Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online CONFERENCE PAPER ARCHIVE

IFAC-PapersOnLine 49-15 (2016) 212–217

3D Navigation Mesh Generation for Path Planning in Uneven Terrain

Sebastian Pütz * **Thomas Wiemann** ** **Jochen Sprickerhof** *** **Joachim Hertzberg** ****

* *Osnabrück University, Germany (spuetz@uni-osnabrueck.de)*
** *Osnabrück University, Germany (twiemann@uni-osnabrueck.de)*
*** *Osnabrück University, Germany (jspricke@uni-osnabrueck.de)*
**** *Osnabrück University and DFKI Robotics Innovation Center, Osnabrück Branch, Germany (joachim.hertzberg@uni-osnabrueck.de)*

Abstract: We present a 3D mesh surface navigation system for mobile robots. This system uses a 3D point cloud to reconstruct a triangle mesh of the environment in real time that is enriched with a graph structure to represent local connectivity. This *Navigation Mesh* is then analyzed for roughness and trafficability and used for online path planning. The presented approach is evaluated with a VolksBot XT platform in a real life outdoor environment.

Keywords: Robot Navigation, Path Planning, Surface Reconstruction, Mesh Generation

1. INTRODUCTION

In flat terrain most obstacles can be safely perceived by using horizontal 2D laser scanners. Compared to that, it is much more difficult to operate in rough terrain and to check the trafficability of uneven ground. Robots operating outdoors like in rescue operations or exploration of unknown environments need to cope with such uneven terrain and must still be able to find a path to their goal. Therefore, they have to classify if something is a potential obstacle or if they can pass it, e.g., by traversing over it. To reach the target, the trafficability of the ground between the current position and the goal pose is essential. Rough terrain involves certain risks, such as holes in the ground, bold peaks or sharp objects. There might be heavy obstacles that pose danger to the robot and that must be avoided in any case. But there might also be obstacles the robot can deal with at higher costs (energy, execution time) in order to reach the target.

We have developed a general mesh planner extending the ideas of Breitenmoser and Siegwart (2012) and Gingras et al. (2010). This paper presents our approach for local planning and robot control in the current field of view and demonstrates the usability on a mobile robot operating in a real world outdoor environment. Unlike 2D grid map approaches, this 3D planner works on triangle meshes instead of 2D grid map planes. Working with such 3D surfaces in navigation has the advantage of conformity of the navigation costs based on distances, height differences, roughness, forbidden areas and other criteria. Additionally, meshes represent 3D space directly and can easily be annotated with semantic labels as described in Deeken et al. (2014). Compared to 2.5D solutions, full 3D mesh surface navigation algorithms enable navigating through a multi level environment, such as multistory buildings or tunnel systems. In particular mesh navigation is appropriate for climbing robots or other robots with the ability to access walls or ceilings.

In this paper we present an open source, robot-independent 3D mesh navigation solution for robot navigation with high extensibility.

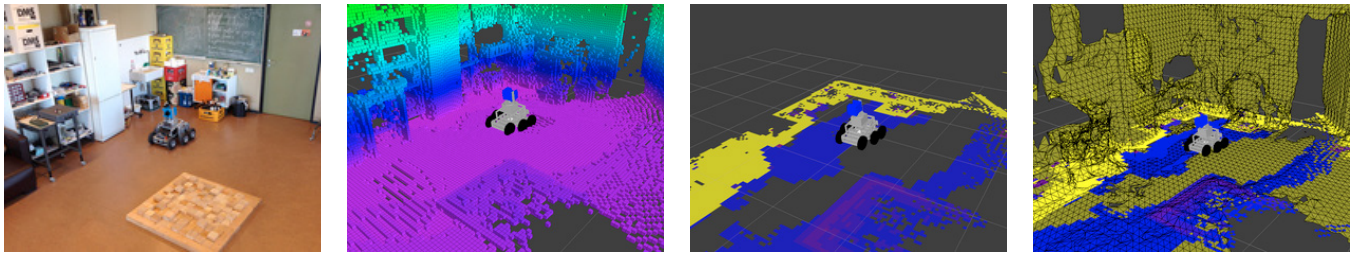
2. RELATED WORK

2.1 Octree Mapping and Digital Elevation Maps

Many navigation and path planning approaches use Octrees or similar representations that are created from 3D point cloud data. A popular implementation for it is the OctoMap package in ROS (Hornung et al., 2013). A planning system for Octrees is described in Morisset et al. (2009). It decomposes the 3D Octree map into several regions that are locally 2D. These regions can than be used like a ordinary grid map for path planning. Also, semantic classification of the represented surfaces can be integrated to speed up the computation. Fig. 1b shows an example of the Octree representation of a natural scene.

Occupancy maps, like Octrees, represent obstacles in a binary way in form of a grid map. These maps only define obstacles, but not the trafficability of obstacles in a specific context. For example, an obstacle can provide drivable ground, if the robot is on top of it, but also an inaccessible ledge, if the robot is located at a lower level. Generally, obstacle detection depends on the obstacle's size and the distance to the obstacle, as evaluated in Schwarz and Behnke (2014). To deal with these shortcomings, elevation maps build on top of simple occupancy maps. Starting with height maps, where a height z is stored in the cells of the grid map with $z = f(x, y)$. These solutions are usually called 2.5D maps (cf. Fig. 1c). A special type of 2.5D maps are *Digital Elevation Maps* (DEM). These maps are used to compute local trafficability maps, e.g., by calculating the navigation costs based on the height differences on multiple scales (Schwarz and Behnke, 2014). However, these techniques are not able to handle multiple overlapping levels, such as tunnel systems or multistory

2405-8963
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.07.734



(a) Lab example scene with a step field.

(b) Octree representation of the scene.

(c) 2.5D Map (DEM) representation of the scene.

(d) Mesh representation of the scene.

Fig. 1. State of the art map representations to estimate trafficability in 3D in uneven terrain.

buildings and are not practicable for climbing robots. For evaluation we implemented the DEM trafficability estimation schemes presented in Schwarz and Behnke (2014) in a *costmap_2d* layer plugin for *move base* in *ROS*. An example DEM costmap is shown in Fig. 1d together with the reconstructed mesh for comparison.

2.2 Terrain Reconstruction

An alternative approach is described in Gingras et al. (2010) and Breitenmoser and Siegwart (2012). This method is able to handle multiple levels by reconstructing the rough terrain into a triangle mesh. Such triangle mesh representations are much more flexible and can be used for multiple purposes like environment representations in robotic simulators (Wiemann et al., 2013), visualization for human robot interaction and ground classification or path planning (Wiemann et al., 2010).

In such a representation, the alignment of surface parts or change between adjacent triangles can be evaluated for drivability estimation. This allows to determine navigation costs based on distances, height difference, roughness, forbidden areas and semantic information.

3. SYSTEM ARCHITECTURE

The components of our approach are shown in Fig. 2. The main input is a triangle mesh constructed with some kind of surface reconstruction procedure. In principle, arbitrary meshes from different sources like LVR (Wiemann et al., 2012) or PCL (Rusu and Cousins, 2011) could also be used. In this paper, we use the *Organized Fast Mesh* method to generate a triangle mesh surface representation from 3D laser scanner data at the current position of the robot in real time (Holz and Behnke, 2012). In this paper we do not present an approach for global mapping. However, our approach also works for meshes representing larger environment sections, coequal with some kind of a global map.

First, a so called *Navigation Mesh* is generated and analyzed to estimate distances, height differences, and roughness. If specific safety thresholds are violated, these areas will be marked as lethal obstacles, since the robot must avoid them. Areas around such lethal obstacles are inflated (marked as dangerous) and graph optimization algorithms are applied, e.g., *Graph Edge Region Growing* to implicitly smooth the discretized mesh path. Now it is possible to apply shortest path algorithms on the resulting optimized *Navigation Mesh* to compute paths taking the evaluated

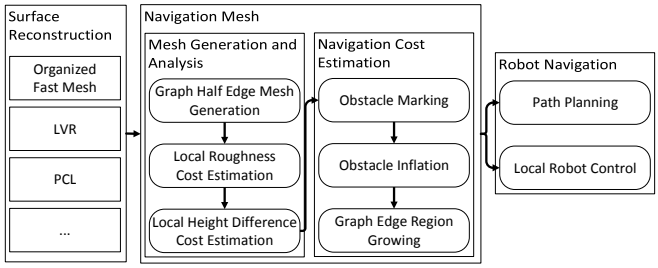


Fig. 2. Structure of our terrain classification approach. Triangle mesh representations are converted into a graph that is used for planning using navigation costs estimated for the represented terrain.

criteria into account. Besides global navigation, the *Navigation Mesh* can be used for a local control of the robot. Details on the single computation steps are presented in the following sections.

4. SURFACE RECONSTRUCTION

4.1 Organized Point Clouds

The organized fast meshes we use in this paper rely on organized point clouds. The data flow to generate them is displayed in Fig. 3. After removing outliers from a single 2D laser scan and applying a robot self filter, we assemble the single 2D laser scans to one organized point cloud. In such a representation, neighboring points are stored in a matrix structure resulting in a depth image. To generate this matrix, we exploit the fact that we know the polar angles ϕ and θ for every single point. Our rotation unit delivers for every single point the ϕ value. The θ value can be reconstructed from the order of points in each 2D scan taking the point count and the resolution into account. In summary: The Cartesian coordinates (x, y, z) of a scan point corresponding to the spherical coordinates ϕ and θ neighboring scan line distance values are stored in a matrix structure. This structural knowledge about the data allows us to connect neighboring points in a single 360 degree scan to construct the mesh. Unsensed or removed points are marked with *NaN* to maintain the matrix structure. Another advantage of the organized structure is that it enables a fast and robust computation of point normals by using integral image techniques such as *Average 3D Gradient*, *Average Depth Change* or *Covariance Matrix* as described in Holzer et al. (2012).