3D Maps Registration and Path Planning for Autonomous Robot Navigation

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Abstract—Mobile robots dedicated in security tasks should be capable of clearly perceiving their environment to competently navigate within cluttered areas, so as to accomplish their assigned mission. The paper in hand describes such an autonomous agent designed to deploy competently in hazardous environments equipped with a laser scanner sensor. During the robot’s motion, consecutive scans are obtained to produce dense 3D maps of the area. A 3D point cloud registration technique is exploited to merge the successively created maps during the robot’s motion followed by an ICP refinement step. The reconstructed 3D area is then top-down projected with great resolution, to be fed in a path planning algorithm suitable to trace obstacle-free trajectories in the explored area. The main characteristic of the path planner is that the robot’s embodiment is considered for producing detailed and safe trajectories of 1 cm resolution. The proposed method has been evaluated with our mobile robot in several outdoor scenarios revealing remarkable performance.

I. INTRODUCTION

The development of efficient methods that allow reliable robot navigation and deployment in hazardous environments, remains an active research topic [1]. The proof is that the robotic urban search and rescue community bears a handful of robots in the rescue and recovery operations of many recent devastations, such as the 2004 Mid Niigata earthquake in Japan [2]. Moreover, in [3], the framework of the NIFTi project is presented, which took place after a sequence of earthquakes in the region of Emilia-Romagna in Northern Italy. This framework presents the successful deployment of a team of humans and robots that produced significant achievements in the domain of urban search and rescue.

The accurate mobile robot navigation is of great importance especially when it concerns applications in the rescue domain. In [3], an integrated system of high level planning and execution with incoming perceptual information from vision, SLAM and topological map segmentation is proposed. This paper describes a system that focuses on two different objectives [4], which are essential for the navigation of mobile robots in unexplored hazardous environments: (i) the development of an accurate 3D reconstruction and registration algorithm suitable to produce dense 3D maps and precise estimations of the robot’s motion and (ii) the integration of a path planning algorithm within the resulted 3D map in order to produce a collision free trajectory. It utilizes the D* Lite [5] path planning algorithm including specific optimizations to take into consideration the robot’s embodiment during the trajectory calculation.

Several approaches exist for deriving a collision free trajectory utilizing point clouds especially for outdoors scenarios. The work in [6] proposes a framework for street robot navigation by detecting low vegetation based on 3D scans. This method classifies three-dimensional scans of the robot environment into two classes, namely the flat vegetation and the streets. A support vector machine (SVM) classifier is utilized on the laser scanner remission values which rely on the material of the measured surface, the distance and the angle of incidence. The work in [7] proposed the usage of 3D Normal Distributions Transform (3D-NDT) as a path planning data structure. Although NDT was initially presented as a 2D laser scan registration technique, the work in [7] proposed modifications to derive an accurate path planner, namely a collision check routine and a check whether it is feasible for the robot to move from one cell having a certain configuration to another.

II. 3D SCENE PERCEPTION

There are several robot set ups and registration algorithms cited in the literature for generating an accurate 3D scene representation. Speed and accuracy are the two most critical aspects in such configurations. The set up followed in this work as well as the registration technique are described in detail in this section. The platform is the wheeled robot ERA-Mobi. Regarding the point cloud formation, the SICK LMS500 PRO 2D laser scanner was mounted on the PTU and configured for vertical scanning. Last, a 3DoF orientation tracker from Xsens accompanies the system enabling the orientation measurement of the robotic platform.

The point cloud registration is accomplished into two distinct steps. First, a rough estimation of the transformation matrix is given using the FPFH [8] features followed by
the ICP algorithm as a refinement step. FPFH are multidimensional features describing the geometry of a point belonging to a 3D point cloud allowing the on-line calculation of those features, making it suitable for on-line applications.

The required rigid body transformation typically should conform with a sum of quadratic differences minimization criterion, resulting to a singular value decomposition (SVD) optimization problem. By applying the motion transformation on the respective 3D point clouds we obtain a rough alignment and, as a result, the 3D map retains erroneous registrations. It is worth mentioning that for this rough alignment an initialization step takes place regarding the orientation of the robot by exploiting the orientation tracker device. Hence, the initially transformed point clouds are considered for the correction of the motion estimation. The most commonly used algorithm to fine register the 3D point clouds is the ICP one. However, the novelty of the proposed work is that our ICP algorithm considers only the points that belong to specific geometric surfaces in consecutive time instances. The successive point clouds share great amount of spatial proximity, due to the fact that a coarse alignment occurred during the motion estimation procedure. The benefit from this procedure is twofold: firstly we avoid multiple iterations restricting the rigid body transformation search by one order of magnitude in calculation time and, secondly, we increase the likelihood to achieve an accurate solution. These advantages are feasible due to the fact that the considered points are contained in two successively observed scenes. Concerning the two successive 3D point clouds $P'$ and $P'$, we utilize a point-to-plane ICP algorithm [9], which seeks for a transformation $K$, that registers the two point clouds.

III. ROBOT NAVIGATION

Once the registration procedure between the 3D point clouds has been completed, the derived transformation is applied and a new point cloud results by merging the previous ones. The new cloud contains various points that have identical coordinates and, thus, a filtering procedure is performed. The voxelized grid approach followed leads to a significant reduction to the number of points, facilitating the manipulation of the data. The voxels have an edge of 1 cm, thus the points within each voxel are approximated by their centroid. The point cloud is referred to the SICK laser scanner, thereafter the floor is removed by applying the RANSAC plane detection algorithm. It is expected that the largest plane in the examined scene would be the floor and, therefore, the RANSAC algorithm operates vertical to the robot axis. This interval is deduced by the following two considerations: i) these points should have zero values on the corresponding axis, and while the robot platform can shift over 2 cm obstacles, points within the range of [0, 2] cm should be also removed ii) taking into account the standard deviation (1 cm) as indicated by the manufacturer, the deviation is appended on both sides of the aforementioned interval. Likewise, points having respective height value over 1.5 m are also removed since it is impossible for the robot to collide with them. The remaining points are top-down projected and a 2D map of a centimeter accuracy is acquired.

All points of the 2D map are declared as non-traversable in the path planning algorithm. At this point, if a path planning procedure was executed, then, in order to derive the shortest path, the successive points of this path would probably have to pass very close or next to the obstacles. Regarding the path planning procedure itself, this would be a correct path, since the robot is assumed to be punctual. By considering the robot’s embodiment, avoidance of such paths is attained by assigning certain cost values to the neighbor points of the non-traversable ones. In more detail, the ERA-Mobi platform’s length and width are 40 cm and 41 cm, respectively. That is, the most distant point from the center of the platform is at 28.64 cm and, since the resolution of the map is of the order of one centimeter we round that value to 29 cm. For every non-traversable point $ob^i$, its neighbor cells that abstain up to 29 cm acquire penalty cost values according to the 2D Gaussian function having standard deviation $\sigma_x, \sigma_y = 1$, i.e. $f(x, y) = e^{-((x-\text{ob}^i)^2/2+y-\text{ob}^i)^2/2}$, where $\text{ob}^i_x, \text{ob}^i_y$ are the coordinates of $\text{ob}^i$. If two or more non-traversable points have overlapping neighbors, then these cost values of those points are accumulated. This process creates a trade-off between the shortest and the safest path. It is obvious that the latter procedure can be adopted to any platform, resulting a different size of neighborhood.

The derivation of such a detailed map in conjunction with the cost assigning process enables the extraction of a particularly detailed and safe path. Such a dense path is a notably approximation of a continuous trajectory. Even if the D* Lite operates in a discrete space, the resolution of the implementation produces sufficient accuracy to navigate within the environment. The enhanced map is provided as an input to the D* Lite method. The latter treats the problem as a graph-traversal one and due to the resolution of the map the distance between two nodes in the graph corresponds to 1 cm in the real world.

IV. EXPERIMENTAL RESULTS

Considering the first outdoor scenario, the registration procedure is illustrated in Fig. 1(a) where the transformation matrix between the point clouds is correctly computed while Fig. 1(b) depicts the resulted 2D map. The average time of the rough registration procedure using the FPFH features was 38.4 sec, while the refinement using the ICP lasted 2.9 sec. The computation of the path has mean time 2.4 sec, while Fig. 1(c) illustrates the paths derived by D* Lite, where the purple line indicates the path in which the embodiment of the robot was considered, and the red one shows the route without taking into account the respective embodiment. The second outdoor scenario took place in a significantly larger area. The distance between the two 360$^0$ laser scans was 35 m, yet the registration of the point clouds was legitimate as illustrated in Fig. 2(a). It is worth mentioning that the computational time for the registration remained almost the same as in the previous outdoor scenario. The respective 2D map is depicted in Fig. 2(b) where the ground was also
Fig. 1. a) Registered point clouds from outdoors exploration, b) the derived map after the top-down projection, c) the resulting trajectories with and without the consideration of the embodiment.

Accurately removed. The calculation of the path lasted almost the same as in the later case, and again, as illustrated in Fig. 2(c), the robot does not navigate nearby obstacles, offering a safer path to the goal. Table I summarizes the execution times of each routine separately for the aforementioned scenarios.

|                | First case ± std | Sec. case ± std |
|----------------|------------------|-----------------|
| FPFH           | 38.4 ± 6.4       | 38.7 ± 6.1      |
| ICP            | 2.9 ± 1.7        | 3.0 ± 1.8       |
| D* Lite        | 2.4 ± 0.3        | 2.5 ± 0.4       |

V. Conclusion

In this work, a novel integrated system for autonomous robot navigation has been presented utilizing only a laser scanner sensor for the 3D perception of the environment. For every robot motion update, the system generates a 3D map of the environment and by utilizing accurate registration techniques, a consistent 3D map of the explored area is produced. The extracted 3D map is further exploited by the robot for estimating detailed paths within the explored scene for safe navigation. The proposed system is a complete navigation framework that can be deployed in hazardous or post-disaster situations aiming to assist rescue activities.

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