Application of 3-D Probabilistic Occupancy Models for Potential Field Based Collision Free Path Planning

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Abstract

Probabilistic occupancy grid building algorithms for 2-D space modeling have been recently extended to 3-D applications. These models provide an enhanced representation of space and therefore prove to be very useful for telemanipulator path planning. The cluttering state of space being stored as an occupancy probability, the search for a free path is efficiently realized with the help of repulsive and attractive potential fields. These are computed as functions of the occupancy probability without the need for a distance table. Potential fields are also stored as octrees for improved compactness and 3-D data processing efficiency. The multiresolution property of octrees is helpful in reducing the number of steps required during the free path search. This approach is used for a telerobotic maintenance application of electric power lines.

1 Introduction

Significant results have recently been obtained in modeling 3-D cluttered spaces by means of probabilistic octrees computed from raw range images [6]. In parallel, potential field based path planning techniques using occupancy models have provided good results both in 2-D and 3-D space. For instance, Laliberté and Gosselin [5] have succeeded in eliminating the local minima occurrence by refining the discrete potential field approach introduced by Barraquand *et al.* [1].

In this paper, probabilistic octree models are introduced into the discrete potential field based collision free path planning strategy. As opposed to discrete occupancy grids that only provide *empty*, *occupied* or *unknown* states of the cells [2, 4], a numerical estimate of the occupancy probability ranked between 0.0 and 1.0 is associated with each voxel in order to provide information that is more suitable to safe path planning. Between the cluttered areas and free space, a progressively descending level of occupancy is computed. The sharpness of this region is related to the uncertainty level originating both from the sensor and the registration errors. As the uncertainty grows while gathering range data on the scene, the transition area gets smoother.

Such a behavior provides a means to efficiently compute a repulsive and an attractive potential field which will be used to plan a free path that ensures that the robot will stay sufficiently far away from the obstacle boundaries. The same safety level would not have been guaranteed with a discrete occupancy model since the object boundaries are sharp. With the probabilistic octree model of the environment, the minimal distance to impose between the robot and the obstacles automatically grows with the level of uncertainty on the measurements. Moreover, since the repulsive potential field value must show a continuous progression from empty space to cluttered space, it can be evaluated everywhere directly from the occupancy probability. The attractive potential field that leads the robot through free space can also be processed starting from the probabilistic octree. In this paper, comparison is made with the potential field building scheme from discrete occupancy grids in order to demonstrate the advantages inherent to the probabilistic approach.

2 Computationally Tractable Probabilistic 3-D Modeling

In order to build 2-D probabilistic occupancy maps, Elfes has proposed to estimate the state of each cell in an occupancy grid by determining the conditional probabilities of all possible environment configurations [3]. Unfortunately, when such an approach is extended to 3-D space, it results in a combinatorial explosion in the number of configurations and therefore in an untractable modeling algorithm.

In a previous work [6], a new formalism of the Bayesian occupancy probability estimation has been proposed to circumvent the computational complexity associated with the processing of such numerous configurations. The proposed technique consists in using a closed-form approximation of the characteristic occupancy probability distribution function (OPDF) which results from the numerical evaluation procedure introduced by Elfes. Working on range measurements, this approximated OPDF directly computes the occupancy probability of a given volume of 3-D space centered on the sensor viewpoint. This provides a set of local spherical occupancy grids that are next merged into a global Cartesian grid that is encoded as an octree for memory space saving considerations. During the merging process, advantage is taken of the multiresolution property of octrees to avoid useless volume matching.

Simulation and testbed experiments revealed that this approach can provide probabilistic octree models of 3-D space in an acceptable computing time. Figure 1 shows an example of such a model of a typical scene in the application under study: the top of an electrical pole with the beam, the insulators and three wires. Gray shading of the cells corresponds to the probability of occupancy: white being 100% (*occupied*) and black 0% (*empty*). For clarity, only voxels having a probability of occupancy higher than 50% (*unknown*) are displayed.

Once a probabilistic occupancy model is available, its content can be used to build a repulsive and an attractive potential fields which will guide a telemanipulator towards a given goal while keeping it far enough from the obstacles such as the live wires. Potential field estimation techniques that make use of the occupancy probability are presented in the following sections.

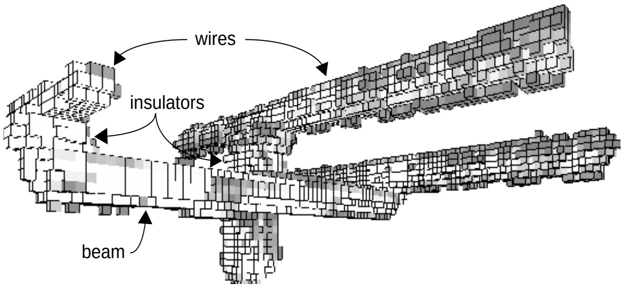

Figure 1: Probabilistic model of the top of an electrical pole.

3 Repulsive Potential Field

With discrete occupancy grids, a widely used scheme to build the repulsive potential field consists in computing a distance table from the nearest obstacle. Once this table is evaluated, the repulsive field is computed as inversely proportional to the distance. Such a field is shown in Figure 2. The uncertainty on the object position and orientation must be dealt with in selecting a sufficient, or even an oversized, arbitrary security margin around each of the obstacles. Since the repulsive force inside this margin must be set to a maximum value, this results in large highly repulsive areas that reduce the free space being available for the robot to move. This can lead to a failure of the path planning task.

Probabilistic occupancy models alleviate the constraints of the original scheme. First, the repulsive potential field can be computed directly from the occupancy probability of a given cell. Since the occupancy probability progressively grows with the proximity of an obstacle, the repulsive potential field is evaluated as a function of the probability occupancy without the need to compute a distance table. Moreover, as it has been demonstrated in [6], the probabilistic occupancy model provides a complete knowledge about the uncertainty on the obstacle position and orientation. This supplementary information is encoded into the occupancy probability. For this reason, there is no need for a security margin to be added around the obstacles.

On the other hand, since probabilistic occupancy models contain areas which are tagged with a *0.5* occupancy probability corresponding to unknown regions including the center of obstacles, care must be taken that these parts of 3-D space be mapped by a repulsive potential field

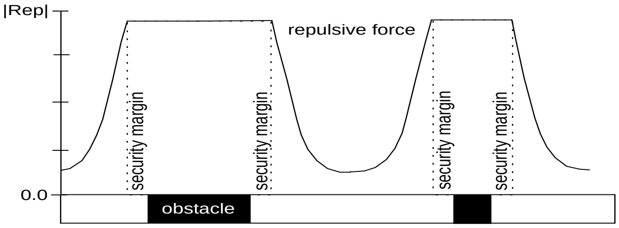

Figure 2: Repulsive potential field computed from a discrete occupancy grid and a distance table.

that will not allow the path planner to consider the inside of an obstacle as free space. In order to ensure this, a proper repulsive potential function has been developed. It is based only on the occupancy potential value, *p[occ]* from a given cell. The repulsive force, F_{rep} that will apply to control points distributed along the robot structure is computed as follows:

$$F_{rep} = \frac{1}{1 + e^{-10(p[occ]-0.4)}} \qquad (1)$$

Considering two obstacles in space measured by the range sensor from their left and right sides respectively, the occupancy probability and the repulsive force in the surroundings of these obstacles are shown in Figure 3. Compared to the repulsive field obtained from a discrete model of the same environment (Figure 2), the center of large obstacles exerts a lower repulsive force than their surface. This is a normal consequence of the fact that the occupancy state of the interior of objects cannot be measured. Nevertheless, the choice of the repulsive function in terms of the occupancy probability ensures that the repulsive field associated with an unknown space is never less than 0.73. The path planner is therefore programmed to avoid any area where the repulsive force is lower than this value.

The repulsive potential field is computed by a traversal of the probabilistic octree encoding the environment model. This process provides a new octree of a similar topology but with different values associated with each cell. These values are the repulsive force for each region of space in accordance with the obstacle distribution.

4 Attractive Potential Field

The attractive potential field guides the robot end effector towards the goal in Cartesian space.

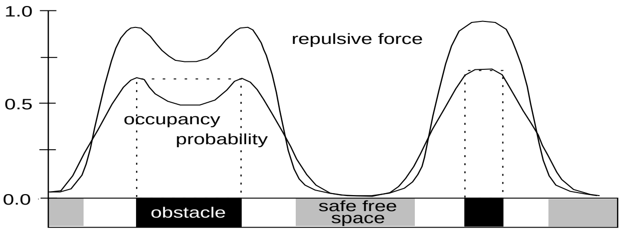

Figure 3: Repulsive potential field computed from a probabilistic octree.

The strategy that has been developed by Laliberte and Gosselin [5] consists in building an attractive discrete potential field that contains no local minima except at the goal point in order to allow the robot to follow the steepest gradient of potential while it moves from a given configuration to the goal. To build the discrete potential field, the free space skeleton must be previously computed by means of a wave propagation technique starting from the obstacle boundaries. This ensures that the path followed by the robot stays far away from the objects. Once the skeleton is identified, cells that are member of this skeleton are visited successively, starting from the goal, on the basis of their neighborhood. A progressively growing potential value is then tagged to the cells as they are farther from the goal. Since this approach has been developed on the basis of single resolution occupancy grids, all steps towards the goal have the same amplitude.

An approach is now proposed that makes use of probabilistic multiresolution octrees in order to compute an attractive discrete potential field that is free from local minima. Instead of extracting the free space skeleton from a wave propagation starting on the obstacle boundaries, a traversal of the probabilistic octree is performed and cells whose occupancy probability is lower than a given threshold are tagged as candidates for the robot to follow. It results in a network of channels that are free and sufficiently far away from all obstacles in their vicinity. This network is encoded as the attractive potential field octree.

Once this network is defined, the member cells are sequentially visited on the basis of their neighborhood, starting from the cell corresponding to the goal to be reached by the robot. Consequently, a single minimum attractive potential field is built that precludes trapping in any local minima. Figure 4 shows an example of such an attractive potential field computed on a 2-D

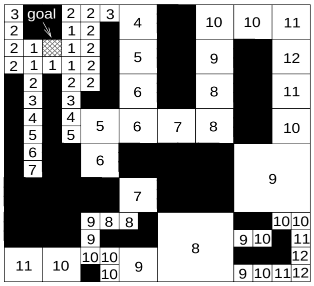

Figure 4: Example of a 2-D multiresolution single minimum attractive potential field.

multiresolution occupancy grid. Black cells corresponds to obstacles and unsafe areas. Labels in the white cells correspond to the potential level or, in other words, to the distance in terms of cell unit to cross before reaching the goal. Since cells are not of the same size, advantage is taken of the largest ones in order to shorten the path planning process.

Given a starting configuration corresponding to a cell, three criteria are used for the selection of the best neighbor cell to reach: 1) the neighbor cell with the minimum distance, 2) the neighbor cell with the minimum occupancy probability, and 3) the largest sized neighbor cell. Since only the end effector of the manipulator is submitted to the effect of the attractive potential field, all three criteria are helpful in order to find a path that is probably not the shortest one, but that allows the end effector to reach its goal while avoiding collisions between the manipulator structure and the obstacles.

5 Conclusion

In this paper, probabilistic octree characteristics have been exploited in order to build repulsive and attractive potential fields used to plan collision free paths in 3-D cluttered environments. The continuous nature of the occupancy probability encoded in such models allows the computation of the repulsive potential field without the need to compute a distance table. Similarly, the domain of free space located far enough from the obstacle boundaries is processed by means of a simple threshold on the occupancy probability to define the attractive potential field location.

Moreover, since a probabilistic octree includes knowledge about the uncertainty on the obstacle position and orientation, there is no need to impose an arbitrary security margin around the obstacles in order to ensure the robot's safety. In the area where an obstacle is not clearly defined, the occupancy probability is a direct measurement of this situation. Therefore, if both potential fields are computed on the basis of the occupancy model, the fields will take into account these uncertainties and will not lead the robot through those areas.

Acknowledgments

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