Landmark-based world model for autonomous vacuuming robots

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Abstract

A novel world model and region filling algorithm is presented for autonomous vacuum cleaning robots working in completely unknown indoor environments. The topological world model proposed uses corners as landmarks. As corners are naturally occurring features, the world model requires no alteration to the environment. The world model stores information about the topology of the environment together with cleaned status of areas. It is built incrementally while the mobile robot covers the environment. The mobile robot uses a region filling algorithm to systematically clean the environment in a zigzag pattern. The filling algorithm makes use of the topological information of the environment from the partially constructed world model to decide where to go next when an obstacle is encountered. The environment is completely covered when the world model is fully defined, ie fully connected. A feature of the proposed system is that no separate exploration phase is required to construct the world model. The world model and the region filling algorithm have been successfully implemented on a simulated robot.

Keywords: vacuum cleaning, mobile robots, landmark-based representation

1 Introduction

Autonomous domestic vacuum cleaners will be welcomed in most homes as vacuuming is a chore that provides little intrinsic satisfaction. For a proper clean, the robot has to completely cover all floor area in a room. A map of the environment ensures that no area is missed by the robot. Cao [2] first recognised the different requirements of map construction for region filling navigation and point-to-point navigation. In point-to-point navigation, a map of the environment is built in an exploration phase to expose all path segments. This map is then used for planning optimal paths between points during navigation. In contrast, a vacuum cleaning robot implements region filling navigation. In other words, it must visit all exposed floor area each time it vacuums. Therefore, it is more convenient and efficient to build the map while vacuuming. Even though a separate exploration phase is superfluous, vacuuming navigation may be improved after the first vacuuming episode by using the previously built world model. The world model also needs to contain information specific to vacuuming, for example, the area cleaned.

Since Cao various people have worked on the problem of world modelling for autonomous vacuuming robots. Hofner [7, 6] has developed a path planner for cleaning robots working in public areas. However, the system relies on a priori knowledge of the environment. For domestic vacuum cleaners, it is preferable that users do not have to input full floor plans of their houses.

González [4] uses an occupancy grid to describe the environment. The floor area is subdivided into rectangular regions. As a result, it can only handle rectangular obstacles. Lang [10] does not use any standard world modelling methods. The robot first follows the outermost walls of the room. At the same time, coordinates of points along the walls are remembered and marked as ends of cleaning tracks. Afterwards these tracks are followed to completely cover the area within the outermost walls. The problem with this approach is that the points are remembered as absolute coordinates only and dead reckoning is used to locate and follow these tracks. As a result, the system is very susceptible to odometry error.

Recognising the need for localisation to reduce the odometry error, Ulrich [12] has proposed a navigation strategy that allows the robot to recalibrate its odometry while cleaning. First the robot maps the border of the room and records the length of walls and compass readings along them. This is stored in an occupancy grid. Once the border is mapped, the robot chooses the direction with the most uncleaned pixels and move on a straight line in that direction until reaching a wall or an obstacle. If the trajectory ends with a wall, the robot can recalibrate its estimation of its orientation and one x-y component of its odometry. To keep a good estimation of its odometry, the robot chooses paths that end successively with perpendicular walls. With this navigation strategy, odometry estimation can be kept accurate without the use of a complicated localisation module. The only problem is that the cleaning paths generated are highly redundant as already cleaned surfaces are covered repeatedly to reach the opposite wall for recalibration.

Landmark-based representation methods provide an alternative to using only metrical information to construct world models of environments [8, 9, 11]. A topological model is created using natural landmarks as nodes, and connectivity between landmarks as edges. This way of representing the environment is very similar to that used by humans and other mammals. For example, we would say that the supermarket is to the right of the bookstore and across the road form the restaurant. In contrast to metrical methods, these landmark-based methods are robust against sensor and actuator noise. For example, in [13], Zimmer successfully implemented a world modelling and localisation system using neural networks on a very low budget mobile robot platform with only touch and light sensors. For domestic autonomous vacuum cleaners, the cost and size of mobile robot platforms should be kept at a minimum. Therefore, landmark-based methods are suitable for world modelling for this application.

Dyson, a vacuum cleaner manufacturer, has also developed a domestic autonomous vacuum cleaner, DC06. Unlike all the above methods, which use zigzag patterns (see figure 1), it makes use of a spiral pattern for covering floor area. Hofner [5, 6]

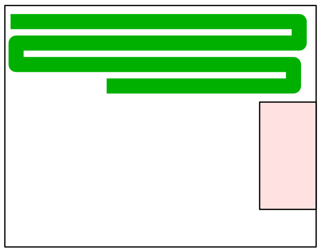

Figure 1: Region filling using a zigzag pattern.

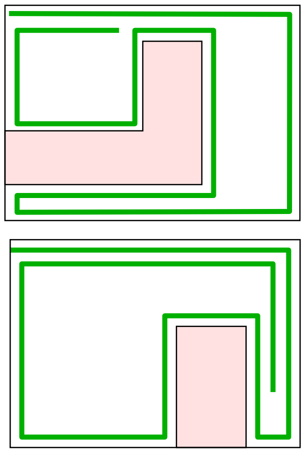

Figure 2: Navigation is more difficult with a spiral pattern.

showed that zigzag patterns generate simpler paths for planning and navigation. This can be seen in situations like those depicted in figure 2. In both cases, zigzag paths require only simple wall following to reach an uncleaned area, while spiral paths require more complex navigation. The fact that zigzag patterns generate simpler paths is also evident in computer raster graphics where region filling operations always uses zigzag patterns [3].

2 Topological World Model

2.1 Representation

Natural landmarks are naturally occurring distinctive features that can be detected by sensors [8]. An environment can be described with the relative positions of these features. In the proposed system, concave and convex corners are used as landmarks. These two features are chosen because they can be easily detected using distance sensors, such as infrared. These landmarks are linked together by travel paths to produce a topological world model. The

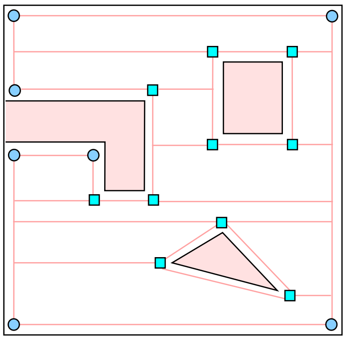

Figure 3: Topological world model for a typical environment.

travel paths are denoted as either right or left wall paths. The topological world model can be stored as a bidirectional graph, where landmarks are the nodes and travel paths are the edges. A robot's location at any moment is given by the node it is at or the edge it is on. Figure 3 shows how a typical environment is represented. Note that some edges join a landmark to the middle of a travelling path. This is because the landmark is detected while travelling down a path using a zigzag cleaning pattern.

The topological world model constructed serves two purposes. Firstly, it stores information about whether an environment is completely covered. All edges are connected at both ends either to nodes or travelling paths. When the robot arrives at a new landmark, a new node is added, along with a new edge for each unexplored direction. Therefore, edges that are connected at one end only are linked to unexplored, thus uncleaned areas. Only when all edges are properly linked is an environment completely cleaned. Secondly, this world model is used for planning paths between landmarks to reach uncleaned areas. The world model is searched to find a path from source to destination using any standard graph search algorithms.

2.2 Navigation and Incremental World Model Construction

The world model of an environment is constructed while the robot is cleaning. Nodes are added to the topological world model whenever a robot is at a convex or concave corner. Starting from a corner, the robot moves systematically down the room in a zigzag pattern as shown in figure 1 in section 1.

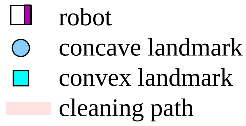

Figure 4: Symbols used in the examples.

Thus it moves forward until reaching a front obstacle, at which point it moves down to the next track and starts moving forward along it until reaching a front obstacle again. The distance between tracks is easily adjustable. It is usually set so that there is overlapping between tracks to ensure a more thorough clean. Thus the gaps between tracks shown in figure 1 are only for illustrating the idea of a zigzag pattern and are not present in a real implementation. At the end of a track, the robot may not be able to move on to the next one. This will happen, for example, when the robot arrives at a concave corner. In this case, a search is done on the topological world model to find any edges that are not connected at both ends. These nodes are linked to uncleaned regions. Using the result of the search, the robot travels from one landmark to another using a wall following control strategy until reaching the selected node. When it arrives at the destination, the robot starts cleaning again using the normal zigzag pattern. If the robot ever gets lost, it will follow the walls until it can relocate itself by using the sequence of edges and nodes information.

2.3 Case Study

This section explains the proposed system in more detail using examples. Figure 4 shows the symbols that are used throughout the diagrams in the examples.

2.3.1 Addition of new nodes

The algorithm assumes cleaning starts at a corner of a room. This means the initial topological world model always has one concave corner node (figure 5(a)). From its starting point, the robot moves forward. When it reaches the other corner, a new node, and an edge that links the two nodes, are added to the world model (figure 5(b)).

2.3.2 Completion of a region

Figure 6(a) shows a robot that has just finished cleaning a region and has no more new tracks left

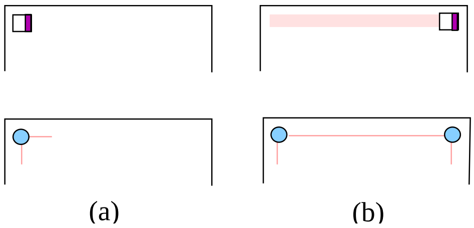

Figure 5: Adding a new node. (a) Robot starts at a concave corner. (b) A new node is added when a new landmark is detected.

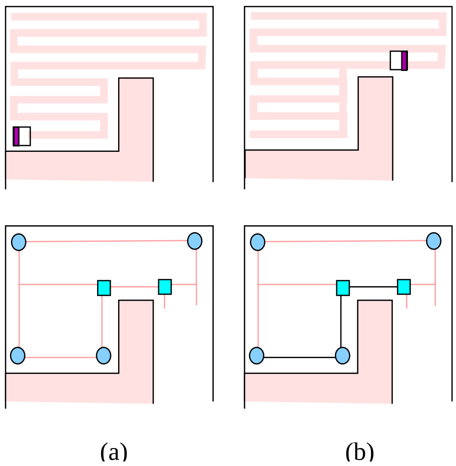

Figure 6: Searching for uncleaned region. (a) No more new tracks at current position. (b) A path to an unfinished node is found. Robot travels along selected path to reach the unfinished node.

next to its current position. A breadth-first search is done on the topological world model to find the path to the closest node that has less than the maximum number of edges. In this example, the path returned by the search algorithm is highlighted in figure 6(b). The robot then travels along the selected path by following walls until reaching the designated node. Once reaching the designated node (6(b)), the robot can start the normal zigzag region filling pattern again.

2.3.3 Free standing obstacle

Figure 7(a) shows the situation where a free standing obstacle is detected. Since the obstacle is not connected to any wall, once the robot leaves it, it cannot be reached again using the wall following strategy described in section 2.3.2. Therefore, it is necessary for the robot to clean all areas around it before moving on. Thus the robot moves up along the last boundary as shown in figure 7(b). Once

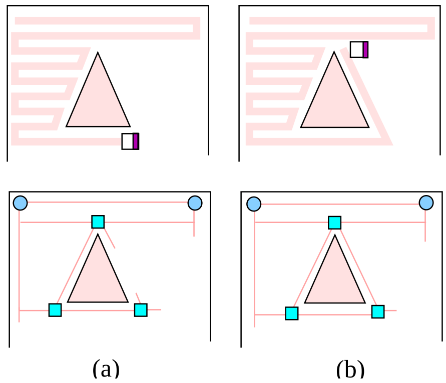

Figure 7: Free standing obstacles. (a) An obstacle that is not connected to a wall is detected. (b) Robot moves to the top of the obstacle.

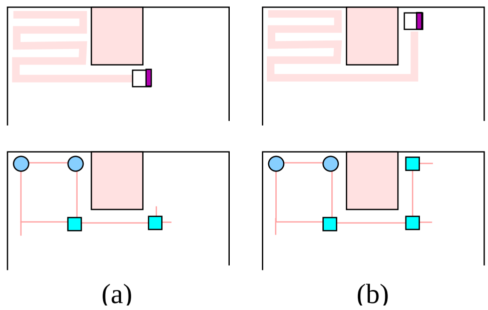

Figure 8: (a) A new 'top side' region is discovered. (b) Robot cleans the newly discovered region first.

it reaches the top of the free standing obstacle, it reverts back to its normal zigzag cleaning pattern.

2.3.4 Discovery of an additional region

The zigzag cleaning pattern tries to fill the entire environment from top to bottom. Sometimes, a new region on the 'top side' is discovered. An example of this is shown in figure 8. In this case, the robot cleans the newly found region first before moving on to clean the rest of the room.

3 Results

The proposed topological world model and region filling algorithm described in section 2.3 has been implemented on a simulated mobile robot. It has two wheels and is equipped with 24 short-ranged distance sensors and 8 tactile sensors. Figure 9 shows a screenshot of the simulator.

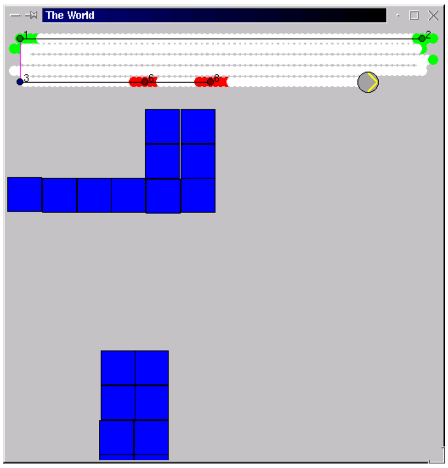

Figure 9: Screenshot of simulator.

Behavioural control [1] is used to coordinate the robot's actions. Behaviours implemented include wall following, and obstacle avoidance. The priority of these behaviours is controlled by a finite state machine. For example, in the normal cleaning state, behaviours that implement "cruise forward" and "move to next track" are active. State switching depends on both the current situation and the topological world model constructed. When a free standing obstacle is detected, the controller switches state and the wall following behaviour is activated.

A feedforward neural network with eight hidden neurons is used to classify distance sensor data into convex corner, concave corner, or neither. Around 120 data samples from each of these classes is used to train the network. The neural network is used to detect when the robot is at a landmark.

The simulated robot can successfully vacuum all of the examples shown in this paper. It can handle any rectangular room with rectangular and triangular obstacles.

4 Conclusions

This paper described a new world model for autonomous vacuuming robots. The representation is based on the landmark-based approach. Humans, and other mammals, model their environment using topologies of landmarks. This type of representation does not rely solely on an absolute coordinate system. Therefore, a coherent world model can be constructed with noisy sensors data as long as the landmarks are properly recognised. This is especially useful in completely unknown environment where no a priori world model is available for localisation.

Almost all existing region filling algorithms use occupancy grids for their representation [4, 12]. This is because grid maps provide a per floor area representation. As a result, it is easy to mark whether an area is cleaned. In comparison, landmark-based representations do not provide a direct representation of floor area. Landmarks can be of varying sizes and open space is not represented at all.

Although the work presented in this paper is preliminary, it proves that it is feasible to carry out region filling navigation using a landmark-based world model with obstacles of various shapes. Further work is needed to implement the proposed system on a physical robot.

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