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Chapter 1 : Hierarchical Voronoi Graphs - PDF Free Download

The routes a robot can take can be abstractly described in terms of graphs where alternative routes are represented by alternative branches in these route graphs. Keywords Extension Mapping system Mobile robots Robot mapping Robot planning Robot routing Spatial reasoning Spatial representations Topological maps Voronoi graphs artificial.

They share the ability to perceive their environment and extract spatial information from their perceptions. They store spatial information over time and this information affects their future decisions and actions. And they are able to affect the state of their environment by their actions. Hence, a spatial agent benefits from the ability to integrate local observations and to derive spatial relationships on a larger scale. The details of how spatial information is extracted, stored, and processed in humans and animals are still largely unclear and subject of ongoing research across many disciplines. The results, positive and negative ones, can then be used to draw conclusions about spatial information processing in natural agents. We use these terms in a broad sense for the entire collection of long-term spatial knowledge held by an agent. The set of competences considered comprises the learning of a cognitive map based on observations of the environment referred to as mapping and its utilization for navigation including localization, path planning, etc. The main problem we are concerned with is the robot mapping problem of autonomously constructing and maintaining a suitable spatial model, a problem which has sparked off a vast amount of research over the last few decades but still provides many challenges. Advanced navigational capabilities like route planning are not conceivable without some kind of spatial representation that describes relations between distinct places known to the agent and that can serve as a basis for planning and decision making. However, this still leaves a wide area of possibilities about what kind of information is actually memorized, how it is stored and organized, and how these knowledge structures can be constructed from perceptions collected over time. In the AI and robotics community, a common approach is to provide a mobile robot with a set of basic reactive procedures e. In addition, only some properties of the world are measurable by the robot at all, and these measurements are error-prone and noisy. The same holds for the actuation, which leads to uncertain results of performing a particular action. Finally, even if sensors and actuators would be perfect, the fact that every somewhat interesting section of the world can only be modelled efficiently by making use of approximations inescapably leads to uncertainty about the state of the world. Rather it is necessary to consider alternative models, and the robot might have different degrees of belief in the different alternatives. As a result, adequate methods to model and manage the uncertainty need to be conceived. As we see, there exist two different perspectives to look at the robot mapping problem: Both aspects have to be considered in order to develop adequate solutions to the robot mapping problem. It is, however, also often used in a more specific sense see Smithson, , for a taxonomy of different kinds of imperfect knowledge. Localization, for instance, necessitates the storage of information that allows the agent to recognize already visited places of the environment. This typically involves information about salient features and spatial relations holding between them. For path planning, the set of qualitatively distinct ways through the environment is needed together with information for deciding on a particular route. Communication with other agents e. From the point of view of a data structure, the cognitive map of an agent operating under time constraints should be organized in a way that allows performing the required operations localization, incorporating new observations, route planning, etc. As there usually exist trade-offs between the efficiency of different operations, a reasonable demand is that the spatial model is optimized for best overall performance. In addition, in order to represent large environments, the cognitive mapping approach needs to scale well with the size of the represented environment in terms of efficiency of the operations and space consumption. Scalability demands a certain degree of sparseness and abstraction in the representation. Therefore, it is often a good approach to refrain from storing information that is directly perceivable when it is required or that is likely to change. In the literature on mobile robot mapping, map construction is often studied as a problem per se, largely ignoring operations that should be realized based on the map. As a consequence, the proposed approaches are usually optimized for localization and updating the map, and involve simple sensor-near representations. While approaches like grid maps and geometric maps describe the boundaries of the free accessible space and thus allow for performing route planning though with some computational effort , landmark-based maps consisting solely of positions of salient features do not allow the derivation of routes at all. On the other hand, approaches involving so-called topological maps are often directly based on the graph of distinct routes through the environment and are close to optimal with respect to the efficiency of route planning. However, they often lack the detailed geometric descriptions required for robust localization. Comparatively little research has been done on complex and heterogeneous forms of spatial representations. Whenever the robot performs an action, for instance locomotion, the uncertainty about the state of the world increases. New observations, on the other hand, can decrease the uncertainty when they include known features of the environment. The simplest but also most error-prone way is to maintain a single model without representing the degree of belief in the relations and properties stored in the model at all. For every new observation the model is modified, resulting in a new world model. Approaches following this notion usually lack the ability to recover from errors made in earlier steps Better results can be expected if for every relation or property in the cognitive map, the degree of belief in this fact is explicitly represented. The new world model is then the most likely one given the old model and the current observation. The predominant approach for describing and propagating belief values used in robotics is probability theory. However some approaches use other methods like Dempster-Shafer theory or fuzzy logic. A different way to take uncertainty into account is to maintain a set of world models instead of just a single one. Two approaches can be found in the literature: First, a likelihood distribution over the space of all possible world models is maintained at any time. Every time an action is performed or a new observation becomes available, the likelihood distribution is updated accordingly. The likelihood distribution can usually only be represented approximately in these approaches. Second, a discrete set of hypotheses is tracked with or without belief values assigned to each hypothesis. Every time a hypothesis together with the current observation can be interpreted as two or more successive world models, all these interpretations are included in the set of overall hypotheses. The downside of approaches that track multiple hypotheses simultaneously, however, is increased computational costs. The predominant approach in the last years has been to employ a plain global grid map or feature-based representation scheme combined with an uncertainty handling method that updates the likelihood distribution over all possible world models based on the recursive Bayes filter. Within this class of approaches, much progress has been made through the development of sophisticated mathematical methods to represent and update the probability distributions. This raises the interesting question about whether the success of these approaches can be ascribed simply to their powerful uncertainty handling mechanisms rather than to the way they represent the spatial information. More abstract representations like topological maps typically only employ very simple mechanisms for dealing with uncertainty, committing to a single hypothesis whenever incorporating a new observation. Therefore, these approaches currently do not achieve the same level of robustness and reliability. However, as pointed out earlier, 1. As a result, we think that more attention should be directed towards investigating ways to adapt the proven uncertainty handling methods for more abstract representation schemes with the goal of achieving a comparable level of robustness and reliability. In this book, we lay the groundwork to achieve this with regard to one particular spatial representation approach. As we will see, this kind of representation is well suited to represent environments which possess a clear route structure. Hence, a typical scenario we consider in this book is that of an office-like indoor environment. One means to derive the route structure of a planar environment from sensor data is the generalized Voronoi diagram. It can for instance be computed from a geometric 2D description extracted from range data as provided by a standard laser range finder. The Voronoi diagram can then be abstracted into a graph, the generalized Voronoi graph see Fig. Illustration of the most important representational concepts we are concerned with in this work: These hierarchical Voronoi graph representations allow performing important operations either on the most appropriate level of detail or in a hierarchical manner. Most approaches involving a route graph representation only maintain a single model and tend to fail when a wrong decision is made in the construction process e. It is our belief that to achieve a sufficient level of robustness of route graph model learning, techniques to deal with uncertainty at different levels and methods to recover from wrong decisions are required. In particular, the combination of route graph representations with established multi-hypothesis tracking methods is a promising direction of research. Furthermore, we want to demonstrate that this approach indeed leads to an improved robustness in the model acquisition process. The work is based on three main theses which have greatly influenced our approach to the robot mapping problem: In order to realize high-level spatial cognitive abilities like spatial reasoning and communication about space on mobile robots, abstract levels of representation and complex organizational forms of spatial knowledge are required. By combining abstract representation approaches with uncertainty handling and multi-hypothesis tracking methods, a similar level of robustness can be achieved as currently shown by the state-of-the-art approaches based on low-level sensornear representations. Relying on relations that can be more reliably observed reduces the problem of uncertainty handling and increases the scalability of the mapping approach. The first two theses have already been touched upon previously. The third thesis expresses our believe that although most of the uncertainty handling methods have been developed for coordinate-based representations using a single absolute frame of reference, even better results can be achieved when combining them with representational approaches that are based on more abstract relations and employ multiple frames of reference. Relying on more abstract relations means that, on the one hand, the level of uncertainty in observations is decreased and, on the other hand, the size of the space of possible hypotheses about the state of the environment is reduced or even turned from a continuous space into a discrete one. Using finer relations only to describe local configurations of objects for which these relations can be determined quite reliably 1. In the concrete work concerning our goal of providing techniques that allow robust model learning for our hierarchical Voronoi-based route graph representation, these notions are implemented in the following way: We only resort to detailed geometric information to specify the relative positions for local configurations of nodes. Mapping on the global level instead is based on abstract relations of connectivity and very coarse relations restricting the positions between the most relevant nodes. The high degree of reliability in the observations of these relations allows us to treat them as hard constraints and employ them to discard potential candidates when forming hypotheses at the local level correctly identifying perceived nodes or global level determining the correct topology of the route graph. In detail, the techniques for robust route graph model acquisition developed in this book tackle the problem at three levels. First, at the level of reliable extraction and automatic abstraction we consider the problem of constructing the proposed hierarchical representation from 2D range data. We develop techniques to assess the relevance and stability of nodes in a Voronoi graph derived from noisy sensor data, to autonomously create a hierarchy of coarser levels of representation, and to complement this representation when new information becomes available. Second, on the level of local configurational knowledge we investigate the data association problem for Voronoi graphs, which requires the identification of corresponding elements in two Voronoi graphs. We extend existing data association approaches by including topological constraints and by incorporating the relevance of nodes into the matching process. Third, at the global level we study the problem of map construction as the problem of abducting the simplest model that explains the history of observations, an approach that has been advocated by Kuipers Kuipers et al. The result is a multi-hypothesis tracking approach that computes a minimal consistent route graph model. We are especially interested in the question of the degree to which coarse directional information shrinks the search space of possible route graph hypotheses. In doing so, we apply techniques of spatial modeling and consistency checking developed in the area of qualitative spatial reasoning, and analyze the effects of qualitative direction and planarity constraints. In the following, we briefly summarize the main contributions of this text. A hierarchically organized representation consisting of multiple linked Voronoi graph layers describing a planar environment at different levels of granularity and containing additional annotations to the graph structure. Measures and computation algorithms to assess the relevance of nodes in a Voronoi graph as well as their stability under noisy conditions. Methods that enable a robot to derive coarser Voronoi graphs and build up a complete hierarchical representation. A matching algorithm for Voronoi graphs that incorporates different kinds of constraints to achieve reliable data association. A best-first branch and bound search algorithm for minimal model computation using pruning based on planarity and consistency of qualitative direction information. Systematic analysis of the effects of absolute and relative direction constraints as well as planarity constraints on the space of possible route graph hypotheses. A complete mapping system for 2D range data that combines multi-hypothesis tracking and Voronoi-based route graph representations and merges the individual results of this work into an overall system.

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