Adaptive Approaches to Basic Mobile Robot Tasks

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PhD Thesis

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Declaration

This thesis has been composed by the author himself and contains original work of his own execution. Some of the work reported here has previously been published:

[Zimmer95a]
Uwe R. Zimmer
Self-Localization in Dynamic Environments
submitted for publication

[Zimmer95b]
Uwe R. Zimmer
Robust World-Modelling and Navigation in a Real World
submitted for publication

[Zimmer94a]
Uwe R. Zimmer
Connectionist Decision Systems for a Visual Search Problem
Proc. of the IIZUKA ´94, Fukuoka, Japan, August 1-7, 1994, Invited paper

[Zimmer94b]
Uwe R. Zimmer, Cornelia Fischer, Ewald von Puttkamer
Navigation on Topologic Feature-Maps
Proc. of the IIZUKA ´94, Fukuoka, Japan, August 1-7, 1994

[Zimmer94c]
Uwe R. Zimmer, Ewald von Puttkamer
Realtime-learning on an Autonomous Mobile Robot with Neural Networks
Proc. of the Euromicro '94 Realtime Workshop, Vaesteraas (Västerås), Sweden, June 15-17, 1994

[Zimmer94d]
Uwe R. Zimmer, Ewald von Puttkamer
Comparing Environment-Learning Strategies on an Autonomous Mobile Robot
Proc. of the IWK ´94, Ilmenau, Germany, 27. - 30. September 1994

[Zimmer93a]
Jörg Bruske, Ewald von Puttkamer, Uwe R. Zimmer
SPIN-NFDS Learning and Preset Knowledge for Surface Fusion - A Neural Fuzzy Decision System -
Proc. of the ANZIIS ´93, Perth, Western Australia, December 1-3, 1993

[Zimmer93b]
Herman Keuchel, Ewald von Puttkamer, Uwe R. Zimmer
SPIN - Learning and Forgetting Surface Classifications with Dynamic Neural Networks
Proc. of the ICANN ´93, Amsterdam, The Netherlands, August 1993

[Zimmer92]
Ewald von Puttkamer, Christopher Wetzler, Uwe R. Zimmer
ALBATROSS - The Communication Scheme as a Key to Fulfil Hard Real-Time Constraints
Proc. of the Euromicro '92 Realtime Workshop, Athens, Greece, June 3-5, 1992

[Zimmer91]
Ewald von Puttkamer, Uwe R. Zimmer
ALBATROSS - An Operating-System under hard Realtime-Constraints
Real-Time Magazine, Diepenbeemd 5, 1650 Beersel, Belgium, Vol 5, Nr. 3, 91/3, ISSN 1018-0303

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Abstract

The present thesis addresses the research field of adaptive behaviour concerning mobile robots. The world as "seen" by the robot is previously unknown and has to be explored by manoeuvring according to certain optimization criteria. This assumption enhances the fitness of a mobile robot for a range of applications beyond rigid installations, demanding normally significant effort, and offering limited ability to adapt to changes in the environment.

A central concept emphasized in this thesis is the achieving of competence and fitness through continuous interaction with the robot's world. Lifelong learning is considered, even after achieving a temporally sufficient degree of adaptation and running in parallel to the actual robot's application. The levels of competence are generated bottom up, i.e. upper levels are based on the current robot's experience modelled in lower levels. The terms (the skills are formulated with) employed on higher levels are generated through real world interactions on lower levels.

The robotics problems discussed are limited to some basic tasks, which are found to be relevant for most mobile robot applications. These are exploration of unknown environments, stable self-localization with respect to the current world and its internal representation, as well as navigation, target extraction, and target recognition.

In order to cope with problems resulting from a lack of proper a-priori knowledge and defined and reliably detectable symbols in unknown and dynamic environments, connectionist[1] methods are employed to a great extend. Realtime constraints are considered at all levels of competence, with the natural exception of global planning.

The research field of target extraction and identification with respect to mobile robot constraints leads especially to the discussion of visual search (steering), extraction of geometric primitives even at system start-up time, and to the generation of symbols out of subsymbolic processing. These symbols can be reliably recognized and should be suitable for a following symbolic planning level, outside the focus of the present thesis. The presented approach ensures a large degree of adaptability on all levels, not discussed before to this wide extent, or even investigated for the first time regarding some components (e.g. visual search with highly focused devices).

The exploration, self-localization, and navigation tasks are attacked by an integral approach allowing the parallel processing of these tasks in a dynamic environment. The stability and reliability of the discussed techniques are proven on the base of realtime and real world experiments with a mobile platform. The high error tolerance and low demands concerning the used sensor devices, as well as the small computation power required, are (currently) unique features of the presented method.

1. also denoted as "artificial neural networks" or even more general as "subsymbolic methods"

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Part I Motivation

Chapter 1 Introduction

This thesis investigates a research field at the intersection between classic robotics and adaptive methods. On the robotics side the discussion is dedicated to mobile robots, which carries all necessary computational power on-board, i.e. in a sense autonomous machines. This field is represented by hundreds of groups, where mostly strong industrial requirements are considered. Introducing adaptive capabilities will limit the number of relevant projects significantly. Furthermore, when adaptive methods are applied in parallel to different stages of processing and modelling, the "research-gap" this thesis would like to narrow is outlined.

Research Field

The interdisciplinary research field "animats", where shared interests between psychologists, physiologists, computational neuro-scientists, and others led to a common initiative, is the playground for the ideas discussed in the present thesis. The animat approach can be outlined by the central aim to understand how autonomous machines respectively animals can survive and adapt to their current environment. Due to the long term and wide spread research activities, a couple of synonyms and side-streams can be categorized:

- "Comparative or Biomimetic Cognitive Science" [Roitblad92]
  "Simulated Animals or Animats" [WilsonF90]
- "Behaviour-based Robots" [Maes92], [Maes90], [Mataric90]
  "Goal-driven Behaviour-based Robots" [Mataric92]
  "Intelligence without Representation" [Brooks87]
  "Minimalist Mobile Robots" [Connell90]
- "Task-based Behaviours" [Tani94a], [Tani94b], [Tani93]
- "Really useful Robots" [Nehmzow93], [Nehmzow92b], [Nehmzow91], [Nehmzow90], [Nehmzow89]
- "Computational Neuroethology" [Cliff93], [Cliff92], [Cliff90]
  "Evolutionary Robotics" [Harvey93], [Harvey92]

In order to identify a major goal of this research field, motivating parts of the present thesis, a quotation concerning the general animat methodology is given;

> *"The basic strategy of the animat approach is to work towards higher levels of intelligence from below – using minimal ad hoc machinery. The essential process is incremental and holistic […] it is vital (1) to maintain the realism and wholeness of the environment […] (2) to maximize physicality in the sensory signals […] and (3) to employ adaptive mechanisms maximally, to minimize the rate of introduction of new machinery and maximise understanding of adaptation" ([WilsonF90], p. 16)*

Basic Mobile Robot Tasks

Approximations to the solution of a set of basic mobile robot tasks (defined in the next chapter) are given, where adaptive methods are employed on most layers. The discussed set of mobile robot tasks is complete in the sense that it is sufficient for the composition of a wide range of robotics applications.

The discussed tasks include:

- **Self-Localization**
  The problem of localizing the dynamic robot continuously in relation to the current (previously unknown) environment is a elementary task for any robot, with some global memory. In the present thesis worse conditions, like large drifts-effects, noise, low sensor resolutions, and systematic errors are assumed, in order to emphasis real world relevance of the proposed solutions.
- **Navigation**
  Navigation is obviously a basic task for each mobile robot, where a couple of different navigation demands can be considered. "Global navigation" refers to the problem of planning in the complete domain of the explored (and therefore known) environment, whereas "local navigation" handles problems of local manoeuvring without the necessity of global world models. Both problem fields are attacked in this thesis.
- **Target Extraction and Recognition**
  In order to fulfil demands beyond the pure navigation (respectively transportation, observation, etc.), targets from the current environment have to be identified as useful or meaningful for a certain application. Due to the fact that unknown environments are discussed here, the generation of such target symbols should be adaptive with regard of the current environment, in order to offer representations of even unforeseen situations (respectively objects, obstacles, dangers, etc.)

Modelling the robot itself (e.g. its kinematics) is not explicitly discussed here. Nevertheless the structures generated in the context of spatial navigation include some of this models.

Assumed World

The considered robot is dedicated to working environments, unknown in the specific instantiation. The robot's a-priori knowledge of the expected world is limited to elementary pre-processing of the sensor readings (e.g. normalization), basic "instincts" (e.g. emergency shutdowns, or curiosity), algorithms extracting primitives (i.e. not the primitives itself), and a couple of optimization criteria. Furthermore the robot's world is assumed error-tolerant in order to enable some kinds of reinforcement learning.

Adaptive Methods

Due to the fact that the a-priori knowledge in the given context is not sufficient to define expected symbols, mainly connectionist (sub-symbolic) methods are applied. The range of employed artificial neural network models (denoted "neural networks" in the following) includes the following principles:

- **Self-organizing maps**
  The major principle of unsupervised neighbourhood adaptation is used in a couple of different realizations, where dynamic aspects, realtime requirements and lifelong learning are considered.
- **Radial basis function networks**
  When an explicit feedback can be given for the training of associative modules, radial basis function networks are employed due to their high adaptation performances.
- **Multi-layer-backpropagation networks**
  In the context of **neural fuzzy decision systems**, where radial basis function networks can not yet be applied without limitation, multi-layer-backpropagation networks are used. The discussed **fuzzy logic systems** are dedicated to applications where exact (quantitative) input and output information can be considered. Additionally, recurrent backpropagation is applied in some components.
- Some more specific models, like **Grow-and-Learn (GAL)**, or **Adaptive Resonance Theory (ART)** are employed for some classification tasks.

1.1. Thesis Structure

After defining the considered basic tasks more precisely in the next chapter, and concluding the motivation (part I of this thesis), the remaining chapters can be categorized in three further parts.

ALICE (Part II)

The tasks referring to spatial modelling respectively navigation behaviours of the robot, are discussed here. The generation of dynamic, self-organizing maps of sensor situations in one exploration phase, is introduced for the first time in this thesis. Experiments in a real world and hard realtime domain are performed on a platform called *"ALICE"*. Navigation abilities are demonstrated regarding local as well as global navigation. The central idea of the *ALICE* project is a simple, but adaptive mobile robot of practical relevance, where extremely worse conditions (regarding drift, sensors, systematic errors, and available computer power) are assumed.

SPIN (Part III)

The *SPIN*-project is introduced as a suggestion for the generation of geometric 3-d symbols out of current working environments, where the a-priori model of the expected world is kept as small as possible. In the context of this task, visual search (steering), and several completion and clustering methods are introduced and applied. The discussed methods together with the proposed overall structure try to improve stability and reliability aspects in the object recognition domain of mobile platforms. In order to emphasize the realtime aspects, an introduction to the realtime operating- and communication-system *ALBATROSS* together with the integration strategy of *SPIN* into a hard realtime system is given.

Conclusion and Appendix (Part IV)

The work is discussed critically in this final part, where especially the realtime and real world relevance of the individual components is summarized. A bibliography consisting of more than 500 entries concerning robotics as well as connectionist and animats issues is attached, due to the wide focus of discussed subjects and given references.

1.2. The Reader

Some assumptions about the reader of this thesis are considered. Due to the large number of discussed concepts as well as the available (and given) references, most of potential introductions and motivations are rather briefly. The reader is encouraged to refer to the bibliography in order to get the whole impression. Especially the connectionism (or artificial neural networks) field is not explicitly introduced here. Thus the reader should have some experience in connectionist methods, or use the following, elementary references for a sufficient introduction. [Rumelhart85] gives a solid formalism for the general field of parallel distributed processing (PDP), whereas [Hertz91] focus on the theoretic aspects and some proofs regarding common connectionist concepts. Finally [Kohonen84] concentrates on self-organization and its mathematical aspects.

A common formalism in the robotics field is not yet established. Thus the discussed robotics problems are introduced and motivated in this thesis. Similarly, due to the large number of different notations in fuzzy-logic, the author has introduced all relevant formalism here.

Chapter 2 Basic Tasks

The central approach in this thesis is to point out and approximate basic mobile robot tasks, by applying adaptive (connectionist) structures. Therefore these basic tasks have to be identified and categorised. In order to define the focus of this work more precisely, the actual list of attacked problems will conclude this chapter.

It is assumed that these tasks are strongly related to the employed world models. This is especially emphasized thought the fact that this thesis considers mainly adaptive mobile robots, where the adaptability is expressed in changes of world models at any level. Therefore the world models (respectively their structure and hierarchy) will play a central role of the whole structure.

The systematic of world models chosen here is oriented by a hierarchy of frames of world-modelling in a "universal" mobile robot. These world models can be explicit or implicit, behaviour-oriented or feature-oriented, learned or pre-programmed, statistical or exact, qualitative or metric. In any case there are multiple groups of world models necessary and thus it is tried to imply the basic tasks from the basic world models, which can be found (or interpreted) in any approach[1]. The main hierarchy is given by three levels of competence in a mobile platform: controlling the robot itself, manoeuvring in the environment, and operating in the environment according to the application. On each level, specific world knowledge is required referred to as **mobile robot models**, **spatial models** and **application models** (figure 1). Each model can be adapted during interactions with the current working environment.

Individual models can represent features from different levels. Thus each model can belong to multiple world model levels. For example the application models can completely include the spatial models in case of pure transportation or exploration applications.

2.1. Mobile Robot Models

This first class of world models concerns the mobile platform itself. Problems like inverse kinematics, optimal control regarding a platform-specific optimization criteria, and elementary (security) reflexes have to be considered here. The field of inverse kinematics opens a wide research area, driven by the need of good and effective inverse kinematic processing in any kind of robot or mobile platform. Problems are getting worse here with increasing weights, limited accelerations and complex kinematics.

The present thesis is not explicitly dedicated to this group of problems. Due to the fact that this layer of world models have to be implemented anyway, in order to reach a development state of a physically mov-

1. this is seemingly a contradiction to Brooks ([Brooks87] "Intelligence without representation"), who states that mobile robots do not need any world models. Yet this is a problem of terminology, because he excludes spatial (adaptive) world models only, i.e. not any world model.

ing machine, the author has tried to temper the problems by choosing a light weighted, omnidirectional platform with relatively high accelerations. Furthermore optimization criteria, concerning path control as a control task are not taken into consideration.

But to make it clear: there is a huge need for optimal and (even more important) adaptive control of mobile platforms – yet, this is outside the focus of this work. In a sense of overlaying world models, the adaptation steps on the next layers can be interpreted as adaptive control, but the reader has to keep in mind that the applied optimization criteria are defined by the task or by the demands of free-space manoeuvring and not by the robot itself.

The author would like to mention one article from the wide field of works concerning adaptive control [Takagi85], due to the fact that he has introduced connectionist-symbolic (Neuro-Fuzzy) methods for this research direction.

2.2. Spatial Models

The form of spatial representation chosen for a specific mobile robot, is influenced by a range of restrictions, as listed in the following:

- **Employed Navigation Methods**
  The range of known navigation strategies is rather unbounded. A discussion of methods based on metric models, and applicable for mobile robots can be found in [Hoppen91].
- **Demanded Self-localization Abilities**
  The second aspect, even as important as the navigation abilities, is the robot's relative self-localization, which is also based on spatial models. The correlation of the current position or other internal states with the actual world and the current world model is an elementary demand for any mobile platform, whenever no absolute positioning devices are assumed.
- **Demanded Accuracy, Reliability, Stability, Consistency, …**
  A large number of parameters, determined by the actual application have to be considered. One of the prominent design decisions here is the choice between metric and qualitative representations.

It should be specially emphasized here, that these models are especially dedicated to the demands of manoeuvring, i.e. *not* of manipulations respectively *not* of a potential user-interface. Therefore the criterion for an optimal spatial model can be formulated straight forward, although this is not easy to evaluate:

"The performance of the navigation is the only optimization criterion for spatial models"

Due to the fact that the navigation employs the internal relative position, the self-localization task is included as a sub-goal in this demand. Further criteria given by the major navigation requirements, concerning realtime abilities, degree of consistency, accuracy, etc. have to be fulfilled. A general, recent discussion of spatial models can be found in [Prescott94a].

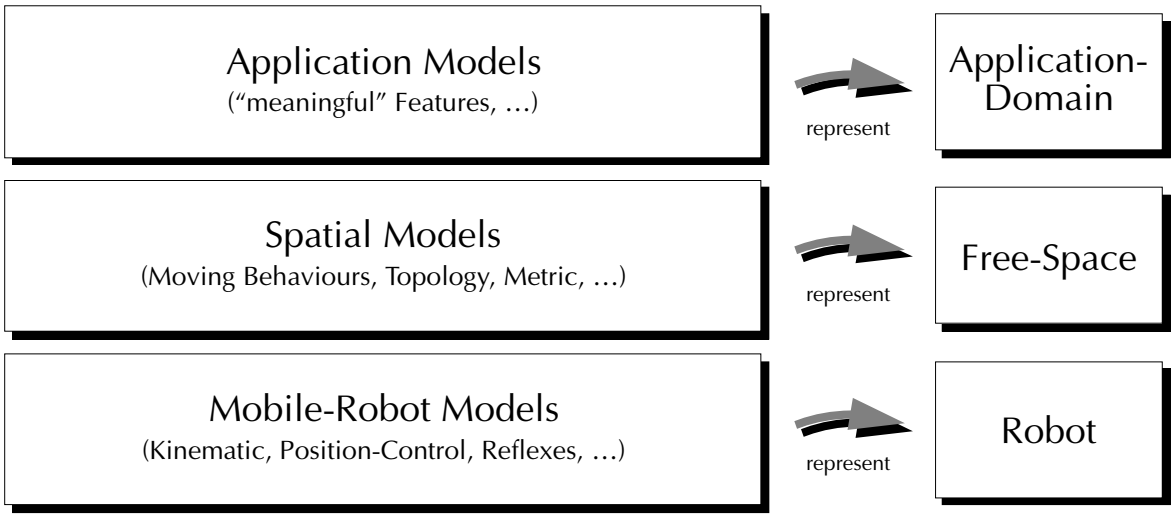

Figure 1: Levels of world models

2.3. Application Models

If the application exceeds navigation, targets for manipulation or other operations have to be defined, represented, and identified. The domain of models appears even larger than in case of spatial models, because a closed optimization specification is often hard to define. The situations or constellations that should be identified, based on the application models, can rely on any kind or combination of sensor readings.

One group of application models handles geometric targets, extracted from previously unknown environments. This application field seems to be of wider relevance, because geometric abilities like form recognition are general strategies, employed in biological systems for a wide range of tasks. If furthermore the representation of the geometric forms as well as the recognition process itself is adaptive with regard of the current environment, the major motivation for the *SPIN* system are outlined. The *SPIN* system will be introduced and discussed as a suggestion for the application layer in the present thesis, including adaptive geometric abstractions, identification of forms at different stages, and the generation of symbols, based on common structures gathered from the current working environment.

2.4. Basic Tasks

A mobile platform in unknown environments, not prepared in the form of defined absolute positions (landmarks) is considered in the following. Furthermore it is assumed, that the robot's sensor equipment is adequate for the working environments, i.e. any feature meaningful for manoeuvring, for the application, or concerning the robot's security aspects can be detected. Then elementary tasks, essential for any mobile platform can be formulated:

- **Exploration**
  This task concerns the problem of gathering information from the actual working environment efficiently, due to some optimization criteria.
- **Spatial Modelling**
  The information sampled from the working environment has to be integrated as a spatial representation, applicable for a navigation task.
- **Self-Localization**
  Based on the spatial model, the robot has to preserve control over its position and orientation in relation to the current environment. The solution of this task states an essential precondition for the navigation task.
- **Navigation**
  Employing the spatial model together with the knowledge about the robot's relative position, the task of finding adequate manoeuvres, in order to reach a given goal position, has to be solved.
- **Target Representation and Identification**
  Beyond the pure free-space representation (applicable for navigation), the platform has to represent and identify potential targets in the current workspace. Due to the fact that the environment was previously unknown, the definition of targets is usually an interactive process between the operator and the mobile robot.
- **Symbol Generation**
  In order to allow symbolic planners or even a user-interface, parts of the accumulated world models have to be presented in a symbolic form.

None of these tasks are attacked for the first time, but still, no generally accepted methods for any of these fields are known. The first four aspects are considered in the *ALICE* project (☞ chapter 1 to chapter 2), whereas the remaining two tasks are attacked in the *SPIN* project (☞ chapter 7 to chapter 5).