Indoor Exploration Using a Sonar Sensor Array: A Dual Representation Strategy

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Abstract

This paper presents an environmental acquisition strategy for a mobile robot using an advanced sonar sensor [13] to achieve mapping navigation in an a priori unknown, imperfectly structured indoor environment. Most existing feature based strategies rely on unrealistic assumptions about the environment, while their grid based counterparts hinder localisation which leads to rapid degradation of map quality. A dual representation strategy is proposed here which exploits the strength of both a feature map and a grid map. With the advanced sensor, the environment is scanned and the obtained features are classified into planes, corners, edges and unknowns. The feature map is only updated with the first three types of features. Being sharper and more realistic than other representations such as uncertainty/bayesian maps, continual localisation is made possible. The grid map is updated with all measurements, including the unknowns resulting from complicated objects, to enable obstacle avoidance. On the grid map, Distance Transform based exploratory path planning [7] is implemented. Adaptation has been made so that an explore-local-first behaviour is exhibited. The paths generated by the Distance Transform are validated with a new local path validator that accounts for the limitation of sonar perception

1. Introduction

A robot requires path planning strategies to acquire full autonomy. The path planning strategies should generate a hazard-free path, based on its current and past perceptive information, to bring the robot to a pre-determined destination. If exploration is the desired objective for a particular application, the method for 'reaching the destination' should be repetitively applied until the entire free space has been explored. Years of research has given birth to multitudinous strategies which can be broadly divided into two streams: feature based and grid based.

With a feature based map, the environment is modelled by a set of geometrically simple primitives such as polygons and straight lines. Popular strategies associated with this approach are potential field [11,23], A* [8] and Dijkstra's algorithm [14]. Potential field based schemes often suffer the problem of local minima, and two of the solutions proposed to tackle this problem are Brownian motion approach [15] and multiple fields approach [3]. A* and Dijkstra's algorithm rely on the vertices of the polygonal objects. When the obstacles are not polygonal, they cannot be directly applied. The Probabilistic Roadmap approach [10] and Randomised Roadmap Method [1] have been contrived to get around this constraint. Two of the most famous tactile sensing based strategies, Bug1 and Bug2, can be found in [17], and the research works which extend from the 'Bug' tradition include Alg1 [21], VisiBug and TangentBug [9]. Obstacles can be grown to accommodate the physical size of the robot, but none of the above proposals, in the authors' opinion, can be easily extended to incorporate complicated features (i.e. imperfectly structured environment) and exploration. Problems also arise if the polygonal obstacles are not 'closed', which is common for the task of map building.

With a grid based map, the environment is tessellated into a grid map of $m \times n$ cells, with no structural restrictions. The cells contain attributes such as (i) occupancy and distance values, as in the Distance Transform [7] approach, or (ii) probability of occupancy, as in the bayesian/uncertainty map approach [16], or (iii) evidential values as in the Dempster Shafer inference rule approach [20], or (iv) some purely heuristic schemes [18,19,22]. It should be noted that (ii) to (iv) are all targeted towards a wide beam sonar sensor. To improve efficiency, a quadtree representation [2,24] has been proposed. By focusing on the probabilistic or heuristic relation between the world targets and the ultrasonic

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reflections, all of the aforementioned models ignore the fundamental problem of localisation. Consequently, accumulation of motion errors lead to rapid degradation of map. In the authors' opinion, robust localisation cannot be satisfactorily achieved with a grid map. The usefulness of certainty map in path planning is also debatable. Other than the Distance Transform, exploratory behaviour is difficult to implement. The exploration strategy presented in [6] relies on assumptions difficult to satisfy in the real world.

This work is carried out with an advanced sonar sensor [13] that classifies targets into planes, corners, edges and unknowns. It introduces a dual representation approach which exploits the strength of both grid and feature based approaches. The major features/ contributions are:

1. A feature map is built using the Kalman Filter with planes, corners and edges. The resultant map outperforms other sonar maps in terms of sharpness and reality, hence facilitates localisation.
2. A grid map is updated with **all** measurements including the unknowns possibly arising from complicated objects in a real environment, so that most obstacles are recorded. The Distance Transform is then applied on the grid map to produce globally convergent paths necessary to guarantee complete exploration of the area of interest. Modifications have been made on the original Distance Transform so that an explore-local-first behaviour is exhibited.
3. A new local path validator is integrated to validate the path produced by the Distance Transform. If a path is found to lead to collision, the destination cell is declared impenetrable, and the Distance Transform is re-applied and an alternative path is selected. The local path validator performs risk avoidance based solely on the sensor measurements made only at the **current position** of the robot.

This paper is structured as follows. Section 2 briefly describes the robot and the characteristics of the sonar sensor array we use. Section 3 discusses the use of a grid map and the Distance Transform in planning a global path, and highlights the explore-local-first modification. Section 4 introduces and illustrates the principle of the new local path validator. Section 5 recalls the authors' previous work on feature based mapping and localisation which motivates this work and runs in parallel with the grid based exploration strategies. This is followed by section 6 on experimental results. The paper culminates in discussion and conclusions.

2. Mobile Robot and Sonar Sensor Array

All experiments were performed with our robot, Werrimbi, shown in Figure 1. It explores its surroundings with a custom sonar array (Figure 2) which classifies common indoor features into **planes**, 90° **corners** and **edges** as well as accurately estimating their range and vertical and horizontal bearing angles. See [13] for a complete description. The sensor repetitively fires TR1 and listens to TR1 R0 and R2 while panning anticlockwise at 90°/sec to locate the directions of potential targets. Then, it pans clockwise, slowing down at the directions of the potential targets found earlier, and fires T0 and listens, then fires T2 and listens to classify targets.

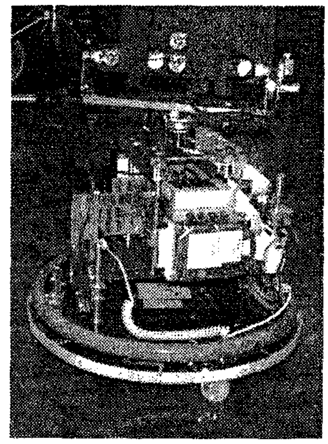

Figure 1: Werrimbi, our mobile robot

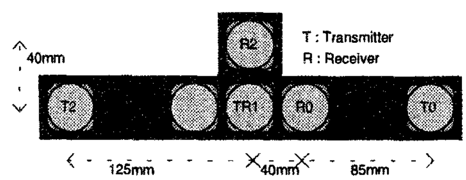

Figure 2: The sonar sensor configuration

3. Global Path Planner

Having chosen a grid map to register all perceivable obstacles by our sonar sensor, a global path planner is essential to ensure complete coverage of free space and convergent planning. Among various grid based methods, the Distance Transform [7] is well suited to this task.

3.1 The Original Exploratory Mode Distance Transform

The Distance Transform evolves from the concept of propagating distance value from the goal cell(s) to every reachable cell in a tessellated map. At the outset, the environmental space is tessellated into square cells as shown in Figure 3. Obstacles and free cells except goals are assigned a high distance value henceforth known as the **Distance Transform Infinite**, whereas the goal cell is assigned zero. These cell values are updated in two passes: forward raster and reverse raster.

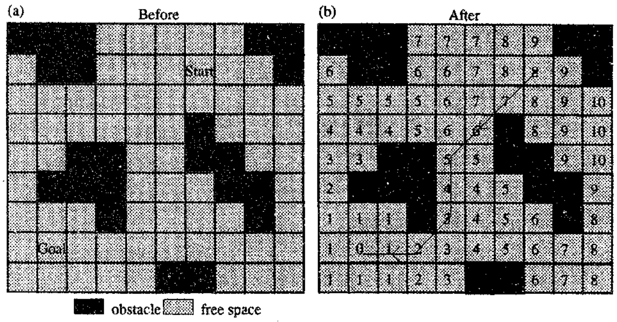

Figure 3: (a) Configuration space before Distance Transform showing start and goal positions (c) Cell values after Distance Transform and the resultant path via steepest descent

During each pass, every free cell with non-zero value is assigned one plus the least values of its four neighbours, previously visited on that pass. The process is iterated by alternating between the two passes until the cell values remain the same. The shortest path from any cell to a goal is found by steepest descent until a goal is reached. In an initially unknown environment, the unknown cells are treated as empty until proven otherwise. The strength of Distance Transform is that risk management or exploration can be effortlessly integrated into the basic algorithm. To achieve exploration, all the unknown cells are regarded as goal cells until their status are uncovered. When the status of all unknown (goal) cells have been revealed, Distance Transform can no longer alter their initially assigned high distance values. **This signals a mission completion.** This happens if the robot finds itself navigating in a closed environment, or every reachable cell on the grid map has been visited. The pseudo code can be found in [7].

The choice of grid resolution is a compromise between computational speed and map quality. If the cell size is small compared to the size of the robot, a high quality map can be generated and the obstacle can be grown for the purpose of obstacle avoidance, without blocking the entries to narrow passages. However, the concomitant processing cost is usually high. In some research work, the grid map is meant for localisation also, so a fine resolution becomes inevitable. In this implementation, a local path validator is used to guide the robot away from local obstacles, and the grid size is set to *the radius of the robot*. Since the sole purpose of the grid map is for recording navigation history, the resolution is only of secondary concern.

To navigate, the robot moves from the centre of one cell to the centre of next cell. Eight-connectivity is also supported, which means that the robot is allowed to move diagonally across to another cell.

3.2 Explore-local-first Behaviour

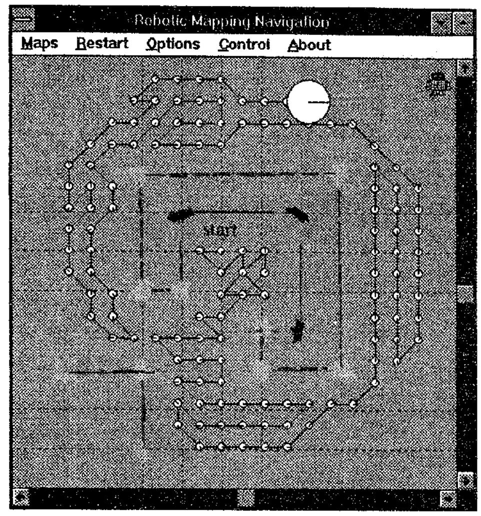

Figure 4 : Explore-local-first behaviour makes the robot explore the nearby area first (Simulation)

The original exploration strategy has the robot moving as far as the grid map permits (i.e. the dimension of map in each horizontal and vertical direction). A robot using this strategy wanders far away from the initial position until it is blocked by an obstacle which possibly turns the robot back. For our purpose, a more pragmatic strategy should have the robot exploring local area first (i.e. area closest to its initial position) and gradually advancing outwards to the unknown regions further away. This is done by a minor modification to the strategy: First, the robot attempts to move to an unexplored cell which is closest to the starting position. If there is no unexplored cell, the robot opts to move to the cell nearest to the starting position with a smaller distance value. The simulation of such behaviour is shown in Figure 4, whereby the robot attempts to explore the area in an approximately spiral fashion. This modification also allows the grid map to be expanded on-demand.

4. Local Path Validator

A local path validator is implemented in addition to the global planner for two reasons. Firstly, the grid resolution is chosen to favour processing efficiency at the expense of obstacle growth, so a local planning strategy is needed to guide the robot away from obstacles. Secondly, as mentioned in section 2, the perception of the sonar sensor is limited to three types of discrete, elementary indoor landmarks, namely plane, corner and edge and unknown. The host objects of these measurements would almost certainly occupy a larger physical size. A grid map, in its original formulation, is inadequate for accommodating the perceptive limitation of sonar. An example is given in Figure 5: The robot can only detect the part of a smooth wall which is perpendicular to the line of sight due to specularity, so only one cell along the wall is declared as occupied. Without a local path planner, a path which leads the robot to the centre of the the gray cell is considered valid but it will cause collision. A complementary local path validator which hypothesises about the local measurements made at the **current** position of the robot is therefore adopted.

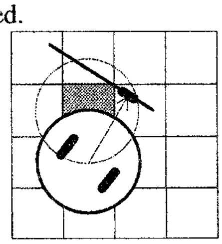

Figure 5 : A possible hazard for a robot using our sonar sensor, if a local path validator is unavailable

4.1 The Underlying Principle of the Local Path Validator

The principle behind the local validator is as follows. First of all, a cell with a smaller Distance Transform value (i.e. closer to unexplored area) than the current cell and closest to the initial position is selected. To move to that cell, one possible path is one that leads from the current robot's position to the centre of the chosen cell, and is denoted by L here. Let D be the radius of robot plus a safety margin. The path validator ensures that all local features detected at the current robot's position **only**, and their extensions if applicable, do not fall into the collision zone (light gray) depicted in Figure 6. Using the orientation information, a plane feature is extended infinitely along its tangent direction. It is also assumed that an unknown observation is produced by a complicated object which spans an infinite planar dimension orthogonal to its line of sight. No extension is assumed for a corner feature and an edge feature.

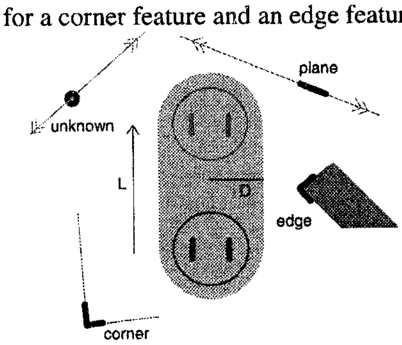

Figure 6 : Collision zone (light gray) for a planned path. The double arrows sign means infinite extension.

However, if the initial distance between the feature and the robot is **already** smaller than D, then for all cases, the planner ensures that the destination must be at least D away from the robot. This can happen, for example, if the robot is placed very close to an obstacle the instant it is turned on. If the candidate path is found to lead to collision, the destination cell is considered **impenetrable**, and a second cell is chosen by invoking the explore-local-first scheme presented earlier.

4.3 Assumptions Behind the Local Path Validator

Extension for a plane feature is logical as they are produced by objects with finite planar surfaces present in a typical indoor environment, such as walls, desks, filing cabinets, boxes and columns. For an unknown feature, it is assumed that the extension perpendicular to the line of sight gives the most pessimistic estimation of the actual physical occupancy of the host object. This assumption is illustrated in Figure 7.

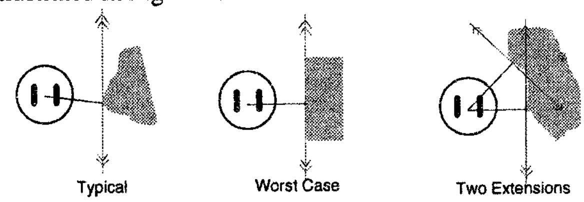

Figure 7: The extension perpendicular to the line of sight of an unknown is assumed to give the most pessimistic estimation about the actual physical occupancy of its host object

Although both planar and unknown features sensed at the current positions are extended when validating a local path, such extensions are never updated into the occupancy map and the feature map. This ensures that valid passageways between two non-parallel extensions are not blocked. The reader is referred to the example in Figure 8.

An edge is not extended perpendicular to its line of sight because it is assumed that the other parts of its host object always extend **away** from the plane perpendicular to its line of sight. This is true for most polygonal objects such as boxes and filing cabinets, as well as cylindrical objects such as poles and table legs. In that case, a short path which leads the robot to the vicinity of such a virtual plane should not cause any hazard. An example is given in Figure 9. The arrows emitting from the robot indicate four paths which would be predicted as safe even though they lead the robot closer to the obstacles. This argument justifies a simple distance test for an edge.

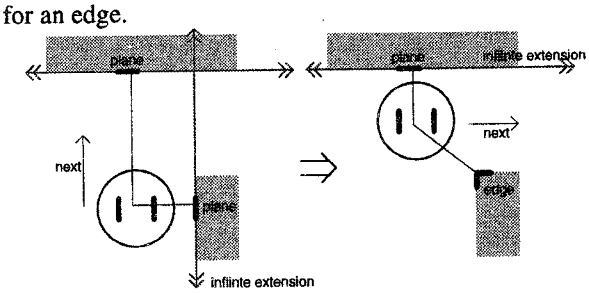

Figure 8: Infinite extensions are applied to features detected at the current robot's position but they are not updated to the feature map or grid map. This ensures that certain passageway is not blocked.

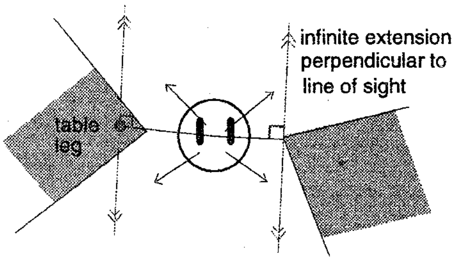

Figure 9: Other parts of an edge's host object normally extend away from the plane perpendicular to its line of sight.

No extension is assumed for a corner also because it is assumed that another part of its host object which is closer to the robot, such as a plane, an edge or an unknown, is always detectable. Under such circumstances, the distance constraint imposed by the closer edge, or the extension constraint imposed by the closer plane/unknown determine the validity of a path. The reader is referred to Figure 10.

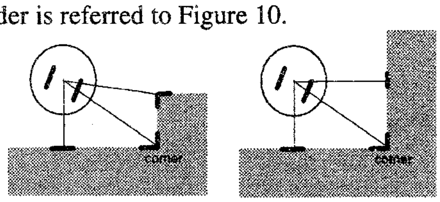

Figure 10: The robot sees other parts of a corner's host object which are closer to the robot than the corner, such as planes, edges or unknowns

The local path validator discussed here has been found to be successful in a wide range of experiments.

4.3 Obstruction of Impenetrable Empty Cells

If the local path validator determines that a particular cell, despite its supposedly empty occupancy, is impenetrable, it has to obstruct the cell and re-apply Distance Transform. Otherwise, the robot would be trapped, unable to navigate to some other unknown cells via previously visited empty cells. To obstruct that cell, the occupancy of that cell is simply declared 'occupied'.

5. Simultaneous Mapping and Localisation

The motivation behind this path planning work is to give the robot the autonomy required to explore an unknown, real life indoor environment and concurrently building a map. An uncluttered indoor environments normally consists of landmarks such as planes, corners and edges which are useful for localisation. This work is also a continuation to a work on mapping and localisation [5]. In summary, odometry and sensor measurements are fused in a minimum mean square error manner to generate accurate estimation of the configuration of the robot and various map entities. The estimation is enhanced by the exploitation of relational constraints among features. Fusion is achieved with a **Julier-Uhlmann Kalman Filter (JUKF)** which improves the accuracy of covariance propagation through nonlinear equations and eliminates the need to derive Jacobian matrices. The result is a feature based map which forms the second part of this 'dual representation'.

If the environment is too cluttered, no localisation is possible, but due to this dual representation strategy, the exploration of free space and the obstacle avoidance behaviour are not severely affected, as shown in the experimental results.

6. Experimental Results

As mentioned in section 2, sensing is accomplished with an advanced sonar sensor array [13]. The motion of the robot is realised with an accurate two wheeled odometry system. The design, calibration and modelling for this odometry system is detailed in [4]

Experiments have been carried out in two real indoor laboratory environments shown in Figure 11 and Figure 13. The line segments are planes, the dark pointy features are corners and the light pointy features are edges. Both are cluttered with boxes, crates, robots, columns, tables, desks and some geometrically complicated objects. The robot went through the complete cycle of scanning, map building, path planning and navigation. Whenever path planning is executed, the 'current cell' in which the robot is in is always derived from the post-JUKF position and orientation. In the first environment, the robot was manually stopped after an hour because the complete exploration of the entire room would take hours. For the second environment, the robot stopped automatically at the completion of exploration. In both environments, the robot was able to travel around safely while gingerly avoiding various obstacles. While the real world landmarks are regarded as very complex to identify for most conventional sonar sensor configuration, our sonar array manages to sift out the salient features which are useful for localisation from these complex landmarks and build a feature map for each environment, and they are shown in Figure 12 and Figure 14. Despite frequent rotations, these landmarks allow consistent feature maps to be built, which in turn prolong the consistency of the grid maps.

7. Problems to be Resolved in the Future

An issue to be addressed is the quality of grid map after prolonged navigation. The current implementation does not update existing obstacles in the grid map with the latest information of the existing environmental features continually produced by the Kalman Filter [5]. Also, since the phantom target removal algorithm proposed in [5] depends on a reasonably complete feature map and a 'structured environment' assumption, not all of them can be identified early enough to be discarded. Hence, unavoidably they contribute to some occupied cells on the grid map. Even if certain features are validated as phantom targets at a later stage, the occupied status of the corresponding cells cannot be simply reversed to empty as their status might be contributed by some other obstacles which are actually not phantom. This problem can in fact be solved by periodically refreshing the grid map using the latest feature map and the phantom target removal algorithm. The penalty is the concomitant processing delay.

8. Conclusion

The dual representation strategy acquits well in the task of environmental acquisition in real indoor environments, such as those containing bookshelves, chairs, tables and etc. The strength of grid map is in path planning and registering complex objects; The strength of feature map is in representing geometrically simple features and supporting localisation, whereas the strength of local path validator is in achieving local risk avoidance. The three strengths are married in a complementary manner to develop a path planning strategy which is robust and tolerant to the shortcoming of sonar sensor based mobile robot. The wall following algorithm in [12], while developed for a monocular sensor, can be adapted to the existing algorithm should such behaviour become preferable.

9. Acknowledgment

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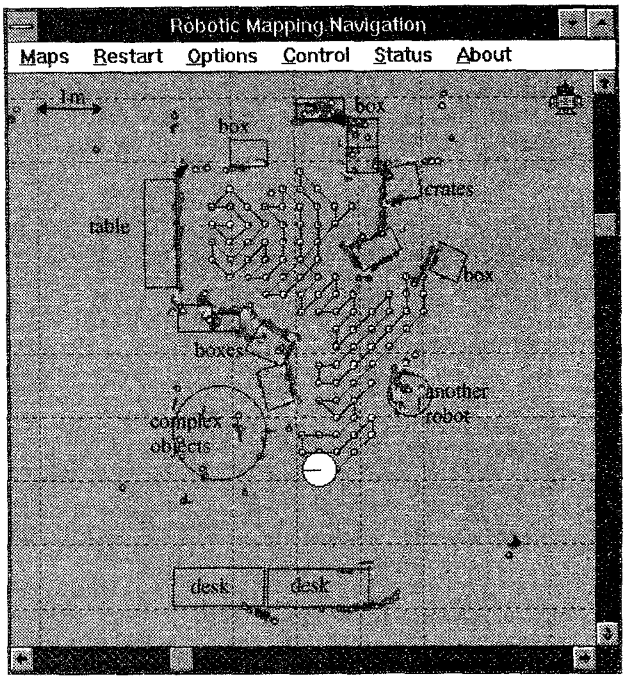

Figure 11 : Raw data from the exploration of the first real indoor environment

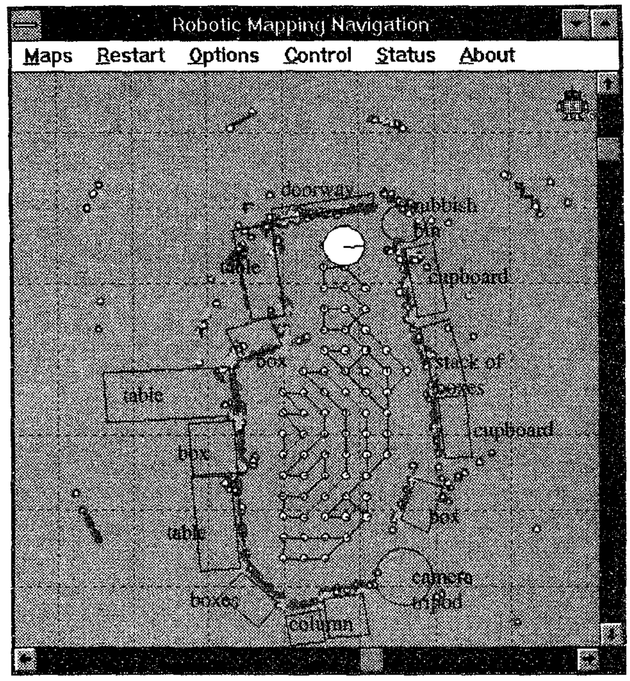

Figure 13 : Raw data from the exploration of the second real indoor environment

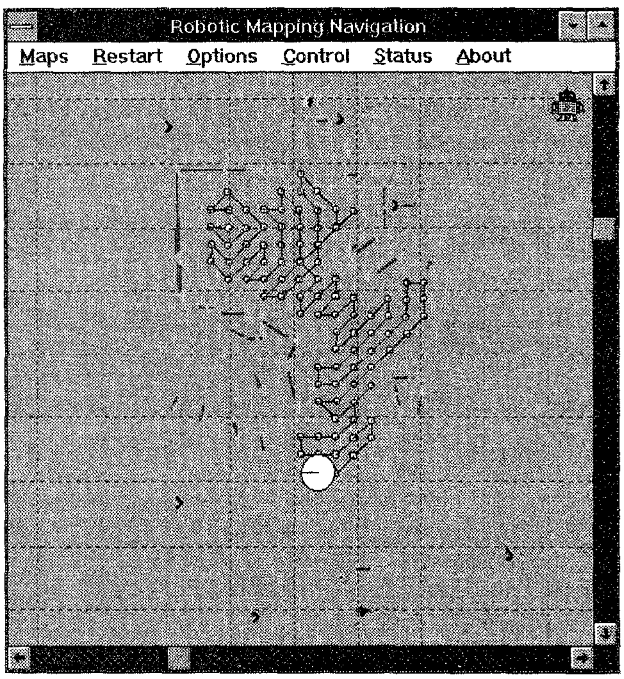

Figure 12 : Feature map for the first environment, built with Julier Uhlmann Kalman Filter

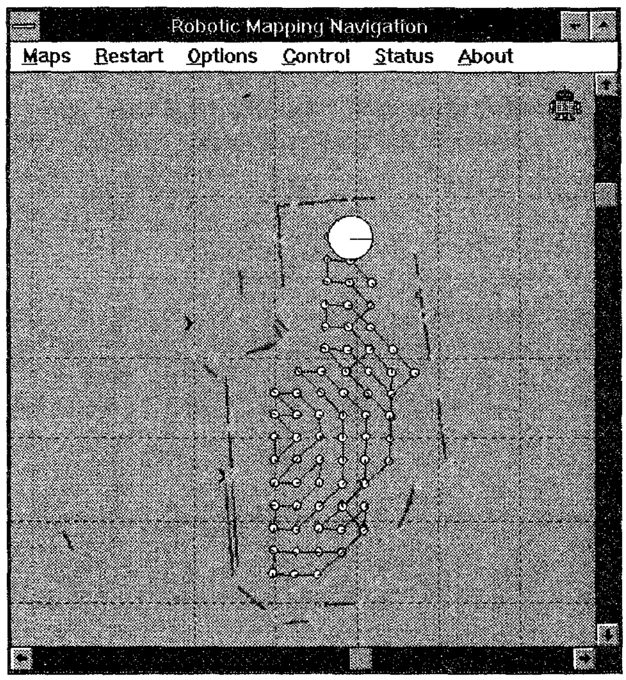

Figure 14 : Feature map for the second environment, built with Julier Uhlmann Kalman Filter