Abstract

In order to navigate efficiently in its working space a mobile robot has to use some kind of map. To be completely autonomous the robot has to generate such a representation automatically by exploring all reachable area of the a priori unknown environment. Thus an exploration strategy for generating a complete and accurate map within minimal time is a key feature. This paper presents an integrated mapping and exploration approach that uses a 3D reconstruction technique for extracting a ground plan of the environment and for detecting interesting places (NBVs) that trigger the exploration process.

1 Introduction

The challenge of each exploration process is to determine the optimal sequence of positions at which the robot performs environmental sensing to improve the partial map of the working space - regardless whether this sensing is performed online (while the robot is moving) or at distinct places. The main criteria to select the next best viewing pose (NBV) are expected information gain, cost of traveling to this pose and the chance of reducing the localization error (enhancing map accuracy) [1].

Independent of its type any map is divided into known and unknown space at each point of time during exploration. However, environmental features that are extracted from the collected sensor data determine how good the robot can keep track of interesting places in the unknown space: places that are worth to explored next due to a maximization of the mentioned criteria.

For example, a grid map only contains information about occupied and free areas. Since none of them is more interesting, NBV candidates lie at the frontier between known and unknown space. The corresponding well-established exploration strategy is denoted as frontier-based exploration. Although some enhancements to this strategy have been realized in the past its main drawback is the lack of global overview of the working space which leads to inefficient exploration paths (e.g. oscillations) [2].

If the robot had some knowledge about the structure of rooms within the building to be explored this process could be organized more efficiently: first the current room and open doors have to be acquired as good as possible (local exploration), then one of the doors should be entered to continue exploring the next room (global exploration). This leads to a topological map with rooms as nodes and doors as their connection and may be enriched by geometric information about the room extensions.

In [3] a 2D version of such an exploration strategy has been developed: the structure of rooms is extracted online from distance data provided by two planar laser scanners and is mapped as collection of rectangles. The main problem of this approach is the limited view towards room walls in highly cluttered areas due to a sensing plane close to the ground parallel to the floor. Thus, using the 3D reconstruction technique described in [4] an optimized exploration approach has been realized based on extracting the extension of floor, ceiling and room walls from 3D point clouds that are collected at distinct NBVs via a 360° scan (panorama scan). The NBVs are determined based on expected information gain (comparing floor and ceiling layout, properties of cells of an accompanying grid map), cost (path length) and dispersion (distance to past NBVs).

The remainder of this paper is organized as follows: first a summary of related work is presented in section 2, then the robot and applied sensor systems are described in section 3, the obstacle avoidance system is introduced in section 4 and grid map based navigation is sketched in section 5. The obstacle avoidance system and navigation strategy have been discussed in detail in [2], so here only the key features are summarized as supporting technique for the new exploration approach. The 3D reconstruction approach is explained in section 6 and the NBV evaluation is propounded in section 7. Experiments performed in a realistic 3D simulation scene as well as in a real office scenario are evaluated in section 8. Finally the achieved results are assessed regarding future improvements in section 9.

2 Related Work

A sound classification and evaluation of existing exploration approaches is given in [1]. On a scale from simple to high sophisticated strategies the first class uses prede-
fined trajectories, e.g. concentric circles, figure eight or star shaped movements [5]. The next class uses random motions towards unexplored areas, that means taking frontiers of known areas into account without explicitly calculating NBV candidates [6]. Mistakenly the room based exploration system of [3] has been added to this class although it follows a sound deliberative philosophy of first exploring the current room, searching a door and continuing exploring a neighboring room (switching between local and global exploration). Despite triggering the motion by walls and doors without explicit NBV calculation there is no random motion: hence it is clearly a representative of an online exploration, that means continuous adaptation of the NBV instead of the classical sense-think-navigate approach.

Most existing exploration systems belong to this latter class, but they differ widely in the evaluation function for scoring the NBV candidates. General criteria are guess of information gain (IG), estimated cost (C) of traveling towards the NBV, expected chance of relocalization (L) at the goal pose and dispersion (D) in case of multi-robot systems. [7] uses only the cost criterion for selecting the NBV at a frontier between known and unknown space. [8] and [9] evaluate information gain and cost. [10] and [11] use a weighted sum of three criteria IG, C, L.

All these approaches use an ad hoc function that is created manually and validated via experiments. In contrast to this [1] exploits information theory for calculating the NBV as difference of expected and ideal information gain. This formula inherently considers also cost and map accuracy. Compared to the state of the art this paper proposes a novel method for generating NBV candidates based on the 3D structure of the environment and a sound strategy for scoring them according to the available knowledge.

3 Robot and Sensor Systems

Figure 1 shows the robot and sensor systems used to evaluate the proposed exploration approach. The 2D scanners measure the distance to closest objects in a plane parallel to and 10 cm above ground.

A belt of 20 ultrasound sensors detects raised obstacles, e.g. jutting out edges of table tops. A rotating 2D scanner provides 3D distance information about all objects between floor and ceiling in the front side motion corridor. At the NBV positions the rotating motion is stopped and the robot performs a 360° turn to collect a 3D point cloud of the environment (panorama scan).

4 Obstacle Avoidance

Obstacle avoidance is based on all three sensor systems. Several Cartesian and polar sector maps are filled online with the provided distance data [2]. These maps serve as virtual sensors that trigger a cascade of motion behaviors: anti-collision, keep distance to objects at the left and right side and evade from traps. For each virtual sensor and aspect one behavior is implemented and their output is fused to adapt the desired robot motion. This online strategy and 3D space coverage guarantees that the robot never hits any object (as long as it does not approach the robot too fast) so it can safely pass unknown areas during exploration.

5 Grid Map Based Navigation

The distance information of all three laser scanners is exploited to fill a global 2.5D occupancy grid map. The occupancy information is coded as counter value per grid cell (0 means unknown, ≥ 1 means occupied) in order to mark the uncertainty of this data. The map is updated at the NBV positions from the 3D point cloud as well as during navigation. To assure map accuracy a continuous relocalization based on the DP-SLAM method is applied [12]. Hence there is no explicit localization at the NBVs so this criterion does not influence the exploration strategy.

To navigate towards an NBV a motion path is calculated as sequence of adjacent grid cells. The estimated effort to follow such a path takes the occupancy information of the cells into account (mere value and location close to obstacles). This serves as cost criterion during exploration. Furthermore the path is transformed into an elastic band [13] to perform a continuous free space analysis during motion.

6 3D Reconstruction of Rooms

In [4] an approach for extracting large planar structures from a 3D point cloud has been presented. Dividing the data into a regular grid of cubic cells, a set of best fitting local planes is calculated via the RANSAC algorithm, principal component analysis and least-square optimization. Afterwards similar neighboring planes are fused in a least square sense. The output is a set of floor, ceiling and wall (candidate) planes for each 3D panorama scan. In order to exploit this data for efficient exploration the planes serve to set up a ground plan map of floor and ceiling. This is motivated by the underlying observation that typical indoor environments consist of a ground plane (the
one on which the robot is moving) and a ceiling plane (the highest visible plane). As the experiments show, the resulting increase of exploration efficiency justifies this small amount of predefined world knowledge.

Assuming open doors and no furniture objects, the floor plane is limited by room walls but can be represented as a single connected polygon. The ceiling plane however is interrupted by room walls (since doors normally do not reach the ceiling) so it is a collection of polygons. Considering furniture and closed doors, both ground plans are modeled as such a collection:

floor ground plan := \{polygon \ p_i | p_i \ horizontal plane on which the robot moves\}
ceiling ground plan := \{polygon \ p_i | p_i \ highest visible horizontal plane\}

No matter whether the wall based separation of the ceiling reliably works or not there will always be a difference in the layout of both ground plans (otherwise the floor would be an exact copy of the ceiling). Exploiting this difference is the core idea for the proposed exploration strategy. Handling these polygon sets and corresponding operations (union, difference) is done via CGAL\(^1\). An example of ground plans is shown in figure 4 and figure 5.

7 Selecting the NBV

Basically the exploration process uses the general sense-think-navigate scheme proposed by [1] as shown in figure 2. At each NBV including the starting pose a 3D panorama scan is acquired, the grid map is updated and a new set of 3D planes is extracted. The floor and ceiling planes are added to the existing ground plans via polygon union. Hence overlapping polygons in each set are fused automatically, disjoint polygons are added as new ones to the set.

The difference between the ground plan of floor and ceiling is a new set of polygons that marks interesting areas: space visible only at the ceiling may represent inaccessible areas of the floor (e.g. covered by a table); space visible only at the floor may represent a connection to the next room (i.e. open door) since a 3D scan “flows” through a door on the ground level, but is stopped by the wall at the ceiling. Thus NBV candidates are the center positions of the most promising difference polygons \(p_i\):

\[
\text{NBV candidates} := \{c_i | c_i \text{ center of } p_i, p_i \in \text{difference ground plan}\}
\]

The most promising pose \(\hat{c}_i\) of all these candidates \(c_i\) is calculated as the maximum of the evaluation function \(f(c_i)\):

\[
f(c_i) = \lambda_a \cdot \text{area}(p_i) + \lambda_u \cdot \text{unknown_cells}(c_i) - \lambda_c \cdot \text{cost}(c_i) - \lambda_o \cdot \text{occupied_cells}(c_i)
\]

\[
-\lambda_d \cdot \text{distance_to_past_nbv}(c_i). \quad (1)
\]

The area of a difference polygon marks the expected information gain in terms of the ground plane map, the number of unknown cells within a sensing circle of a given radius around \(c_i\) represents the same aspect in terms of the grid map. Negative factors are the cost of the navigation path, the number of occupied cells in the sensing radius (accessibility of the NBV) and the dispersion, i.e. proximity to all past NBVs. These factors are calculated as relative values for each \(c_i\) using the minimum over all \(c_i\) for dispersion and the maximum otherwise. The weighting factors \(\lambda_{a,u,c,o,d}\) have been introduced to control the influence of individual parameters which is common sense of any “ad hoc” function [1] that combines several exploration aspects. Naturally their values have to be chosen carefully to achieve reasonable exploration results (see section 8).

Finally the winner NBV is approached on the calculated path that is optimized continuously by the elastic band analyzer. When the NBV has been reached or marked definitely as inaccessible the next exploration loop is started. The whole process is stopped when there are no more or only too small polygons in the difference ground plan.

8 Experiments

The developed exploration approach has been successfully evaluated both in a simulated and a real office scenario. The simulation experiment is based on the SimVis3D framework [14] for generating realistic noisy sensor data. This way all sensors (ultrasound, planar and 3D scanner) provide distance information as on the real robot. As shown in figure 3 the working space is represented as an

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L-shaped hallway with office rooms of different sizes at both sides of it. This scene of about 880 m$^2$ is the same as in the experiments with the dynamic frontier based exploration presented in [2]. Thus the results can be directly compared. Furthermore it is close to the real testing area which differs only some room layouts: e.g. the big lab room (cf. [2] fig. 9) now is a smaller meeting room and the hallway contains a circular stair at the south-east corner.

Figure 3: Simulated office scenario (based on SimVis3D)

In order to check the efficient sequence and dispersion of NBVs only static objects are present, localization errors are neglected and doors are omitted to allow the robot to quickly enter even small rooms. Although these are rather artificial conditions, the presented experiment serves as proof of concept to show the power of the exploration strategy. For performing all test runs with the same setup of parameters of the robot control software one additional restriction has been made that is not really necessary in static environments: the 3D point cloud that is collected during the panorama scan at the NBV positions is only used for extracting the floor and ceiling plane, but not for updating the grid map. This is due to people walking occasionally through the scene during the panorama scans in reality. The corresponding distance samples do not falsify the 3D reconstruction and resulting ground plans, but complicate the consecutive evaluation of NBV candidates because of difficult path planning. Of course, these dynamic obstacles disappear from the grid map as soon as the robot scans the respective area again, but this happens not until it starts approaching the next NBV. The only negative consequence of this restriction is the sparseness of the grid map compared to the ground plan map (see figure 4), but this does not affect the exploration process.

During all experiments the same setup of the evaluation function 1 with $\lambda_a = 5$, $\lambda_u = 1$, $\lambda_c = 5$, $\lambda_o = 1$, $\lambda_d = 10$ has been used. These values limit the influence of grid map based scoring of NBV candidates ($\lambda_{u,o}$), balance expected information gain and cost ($\lambda_{a,c}$) and maximize dispersion of NBVs throughout the working space ($\lambda_d$). As the experiments show these are feasible values that drive the robot quickly towards unknown areas, but must naturally be seen as starting point for further optimizations.

Figure 4: Status of grid map (occupied areas marked red), ground plan map (ceiling surface represented as magenta polygons) and traveled path (green) after 30 exploration steps (numbered NBVs) in a simulated office scenario. The compass rose marks the real geographic position

Figure 4 shows the recorded grid map, ground plan of the ceiling, NBV positions and navigation path after 30 exploration steps. The experiment took about 70 minutes and the length of the traveled path is about 17.9 m. The robot started in the big meeting room that is covered by NBVs 0, . . . , 4. With positions 5 and 6 the south-east part of the hallway is covered and positions 7 and 8 serve to acquire the adjacent offices to the south. NBVs 9 and 10 are needed to complete the end of the hallway. Here the first exploration “defect” appears since position 10 is obsolete. NBV 11 covers the next small room to the north (this is the area of the circular stair in reality, see figure 5). Although one would expect to enter the adjacent room now, this is only done with NBV 18. So the robot decides to go back to the hallway and to scan the neighboring room at position 12. Although this room is not completely acquired the open end of the corridor to the west is more attractive (NBV 13). Then the next office to the south is recorded at position 14. Instead of continuing in the corridor now the open door in the meeting room at NBVs 15, 16 seems to be more attractive. At this point the first oscillation occurs: the adjacent room is not acquired until NBV 19 because the robot first goes back to the missing room at the south-east end (NBV 17, 18). Additionally position 17 seems to be obsolete but is caused by the long path from position 16 and the limited
number of 10 replanning steps per NBV approach. After that the open end at the north of the hallway is explored with NBVs 20, . . . , 25 and then the loop around the meeting room is closed with positions 26, 27. Position 28 leads to an adjacent office, before NBV 29 heralds in the next oscillation.

In sum the exploration process works reasonably regarding the acquisition of all reachable areas and the dispersion and sequence of NBVs. The only defects concern the accumulation of NBVs 9 and 10 and the two described oscillations (with resulting NBV accumulation 11, 17 and 25, 29). These anomalies are caused by the weights of the factors during the evaluation of NBV candidates (cf. equation 1). Since their values have been chosen in an ad hoc manner further research on the influence of the individual parameters is necessary. But this problem also exists for frontier based exploration and is the main drawback of any scoring function that combines several exploration aspects.

Concerning the grid map and ground plan of the ceiling the simulation experiment yields the optimal result without localization errors: the walls and openings (doors) of all visited rooms are clearly contained in the grid map and mostly represented as disjoint polygons in the ground plan. This separation only fails at NBVs 14, 24, 28 due to the panorama scans directly at the frontier between two rooms and the rough digitalization of the space via a grid of $10 \times 10 \times 10$ cm$^3$ cells during 3D reconstruction.

To provide evidence that the exploration strategy also works under real world conditions a series of test runs has been performed in a hallway/office scenario similar to the simulated one. Figure 5 shows the sequence of NBVs, traveled path, recorded grid map and ground plan of the ceiling, again after 30 exploration steps. This run took about 105 minutes and the path length was about 47.5 m. This increase is due to several uncertainties: localization errors, semi-static objects (doors sometimes open, sometimes closed) and people walking occasionally through the scene. Hence the length of a path to approach an NBV is not as straight as before.

The sequence of NBVs is similar to the simulation experiment: first the meeting room and adjacent areas are scanned (NBV 0, . . . , 4), then the south-east part of the corridor (5, . . . , 7) is recorded. Due to furniture (tables, shelves) covering large parts of the meeting room it is left earlier than in simulation. The first oscillation occurs at positions 8, 9. Afterwards the south-east area in the corridor around the circular stair (negative obstacle in the grid map) is completely recorded at NBVs 9-11. Then the robot continues exploration at the open west end of the corridor (NBV 12). Entrance hall and north part of the corridor are acquired in sequence 12, . . . , 23 with another oscillation at positions 17, 18. Since the doors to the office rooms adjacent to the north part of the corridor and to the workshop are only sometimes open, there are just small parts visible in the ceiling ground plan. Storeroom and adjacent office at the south-west end of the corridor are visible merely through transom windows. The resulting differences in ground plan of floor and ceiling causes NBVs 24 and 25. But according to the occupancy information in the grid map there is no valid path to an NBV candidate inside these rooms. Finally the office at NBVs 26, . . . , 29 had been opened to allow the robot recording this room. The grid map shows how cluttered the reachable space is, so opening doors to other offices had been skipped. However the robot remembers all possibly interesting but currently inaccessible areas in the ground plans.

Figure 5: Status of grid map (occupied areas marked red), ground plan map (ceiling surface represented as magenta polygons) and traveled path (green) after 30 exploration steps (numbered NBVs) in a real office scenario

In sum the exploration strategy also works reliably in uncontrolled real world scenarios. Even in long corridors without branching rooms (positions 16, . . . , 22) there is enough difference between ceiling and floor to generate feasible NBVs. This situation is most challenging compared to frontier based exploration: frontiers always exist until all space is acquired, but here monotonous free spaces are of lower interest due to similar floor and ceiling areas. Obvious differences to the simulation result are the depth-first exploration path (corridor before rooms) due to closed doors, as well as orientation and roughness of grid map and ground plan due to localization uncertainties: walls cover more grid cells and the separation of rooms into disjoint

\[ E \rightarrow W \]

\[ S \rightarrow N \]

south hallway

north hallway

- office rooms
- missing walls
- storeroom
- circular stair
- workshop
- entrance area
- office room
ceiling polygons fails. In fact two walls of the meeting room are completely missing in the ground plan. However this only limits the usability of the recorded polygonal map, but does not affect the exploration process as the occupancy information of the grid map is always evaluated. To provide a remedy the localization error has to be reduced and the 3D reconstruction has to use a fine-grained resolution, leading to an increased computational effort.

9 Conclusion and Outlook

In this paper a novel exploration strategy for structured indoor scenes has been presented that evaluates the ground plan of floor and ceiling for detecting the most interesting places as NBV. It is based on a sound strategy for 3D obstacle avoidance, grid map based navigation using the elastic band method for passage analysis and path planning, the DP-SLAM approach for continuous relocalization and a reconstruction technique for extracting the room structure from a 3D point cloud.

The main contribution regarding existing exploration strategies is the sophisticated generation of NBV candidates at the “difference areas” of floor and ceiling and the scoring of NBVs by weighting expected information gain, travel cost and dispersion. The conducted experiments show the functionality of this approach both in simulation and real world scenarios. Future work consists of fine-tuning the NBV evaluation function, i.e. selecting optimal weights for the contributing factors. Furthermore a sound comparison between existing exploration strategies, e.g. [7], the approach developed in [2] and the strategy proposed here will be performed regarding map accuracy, coverage and exploration time.

References


