Multi-layer Patching Algorithm for Skeleton-based Path Planning

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***Abstract*—This study proposes an optimal path planning algorithm for autonomous mobile robot navigation in a known environment, whereas avoiding possible unknown obstacles. The algorithm incorporating an off-line and an on-line locomotion mechanisms. The off-line path planning is based on skeleton extraction to establish a medial axis graph. With the use of the skeleton graph, the shortest path can be generated. In this study, a multi-layer patching algorithm is proposed to record information required in the on-line stage when unknown obstacles block the pre-determined path. Taking advantages of the Dijkstra's algorithm and the skeleton graph, the proposed multi-layer patching algorithm is capable of avoiding obstacle and overcoming the local minima problem. From the simulation results, the feasibility of the proposed algorithm is confirmed in several experimental results.**

***Index Terms*— path planning, autonomous mobile robot, skeleton extraction, obstacle avoidance, multi-layer patching algorithm**

I. INTRODUCTION

Robotics technology has shown extremely advances in recent decades, especially mobile robots, which have great potential markets in many fields in industry and in home service. Mobile robots not only can replace workers in the manufacturing industry but also replace humans in military, service, entertainment, and other fields. Businesses of all types, auto manufacturers, hospitals, hotels, need point-to-point mobile devices. There are a variety of cost-saving reasons, mainly it is now achievable, cost-effective, and proven to be useful. In order to make point-to-point delivery, mobile robots must have high efficiency in locomotion and have the knowledge of perception for complicated environments. In other words, mobile robot systems need the locomotion mechanisms to move in a collision-free manner throughout its environment in an possibly globally optimal way. To set up reliable collision-free locomotion mechanisms in an globally optimal way, the mobile robot system must be an autonomous system, which means that the system can be adaptive to what it encounters so as to have a solution in an optimization sense. Generally, the most necessary functions for the locomotion mechanisms are path planning and obstacles avoidance, which can lead the robot to its destination in an optimal and safe way.

Many existing approaches for mobile robot path planning fall into two categories, off-line planning and on-line planning. Before motion begins, off-line planners compute the entire path to the destination, while on-line planners generate the trajectory to the destination incrementally, during motion. According to a known planar map, the off-line planners can generate the globally optimal solutions, whereas the on-line planners can plan the locally optimal solutions based on the partial view of the environment. However, off-line planners can find the optimal solution, but may not be able to handle new obstacles sensed on line. On the other hand, on-line planners can deal with any on line situations, but may not be able to go through a global search to get a globally optimal path.

In this study, a skeleton-based path planning in generating the globally optimal solutions is considered. Among those algorithms for solving the shortest path problem, the most famous algorithms are Dijkstra's[1] and A*[2]. These two algorithms can effectively solve the shortest path problems. However, when the robot encounters obstacles, the derived path for the robot may be too close to the obstacles. Hence, the concept of line of sight is employed to form a skeleton-based path planner to find out the shortest path that will be smoother than the A* algorithm. In order to benefit from the mobility, an adaptive pure pursuit path tracking is proposed to make a safety look ahead distance for the robot turn so that the robot will not be too close to obstacles.

Dijkstra's and A* are to find the optimal path from the map. However, when a robot moves along the obtained path to the destination, the robot may encounter unexpected obstacles or so-called dynamical obstacles. Usually, such obstacles are detected by devices like laser rangefinders. It can be expected that when detecting such an unknown obstacle by laser rangefinders, the robot cannot know the whole shape of the obstacle. It is unable to judge directly the obstacle being small or big in the partial view of the environment and thus, it may be difficult to determine how to patch the path obtained. Thus, in this study, based on the original skeleton structure, a real-time multi-layer patching algorithm is proposed to resolve such a dynamic obstacle problem. In the case of the path being completely blocked, the robot cannot move on the path originally obtained, the system will select a feasible path from the multi-layer patching paths based on the current situation, It should be noted that the multi-layer patching paths is off-line planned in an optimization sense. With the information in the multi-layer patching paths, the robot can reach the destination successfully in an optimization sense and does not need to recalculate the optimal path through the original map. From our experiments, it can be found that the proposed approach can effectively find the optima path to the destination when encountering dynamical obstacles and the system does not need to go back to search the whole map to find the optimal path.

In this paper, after this introduction, Section 2 shows the system structure considered and the literature reviews of related research. Section 3 introduces the off-line planning used. How to make the map pre-processing, to define multi-paths, and to plan the optimal path are given. Section 4 is about on-line path planning of the multi-layer patching algorithm. The locomotion mechanism to avoid obstacles is discussed here. Section 5 shows the experiment results by using those mechanisms

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proposed. Finally, in Section 6, some conclusions and suggestions for the further research and future developments are given.

II. System Structure and Literature Review

The complete system architecture of the proposed approach is shown in Figure . As shown in the figure, a known flat map is considered first. Then, the configuration space is considered for the map and skeleton extraction is carried out to define all skeletons in the map. The skeleton construction process will generate the junction points and the skeleton graph. A globally optimal path can be obtained by layering the paths based on the junction points and the skeleton graph. Along this path, backup multi-layer patching paths for on-line planning are then generated. The detailed algorithm will be presented later. If the original path becomes not feasible, the multi-layer patching algorithm can be considered for on-line planning and lead the robot to the destination regardless of the obstacle shape.

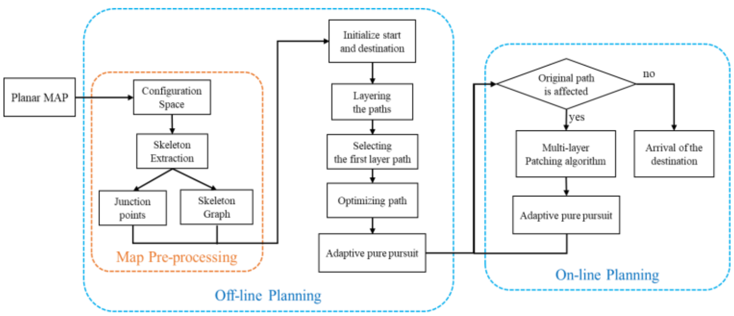


Figure 1 System process

Path planning is to find a feasible path of a mobile object to meet moving demand. A lot of research works have been done in this field to seek for collision-free paths from an initial position to a goal position [3]. The basic path planning is about geometric planning [4, 5]. It is to search for an obstacle-free path from the starting point to the target and to avoid all obstacles in the environment. Most off-line planners are based on the geometric representation to globally search for the shortest path from starts to targets. The geometric planning may include the roadmap or graph to generate the free-space topology, such as Voronoi Diagrams [6, 7] and Skeleton Extraction [8, 9] by combining the search algorithm like Dijkstra's [1] and A* [2].

After path planning for the entire map, the navigation has been generated. The algorithm of the on-line planning is to navigate the robot to reach the goal, whereas to avoid unknown obstacles. Potential field [10] and VFH(Vector Field Histogram) [11, 12] are the common methods for obstacle avoidance in the on-line planning. The main disadvantage of this kind of approaches is that it may encounter local minima problems when dealing with concave obstacles. For the local minima problem, the off-line planning algorithm is based on the path by skeleton extraction. The result of the skeleton extraction can show the all of the possible paths in a map. Hence, it is possible to provide in complex maps to be used to generate backup plans for the on-line planning. This kind of on-line planning can be viewed to be based on the path obtained by off-line to solve the problem of local minima.

To establish multiple paths, several ideas have been proposed [13, 14]. Among them, a popular algorithm is the K-shortest paths[15]. This algorithm calculates multiple paths from the start position to the target position. But this kind of operations is useless for our task about online planning for obstacles. Nevertheless, the concept is adopted to make multiple-layers paths for the scenario of obstacle obstruction in on-line planning.

III. Off-line Planning

This section illustrates the process of building a safe and simple globally optimal path for a robot in a complex map. Many algorithms are to find only one shortest path on a complex map. In this study, a global path planning algorithm that not only has the shortest path but also records multi-paths for backup is proposed. In this method, there are three steps: map pre-processing, global path planning, and path tracking. They are described in the following subsections.

3.1 Map Pre-processing

In motion planning, a key concept is configuration space or C-space for short. The configuration space is mainly to ensure that the moving space does not cause a collision between the robot and the obstacle. In path planning studies, a robot becomes a point in the C-space. In traditional path planning algorithms, C-space is often employed to make path planning because to move a point on a C-space map instead of a robot on a regular map is much easier. To put it briefly, C-space is based on the size of the robot and can be gained by expanding the workspace for the planar robot.

In this study, the initial path planning is conducted in a map under the description of skeleton. Skeleton extraction [16] from an image retains a line with only a pixel width. The image after skeleton extraction maintains a shape features of an original image as well as all the information about the structure. In shape analysis, the skeleton of a shape is equidistant from its boundaries, and it preserves the structure of the shape. The skeleton of the notion is defined as a result of the Medial Axis Transform (MAT) or Symmetry Axis Transform (SAT) by H. Blum [17].

Through the references [9,18], the skeleton extraction process maintains the connectivity of one-pixel thick skeleton. A one-pixel width curve point whether it has more than two curve pixels among its 3 x 3 neighborhood, is defined as junction point (triple points). To detect the junction points of a skeleton image, structuring elements taken into consideration include the two fundamental configurations corresponding to the junction point, A and B, shown as in Figure . Considering various configurations, two primary configurations A and B are rotated 45 degrees, or its multiples.

(a) (b)

Figure 2 The basic configurations of A and B are defined as (a) and (b)

To select starting points and target points at any place in the map, the skeleton and junction points are effectively utilized in planning. To define the initialization for a starting point and a target point is to find he closest junction points the skeleton map. The dilation morphological operation with a circular shape is employed to gain the closest junction points about the starting point and the target point.

3.2 Global Path Planning

About global path planning, the mainly purpose is to find the shortest path and backup the multi-layer paths for the shortest path, it can be separated into two parts: layering the skeleton paths and incremental line-of-sight.

3.2.1 Multiple-layer paths

In this study, multi-layer paths are generated by Dijkstra's algorithm and the concept of the K-shortest paths [15]. The K-shortest paths algorithm is to find those K shortest paths that are all from the start to the destination. In our algorithm, multi-layer paths are to generate the global shortest paths from a starting point as the point on the found path before the breaking (or cut-off) point , which is the point that is blocked by obstacles. Based on those found paths, it can produce multi-layer patching paths and is used to confirm the reachability of on-line planning. Assume there is a network graph of the skeleton as shown in Figure . The process of the proposed multi-layer paths algorithm is stated in the following:

Step1. Use Dijkstra's algorithm to search for the shortest path of those junction points from point S(start) to point T (target), then put it to layer1.

Step2. Consider that a junction point on the path is block. Then use its preceding point as the starting point to construct the shortest path by Dijkstra's algorithm. This become a path on Layer2. As in Figure 3, assume that S to J_2 is blocked, the algorithm can search for the other shortest path to the point T. The process is sequentially applied for each connect ($J_2 \rightarrow J_3$, $J_3 \rightarrow T$) of the original path. All resultant paths are the multiple paths in layer2.

Step3. The same process in Step 2 can also be conducted to form layer3 as shown in Figure 4.

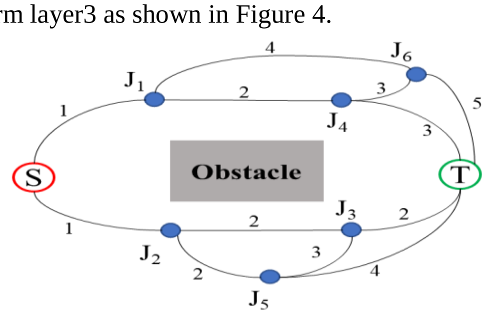


Figure 3 The network graph of skeleton

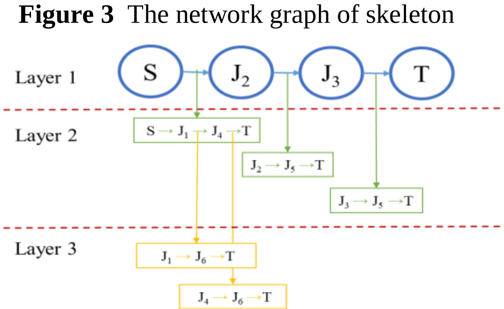


Figure 4 Graph of the layering

For illustration, Table 1 shows the results of the K-shortest paths [15]. It can be found that the paths are all from S to T. But when the system hopes to find alternative paths while encountering obstacles, those paths are useless because those obstacles may not be so lucky to appear at those breaking points.

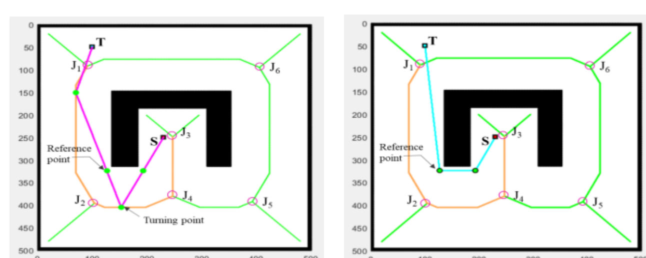
Table1 Result of the K-shortest paths algorithm

The first 5 shortest paths	Path	Cost
1st	$S \rightarrow J_2 \rightarrow J_3 \rightarrow T$	5
2nd	$S \rightarrow J_1 \rightarrow J_4 \rightarrow T$	6
3rd	$S \rightarrow J_2 \rightarrow J_5 \rightarrow T$	7
4th	$S \rightarrow J_2 \rightarrow J_5 \rightarrow J_3 \rightarrow T$	8
5th	$S \rightarrow J_1 \rightarrow J_6 \rightarrow T$	10

3.2.2 Incremental line-of-sight and adaptive pure pursuit algorithm

In practical the original skeleton path actually is not the shortest moving path. Hence, the concept of line-of-sight is employed to convert skeleton paths to available moving paths. Originally, line-of-sight is used to link corners of obstacles to form paths. The proposed incremental line-of-sight for the skeleton is not only to find the shortest path but also can reduce the turning points of the path. The concept is to sequentially produce straight lines between the points on the layer1 skeleton path, while determining whether the straight line overlaps the C-obstacle or not. If the straight line is overlapped with the C-obstacle, record the overlapping point as the turning point on the layer1 skeleton path. All these points are set as the reference points, then continue to connect the turning point, until the target point is reached. This step is being depicted in (a) (b)

Figure (a). To ensure that the global path is the shortest path, one more step is needed in this method. It is to sequentially connect the starting point to the turning points obtained in the previous step and to judge which straight line is longer and is removed until the target is be connected. The result of the considered example is shown in 錯誤! 找不到參照來源。 (b). Thus, the algorithm of skeleton-based path planning not only can search for the shortest path but also can solve the local minima problem. Thus, the algorithm can also be used for obstacle avoidance.



(a) (b)

Figure 5 (a) First step for the global path and (b) the result of the global shortest path

In the field of path tracking, the pure pursuit algorithm [19] is the basic method and it is a widely used. The concept of the pure pursuit approach is to calculate the curvature that will take the vehicle from its current position to a goal position, while it has a parameter of look-ahead distance. The main point of the algorithm is to choose a proper look-ahead distance. It is analogous to human driving in that humans look a certain distance ahead of the vehicle and steer such that the vehicle would reach a point at the look-ahead distance. In the pure pursuit algorithm, the look-ahead distance is an important parameter. If this parameter can be able to change with the distance between the robot and the obstacle, the tracking trajectory can be more smooth and stable. With the distance between a path and an obstacle is variety, an adaptive pure pursuit algorithm based on traditional pure pursuit method is proposed. The proposed approach can consider a distance value between a path and an obstacle to set a parameter of look-ahead distance. The flow chart is shown in Figure 6 and the details can be found in [18].

In order to verify that the adaptive pure pursuit algorithm is feasible, a simple case as shown in Figure is considered. Through the algorithm, it can be found that the look-ahead distances of these two turning points. The result of the path tracking is shown in Figure . The parameter of the look-ahead distance can be varied with the distance between the path and the obstacle, the tracking trajectory is to be smoother and more stable. By using an adaptive pure pursuit algorithm, the tracking trajectory is obvious improved. Through the adaptive pure pursuit algorithm, the mobile robot can achieved smooth trajectories without collision.

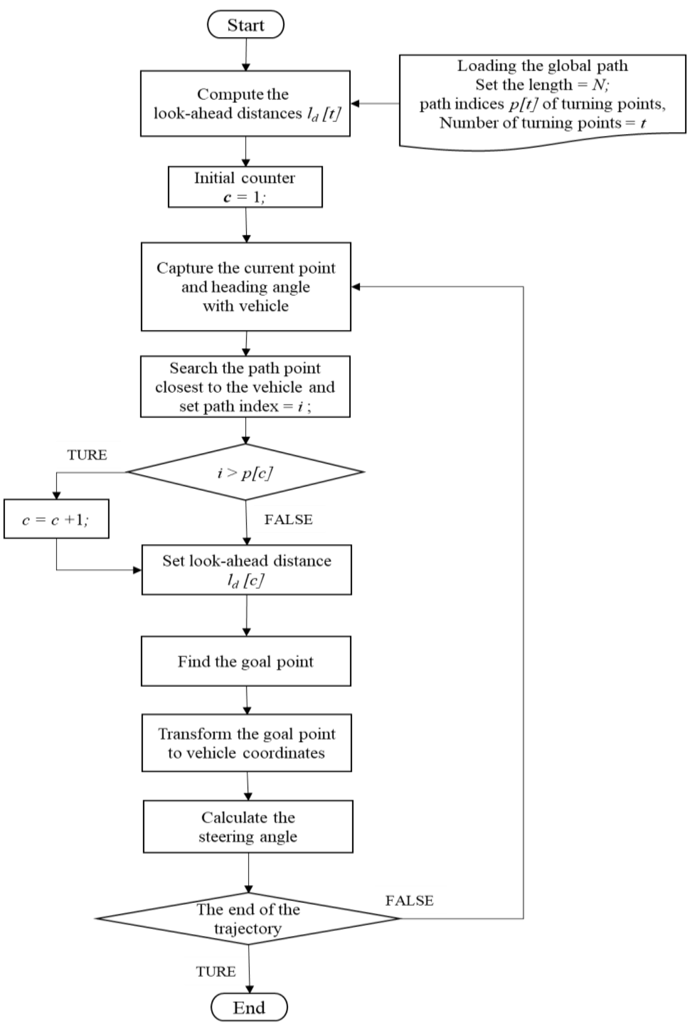


Figure 6 Flow chart of adaptive pure pursuit algorithm

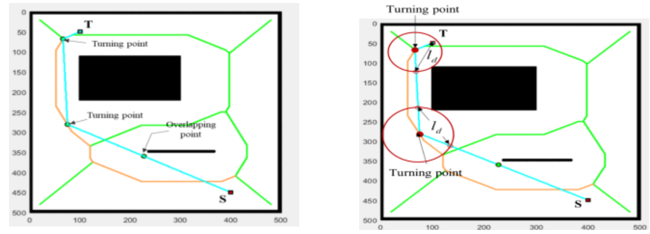


Figure 7 a simple example of adaptive pure pursuit algorithm

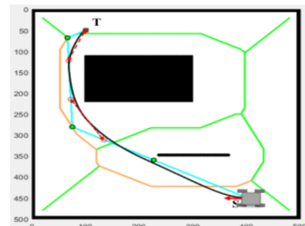


Figure 8 The result of using the adaptive pure pursuit algorithm

IV. On-line Planning

In this part, the main purpose is to avoid obstacles in the motion. In this study, a laser rangefinder is assumed to be used to scan the environment within a given effective range of distance and angle so as to deliver a range measurement of the surrounding objects. The robot follows the previously established global path and progressively detects obstacles. If an obstacle is detected, the system should determine whether this new obstacle will affect the original path or not, and then if yes, the obstacle avoidance is performed. The situations of avoiding obstacle are divided into two parts :

Scenario 1: With obstacles, the robot still can move through the original designated path. In other words, the obstacles do not block the path. Thus only simply to employ on-line obstacle avoidance mechanism, like potential field, is ok. Before the system determines the deformed path is blocked, the robot program has remained in scenario 1.

Scenario 2: In the condition of the deformed path is completely blocked, the system enters to scenario 2, whereas the next layer in the multi-layer paths for the current breaking point is selected to avoid the blocked obstacle and to arrives the destination.

In our implementation, a simple idea is proposed to determine whether the path is blocked or not. An overview of the on-line planning system is shown in Figure .

For the sake of providing an illustration the above process, a path planning problem as shown in Figure is considered. As shown in Figure 10 (b), if the path from A to B can be found, it is in scenario 1 and a simple algorithm is applied to connect them. But, if the path from A to B cannot be found, the deform path algorithm confirms that the obstacle blocks the path and causes the mobile robot cannot move forward. The on-line planning will go to scenario 2. Through the cell array of the multi-layer paths, the corresponding patched skeleton path is found as shown in Figure .

V. Experiment Results

This section is to illustrate the results obtained by our approaches including on-line planning and off-line planning. The experiments are done on the series of the planar maps. First, the shortest path is be generated with skeleton-based path planning. After that, the look-ahead distance setting is examined which is to calculate along with a distance between the current position and the obstacles. With these experiments, the off-line planning can be asserted feasibility in the locomotion mechanism system. Through the map as shown in figure 12, with different start points and target points, of multiple groups to confirm the result of our proposed algorithm in Figure our approach can always find the shortest paths as shown in the figure.

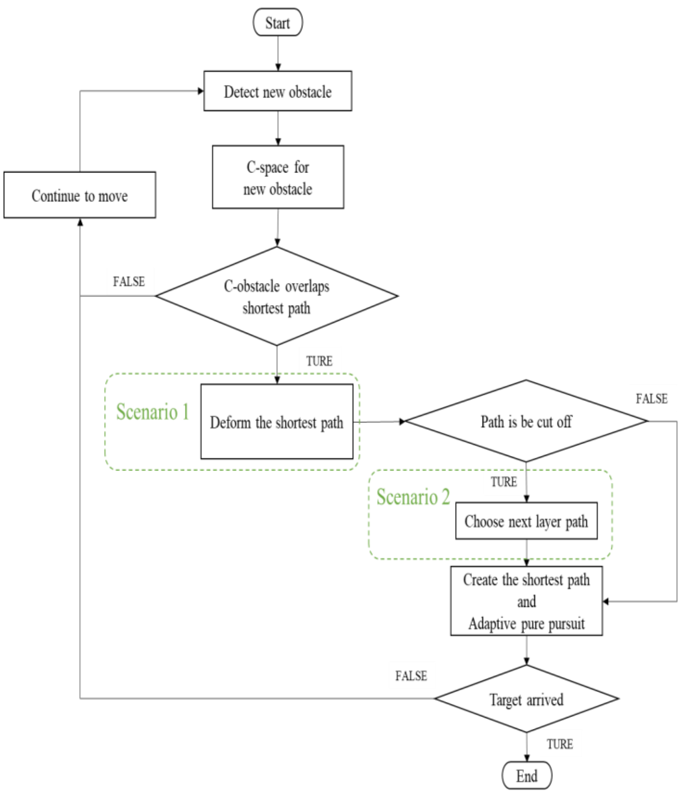
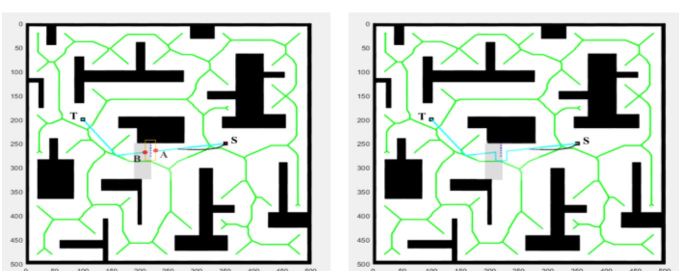


Figure 9 Flow chart of the on-line planning



(a) C-space for obstacle points and find two points (A, B)

(b) Connect A and B

Figure 10 Deform the path from (a) to (b)

The experiments for encountering obstacles are divided in the two scenarios:

1. Bypass the obstacle to arrive the destination. (Scenario 1)
2. Using the multi-layer paths to bypass the blocked obstacle and arrive the destination. (Scenario 2)

When a new obstacle is detected, the system enters scenario 1 first and starts to avoid the obstacle. The obstacle avoidance process is a global path obtained in the previous off-line planning for reconstruction. The results can be shown in Figure . If the system has been confirmed that it cannot move forward, the system will enter scenario 2 and the multi-layer patching algorithm is employed to generate the other path as shown in Figure .

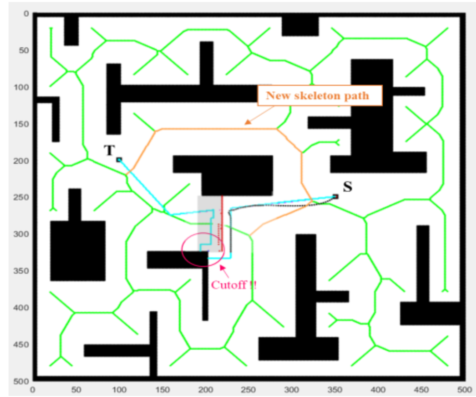
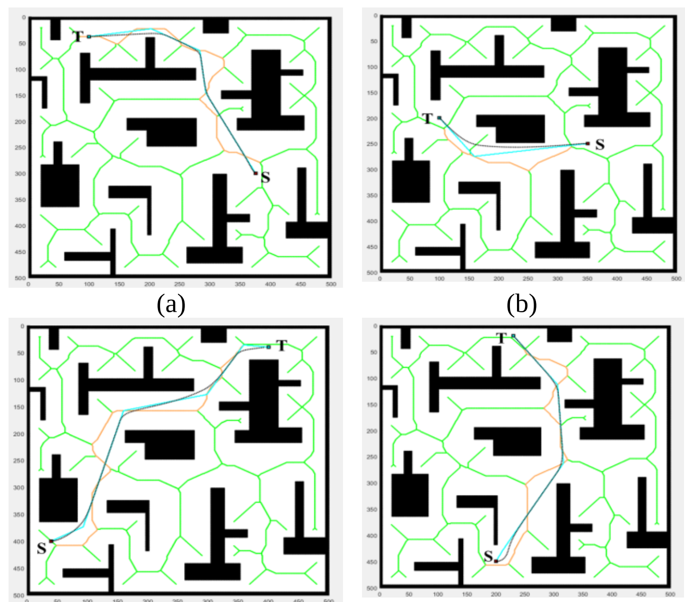


Figure 11 Scenario 2: blocked path and the next layer skeleton path is be found



(a) (b)

(c) (d)

Figure 12 Multiple results with different starts and destinations

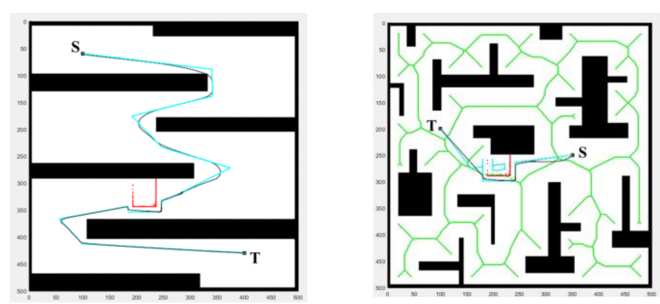


Figure 13 Bypass the obstacle

VI. CONCLUSIONS

In this study, a locomotion system is constructed for mobile robots. The structure of the proposed approach can be divided into two parts: off-line planning, and on-line planning.

For the off-line planning, first, the planar map is proposed for skeleton extraction, and a small data but representative skeleton network are obtained. Then, the shortest skeleton path is calculated from the skeleton network, whereas the multi-layer patching paths are also established. With the shortest skeleton path, incremental line-of-sight is employed to obtain the global executable shortest path. The adaptive pure pursuit is to define paths according to the distance between obstacle and robot to change the look-ahead distance, and the path found is smooth without collision.

In this study, a series of the experiments have been conducted. It can be found that this method can effectively reduce the complexity of the path search when there are unknown obstacles and the optimized for the path found is still ensured. In addition, the method can effectively solve the problem of bending paths, the problem that the path is too close to obstacles, and the problem for local minima. Most approaches in the literature mainly emphasize how to plan the shortest path. There is often no further planning for local navigation. In this study, a patch path algorithm is proposed for on-line planning to avoid unknown obstacles efficiently. Through the off-line planning, more information are obtained from the planar map to be used in the on-line planning. Although the computation time of the off-line planning is large, the off-line information can reduce the times for on-line planning.

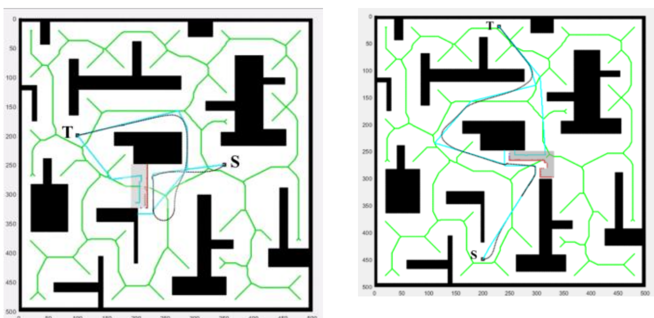


Figure 14 The patching path with scenario 2

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