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Universal path planning for an indoor drone

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ABSTRACT

During the construction and maintenance of building, universal path planning for an indoor drone navigation is needed. There are many two-dimensional (2D) path planning methods, but they are not appropriate for a three-dimensional (3D) indoor environment with many obstacles in it. In this study, we present a novel approach to plan universal paths for drones in a known indoor environment using a voxel model. This approach can make the drone fly at some distance from the obstacles by computing a 3D buffer around the obstacles, using our algorithm 3D propagating approximate Euclidean distance transformation (3D PAEDT). Two types of paths are presented using A* and distance transformation algorithms: *safe shortest path* (SSP) and *safe least cost path* (SLCP). Both paths ensure that the drone maintains a minimal distance from the obstacles. SLCP ensures that the drone flies at a fixed height. Several experiments are conducted to test the approach in a two-story building.

1. Introduction

A drone, also called an unmanned aerial vehicle, is an aircraft without a human pilot aboard. Drones have become smaller, lighter, and cheaper with the development of new technologies in recent years [1,2]. This makes many drone-based indoor navigation applications possible to automate construction process, such as information gathering, taking photos, surveying construction sites, monitoring construction progress [3,4], inspecting built infrastructure [5], and emergency help and rescue. Autonomous indoor navigation has become a foreseeable trend for drones because it saves the operator's time during complicated operations [6–10]. Autonomous indoor navigation functions include localizing, detecting obstacles, path planning, direction correcting, and tracking the trajectories with reasonable accuracy. Path planning is one of the main and fundamental aspects of autonomous navigation. Therefore, it is important to further extend indoor path planning algorithms and methods for autonomous drones.

Indoor path finding for a drone can be subdivided into real-time path finding in an unknown environment [6,9,10] and path finding in a priori-known environment [7,8]. With the technology developments for indoor data acquisition and three-dimensional (3D) indoor modeling, indoor data can be obtained quickly and easily and 3D indoor models with obstacles are increasingly made available [11,12]. Such models are a good basis to investigate approaches for universal path planning. Universal path planning, which can be seen as a key component of the real-time navigation, provides a collision-free continuous path, connecting the start and the goal (target) in a known environment. The current methods for people and mobile robots are commonly based on two-dimensional (2D) floor plans and indoor surface models [13,14]. However, drones fly in the air and can move above and below obstacle (e.g. furniture). There are many static obstacles on the floor, above the floor and near the ceiling, which have to be avoided. Two-dimensional approaches cannot overcome challenges such as “moving under or above obstacles”, “flying at a certain height”, or “avoiding overhanging parts”. Thus, it is necessary to consider 3D paths for drones, considering specific indoor requirements. Furthermore, it is critical that the computed path is safe, i.e. a certain clearance from all surrounding obstacles has to be ensured. These challenges are poorly addressed in the literature. Most previous studies have focused on optimal path planning for mobile robots. Unfortunately, optimal paths tend to “graze” the obstacles to minimize path lengths. Only few studies consider obstacles for indoor path planning [12].

The contribution of this study is an algorithm that achieves safe path planning by calculating a 3D buffer around the obstacles, based on propagation distance transformation. This approach keeps the drone from flying too close to the obstacles and sets the minimal distance from

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the obstacles according to the size of the drone. Using this algorithm, the *safe shortest path* and *safe least cost path* are developed and tested. Both paths can make the drone fly under or above obstacles. The latter path allows a flight at a certain height.

This work is organized as follows. Section 2 presents the literature review. Section 3 presents the workflow. In Section 4, we introduce basic definitions and the 3D propagating approximate Euclidean distance transformation (3D PAEDT) algorithm. Section 5 analyses navigation path options for an indoor drone. Section 6 describes the methods to find SSP and SLCP using the A* and distance transformation algorithms. In Section 7, the methods are tested based on a two-story building model. Finally, conclusions are presented in Section 8.

2. Related work

3D path finding algorithms are closely related to true 3D indoor models. The present 3D models can be classified into two large groups: surface-based and volume-based models [34]. For the purpose of the 3D path finding to be able to solve the cases mentioned in Section 1, volume-based models are more appropriate. The volume-based models provide a straight-forward 3D topology between the volumetric cells (e.g. voxels, tetrahedrons), which are much simpler than the 3D topology maintained in surface-based models. Voxel and octree models are two basic 3D volume-based models.

The voxel model is used to decompose the indoor environment into a set of non-overlapping, equal-sized, simple 3D cells, called voxels. Usually these models result in a large number of units, especially if a fine resolution is required. However, the indoor environment is much smaller than the outdoor environment and therefore the universal path finding can be performed on an off-board computer. Normally, the memory requirement for a voxel model for indoor space is quite acceptable. The octree model is a compressed 3D volume model. Although the octree model can reduce memory consumption, the construction and editing of the octree is time-consuming. Due to hierarchical data structure of the octree, neighborhood operations, as for the path finding algorithm, are more time-consuming for implementation compared to voxel model. Several studies have conducted 3D indoor modeling using voxel models [15–17]; however, the path finding research performed following the modeling is limited. Wurm et al. [18] reviewed the 3D indoor modeling approach and presented a model using octree, called OctoMap, to perform collision-free navigation for mobile manipulation [19]. However, the model is only suitable for the manipulation of robots that move on the floor. Rodenberg et al. [35] and Fichtner et al. [36] have presented an octree approach for navigation of humans, but again considering a navigation on the octree cells that represent the surface where humans can walk on. Their research has shown that 'air' octree cells can become too large and the path for a drone would be rather approximate. Therefore the study presented in this paper is based on the voxel model.

Path planning based on a 2D grid or quadtree has been well-studied for mobile robots. The traditional methods based on 2D grids or quadtree models for universal path planning include A* search and distance transformation. Both approaches can be extended to 3D grids. The A* search algorithm achieves high efficiency using a heuristic function. MacAllister et al. [9] and Xu et al. [10] presented a close-to-optimal 3D path algorithm for the autonomous drone in voxel and octree models, respectively, using the A* graph search algorithm. However, the path's distance from the obstacles was not considered; thus, the path may be very close to the obstacles and unsafe for the drone.

3. Methodology

The concept of distance transformation was first proposed on a binary image by Rosenfeld and Pfaltz [20]. Distance transformation is used to convert a digital binary image that consists of object (foreground) and non-object (background) pixels into another image, in which each background pixel has a value corresponding to the minimum distance from the object by a distance function. The method is widely used in path planning because it easily supports many special navigation behaviors of moving objects [21,22]. Many algorithms on distance transformation have been proposed. Raster scanning algorithms [23–25] and propagation algorithms [26–29] are common techniques to produce distance transformation. In order to plan a safe path, Zelinsky [22] presented an "obstacle transform", a type of raster scanning distance transformation, where the obstacle cells become the targets to prevent the mobile robots from moving too close to the obstacles. However, the distance must be checked several times for all free cells; the process may be slow when it is extended to 3D. Barraquand and Latombe [30] proposed "numeric potential fields" to maximize clearance from the obstacles, but this method can move the solution path too far from the shortest path and may guide the robot through narrow free space channels.

As mentioned previously, flying drones indoors can serve many different purposes. Depending on the application, a different path may be required. In this paper, we consider two specific tasks: flying drones at a safe distance from surrounding objects and flying them at a given height above objects. The first case is important for any path computation indoors. The latter case is of specific importance for maintenance and inspection. For example, a drone can be sent to fly above pipelines mounted on the floor, or for collecting first impression of damages after an incident (e.g. fire, flood). We develop and test two algorithms that can provide:

1) a *safe shortest path* (SSP) that ensures a safe distance from indoor objects, while maintaining the shortest distance to the destination.
2) a *safe least cost path* (SLCP) that ensures a safe distance from objects and a given constant height above the floor and stairs.

Our study combines A* algorithm and distance transformation to plan such special paths for an indoor drone. Our 3D PAEDT algorithm allows to:

- create 3D buffer zone around the obstacles efficiently, in which the drone cannot fly.
- perform 3D propagating distance transformation from the obstacles to ensure the drone's safety and at the same time prevent it from flying through narrow channels.
- compute a 3D distance map from an assumed plane which has a fixed height above the floor and the stairs as an additional cost field for producing SLCP.
- combine with A* to produce 3D path efficiently.

The workflow is shown in Fig. 1. First, a 3D buffer around the obstacles is computed using 3D PAEDT, in which the distance is the

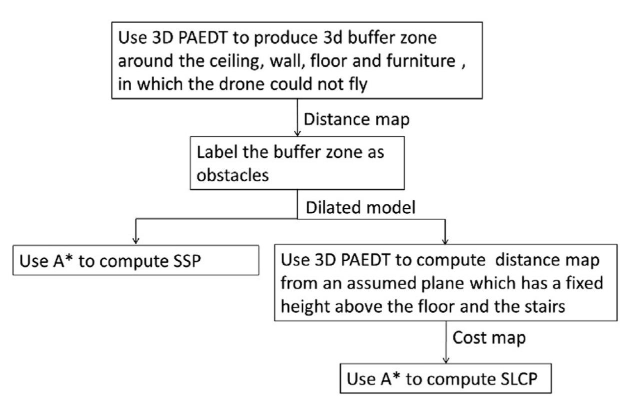

Fig. 1. Flowchart for achieving paths based on 3D PAEDT and A*.