Research article

Path planning using hybrid grid representation on rough terrain

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Abstract

Purpose – Path planning approaches based on conventional occupancy grid maps are problematic in off-road environment because impossible areas include not only obstacles but also landscapes like ramps and pits. The purpose of this paper is to develop a path planning method in a hybrid grid map, which aims to provide a better solution for outdoor navigation.

Design/methodology/approach – A hybrid vision system which consists of one stereo vision and one omnidirectional vision is adopted to provide environmental information for 2.5D grid and 2D grid mapping, respectively. An improved planning method originated from conventional D*-based search algorithm is proposed for more efficient navigation in such hybrid grid maps.

Findings – It is confirmed by simulations and experiments that the path planning in the hybrid grid map is more efficient than that in conventional grid maps. Furthermore, it helps to guarantee a safe exploration for field and planetary robots.

Originality/value – This paper proposes a path planning approach in a hybrid grid map representing unstructured environment. The map consists of two different grid representations with diverse resolutions and structures, named 2.5D and 2D grids. The navigation process is expected to become efficient by reducing the replanning times and track length.

Keywords Robotics, Control applications, Navigation

Paper type Research paper

1. Introduction

With the development of field and planetary robots especially the launch of China's Lunar Exploration Program, it is very important to endow the robots with improved autonomy for safe exploration and efficient navigation. Much effort has been devoted to path planning of mobile robots in the robotics community. The existing research has mainly focused on obstacle detection and avoidance, which generates a feasible collision-free path with minimum distance, time or energy (Lu and Chung, 2005; Najjaran and Goldenberg, 2005; Ting *et al.*, 2002). Most research assume that the robots move in environment with flat ground which can be simply denoted by a representation composed of obstacles and free areas. For field and planetary applications, however, it is very important to endow the robots with ability of obstacle negotiation (ON). The ON navigation system is to steer a robot in such a way that it avoids a hillock that blocks its way but traverses low-profile ramps as necessary (Ye, 2007). The two essential components in such a navigation system are terrain mapping and path planning. Stereovision is frequently used in rough-terrain navigation because of its high flexibility and reliability. Vergauwen *et al.* (2001) realizes localization and terrain modeling for rover through stereo vision deployed on the lander. NASA's several planetary rovers including the famous 2004 twin Mars Exploration Rovers Spirit and Opportunity have integrated stereo vision into the rover's navigation system for Martian surface reconstruction and hazard avoidance (Eisenman *et al.*, 2001). Ishiguro *et al.* (1992) rotates the perspective camera to get the whole omnidirectional view surrounding robot. Aiming to avoid the time-consuming scanning process, Nayar (1988) works to provide real-time stereo in omnidirectional view by adopting a catadioptric omnidirectional system. Lin and Bajcsy (2003) present a new catadioptric omnidirectional system attempting to improve its resolution and accuracy. Cagnoni *et al.* (2007) propose a hybrid vision sensor to acquire 360° field of view (FOV) by combining perspective and omnidirectional vision. For field and planetary mobile robots, the geometrical and physical properties of the terrain add a new dimension to the complexity of the robot path planning problem. Seraji (1999) presents traversability index to address the ease-of-pass property of terrain, based on which a fuzzy logic-based traversability assessment is proposed (Howard and Seraji, 2000). It has been widely applied in off-road and planetary exploration which begins with no *a priori* knowledge of the environment.

Our approach aims to provide an efficient way to navigate a mobile robot on rough terrain represented by diverse grid maps with different ranges, resolutions and structures. Hybrid vision system (HVS), which consists of one stereo and one omnidirectional vision, is utilized to reconstruct the configuration space of the robot. The 2.5D grid maps

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generated according to stereovision results are used for accurate path planning, while the 2D occupancy grid maps allow an efficient navigation by providing a larger FOV of the robot through the omnidirectional vision sensor. The mixed grid map is established during the operation of the robot. The HVS-based path planner not only makes real-time navigation possible by acquiring diverse representations of environment, but also be able to offer a more efficient planning by enlarging the FOV of rover.

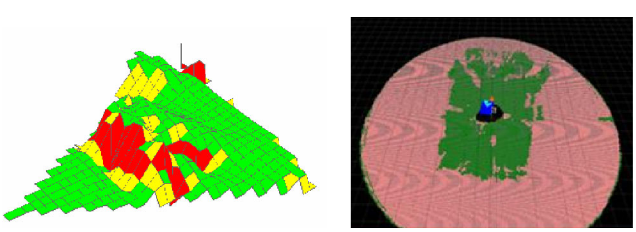
2. HVS-based mapping

Occupancy grid maps are spatial representations of robot's configuration space and have been proven efficient in navigation despite of the availability of a priori knowledge since proposed by Elfes (1989). They are often used as 2D representation to distinguish obstacles from free areas, which make them be widely used for indoor navigation (Habib and Maki, 2007). A lot of efforts have been made to extend the 2D grid maps for navigation in more complex environment. For example, 3D (Carsten *et al.*, 2006) and 2.5D (Gutmann *et al.*, 2005) grid maps are proposed for navigation of underwater robots and biped robots, respectively. The 3D grid map requires more cost of maintenance because it is stored as a 3D array. In our study, we extend the 2.5D grid map to represent the environmental surface. The result from stereo vision is a set of discrete three-dimensional points, each of which can be denoted as $p = [xyz]^{\mathrm{T}}$ (where z is the height value). According to the x- and y-value, we can determine the corresponding grid for every point p. For certain grid s_{ij}, the 3D points located in the same grid make up of the point set $P_{ij} = \{p|x_{(i,j)} \le x < x_{(i+1,j)}, y_{(i,j)} \le y < y_{(i,j+1)}\}$, where $x_{(i,j)}, y_{(i,j)}, x_{(i+1,j)}$ and $y_{(i,j+1)}$ define the horizontal range of s_{ij}. Let n denote the number of points in P_{ij}. The average height h_{ij} of P_{ij} can be computed as:

$$h_{ij} = \frac{1}{n}\sum_{i=1}^{n} z_i, \quad \text{for } p \in P_{ij}. \tag{1}$$

With the average heights of adjacent grids, we can construct a 2.5D grid map representing the environmental surface as shown in Figure 1(a). The omnidirectional vision provides a bird's-eye view (Figure 1(b)) of the circumstance surrounding robot from which we are able to build a 2D grid map indicating the possible obstacles. The stereo and omnidirectional visions provide accurate and wide-range mapping, respectively. So, in this paper, 2D and 2.5D grid maps are both adopted to generate a mixed environmental representation using HVS.

Figure 1 Diverse traversability mapping



(a) (b)

Notes: (a) 2.5D grid map with traversability reconstructed from stereo vision and (b) planar traversability map surrounding rover built through omnidirectional vision

3. Traversability assessment

In order to realize the ON navigation, the robot must be able to address impassable areas dynamically during its operation. The obstacles indicated by the 2D part of hybrid grid map are easily addressed according to the color and texture information in the omnidirectional image. For example, color-based blob analysis is widely used for soccer robots in applications of localization and obstacle avoidance (Yetisenler and Ozkurt, 2006). However, multiple factors have to be taken into account to determine whether the area represented by the 2.5D grid map is passable. Traversability index, first proposed by Seraji (1999), is used to efficiently address terrain's ease-of-traverse for unmanned exploration on rough terrain. This index is developed using the framework of fuzzy logic, and is expressed by linguistic fuzzy sets that quantify the suitability of the terrain for traversal-based on its physical properties. In our study, the patch of 2D part in the hybrid grid map is chosen in such a way that it exactly envelop the robot regardless of its orientation and attitude. Each 2D grid can be subdivided into 16×16 2.5D grids if it is in the FOV of stereo vision. Slope, roughness and height difference extracted from the grid set are used to indicate the terrain's ease-of-traverse. Least square plane (Ye, 2007) is utilized to fit the grid set representing the terrain grids that the robot is to occupy, which can be donated as grid set $\boldsymbol{S}$. The slope can be determined from the normal vector to the least square plane fit which is denoted by $n = [n_x n_y n_z]^{\mathrm{T}}$ and roughness is denoted by the residual of the fit:

$$\sigma = \sqrt{\sum_{i=1}^{n} d_i} \tag{2}$$

where d_i represents the distance between $p_i \in \boldsymbol{P}$ and the fitting plane. With the normal vector of the best-plane fit, the slope of terrain that $\boldsymbol{S}$ represents can be estimated by:

$$\varphi = \cos^{-1}(\boldsymbol{n} \cdot \boldsymbol{b}) \tag{3}$$

where $b = (0,0,1)^{\mathrm{T}}$ is the unit vector of z-axis. Additionally, for each grid s_i belonging to $\boldsymbol{S}$, the elevation of s_i can be calculated according to equation (1). The elevation difference between two adjacent grids can be determined by the absolute difference of their elevations. For specified two adjacent grids, the height difference between them can be calculated as:

$$h_d = |h_{i+1} - h_i| \tag{4}$$

Fuzzy logic frame is adopted to acquire a robust traversability assessment based on the terrain characteristic extraction results. The fuzzy logic-based traversability classifier inputs the terrain characteristics and outputs the linguistic traversability index. Three terrain characteristics, height difference, slope and roughness, are employed to determine the traversability indices. The membership functions of inputs and output are shown in Figure 2.

The fuzzy rules are concluded in Table I. The empty entry in the table means the field has no influence on the index. These experiential results are used to assess the traversability of terrain according to the robot which we employed in the following experiments.

4. Path planning

In order to achieve navigation without *a priori* knowledge of the environment, the path planning method is developed from

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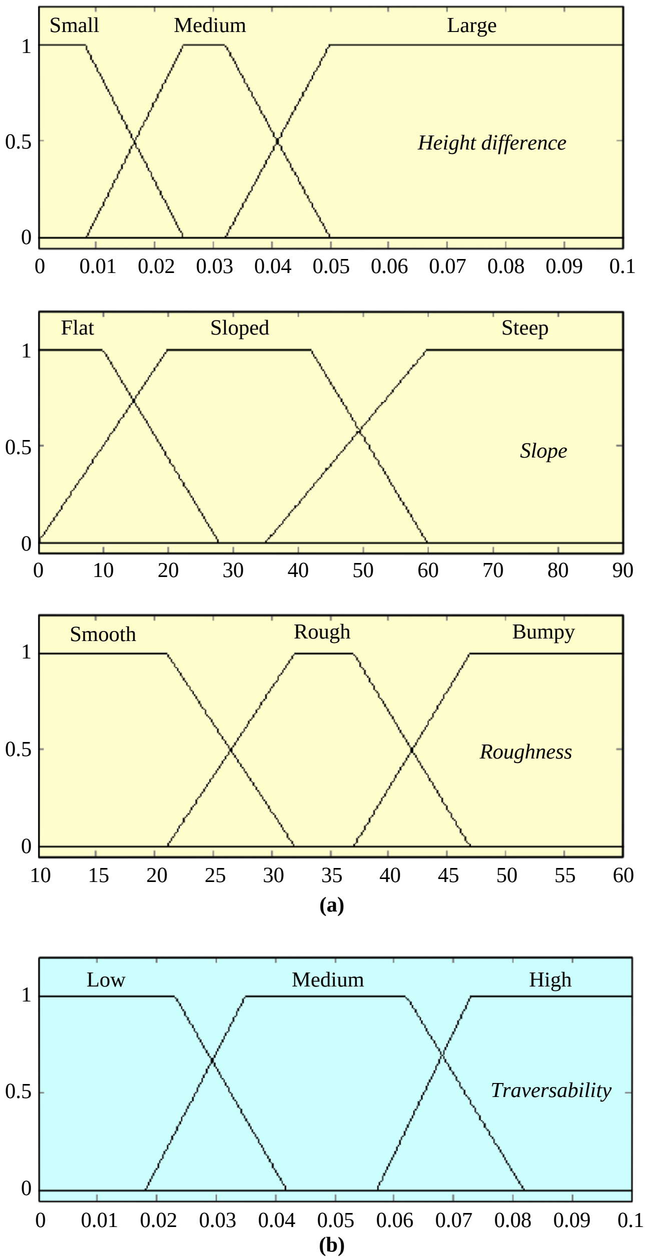
Figure 2 Fuzzy logic membership functions



Notes: (a) Three inputs: height difference, slope and roughness and (b) output: traversability indices

the sophisticated D* search algorithm (Stentz, 1995). Quadtree (Samet, 1988) structure is adopted to maintain the map data, since the configuration space is represented by girds with different resolutions.

For search algorithms of D* family, every grid expanded during the search is assigned a cost function $f(s)$ where s is the grid being evaluated. The function of $f(s)$ is given by:

$$f(s) = g(s) + h(s) \tag{5}$$

where $g(s)$ is the traversing cost along the path from the start grid in the search. The cost $h(s)$ is a heuristic estimate of the remaining path from s to the goal grid. The Euclidean distance between s and the goal is used as the heuristic estimate to focus the search and update only grids that are relevant for computing a shortest path. Besides 2D components, our hybrid map includes 2.5D gird representation. The terrain conditions are also needed to be taken into consideration during path planning. Through defuzzification we are able to get a function $t(s)$ according to the membership function shown in Figure 2(b) which quantifies the traversability index of the grid. Let s' denotes the parent gird of s, the function of $g(s)$ in 2D grid is calculated as:

$$g(s) = g(s') + c(s', s) \tag{6}$$

where $c(s',s)$ is the traversing distance from s' to s. The cost function $c(s',s)$ is approximated as the Euclidean distance between the two grids. We can extend the cost $c(s',s)$ to $c^*(s',s)$ according to the traversability index $t(s)$ during search in 2.5D grid map as:

$$c^*(s', s) = (1 + t(s))c(s', s) \tag{7}$$

In this case, the cost function can indicate the traversing distance as well as the influence of rough terrain that will add additional cost than that of traversing on flat surface. The D* search maintains a priority queue ordered by the cost function $f(s)$. It pops a grid with minimum $f(s)$ in the queue each time as the next grid to go until the search reaches the specified goal. By adopting the improved cost function $f(s)$, the conventional D* algorithm can be used for 2.5D grids with minor modification.

5. Simulations and experiments

Simulations are run to demonstrate the advantage of using hybrid grid representation for path planning on rough terrain. The simulation environment is a 320×320 cell world with each cell representing a terrain area of $0.1 \times 0.1\,\text{m}^2$. Before the simulation, each grid cell is assigned an average height and a preset traversability index. Since the map information is assumed unknown from the beginning, the robot has to perceive the environmental information during its operation. Two simulations are done. In the first simulation, the robot assesses the terrain traversability according to the grid heights within the range of stereo vision. In the second simulation, mixed grid representation is generated through HVS. The traversability index is assessed according to the grid heights and preset traversability value within the range of stereo vision and omnidirectional vision, respectively. Figure 3 shows the artificial terrain with preset height and passable information. The view of stereo vision is a 60°-wide sector from 0.3 to 3 m in front of rover, while the omnidirectional vision perceives circumstance surrounding rover whose radius is between 3 and 10 m.

The trajectories of robot in the two simulations are shown in Figure 4 and the comparison between results from the two simulations is shown in Figure 5. The abscissa in Figure 5(a) shows 400 grids along the trajectory of the robot while the ordinate indicates the number of perceived grids when robot moves to the corresponding grid. Although the trajectory length of the latter simulation using hybrid vision is close to that of the one using stereo vision (Figure 5(d)), the rover is able to perceive a much larger range of environment during execution (Figure 5(a)). Furthermore, using the HVS, we can also save re-plan times (Figure 5(b)) and shorten the time that navigation process consumes (Figure 5(c)), which provides a more efficient approach for the planning problem on rough terrain.

Table I Fuzzy rules for traversability assessment

Height difference	Slope	Roughness	Traversability index
Small	Flat	Smooth	High
Small	Sloped	Smooth	High
Small	Flat	Rough	High
Medium	Flat	Smooth	High
Large			Low
	Steep		Low
		Bump	Low
Medium	Sloped	Rough	Low
Medium	Flat	Rough	Medium
Medium	Sloped	Smooth	Medium
Small	Sloped	Rough	Medium

Figure 3 An artificial 2.5D grid map with preset heights and passable conditions for simulations

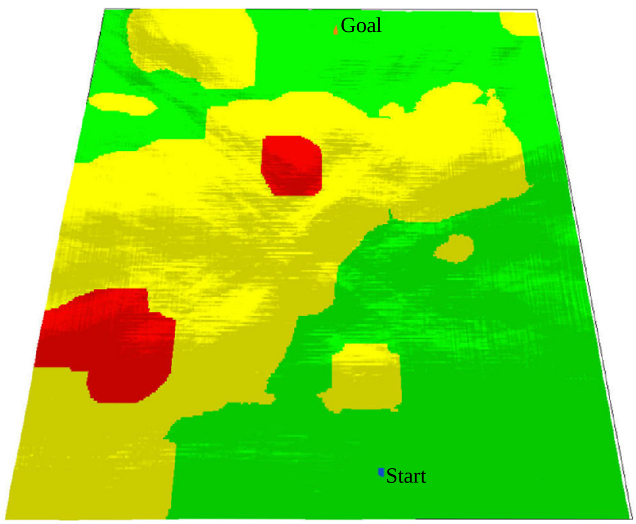
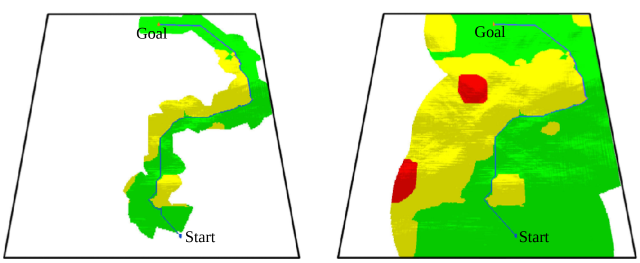


Figure 4 Robot's trajectory



(a) Stereo vision **(b)** Hybrid vision

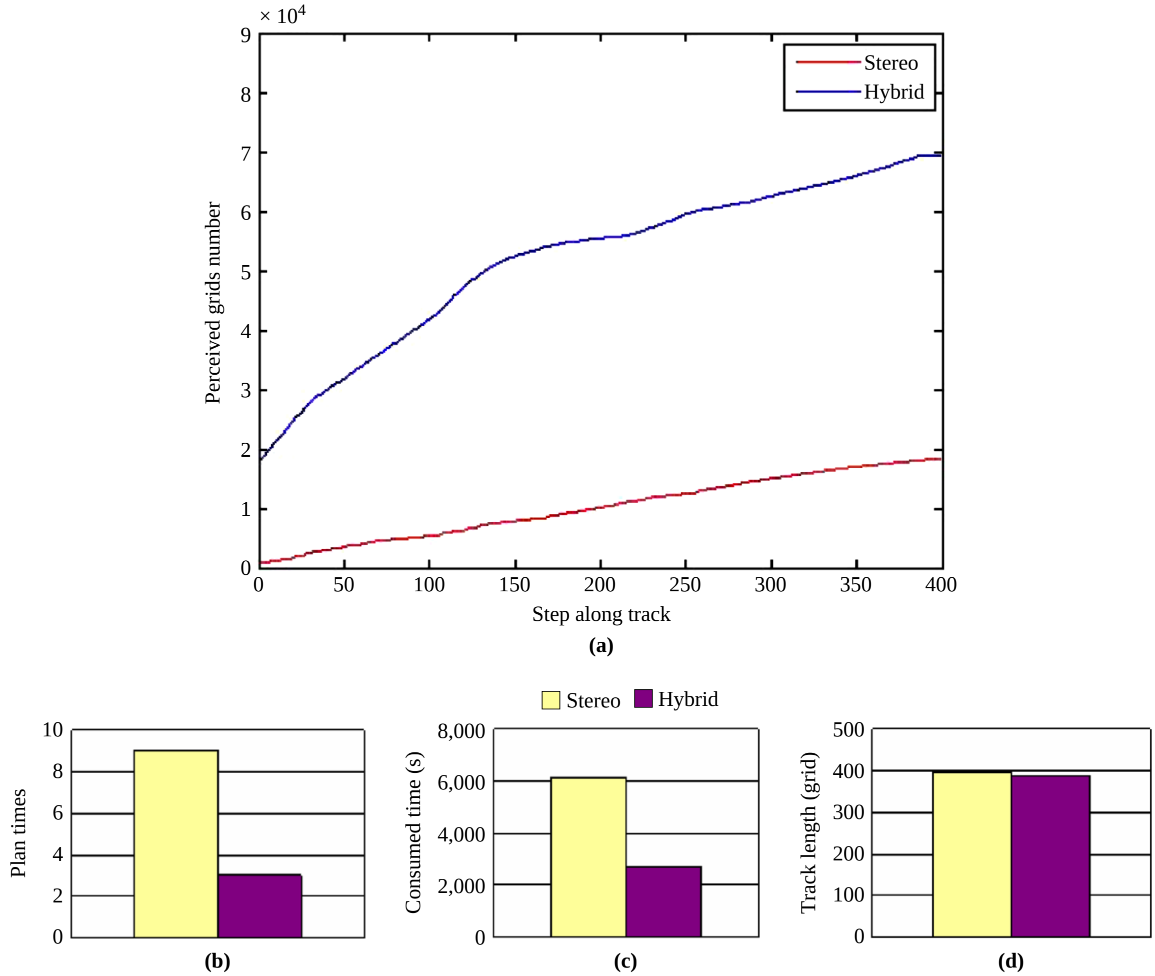
Additionally, we carry out several navigation experiments to testify our planning method. A three-wheel RoboCup soccer robot equipped with HVS, as shown in Figure 6(a), moves towards a specific destination position and avoids all encountered obstacles. The HVS consists of one omnidirectional vision on top and one stereo vision heading forward. Two identical perspective cameras compose the stereo vision system, while a Sony RPU-C251 panoramic camera is deployed in order for the omnidirectional imagery.

The result of path planning in a RoboCup playground is shown in Figure 7. In the experiments, one grid patch covers $1.6 \times 1.6\,m^2$ and maintains the results of traversability assessment upon images from omnidirectional vision. It is evenly subdivided into 256 grids to build a more accurate representation of the terrain surface through stereo vision. The dark red and dark green represent the environmental information detected by omnidirectional vision, while the light red and green are those collected by stereo vision. And the reds indicate obstacles, while the greens denote free areas. The result shows that, with contrary to the navigation with only stereo vision, our method is proven to be more efficient. The omnidirectioanl vision is able to foresee possible obstacles, which also helps to guarantee the safety of robot during autonomous exploration.

6. Summary

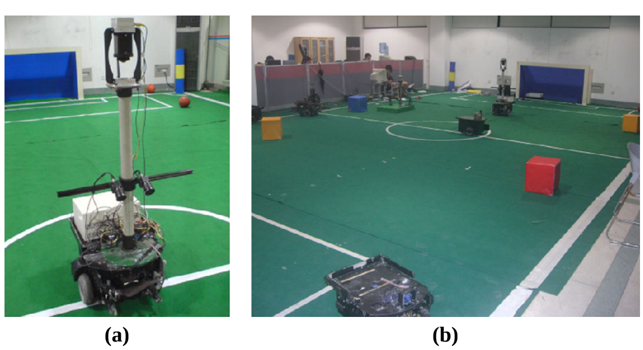
In this paper, we propose a path planning approach based on a hybrid grid representation of robot's configuration space. The HVS that consists of stereo and omnidirectional vision is integrated into our system to provide a robust and efficient perception of environment. The map consists of two different

Figure 5 Simulation results



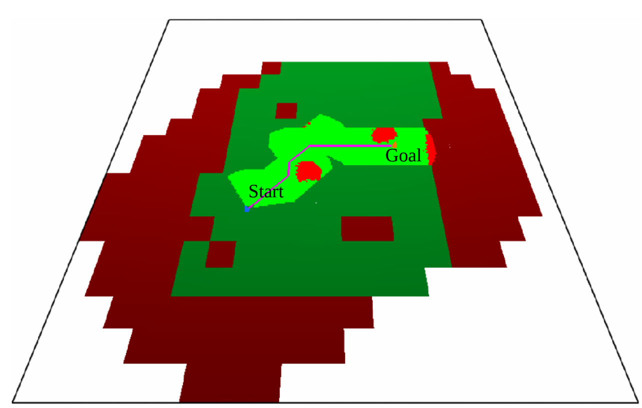
Notes: (a) Number of perceived grids along rover's track during execution; (b) plan times; (c) consumed time and (d) trajectory length

Figure 6 Experiment platform and environment



Notes: (a) A RoboCup mobile robot equipped with hybrid vision sensor system and (b) a RoboCup playground with randomly placed obstacles

Figure 7 Path planning result with HVS in a RoboCup playground with randomly placed obstacles



grid representations with diverse resolutions and structures, named 2.5D and 2D grids. An extended D^*-based path planning method is presented to fulfill the search for feasible path in the proposed hybrid grid representation. Our method is proven to be more efficient by simulation and experiment results. Besides, it can help guarantee the safety of robot by forecasting possible dangerous areas. However, the color-based traversability assessment we used in our experiment is not accurate or stable enough in practice. In the future, we

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will work for an improved traversability classifier for omnidirectional images.

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