Computers and Electrical Engineering 000 (2016) 1–10

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

Kernel based approach for accurate surface estimation[☆]

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ARTICLE INFO

Article history:
Received 3 July 2015
Revised 2 March 2016
Accepted 2 March 2016
Available online xxx

Keywords:
Laser range scanner
Max-margin formulation
Surface estimation
Kernel
Sub-gradient method

ABSTRACT

Accurate surface estimation is a critical step for autonomous robot navigation on a rough terrain. In this paper, we present a new method for estimating the surface of an unknown arbitrarily shaped terrain from the range data. The terrain modeling problem is generally formulated as the estimation of a function whose zero-set corresponds to the surface to be reconstructed. A Laser range scanner has been built for acquisition of range data. The range data from the scanner samples the terrain unevenly, and is more sparse for distant regions from the sensor. The paper describes the surface estimation problem as a max-margin based formulation of a non-stationary kernel function and minimizes the objective function using sub-gradient method. Unlike other methods, additional geometric ray based information is used to eliminate the unnecessary bumps on the surface and increase the precision. The experimental results validate the robustness of the proposed approach.

1. Introduction

Accurate terrain reconstruction is a critical and challenging component to represent the distribution of surface elevation for mobile robot navigation in an unknown, rough and cluttered environment. Successful mobile robot navigation requires an efficient and high quality representation of the surface because of complication arising out of uncertainty, incompleteness and highly unstructured terrain. Of these, uncertainty and incompleteness are virtually universal in mobile robotics because the sensor capabilities are limited. The problem is of interest to a number of applications such as mining, path planning, space exploration, geological surveys and preparation, and different terrain analysis. In case of Laser scanner, the distribution of range data points decays rapidly away from the range sensor, and there may be vast surface regions that return no scanned points at all. The variable resolution of range data points is inevitable due to use of static scanning patterns and discrete sampling. Additionally, in the rough outdoor terrain, complex surface geometry, uneven ground, and the presence of inclines worsens the problem of estimation due to occlusions.

Several methods are known to simplify the problem considerably by representing the terrain as a flat, 2D cost map, but this is inadequate for modeling significantly uneven terrain because hills and rough surfaces are not accurately represented, compelling the vehicle to drive at very low speeds and make conservative judgments. However, an explicit 3D model of the environment based on 3D data points and meshes has limitations when dealing with structurally complex and fine features (rubble) or incomplete range data of the environments. Current methods use interpolation to create a continuous mesh surface where the scan is sparse, but this can be very difficult if the terrain is complex as the interpolation will gloss over the fine detail. The alternative approach is implicit surface modeling, which generates internally consistent 3D

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Guest Editor Dr. X. Z. Gao.

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http://dx.doi.org/10.1016/j.compeleceng.2016.03.001
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models directly from numerical data and structural measurements by a single mathematical volume function (which is akin to surface fitting). The main advantage of implicit surface modeling is that it allows to robustly generate the surface from different types of data, such as structurally complex, incomplete or noisy range data of the environments. The function is computed by spatial interpolation of range data points to define isosurfaces, which are represented as triangulated meshes with a user-defined resolution. In general, isosurfaces are 3D surfaces that embody 3D points of a constant value within a defined volume space. The zero set of this function $f(x, y, z) = 0$ corresponds to the surface. In this paper, the terrain is represented by a continuous elevation function for implicit surface reconstruction, which enables smooth and effective extrapolation for hole filling in the scanned range samples. Using the implicit surface model, the characteristic of the ground for the mobile robot can be predicted more precisely, allowing for faster autonomous driving and longer range path planning. In the proposed method, the surface is estimated using non-stationary kernel functions, which allow nonlinear, complex solutions. The kernel functions are constrained by both positive and negative information from the range sensor.

A non-stationary, isotropic kernel formulation provides flexibility by varying the smoothness of the elevation function according to the spatial data density and uncertainty. Large lengthscale covariances may be preferable for smoothing noisy data points from long-range sensors or for smoothly interpolating sparsely sampled regions whereas small covariances are required for accurate surface estimation where range data is accurate and dense. The problem with the use of a fixed lengthscale covariance, is unavoidable when reconstructing rough surface from range data which is unevenly sampled, as in the case of mobile robots, and hence a non-stationary formulation is suggested. We have followed the formulation of Paciorek and Schervish [1,2], who have introduced a class of non-stationary covariance functions for spatial modeling (e.g., climate data). Spatial surfaces whose variability fluctuates with location have been modeled using a non-stationary spatially changing covariance. Rather than learning the best covariances through Gaussian process models [1,2], we select the variable lengthscales by external cues, such as sensor distance and data distribution. This technique is efficient, intuitive and allows real-time surface reconstruction. The paper presents a new method for the surface fitting problem by formulating it as a classification task of range data using a non-stationary kernel function. In the surface fitting problem, a given set of 3D points with associated labels as interior or exterior of the surface, is considered. In this technique, the surface estimation task lends itself to a max-margin based representation, allowing non-linear/non-parametric and higher dimension surfaces to be computed using the non-stationary kernel function. In addition to the above technique, we also incorporate the complete geometric ray-based (visibility) information about the range data points. Generally, when the range data points are sampled from a range sensor, the information about ray connecting the sampled points to their range sensor location is implicitly known. By incorporating this information as a set of multiple constraints set into the max-margin framework, an enhanced solution to the surface estimation problem can be achieved. Such a framework formulation is attractive because of the stability of the obtained solutions and the range of the functional forms that could be incorporated. We introduce the visibility constraint into mathematical framework and determine a rule for functional sub-gradient descent optimization, yielding a surface estimate with high accuracy which works on different types of data sets. In this paper, the proposed surface reconstruction method is tested on range data which is obtained from the in-house developed Laser Range Scanner (LRS).

The remainder of this paper is organized as follows: Section 2 discusses the related work. Section 3 describes the proposed method in detail. Section 4 presents the experimental results and finally, we conclude the paper in Section 5.

2. Related work

A detailed overview of methods used for terrain modeling has been given by Hufentobler [3]. The explicit elevation maps (or “elevation grids”) are a standard technique for representing dense terrain surfaces. Several strategies exist for generating terrain surfaces, from mesh algorithms to statistical techniques to interpolation (Pfaff and Burgard [4], Hygounenc et al.[5], Jaspers and Wuensche [6]). Triebel et al. [7] have proposed an extension of the elevation maps towards multiple terrain surfaces. The multilevel surface maps extend the opportunity to model terrain with more than one traversal level such as those having overhanging structures and vertical objects. Yamaura et al. [8] have introduced a new technique to reconstruct the explicit surface of an object in terms of a C^1 continuous B-spline function above the *xy*-plane based on the surface normal vectors of the object. The explicit methods use interpolation to generate a continuous mesh surface, but it can be very difficult if the terrain is complex and the range data is sparse. Other approaches to model the surface are an implicit modeling technique. Some popular methods use local nature for deducing the implicit functions, such as level set models [9], local surface models [10], geometric flow [11] or implicit surfaces interpolated from polygon data [12,13]. Due to the use of the local properties for terrain analysis, most of the above mentioned methods often need normal information about the destination surface in order to produce the implicit surfaces correctly. Funk and Dooley [14] have presented a robust 3D scene modeling technique which has predicated the observation that most objects comprise of only a small set of primitives that is generated by a combination of sparse approximation techniques from the compressive sensing domain along with surface rendering approaches from computer graphics.

The kernel based methods provide another solution for implicit terrain modeling [15], the implicit models basically fit a radial basis function, either fully supported [16] or compactly supported functions [17] on range datasets. These methods usually require surface normal information, except in the recent research works [18]. The method computes an implicit model of a hyper surface which is given only by a finite sampling. Yguel et al. [19] have presented the use of sparse wavelets for 3D modeling of the environment from range data, and Fournier et al. [20] have used an octree representation