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TMPU: A Framework for Terrain Traversability Mapping and Planning in Uneven and Unstructured Environments

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Abstract: In this paper, we propose an autonomous navigation framework (**TMPU**) for ground mobile robots in uneven and unstructured environments. The novelty of this framework is twofold: 1) The terrain traversability mapping module is proposed to build a low-resolution 2D (Two-Dimensional) occupancy map by plane analysis based on plane slope and terrain roughness. 2) A multi-resolution motion planning framework is proposed to obtain a high-resolution traversable corridor by A* low-resolution search. Then an improved global planning H-lattice planning is performed on the traversable corridor. Furthermore, extensive experiments are conducted to demonstrate the feasibility and safety of the proposed autonomous navigation framework. All test results show that the computing time consumption is reduced by up to 97.1%, compared with an advanced 3D navigation framework. (Supplemented video link: https://youtu.be/rvYoyR3imEk)

Key Words: Ground mobile robots, Terrain assessment, Motion planning, Uneven environments

1 Introduction

Autonomous navigation systems for ground mobile robots are well studied and widely employed in flat terrain [1], [2]. However, there are many significant challenges for robots working in generic 3D environments, including uneven and unstructured scenes [3]. The work in [3] shows that the capability of the ground mobile robot operating in uneven environments has a wide range of applications. For example, autonomous exploration [4], [5], search and rescue [6], [7], ground mobile robots must handle the uneven terrain. Therefore, developing safe, feasible, and efficient autonomous navigation systems for ground mobile robots in uneven and unstructured environments has a practical application value.

1.1 Overview

In this paper, we propose an autonomous navigation framework for ground mobile robots in uneven and unstructured environments. Fig. 1 shows the overview of the system framework. The terrain traversability mapping module is proposed to accurately and robustly characterize the uneven and unstructured environment. The motion planning module is responsible for efficient and safe navigation. The work procedures of the proposed framework are described as follows. First, the 3D SLAM [8] module is employed to build a OctoMap [9] representation for the environment. Second, the terrain traversability mapping module generates a low-resolution 2D occupancy map by processing the OctoMap. Then, the 2D occupancy map serves as the input for the motion planning module. A high-resolution traversable corridor can be obtained by A* searching on the 2D occupancy map. Finally, the global planning and local planning are executed on the traversable corridor. Section 2 describes the implementation of this framework in detail.

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1.2 Related Work

At present, studies on autonomous navigation in 3D environments have been greatly developed. Krüsi et al. [10] propose a novel global motion planning algorithm that enables planning directly on 3D point cloud maps. In their work, the terrain traversability is assessed by analyzing the local distribution of 3D point clouds and fitting robot-sized plane patches to the map. The disadvantage of this algorithm is that it needs to process a large amount of 3D point cloud data. In [3], the 3D autonomous navigation is summarized in a two-step procedure, including 1) environment perception and modeling and 2) motion planning. Wang et al. [11] propose a new 3D autonomous navigation system that integrates environment perception and planning. The system in [11] first generates a traversable map based on layer differences. Then, a variable step size RRT (Rapidly-exploring Random Tree) approach is employed to search a global path on the traversable map. However, this system is limited to indoor step and slope scenes. A framework capable of navigating in the more complex and uneven outdoors is proposed in [12]. The framework combines the terrain assessment algorithm based on plane fitting, RRT* algorithm, and GPR (Gaussian Process Regression) to obtain a global path. However, there are two obvious problems with this framework, i.e. the robot may fall into the cliff or collide with obstacles. These problems are presented in Section 3 of the paper. In [13], a novel path planning method based on 3D-NDT (Three-Dimensional Normal Distributions Transform) is presented, which directly utilizes the full 3D representation of the environment instead of the limited 3D representation that discards potentially useful information. To enable rappelling rovers to operate on steep terrains, Paton et al. [14] propose a new system that includes tether-aware traversability analysis and a sampling-based planner that plans paths on locally sensed 3D meshes according to traversability analysis. A complete system based on point cloud data is designed in [6]. This work employs lazy tensor voting to realize traversability analysis. Position and configuration are planned separately to allow the ground robot climbing stairs.

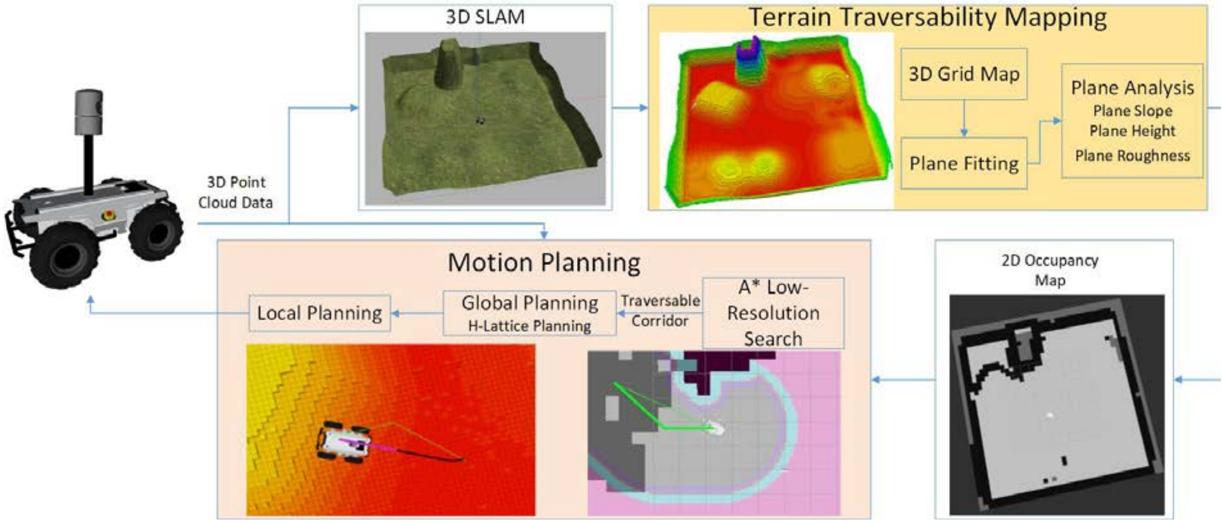


Fig. 1: The overview of the autonomous navigation framework.

Belaidi et al. [15] employ the millimeter wave (MMW) radar data to reconstruct a 3D model of the uneven environment. Then, a polygonal mesh decomposition is extracted by the non-uniform rational B-splines to represent the 3D uneven environment and obstacle surfaces. Next, the optimal path is generated according to the polygonal mesh decomposition.

In summary, existing approaches have the following problems respectively, including 1) some of the approaches are limited to specific scenarios, 2) some of the approaches can only be applied to a specific type of robot, and 3) some of the approaches may result in dangerous operation behaviors.

1.3 Contributions

Motivated by the aforementioned problems of existing approaches, an autonomous navigation framework for ground mobile robots in uneven environments is proposed. In summary, the contributions of this work are as follows:

1) A novel plane fitting approach based on the size of the robot tire is proposed to assess the terrain traversability by computing the plane slope and terrain roughness.
2) A new global planning algorithm H-lattice planning based on plane height is proposed to avoid some negative obstacles or raised obstacles that are not identified by the terrain traversability mapping module.
3) Autonomous navigation is realized in various challenging uneven and unstructured environments. Numerous tests are conducted to verify the advancement of the proposed framework.

2 Methodology

Terrain traversability mapping and motion planning are two crucial components of the framework to realize the autonomous navigation of mobile robots in uneven, rough, and unstructured environments.

2.1 Terrain Traversability Mapping

The goal of this terrain traversability mapping module is to extract the traversable areas of the environment and build a 2D occupancy map, where the traversable areas are mapped to the free areas of the 2D occupancy map. The plane fitting and plane analysis are the cores of this module.

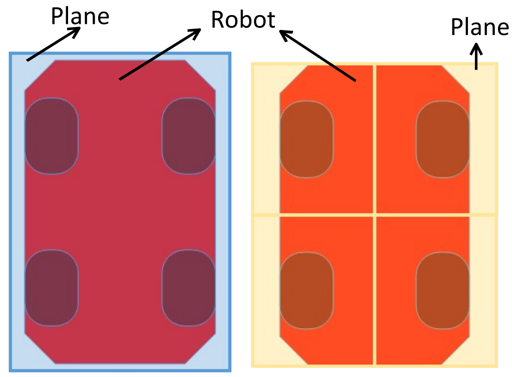


Fig. 2: The schematic diagram of the plane fitting. The blue rectangle is the plane fitted by the existing approach. The yellow rectangle is the plane fitted by the proposed approach.

2.1.1 Plane Fitting

The mathematical representation for a plane P is

$$ax + by + cz = d, \tag{1}$$

where the parameters a, b and c constitute the normal vector $\mathbf{n}$ of the plane P,

$$\mathbf{n} = (a, b, c), \tag{2}$$

the SVD (Singular Value Decomposition) method is employed to compute the parameters a, b and c, i.e. fit a plane. The SVD method can be implemented by the Eigen library.

As shown in Fig. 2, the size of the plane fitted by the existing approach is close to the size of the robot footprint. Different from the existing approach, the size of the plane fitted by the proposed approach is close to the size of the rectangle projected by the robot tire to the ground. The advantage of the proposed approach is that it can ensure the plane passed by each tire of the robot is safe and traversable.

2.1.2 Plane Analysis

The plane analysis is applied to assess whether a plane is traversable, and a total of three metrics are calculated.

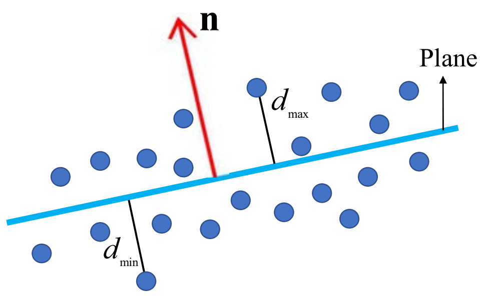


Fig. 3: The schematic diagram of the terrain roughness. $r_p = d_{max} - d_{min}$. d_{max} and d_{min} are signed scalars.

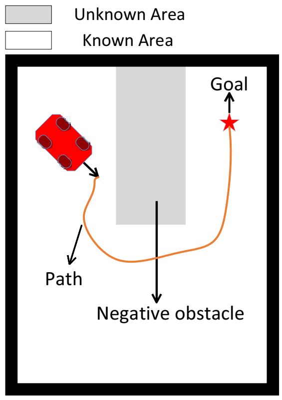


Fig. 4: The schematic diagram of avoiding negative obstacle areas.

(a) **Plane Slope**: Plane Slope s_p is the angle between the fitted plane normal vector $\mathbf{n}$ and the horizontal plane normal vector $\mathbf{n}_h = (0, 0, 1)$. s_p characterizes the steepness of the fitted plane.

(b) **Plane Height**: Plane Height h_p is the height of the fitted plane center point from the horizontal plane.

(c) **Terrain Roughness**: This metric r_p is proposed in [10] to characterize the ruggedness of the terrain. r_p is computed by

$$r_p = d_{max} - d_{min}, \tag{3}$$

d_{max} and d_{min} are the maximum and minimum distances to the fitted plane in the direction of the normal vector $\mathbf{n}$ among all points used to fit the plane, where d_{max} and d_{min} are signed scalars. When a point is below the fitted plane, the computed distance d is negative. Fig. 3 shows the d_{max} and d_{min}.

It is noted that the plane height h_p is used in global planning. We propose an improved global planning algorithm based on plane height, i.e. H-lattice planning. The plane slope s_p and the terrain roughness r_p are used to compute the traversability t of the plane

$$t = \begin{cases} 1, & s_p < s_t \ \wedge \ r_p < r_t \\ 0, & otherwise \end{cases}, \tag{4}$$

where the s_t and r_t are the maximum slope threshold and the maximum terrain roughness threshold of the plane that the robot can traverse. The s_t and r_t are preset according to the traversing ability of the robot.

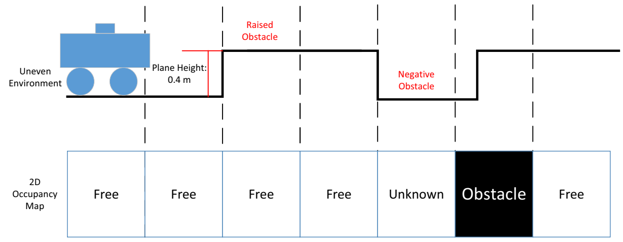


Fig. 5: The schematic diagram of the negative obstacles and raised obstacles that are not identified. Their corresponding grids in the 2D occupancy map should be set to occupied, but due to the problem of the resolution of the 2D occupancy map and sensor perception blind spots, the grids are set to free or unknown.

A 2D occupancy map is built according to the traversability t. When the t of the fitted plane is equal to 1, the corresponding grid in the 2D occupancy map is set to be free, i.e. the plane is traversable. The 2D occupancy map built by the proposed approach is shown in Fig. 9. Finally, the 2D occupancy map is passed as input to the motion planning module of the proposed framework.

2.2 Motion Planning

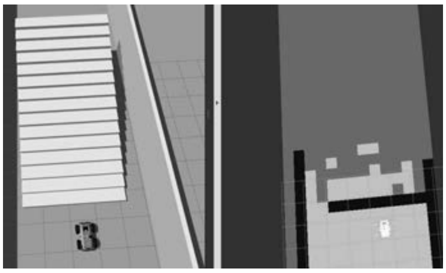
After getting the 2D occupancy map, A* search is first performed on the low-resolution 2D occupancy map, and then the global and local planning are performed on the obtained high-resolution traversable corridor. The specific implementation details are as follows.

2.2.1 A* Low-Resolution Search

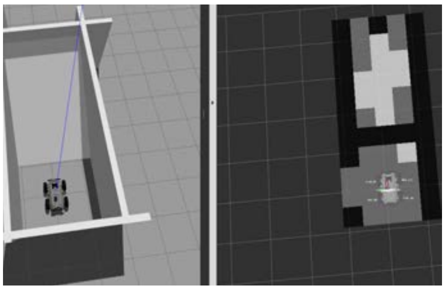
There are two roles of the A* low-resolution search, one is to generate a traversable corridor for speeding the global and local planning, and another is to avoid some negative obstacle areas. The A* search is fast due to the resolution of the 2D occupancy map is low. The global planning is also fast because its node expansion is limited to the traversable corridor whose size is much smaller than the entire map. Fig. 10 shows the traversable corridor obtained by A* searching.

To avoid some negative obstacle areas as shown in Fig. 4, we first judge the state of the grid where the goal is located. The unknown area is traversable when the state of the goal grid is unknown. As the robot navigates to the goal, the state of the goal grid will be updated as known. At this time, the unknown area is updated as impassable. The reason for this is that when the state of the goal grid is known, we think that the robot has already observed the environment around the goal, and the unknown area that has not been observed is very likely to be the negative obstacle area.

It is noted that if the robot is very close to the goal, but the state of the goal grid is still unknown, we consider the goal to be in a negative obstacle area. In this case, it is dangerous if the unknown area is still considered traversable. To avoid the dangerous case, an improved global planning algorithm based on plane height is proposed.

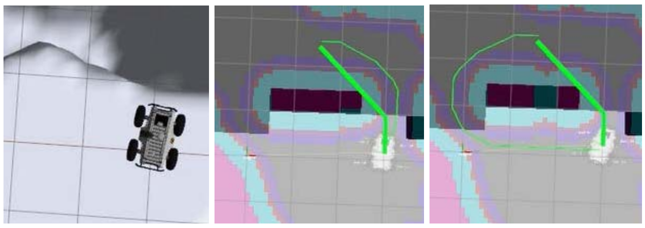


(a) The impassable step scene for robots and the 2D occupancy map of it.



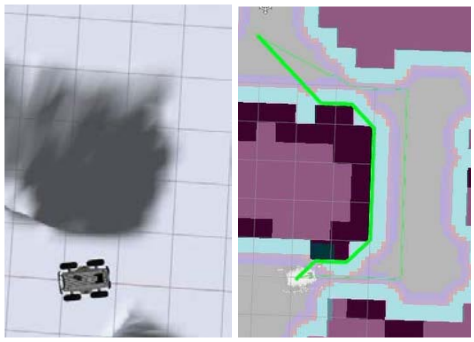
(b) The impassable slope scene for robots and the 2D occupancy map of it.

Fig. 6: The grid state of the 2D occupancy map of the scene that the robot can not traverse will be set to occupied.



(a) (b) (c)

Fig. 7: The proposed H-lattice planning can prevent the robot from falling into the cliff when the goal is in an unknown area.



(a) (b)

Fig. 8: The robot can avoid the negative obstacle area.

2.2.2 H-Lattice Planning

The lattice planning in [1] is improved to avoid the negative obstacles and raised obstacles that are not identified by the terrain traversability mapping module as shown in Fig. 5. These obstacles are impassable and their corresponding grids in the 2D occupancy map should be set to occupied, but due to the problem of the resolution of the 2D occupancy map and sensor perception blind spots, the grids are set to free or unknown. To avoid these obstacles, the extension principle of the lattice planning is modified.

When lattice planning extends from the current lattice to the next lattice, we first judge the angle difference between the planes where the two lattices are located. Then, when the angle difference between the two planes is less than the threshold set in advance, we compute the height difference between the two planes. Finally, if the height difference is greater than the threshold set in advance, we consider this extension to be undesirable.

2.2.3 Local Planning

The local planning in [1] is used to track global paths and avoid obstacles. The local planning algorithm is implemented in the ROS move base framework. We can replace it with other local planning algorithms [16] [17] by modifying the local planner plugin of the move base.

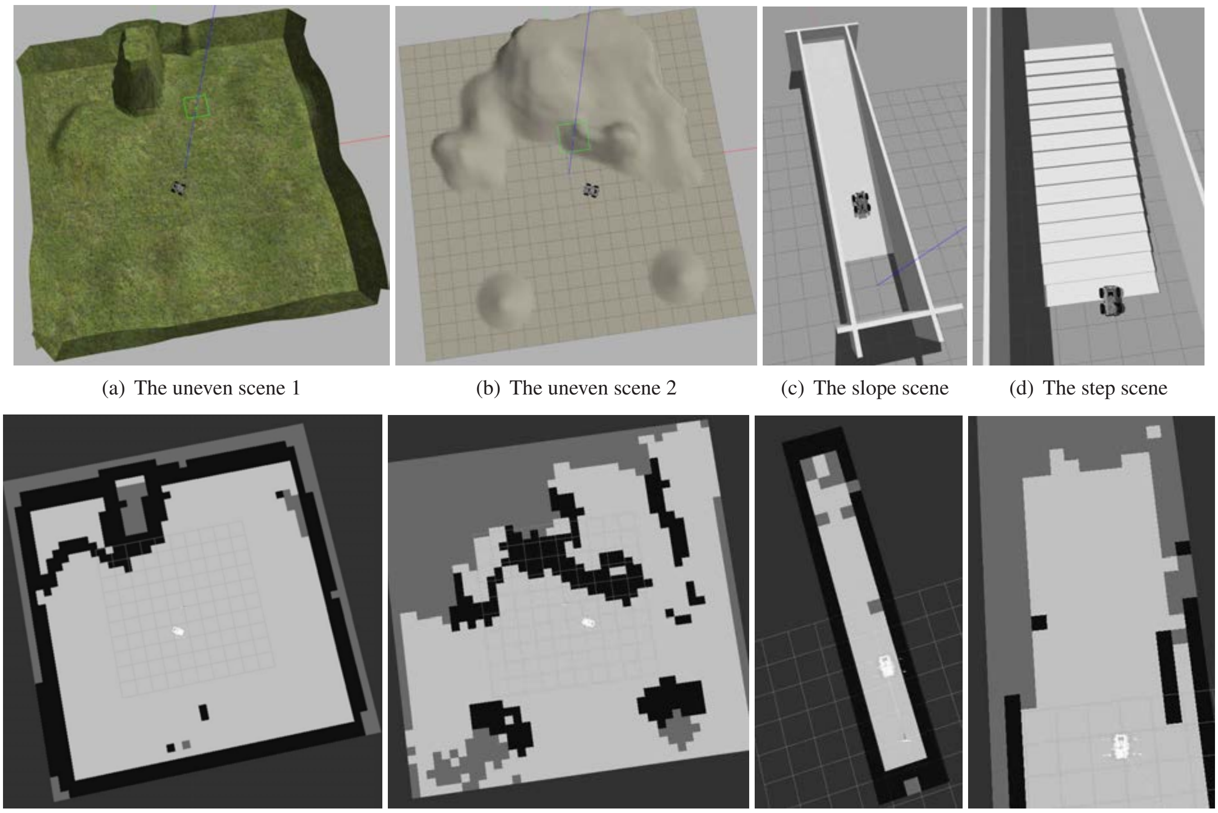
3 Experiments

Extensive experiments are conducted to verify the advancement and feasibility of the proposed framework in various simulation scenarios. The proposed framework is implemented in the robot operation system (ROS) melodic release. We use the robot Scout2.0 in [12] for the experiment. The motion model of the robot is a two-wheel differential drive model. The tests are performed on a laptop with an Intel Core i7-11800H processor and 16 GB RAM. A physics simulation software Gazebo is used to build the simulation environments, including the step scene, slope scene and uneven environment as shown in Fig. 6 and Fig. 9.

As shown in Fig. 6 and Fig. 9, the proposed framework accurately identifies uneven and rugged terrain and generates a 2D occupancy map. The state of the grid of the 2D occupancy map corresponding to the step and slope that the robot can not traverse is set to occupied. And the state of the grid corresponding to the step and slope that the robot can traverse is set to free. The state of the grid corresponding to the unobserved area is set to unknown.

As shown in Fig. 10, the proposed motion planning module can search for a traversable corridor and plan global and local paths according to the 2D occupancy map. Fig. 10 illustrates the autonomous navigation process of the proposed framework in which the robot safely reaches the higher position in the uneven scene. As shown in Fig. 7, the proposed framework can prevent the robot from falling into the cliff when the goal is in an unknown area. The reason is that the proposed H-lattice planning is used to plan a global path. H-lattice planning avoids extensions that the height difference between two planes is greater than the set height difference threshold. In addition, the robot can avoid the negative obstacle area when the goal is in a free area. The reason is that the traversable corridor generated by A* search avoids the negative obstacle area nearby the robot as shown in Fig. 8.

Compared with the existing approach PUTN [12], the path planned by the proposed framework is optimal and smoother. The proposed framework takes less time to assess the terrain traversability and plan a global path than the comparative approach. We conduct tests in the four scenes shown in Fig.



(a) The uneven scene 1 (b) The uneven scene 2 (c) The slope scene (d) The step scene

(e) The 2D occupancy map of the uneven scene 1 (f) The 2D occupancy map of the uneven scene 2 (g) The 2D occupancy map of the slope scene (h) The 2D occupancy map of the step scene

Fig. 9: The simulation scenes and the 2D occupancy map of them. The black area of the 2D occupancy map is impassable.

Table 1: The average total computing time of terrain assessment and global planning for the two frameworks

	Goal Point	Computing Time		Improvement
		PUTN	TMPU	
Scene 1	(5, 5)	618.34 ms	**262.13** ms	57.6%
Scene 2	(5, 5)	479.51 ms	**141.97** ms	70.4%
Slope	(8, 0)	536.85 ms	**15.68** ms	97.1%
Step	(2, -5)	372.41 ms	**143.22** ms	61.5%

Table 2: The performance comparison results of the two frameworks

Framework Performance	PUTN	TMPU
Optimal Path	-	✓
Avoid Unknown Obstacles	-	✓
Avoid Negative Obstacles	-	✓

9. In each scene, the robot is set to the same starting point and goal point. The starting point is set to (0,0). The goal point is shown in Table 1. Each set of tests is performed ten times and the average value of ten tests is computed. The average total computing time of terrain assessment and global planning for the two frameworks is shown in Table 1. All results show that the computing time consumption is reduced by 57.6%-97.1%, compared with the comparative approach.

In addition, the improvement in the following cases is as follows. As shown in Fig. 11, the robot falls off a cliff when the comparative approach is run. However, the robot stops safely when our approach is run. The robot collides with an obstacle when the comparative approach is run as shown in Fig. 11. The proposed approach performs better in this case. The robot safely avoids the obstacle and reaches the navigation goal. The performance comparison results of the two frameworks are shown in Table 2.

4 Conclusion

In this paper, a novel framework is proposed for ground mobile robot autonomous navigation in uneven and unstructured environments. First, the terrain traversability mapping module conducts plane fitting and plane traversability analysis. Then, a 2D occupancy map that is passed to the motion planning module is built by the terrain traversability mapping module. Next, a traversable corridor is obtained by A* searching on the 2D occupancy map. Finally, combined with the lattice planning algorithm and plane analysis, an improved global planning algorithm, H-lattice planning, is proposed to obtain a global path on the traversable corridor. Evaluations are conducted in all kinds of environments, including step scenes, slope scenes, and uneven environments. The results of the evaluation verify our proposed framework has the capability of autonomous navigation in the uneven and unstructured environments.

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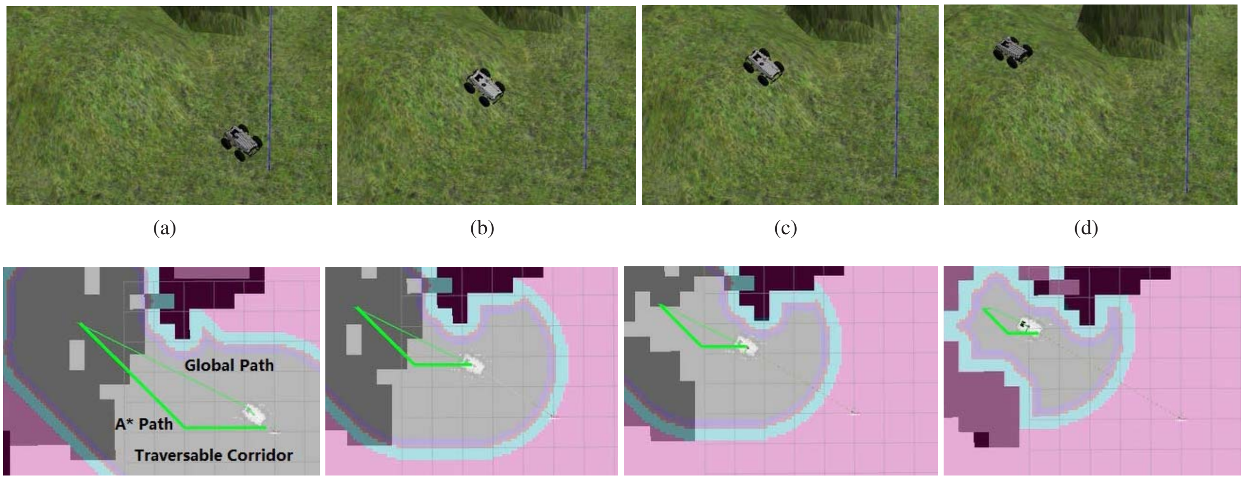
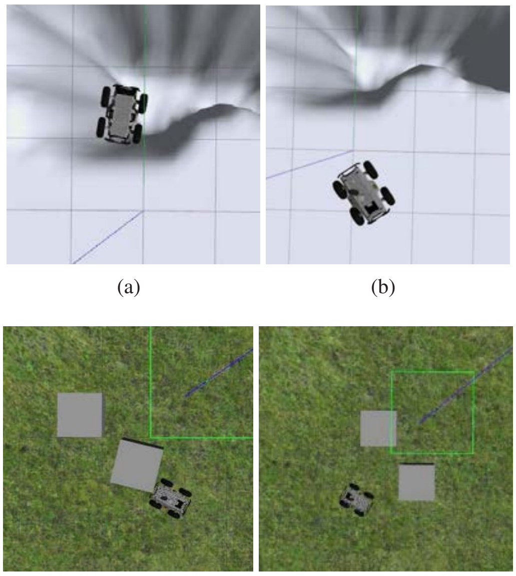


(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 10: The illustrate of the process of the robot autonomous navigation in the uneven scene.



(a) (b)

(c) (d)

Fig. 11: The comparison results in cliffs and unknown obstacles scene. (a) and (c) represent the results of the comparative approach. (b) and (d) represent the results of the proposed approach.

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