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BUILDING GLOBALLY CONSISTENT GRIDMAPS FROM TOPOLOGIES

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Abstract: This paper addresses the problem of recovering metric consistency in a global gridmap for mobile robot navigation in large-scale environments. A hierarchy of robot maps is proposed which integrates topological and grid-based representations at different levels of abstraction. The consistency problem is solved at the topological level, by applying a relaxation technique to generate coordinates for the places in the map. Consequently, the robot is able to recover a globally consistent gridmap without requiring accurate sensors or high computational costs. Experiments on a Nomad 200 robot in a large, real world environment demonstrate the effectiveness of the approach.

Keywords: Mobile Robot Navigation, Occupancy Grids, Topological Maps, Spatial Semantic Hierarchy.

1. INTRODUCTION

Maps are essential for mobile robot control in unstructured environments, being needed for self-localisation, path planning and human-robot interaction. A popular representation paradigm for robot maps is the occupancy grid model, see e.g., (Moravec and Elfes, 1985; Hughes and Murphy, 1992; Oriolo *et al.*, 1998). In this approach, the map consists of a matrix of cells, each containing some measure of the certainty that the corresponding area of the environment is occupied by an object.

If a robot is to function autonomously, it needs the ability to build its own maps. This requirement imposes some severe practical problems for a robot attempting to construct a global grid model in real-time:

- *Dependence on accurate position information.* Large-scale gridmaps can only be updated consistently using exact estimates of the robot position. Under realistic operating conditions it is often very difficult to maintain the required level of accuracy. For example, some systems require *a priori* position information from an external agent (Fabrizi *et al.*, 2000). Others depend critically on accurate sensing, e.g., using laser-range finders (Yamauchi *et al.*, 1998) and stereo vision (Thrun *et al.*, 1998*a*), to reduce positioning errors.
- *High computational cost.* When accurate global position information is not available, the same sensor data must be used both to build the map and to update the robot's position. Most current approaches do so by applying some optimisation technique over the space of possible maps, e.g., (Thrun *et al.*, 1998*c*; Thrun *et al.*, 1998*b*). These solutions tend to require large amounts of mem-

ory and processing power. For example, the technique proposed in (Thrun *et al.*, 1998*c*) requires up to two hours of computation to generate a gridmap with a spatial resolution of 1 meter in a large environment (90 × 90 meters).

An alternative paradigm is provided by topological maps, where the environment is represented as a graph of connected places. In this approach, the problem of self-localisation becomes that of *place recognition* (Kortenkamp and Weymouth, 1994), and the robot does not need to know its precise Cartesian coordinate for map building. The compactness of topological representations also means that computational costs are much lower than for gridmaps. However, these maps do not provide a detailed geometric interpretation of the target environment.

In this paper, a new method is proposed which integrates topological and grid-based representations for the purpose of constructing globally consistent metric models of large, real world environments. The core of the integration is the ability to obtain precise position information from a topological map without requiring accurate sensors and without incurring high computational costs. This information is then used to build a global gridmap. Using this approach, a sonar-equipped mobile robot is able to construct detailed models of large environments.

The proposed method relies on the combination of three existing techniques for robot map building:

- a topological map building strategy (Duckett and Nehmzow, 1999*a*),
- a relaxation technique for maintaining geometric consistency in a graph (Duckett *et al.*, 2000), and
- an off-line algorithm for constructing a global gridmap (Oriolo *et al.*, 1998).

The latter algorithm requires exact position information, which is obtained here by applying the relaxation technique to a self-acquired topological map.

The new method assumes four sources of perceptual information; (i) a place recognition system, (ii) a global orientation, (iii) local distance information, and (iv) range information used to build the gridmap. In this paper, experiments on a Nomad 200 robot are presented, in which the Bayesian self-localisation algorithm described in (Duckett and Nehmzow, 1999*b*) was used for (i), a compass was used for (ii), odometry for (iii), and sonar sensors for (iv). In the experiments, no *a priori* position information or map were provided to the robot.

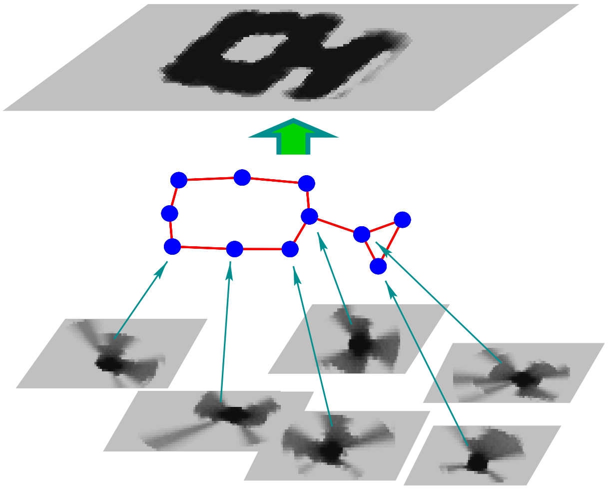

Fig. 1. Hierarchy of Maps.

2. METHOD

The new approach integrates topological and grid-based representations at different levels of abstraction in a hierarchy of robot maps. The basic idea is summarised in Fig. 1.

At the lowest level, the environment is represented by a set of *local* grid models. Each of these grids constitutes a *perceptual signature* for one particular place in the environment; there is no requirement of consistency between the local grids. These local grids are used on-line by the robot for self-localisation.

At the intermediate level, the places are connected by a set of links to create a topological map. Each link is also labelled with metric information describing the relative distance and absolute angle between the two places it connects. Using this information, the relaxation technique described below is then applied to assign a geometrically consistent set of Cartesian coordinates to the places in the topological map.

Finally, the globally consistent metric information derived from the topological level is combined with recorded ultrasonic range data to generate a global gridmap.

These representations are manipulated by applying the following techniques. Detailed descriptions of these algorithms may be found in the papers available online (see References).

2.1 *Topological Map Building*

To obtain the topological map, an incremental map building strategy was applied (Duckett and Nehmzow, 1999*a*), in which the robot continuously tries to expand the territory which has already been covered. The basic idea is that the

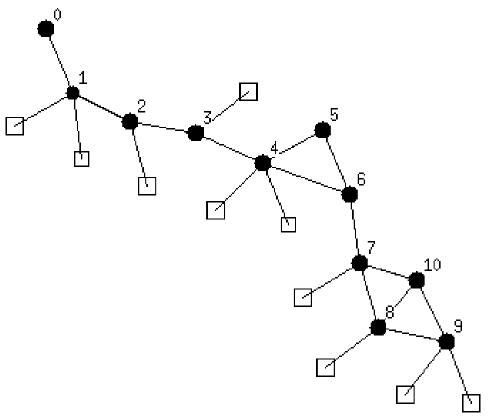

Fig. 2. Example of topological map building. Places predicted by the neural network but not yet visited by the robot are shown by squares. Places visited by the robot are shown by filled circles.

robot travels to the edge of the existing map, and then uses its range-finder sensors to detect more unexplored places. The new places are added to the map, then the process is repeated until the whole environment has been covered (Fig. 2).

A particular feature of the approach is that an artificial neural network is trained to predict the presence of unexplored places in a given direction, fusing together information from the robot's range-finder sensors, see (Duckett and Nehmzow, 1999*a*) for details. The new "predicted" places are added to the map, then subsequent movement by the robot is used to verify whether the predicted places actually exist or not.

During on-line operation, the robot maintains a temporary local grid model in working memory corresponding to its most recent sensory perceptions; this is used for collision avoidance, place recognition (by matching with the stored place signatures) and initialising the perceptual signatures of new places.

2.2 *Relaxation Algorithm*

A major problem for robot map building is that odometry-based dead reckoning cannot be used for accurate position estimation because of cumulative drift errors. To overcome this problem, the iterative optimisation algorithm described in (Duckett *et al.*, 2000) was applied to assign geometrically consistent position information to the places in the topological map. In this algorithm, the coordinates of the places are treated as free variables, and the relaxation method finds a globally consistent set of coordinates using only the local metric relations between places.

With this approach, each link in the topological map can be modelled as a spring which connects two adjacent places i and j, where each link is labelled with the relative distance d_{ij} and absolute heading θ_{ij} between places i and j. Each "spring" reaches minimum energy when the relative displacement between the coordinates of i and j is equal to the vector $(d_{ij},\ \theta_{ij})$ measured by the robot. Thus, global consistency is maintained in the map by minimising the following energy function (a Lyapunov function):

$$E = \sum_i \sum_j^{\prime} (x_i - x_j + d_{ij} \cos\theta_{ij})^2 + (y_i - y_j + d_{ij} \sin\theta_{ij})^2 ,$$

where $\sum_j^{\prime}$ refers to the sum over the neighbours of a given node i.

The basic principle behind the relaxation algorithm can be explained as follows. The idea is to pick each node in turn, and then move it "to where its neighbours think it should be" — see (Duckett *et al.*, 2000) for full details. By repeated application of this rule, the coordinates in the map converge towards a global minimum in the energy function. Furthermore, it has been proven that the algorithm converges to the maximum likelihood solution.

2.3 *Gridmap Construction*

The sonar data recorded at each place, together with the coordinates of that place after relaxation, are used to build a global occupancy grid by standard techniques. In these experiments, the technique proposed by (Oriolo *et al.*, 1998), which is based on fuzzy logic, was applied. There were two main motivations for choosing this particular technique: (1) it maintains distinct maps for the occupied and the empty space, thus allowing the robot to distinguish between unexplored cells and cells on which there are contradicting measurements; and (2) it produces fuzzy gridmaps that can be processed by the technique proposed in (Fabrizi and Saffiotti, 2000) to extract higher level information, which can be used to further expand the map hierarchy. However, it should be noted that the approach proposed in this paper to obtain globally consistent gridmaps can be applied to any occupancy grid construction technique, e.g., (Moravec and Elfes, 1985; Hughes and Murphy, 1992).

Fig. 3. The Nomad 200 mobile robot *Milou* and one half of the test environment (see also Fig. 4).

3. EXPERIMENTS

The maps hierarchy was tested in experiments performed using a Nomad 200 robot equipped with a compass and a ring of 16 Polaroid sonar sensors (Fig. 3). The experiments were conducted in the indoor environment shown in Fig. 4, which is a relatively large office area of size 46 × 12 meters.

Fig. 5 shows the topological map acquired by the robot in one experiment. The picture shows the position of the places in global coordinates before and after relaxation. The derived global gridmap is shown in Fig. 6. The map has a resolution of 0.10 meters, and should be accurate enough for safe navigation and planning. This can be compared to the gridmap in Fig. 7 which was constructed using the robot's compass-corrected odometry instead of the relaxed coordinates — without the relaxation algorithm, the robot clearly fails to build a globally consistent map.

The entire process requires minimal computational resources. Acquisition of the topological map was done on-line. Relaxation was performed as part of the acquisition algorithm. One iteration of relaxation on the full map of 137 places required 20 msec. Since the map was relaxed every time a new place was added to it, only one step was needed each time. The gridmap was generated off-line in these experiments, taking 36 sec to process 6600 sonar readings on a grid of 350 × 450 cells. All times are relative to a 200 MHz Pentium II processor.

4. CONCLUSIONS

Building a global gridmap requires exact position information. In on-line map building systems, this information is usually obtained by correcting the robot's odometry, e.g., using a Kalman filter (Gelb, 1974). However, the Kalman filter is based on assumptions which can be very hard to fulfil under realistic operating conditions.

By contrast, this paper has presented an application of a relaxation technique for building global gridmaps which is based on an underlying topological representation of the environment. Topological maps have the advantage that they can represent much larger areas using the same computational resources, and have a much lower dependency on accurate positioning and accurate sensing for map building.

The work presented in this paper belongs to a growing family of techniques that integrate map representations at different levels of abstraction and granularity. In many of these, the space is represented as a patchwork of locally consistent metric spaces connected to form a global topological map, e.g., (Duckett and Nehmzow, 1999*b*; Gasós and Saffiotti, 1999; Kuipers, 2000; Simhon and Dudek, 1998; Zimmer, 2000). This paper extends this type of approach by exploiting the information in the topological map to recover global metric consistency. In this respect, the closest relative of the new method is the expectation maximisation (EM) technique proposed in (Thrun *et al.*, 1998*b*). While EM-based mapping techniques have produced impressive results, they suffer from a high computational complexity; moreover, EM is not guaranteed to converge to a global optimum. By contrast, in the case of the method described in this paper: (i) relaxation always finds a global optimum, and (ii) computational cost is low.

This work is part of an ongoing effort to develop an integrated hierarchy of robot maps. The different levels of the hierarchy may comprise representations with different semantics, abstractions and granularity. A key advantage of this approach is that it allows the system designer to apply the individual techniques which are most appropriate to a particular level of the hierarchy, and thus to integrate disparate techniques for mobile robot navigation. One next step will be to use the generated global gridmap to derive higher level information, e.g., by applying the techniques for extracting morphological and semantic information concerning the structure of the space introduced in (Fabrizi and Saffiotti, 2000). So far, this work has concentrated on integrating the layers in the hierarchy from the "bottom up"; future work will also investigate techniques for enhancing the functionality of the lower level navigation algorithms using higher level information.

ACKNOWLEDGEMENTS

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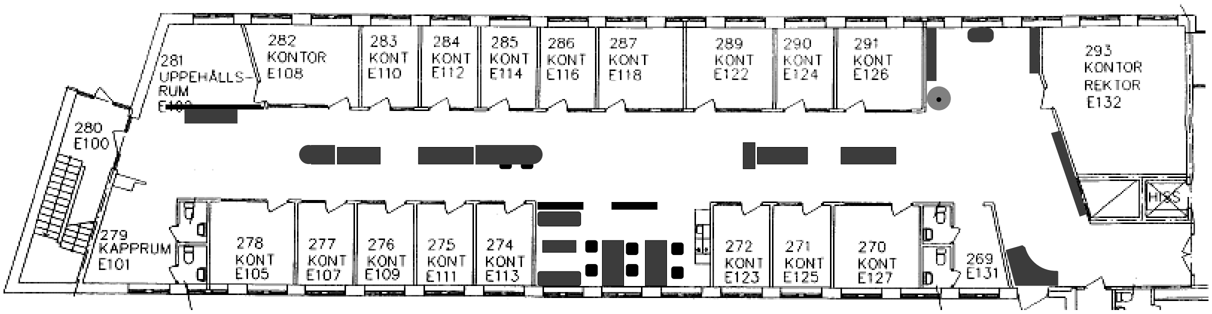

Fig. 4. A floorplan of the test environment.

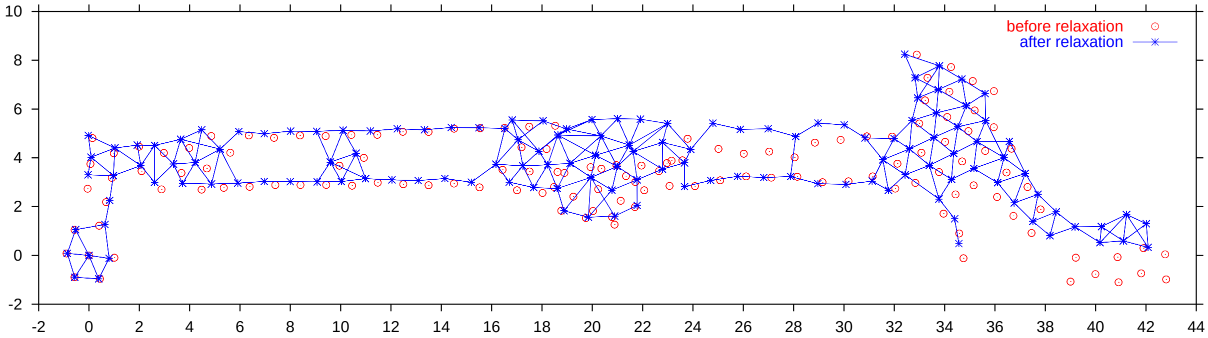

Fig. 5. The self-acquired topological map, showing coordinates before and after relaxation (coordinates are given in meters with respect to the starting position).

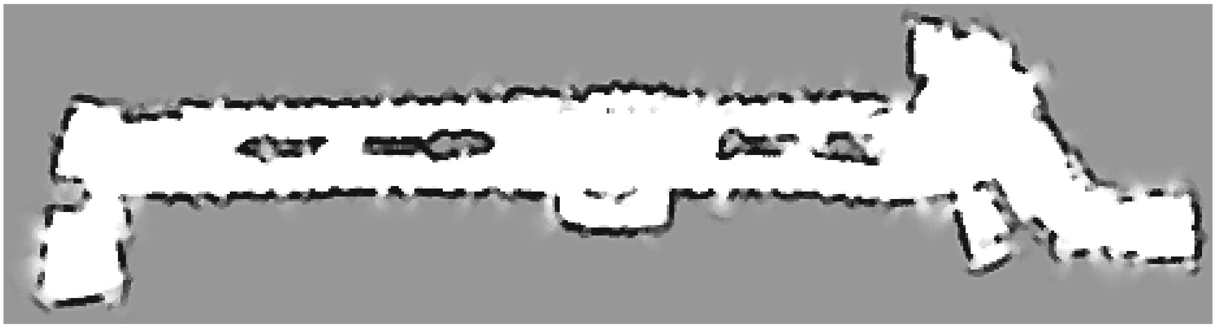

Fig. 6. The global gridmap constructed with the relaxation technique.

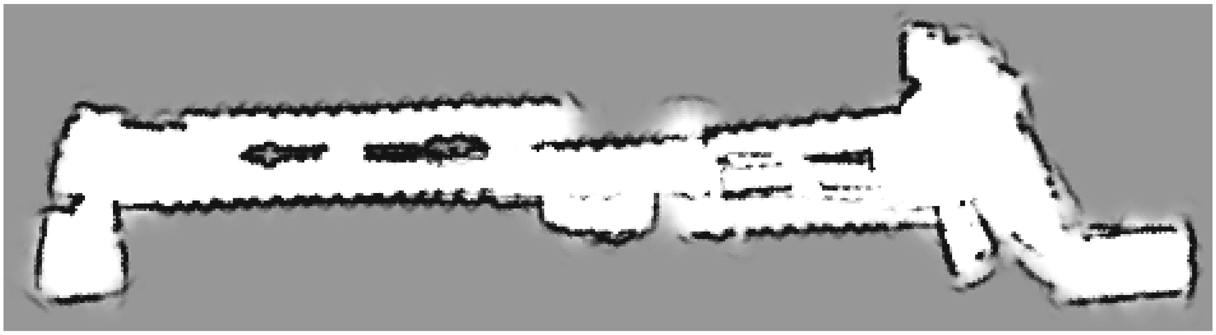

Fig. 7. The global gridmap constructed without the relaxation technique.