real-time applicable method with a varying

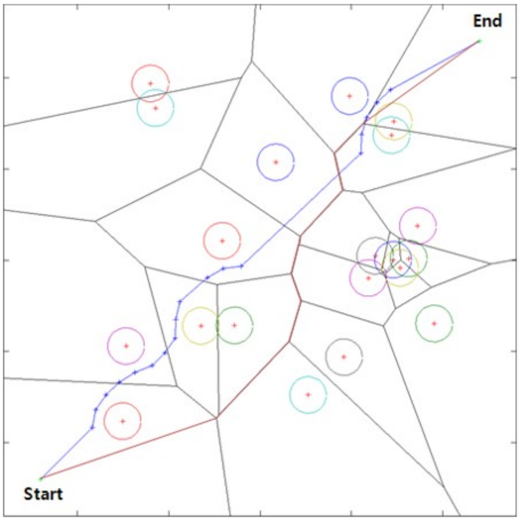

Fig. 26. Comparison example 2.

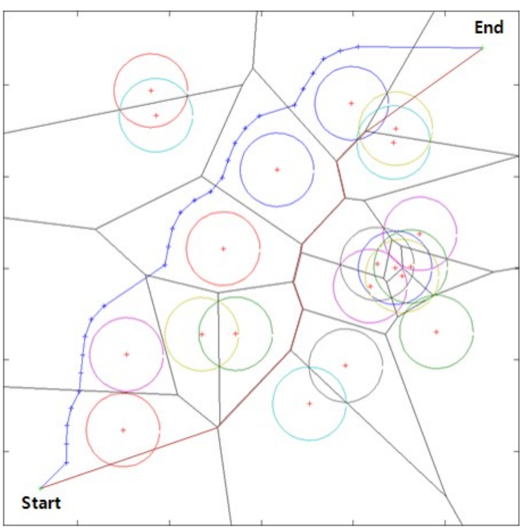

Fig. 27. Comparison example 3.

environment. The most important factor in real-time path planning is the execution time and stability of the methods. With the typical methods such as Voronoi diagram, visibility graph, potential field and trajectory optimization, they need too much time for path planning. Some of them do not provide solution occasionally. But by using our proposed method, we can always get a good solution in a short time, even if it is not the best. Moreover, we do not need to worry about solution convergence. These are the advantages of our proposed method. Therefore, we can easily apply our method to varying environment even if the number, the location and the size of avoidance areas are not fixed. We can apply this method directly to waypoints(reference points) generation, which is used as navigational information.

6. CONCLUSION

In this paper, we propose a fast and effective path planning method to avoid multiple circular avoidance areas. The line segment selection method that we propose can generate waypoints taking the constraints of a vehicle into account such as a minimum distance and angle constraint between waypoints. Therefore, post-processing techniques are not required. Because this method does not use the cost function minimization, we always expect effective and stable results. Global search which uses the varying basis line segment can overcome the limitation of local search.

In this paper, we assume that the avoidance area is circle-shaped. For some cases, this assumption is well applied, but there are many arbitrary shapes in reality. We think that a polygon is more effective to represent the arbitrary shapes than a circle. In the future, we will develop a rapid and effective path planning method to consider arbitrary shapes.

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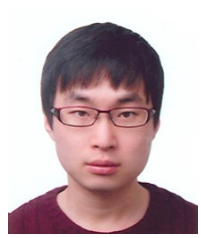

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