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Comparing World-Modelling Strategies for Autonomous Mobile Robots

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The focus of this paper is on strategies for adapting a couple of internal representations to the actual environment of a mobile robot. From the range of approaches, two different (and in a sense orthogonal) basic ideas are discussed, regarding computational effort, stability, reliability, sensor requirements, and consistency as well as their useful applications. The first approach is an exact, geometric technique using line representations extracted from the information produced by a laser-range finder. The second discussed possibility is a qualitative, topologic mapping of the environment using neural clustering techniques. Both presented classes of environment-modelling strategies are evaluated on the basis of principal arguments and of simulations resp. tests on real robots. Experiences from the MOBOT resp. the ALICE[1] project are discussed together with some related work.

1. Introduction

Based on the common idea that an autonomous mobile robot should have the ability to create and update relevant representations of the actual environment in order to be really useful, a couple of "world-modelling" strategies have been introduced.

One of the earliest projects which has handled different abstraction levels simultaneously was the HILARE-project introduced in [8]. A geometric 2d-model consisting of geometric primitives like lines and polygons forms the lowest representation. Based on this model a "cell-graph" (the first topologic representation) is extracted consisting of different "places" in the geometric model together with their neighbourhood relations. A "decomposition tree" clusters the cell-graph regarding room-situations, i.e. neighboured cells may be included in a group of places, which forms one room. Finally the decomposition tree is labelled with names, which are useful or meaningful for an operator resp. a symbolic planner. The HILARE-representations may be used as a well defined basis for further discussions.

Other well known geometric representations are the generalized cones by Brooks [1] and their extensions by Kuan et al. [5], and the configuration space approach introduced by Lozano-Pérez [9]. The number of papers dealing with topologic extractions of geometric models or with the creation of topologic representations immediately is much smaller than the number of geometric approaches. Two of the most interesting works in this field are the qualitative topologic maps introduced by Kuipers and Byun [6] and the ultrasonic-data clustering techniques by Kurz [7].

In the following discussion we will concentrate on one sample for each basic approach (geometric resp. topologic world model). The referred models will be specified in detail in chapter 2. Both of the models are developed in one of our main mobile robot projects, namely the MOBOT and the ALICE projects introduced in the following paragraphs. The strict decomposition into these two distinct models is in the opinion of the authors somehow artificial, but may be used as a basis of discussion.

1-1. MOBOT

The MOBOT-project (running since 1988) is constructed according to the principle of functional decomposition, where a sensor-data-abstraction and a control structure component is distinguished. Different types of sensors are employed to get the maximal information about the actual environment. High-resolution laser-range finders as well as low-resolution ultrasonics and infrared sensors should be composed for the creation of world-models supporting navigation tasks. The mobile robot is a three-wheel platform with a driven and steerable front-wheel and two passive wheels in the back. The functional com-

1. The project ALICE is supported by the EU-project DG XII, F-5 (Teleman) ponents together with their communication links are shown in figure 1. Most of the tests have been made in a simulation environment.

The components that will be referred later are the Primary Feature Extraction (PFE), which extracts lines from the raw laser-radar data and the Composer-Correlator-Geographer block (CCG), which is responsible for updates in the geometric world model (beside some other tasks).

1-2. ALICE

Based on a continuous flow of passive light and touch sensor-samples from a moderate structured and dynamic environment, ALICE produces a continuously adapted, qualitative, topologic map of sensor situations in order to enable the navigation resp. exploration tasks to perform efficiently.

The ALICE-Project consists of two major parts: The real robot and an equivalent simulation environment. With the help of the operating- and communication-system ALBATROSS [10] we are able to use the same object code on both shells, avoiding cross-compilers and other tools.

The mobile robot ALICE is a round (40 cm in diameter, 20 cm high), fully autonomous platform with an omnidirectional kinematic. 24 whisker-light-sensor pairs are distributed symmetrically at the border of

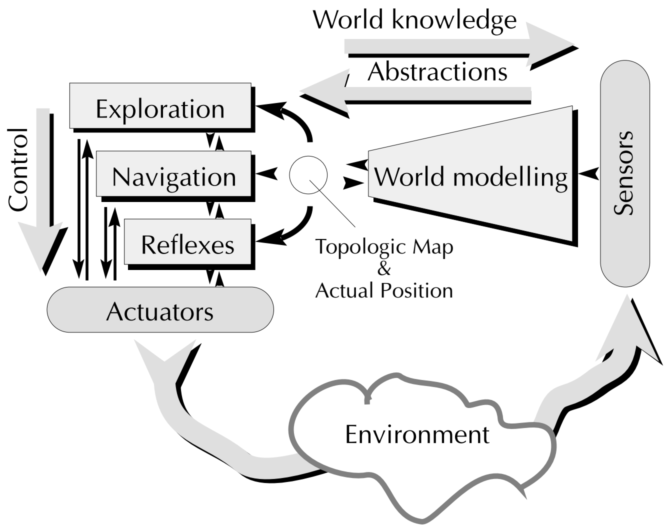

figure 2 : ALICE main-structure

the vehicle and three light-sensors are directed towards the ceiling. Supplementary it is possible to determine a rough internal position by dead-reckoning. The available computer power is limited to one Motorola 68040 processor with 16 MB storage capacity.

The software consists of three major processes:

- *Map-building:*
  Finding an adequate internal representation of the environment as seen by the sensors. Here to-

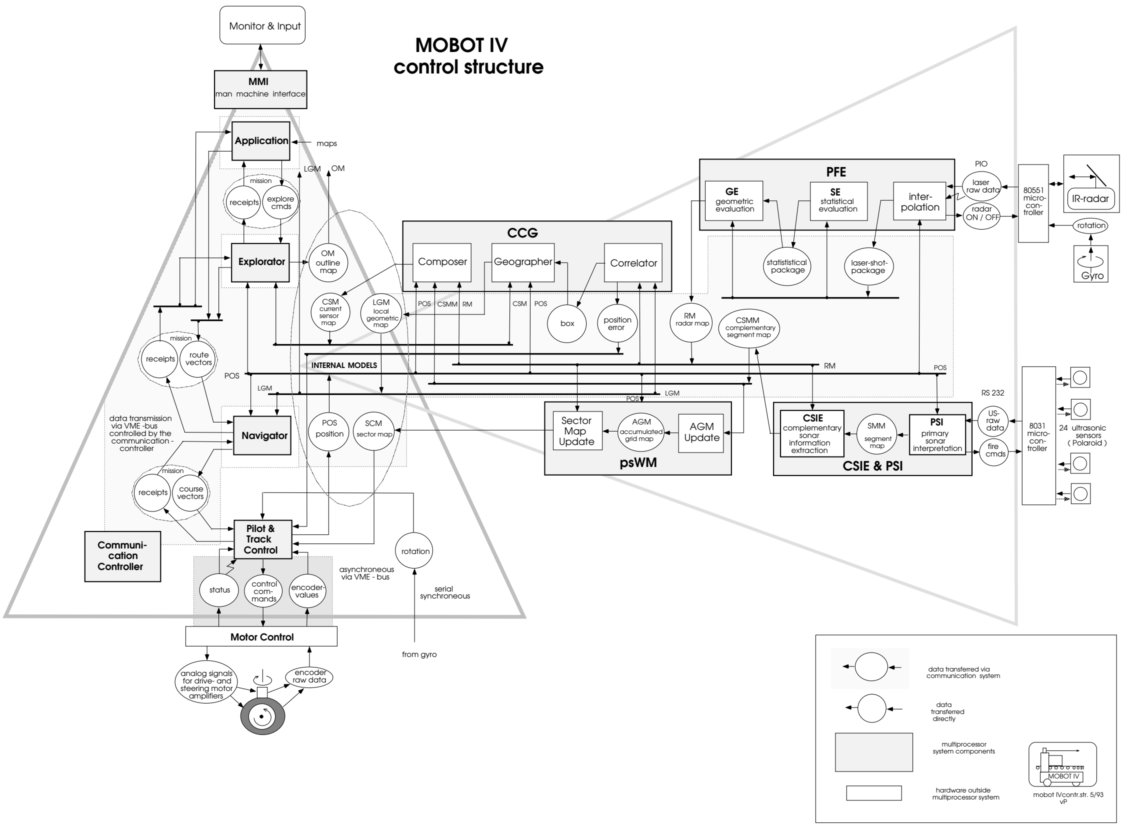

figure 1 : MOBOT-IV control structure

pology-preserving neural network structures are used as the basic concept.

- *Navigation & Pilot:*
  Finding a way (path) to a specified place in the known (mapped) area of the environment and driving along this path, until the robot reaches the target-place or detects a situation which prevents this plan.
  Several reinforcement techniques are used to fulfil this task adaptively (see [13] for details of the navigation technique).
- *Exploration:*
  Finding moves and paths to increase the knowledge, accumulated in the map efficiently.

Although these three components may be seen as different levels of abstraction, they have to be able to operate in parallel. The process of knowledge acquisition by wandering around requires all major components.

2. World Modelling

The processes of generation and update of the different world models will be outlined in the following sections. The operating speed of both platforms is comparable (ALICE: 25 cm/s; MOBOT: up to 50 cm/s). As a reasonable sensor sampling rate 2-5 complete samples/s (e.g. all sensors of ALICE resp. one laser-radar-shot, e.g. 720 distance measurements in the range of 360° on the MOBOT) is assumed in both projects.

2-1. Exact – Geometric

The aim of the exact, geometric approach is to get high resolution representations of obstacles, detected by a laser-range finder. It is tried to include data from other sensor-kinds in this high resolution model, but this will not change the characteristics of the model and is therefore not mentioned in the following. Because of the high accuracy assumed for the laser-range finder, a rigid, grid-based approach cannot be used, due to tremendous memory requirements and long update intervals. So, instead of a grid-based representation, geometric primitives, i.e. line-segments are extracted and used as a compact representation of the actual environment. Distance measurements, which cannot be assigned to lines are ignored or represented in point clusters, due to some heuristics.

The match of the actual laser-scan with the last laser-scan or the whole accumulated world model is the most critical operation regarding the update of the geometric world model. So a correlation of the complete actual laser-scan with the already known environment is performed to compensate the drift effects and other errors influencing the position measurement (see [11] for details). The actual laser scan (and the internal position) is corrected according to the error detected by the correlation-process.

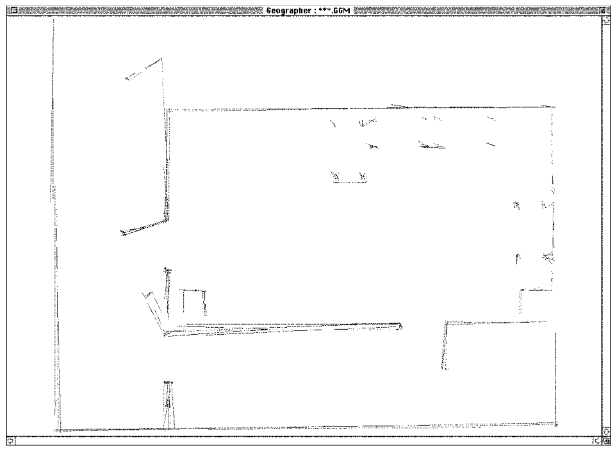

figure 3 : Geometric map

Finally the corrected laser-scan is fused with the geometric map build up so far. As an example for a geometric map see figure 3.

2-2. Qualitative – Topologic

Qualitative topologic maps (QTMs) are an alternative to exact geometric models of the environment (see e.g. [12] as an example of exact geometric mapping based on the data of a laser range finder). Instead of modelling the boundaries of the detected objects, only the sensor-information itself is used to build a “map of sensor-impressions” directly. This concept has already been proposed by Kuipers et al. [6], but the construction process was done by explicit rules, i.e. not by statistical techniques. Our map is constructed by special clustering techniques based on Kohonen's Self-Organizing-Maps. QTMs are able to represent significant different sensor-situations and their neighbouring relationships. Therefore similar sensor-situations (“similar” to a representative constellation found in the QTM) can be detected. So the first basic task for each autonomous mobile system can be fulfilled: “Recognize places, where you have been before (without getting exactly the same

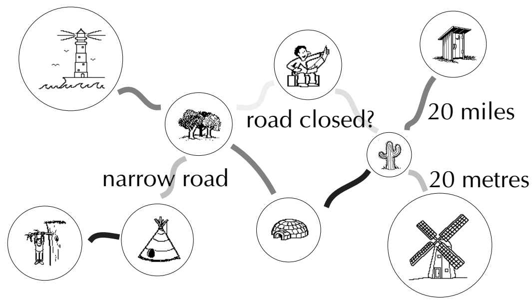

figure 4 : Qualitative topologic map

sensor-measurements)". This task may be summarized by "Qualitative Recognition".

The actual set of sensor-samples is slightly preprocessed and transformed into a vector of 50 unique elements. This vector will be referred to as the situation vector in the followng.

The situation vectors have to be clustered in order to define areas of similar sensor situations. By adding practicable paths (connections) between neightboured situations, the distinct sensor situations are completed to a topographic map.

The underlying neural network model is basically a Self-Organizing-Map in the variation by Fritzke called Growing-Cell-Structures [2] and with several adaptations and extensions described in [4]. The main idea is to use the neighbourhood connections in a dynamic neural network as a representation of topologic neighbourhood in the environment. The network-processes have to be adapted in a way to avoid not reasonable connections in the topologic interpretation, although these connections would make sense, if they are only interpreted by the processes for growing and shrinking the network.

Please refer to [4], [13] and [14] for the technical details of this world modelling.

As an illustration of the main idea of qualitative topologic maps figure 4 shows different places (or situations) together with their neighbourhood relations. One may notice that the connections can be attributed with functional or non-functional information. A more concrete example of such a representation is shown in figure 5, where the different nodes represent different light-situations or the touch with an obstacle. The connections are attributed with information like the last update time or the total number of updates.

3. Evaluation criteria

In the following sections we will discuss several comparable aspects of the introduced world-modelling strategies. These are computation effort, stability, reliability, local correlation, global consistency,

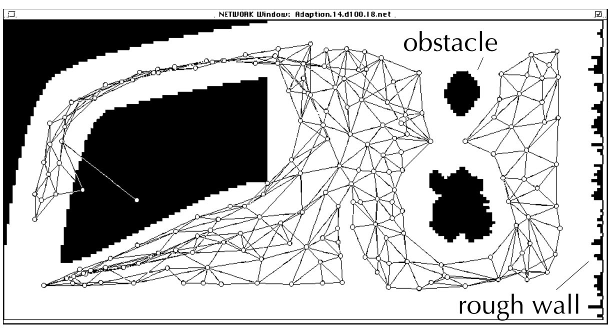

figure 5 : Qualitative topologic map (simulated)

and sensor requirements. The influence of the world model to the navigation task is highlighted in chapter 4.

3-1. Computational Effort

The computational effort in both models is determined though the number of elements, that have to be updated resp. adapted in each sensor-sample cycle. The time for one adaptation step in the QTMs is linear in the number of nodes, which have to be checked. Therefore this number is limited by some simple techniques, in order to be able to operate under realtime-conditions. The actual (realtime-) configuration on ALICE is: 5 complete sensor-samples/s; each sample (situation-vector) in inserted in a FIFO-learning set; 75 situations/s from the learning set are used to adapt the QTM. This is done on one CPU in parallel to a motor-controller, an explorator and other tasks.

The search area for the adaptation process for the geometric maps is limited to approximately one "room" with the help of the so-called "box-feature" determining long orthogonal walls (see [3] for details). Due to this technique, the computational effort can be bounded by a constant, but because of the high bandwidth of the incoming measurements the computations have to be distributed over multiple (680x0) CPUs.

3-2. Stability

In an exact geometric approach it is obviously rather difficult to cope with noise, drifts or other errors. Plausibility checks may refuse disturbed sensor-information, but especially the line-extraction process needs a complete set of accurate measurements to produce usable radar-maps. The line-extraction (geometric evaluation) is the most critical aspect of the geometric modelling in the MOBOT-project. Other tasks like the correlation are quite stable, because statistical methods are used.

Statistical methods are also the fundament for the creation and adaptation of QTMs. Therefore a special treatment of sensor-data regarding the elimination of noise is completely missing. As an example for a QTM produced under realtime-conditions with raw sensor-data please see figure 6.

3-3. Reliability

The benefits from the statistical techniques for the stability may be the problems regarding reliability. A specific situation that occurs only once (e.g. finding a pathway though a narrow corridor) is ignored by the QTM, but not necessarily by the geometric modelling process. The second problem is the usage of "mean values" instead of the exact measurements.

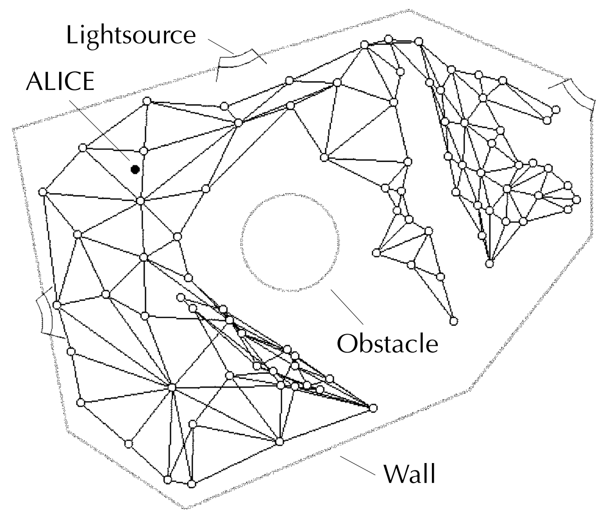

figure 6 : Qualitative topologic map (real)

This may (and will) lead to inconsistencies in the QTM. Therefore the reliability of QTMs can only be expressed in statistical terms, i.e. a “totally correct” modelling is not possible in the general case. On the other hand the reader should remember that the “real world” (or at least the gathered sensor-data) is inconsistent in a sense. So in the opinion of the authors, error-tolerance regarding the world-model is a must for every useful mobile robot.

3-4. Local Correlation

A correlation of the sensor-situation, regarding a local part of the already modelled environment, is necessary for every mobile robot, which has no opportunity to get the absolute correct position (e.g. via satellite-based position determination). What happens if the position-drift effects are not compensated is shown in figure 7, where a geometric map is accumulated with all the position and orientation error. The general strategy is to find the best-fitting mapping between the actual sensor-information and the accumulated map. This is done on a statistical basis in both models. Therefore we are able to compensate drift effects locally up to a certain amount of drift.

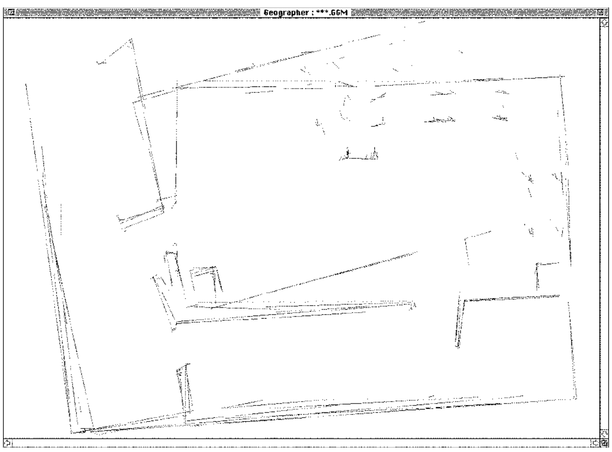

figure 7 : Geometric map (without pos. corr.)

3-5. Global Inconsistency

The local compensation of drift effects is not sufficient regarding the whole world model. Beside some other effects, the central contradiction of autonomous world modelling prevents a global consistency. The correlation is being done on the basis of the world model build up so far. Unfortunately the update of the world model and the correlation of the position is being done simultaneously, i.e. each error accumulated in the world model may be involved in the correlation of the next sensor-data-set and is integrated again in the world-model. In other words, each of the two representations (position & actual environment) is updated (error-compensated) with the errors of the other one.

In order to limit the global drift effects, often updated sensor-situations are chosen as position fixpoints in the QTMs. This strategy produces large and usable maps if the density of the fixpoints is sufficiently high and they are highly interconnected.

3-6. Sensor Requirements

The differences in the sensor-requirements are obvious. For an exact geometric model we need exact distance measurements, as produced by laser-range finders, radar devices, or large-scale video-signal processings. In order to build QTMs, any kind of (short-range) sensors may be considered. In the actual case of ALICE, simple passive photo-resistors together with primitive touch sensors are sufficient. Please notice that most topologic models in the literature are built “on top” of the geometric model and use therefore the same sensor-information.

4. Navigation

For a more complete discussion, the influences for the main consumer of the environment representation, namely the navigator have to be considered.

4-1. Planning

The planning on a QTM is straight forward, i.e. being done with the help of elementary graph search heuristics (e.g. A*) on the network structure itself. When using a pure geometric map, a representation adequate for any path planning technique has to be generated first (see [3] for a possible solution).

4-2. Driving

The support from the QTM while driving from one situation area to the next one is quite small, i.e. no attributes like the width of a corridor or any other metric information are available directly. To overcome this problem the ALICE-navigator [13] learns (on a reinforcement basis) how to drive in specific situations. This is an additional world model. The driving phase using a geometric model is simply following the planned path (as long as the environment is static and completely explored).

5. Conclusion

As the reader may have expected, the selection which world model should be chosen depends widely on the task. But some main guidelines may be derived from the discussion. One aspect is the security (reliability). If that is a central aspect in the robot-task, an exact model will be required to be able to plan save paths. Moreover, if a guarantee for a certain accuracy when following a path is needed, the exact geometric information will be necessary.

On the other hand, if the main focus is on simplicity, stability and qualitative modelling the qualitative topologic map techniques may be the first choice. Especially the small requirements regarding computational effort and sensor equipment is an unique feature.

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