

OUTDOOR NAVIGATION OF MOBILE ROBOTS

Hannu Mäkelä
Navitec Systems Oy
Nikkarinkuja 5
02600 ESPOO
Finland

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Automation and Systems Technology, Helsinki University of Technology for public examination and debate in Auditorium T2 at Helsinki University of Technology (Konemiehentie 2, Espoo, Finland) on the 30th of November, 2001, at 12 noon.

Mäkelä, Hannu, **Outdoor Navigation of Mobile Robots**. Acta Polytechnica Scandinavica, Mechanical Engineering Series No. 155, Espoo 2001, 137 p. Published by the Finnish Academies of Technology, ISBN 951-666-587-X, ISSN 0001-687X.

Keywords: dead reckoning, environment modelling, mobile robot, navigation, position control, sensor fusion

ABSTRACT

AGVs in the manufacturing industry currently constitute the largest application area for mobile robots. Other applications have been gradually emerging, including various transporting tasks in demanding environments, such as mines or harbours. Most of the new potential applications require a free-ranging navigation system, which means that the path of a robot is no longer bound to follow a buried inductive cable. Moreover, changing the route of a robot or taking a new working area into use must be as effective as possible. These requirements set new challenges for the navigation systems of mobile robots. One of the basic methods of building a free ranging navigation system is to combine dead reckoning navigation with the detection of beacons at known locations. This approach is the backbone of the navigation systems in this study.

The study describes research and development work in the area of mobile robotics including the applications in forestry, agriculture, mining, and transportation in a factory yard. The focus is on describing navigation sensors and methods for position and heading estimation by fusing dead reckoning and beacon detection information. A Kalman filter is typically used here for sensor fusion.

Both cases of using either artificial or natural beacons have been covered. Artificial beacons used in the research and development projects include specially designed flat objects to be detected using a camera as the detection sensor, GPS satellite positioning system, and passive transponders buried in the ground along the route of a robot. The walls in a mine tunnel have been used as natural beacons. In this case, special attention has been paid to map building and using the map for positioning.

The main contribution of the study is in describing the structure of a working navigation system, including positioning and position control. The navigation system for mining application, in particular, contains some unique features that provide an easy-to-use procedure for taking new production areas into use and making it possible to drive a heavy mining machine autonomously at speed comparable to an experienced human driver.

PREFACE

This work was carried out at the Laboratory of Electrical and Automation Engineering, Technical Research Centre of Finland (VTT) from 1990 to 1993, at VTT Automation from 1994 to 1998 and at Navitec Systems Oy from 1998 to 2001.

I warmly thank Professor Kari Koskinen of Helsinki University of Technology for advices, discussions, and useful comments during the work. His encouragement was essential for me to begin writing this thesis.

I am also grateful to the reviewers of this dissertation Professor Jouko Viitanen, VTT Automation and Professor Juha Rönning, University of Oulu. Their competent and constructive comments improved the structure and contents of this dissertation.

The technology of mobile robotics is so wide and complicated that no one person masters the whole scope. Thus, the work in this field requires co-operation. Fortunately, I have had the privilege of working with the best experts in Finland. I am grateful to my former colleagues and co-workers at VTT for their very valuable contribution to this work. The co-operation with the people of Helsinki University of Technology has also been fruitful. In addition, working with all these people has also been fun and extremely motivating.

I especially want to thank Thomas von Numers, my colleague at both Navitec Systems and VTT. His contribution has been most valuable especially during the last few years.

I also want to thank the key people at Sandvik Tamrock Oy and Liftec Products Oy for their open-minded visions, good co-operation and the patience to work for the common goals despite the difficulties that we have had.

Last but not least, I want to thank my family for their patience and support and also for reminding me that in addition to work, there is also leisure time.

“Daddy, I remember we used to play sometimes before you started to write the thesis”.

“Don’t worry, it is ready now”.

Helsinki, 24.8.2001

Hannu Mäkelä

TABLE OF CONTENTS

ABSTRACT	2
PREFACE	3
LIST OF PUBLICATIONS	6
LIST OF ABBREVIATIONS	7
LIST OF SYMBOLS	7
1 INTRODUCTION	8
1.1 Background	8
1.2 The scope of the thesis	10
1.3 Summary of the publications	11
2 NAVIGATION IN AN OUTDOOR ENVIRONMENT	15
2.1 Introduction	15
2.2 Dead reckoning	15
2.2.1 Odometry	16
2.2.2 Inertial navigation	16
2.3 Pose estimation fusing dead reckoning and beacon detection	17
3 ARTIFICIAL BEACONS	19
3.1 Introduction	19
3.2 Pose estimation using artificial beacons	19
3.3 Pose estimation methods	22
3.3.1 GPS positioning	22
3.3.2 Positioning based on transponders	23
3.3.3 Ground-based RF systems	24
3.3.4 Laser based positioning	25
3.3.5 Ultrasonic positioning	26
3.3.6 Camera-based positioning	27
3.4 Summary	29
4 NATURAL BEACONS AND MAP-BASED POSITIONING	30
4.1 Introduction	30
4.2 Using natural beacons	30
4.2.1 Teaching the beacons	31
4.2.2 Detection sensors	32
4.2.3 Early research work	32
4.3 Modelling the environment for pose estimation	33
4.3.1 Spatial decomposition	33
4.3.2 Geometric representation	35
4.4 Pose estimation based on natural beacons	35
4.4.1 Pose estimation by feature matching	36
4.4.2 Pose estimation by iconic matching	39
4.4.2.1 Pose estimation based on occupancy grids	39
4.4.2.2 Pose estimation based on iterative closest point algorithm	41
4.4.2.3 Pose estimation based on cross correlation	42
4.4.3 Pose estimation by principal components	44
4.5 Summary	45
5 PATH TRACKING CONTROL	46
5.1 Introduction	46
5.2 Path planning	47

5.3	Path tracking control	49
5.3.1	Path tracking control algorithms for car-type robots	49
5.3.2	Path tracking control algorithms for articulated robots	51
	SUMMARY	54
	REFERENCES	56

LIST OF PUBLICATIONS

- I. Mäkelä, H., Koskinen, K. (1991) Navigation of Outdoor Mobile Robots Using Dead Reckoning and Visually Detected Landmarks. ICAR'91, Fifth International Conference on Advanced Robotics, June 19-22, 1991, Pisa, Italy, pp. 1151-1156.¹
- II. Mäkelä, H., Koskinen, K., Rintanen, K. (1993) Navigation of a Land Vehicle by Fusing Dead Reckoning and Camera Measurements. 1st IFAC International Workshop on Intelligent Autonomous Vehicles (IAV'93), April 18-21, 1993, Southampton, England, pp. 99-104.²
- III. Mäkelä, H., Lehtinen, H., Rintanen, K., Koskinen, K. (1995) Navigation System for LHD Machines. 2nd IFAC ¹Conference on Intelligent Autonomous Vehicles (IAV'95), 12-14 June 1995, Espoo, Finland, pp. 314-319.²
- IV. Rintanen, K., Mäkelä, H., Koskinen, K., Puputti, J., Ojala, M. (1996) Development of an Autonomous Navigation System for an Outdoor Vehicle. Control Engineering Practice, vol. 4, no. 4, 1996, pp. 499-505.²
- V. Mäkelä, H., Kaarmila, P., Koskinen, K. (1998) Convoy Navigation. 3rd IFAC Conference on Intelligent Autonomous Vehicles (IAV'98), 25-27 March 1998, Madrid, Spain, pp. 31-36.²
- VI. Mäkelä, H., von Numers, T. (2001) Development of an Autonomous Outdoor Vehicle for a Steel Plant. Control Engineering Practice 9, 2001, pp. 573-583.²
- VII. Mäkelä, H. (2001) Overview of LHD Navigation Without Artificial Beacons. Robotics and Autonomous Systems 36, 2001, pp. 21-35.²

¹ Reprinted with permission from the Institute of Electrical and Electronics Engineers, Inc.

² Reprinted with permission from Elsevier Science.

LIST OF ABBREVIATIONS

AGV	Automated Guided Vehicle
ALV	Autonomous Land Vehicle
CCD	Charge Coupled Device
CMU	Carnegie Mellon University
DARPA	Defence Advanced Research Projects Agency
EKF	Extended Kalman Filter
GPS	Global Positioning System
ICP	Iterative Closest Point algorithm
JPL	Jet Propulsion Laboratory
LHD	Load, Haul and Dump
PSD	Photo Sensitive Device
RF	Radio Frequency
RTK	Real Time Kinematic
SLAM	Simultaneous Localization And Map building
VME	Versa Module Europe
VTT	Technical Research Centre of Finland (Valtion Teknillinen Tutkimuskeskus)
2D	two-dimensional
3D	three-dimensional

LIST OF SYMBOLS

a, b, c	positive constants
α	steering angle (articulated robot)
α, β	measured bearing in between the beacons
d	distance error to the reference path
D_i	distance between a pair of beacons
dk	curvature increment
ds	distance increment
κ	path curvature
θ	heading of a robot
θ_f	orientation (heading) of the front part (articulated robot)
P_i	beacon no. i
R_f	distance from the front axle to the articulation link (articulated robot)
R_r	distance from the rear axle to the articulation link (articulated robot)
R	area of position uncertainty
σ_{\max}	maximum change of curvature within a given distance
v_f	speed of the front part (articulated robot)
Z_i	vector from observation point to the beacon no. i

1 INTRODUCTION

1.1 Background

Unmanned mobile machines, often called mobile robots, are the equivalent of industrial robots in applications where mobility is required. Typical applications are situations where it is not feasible or possible to bring the work to the robot, as is often the case with industrial robots. The essential properties of a mobile robot are the ability to move without a human driver and to perform the actual work either automatically or by teleoperation. Often the robot works as it moves. Transportation and many tasks in agriculture are examples of this. Sometimes the work is performed while the robot stays still after moving automatically. A drilling robot in a mine or a mine excavator are examples of such applications.

Mobile robots have been under development and also in use in some applications for several decades. They have been built to fly in the air or space, dive in or move on the water and drive on land. The motivation for the development stems from several sources. Space research, more closely unmanned flights to inspect the nearest planets and other celestial bodies has been one of the key application areas for the technology, see for example (Hebert *et al.*, 1989). In space, the use of unmanned technology is almost a must. The weight limitations and safety aspects call for unmanned solutions. Military applications have also motivated researchers to develop the technology for unmanned vehicles. Unmanned small scale aeroplanes, used mainly for military intelligence purposes, are examples of this. Industrial applications emerged as early as the 1960s. Automated guided vehicles, AGVs, following a buried inductive wire, in particular, have gained a wide acceptance. Several mobile robots have also been built for purely scientific research purposes. Usually the researchers have had some practical application in mind. Hazardous civil tasks, like fire fighting or rescue work have been mentioned as potential applications.

The first indoor mobile robots were developed in the 1950s, for example, by W. Grey Walter using analog technology. Walter's robot was able to wander around without colliding with anything (Dudec, Jenkin, 2000). The development of digital computers made it possible to increase the capabilities of mobile robots. One of the first computer controlled mobile robots was Shakey, developed by Stanford Research Institute (Nilsson, 1969). The research work with Shakey concentrated on reasoning and path planning based on sensory data from an onboard camera and an optical range finder. A typical task for Shakey was to find a box of a given size and shape in one of the specified rooms and then move it to a designated position. Other well-known pioneer indoor mobile robots were Hilare I (Giralt *et al.*, 1984) and the SENTRY from Denning (Everett, 1998).

It is natural that the research of mobile robotics started with indoor robots. A structured indoor environment is much easier to work with and the testing there more comfortable than in various outdoor environments. The indoor environment offered, and still offers, many interesting challenges, but gradually outdoor research applications also started to emerge. The research for unmanned outdoor machines for civil purposes started as early

as the 1970s. One of the pioneers was a robot called Cart (Moravec, 1977), which, for example, served as a platform for research into stereo vision.

A boom in the research of outdoor mobile robotics began in the 1980s. The best known research projects were the ALV (Autonomous Land Vehicle) from Martin Marietta and Navlab from CMU (Carnegie Mellon University). The ALV was an experimental autonomous land vehicle project funded by DARPA. Several US universities participated in the project, in particular CMU and University of Maryland (Wolfe & Marquina, 1986). Parallel with the ALV test vehicle, CMU developed another research vehicle called Navlab. Hebert and Thorpe (Hebert *et al.*, 1997; Thorpe, 1990) describe the research activities and test results around Navlab. JPL (Jet Propulsion Laboratory) developed several robots to be used for interplanetary exploration. The prototypes of Mars Rovers, in particular, were widely reported (see e.g. Wilcox *et al.*, 1987).

The first experimental machines suffered from a lack of proper sensors and computation power. Not until the rapid development of microprocessors in the 1980s was it possible to carry onboard a reasonable amount of computation power at a reasonable cost and size. The sensors also developed and matured at that time (Everett, 1995). For example, moderately priced fibre optical gyroscopes, small video cameras, and distance sensors became available in the '80s.

The ESPRIT II Panorama project was one of the largest and most ambitious research projects in Europe. It was primarily targeted at civil applications. The objective was to develop a reasonably low-cost navigation and control system for applications where a sufficiently good a priori map was available. The computer system for controlling the test vehicles was decentralized using conventional VME-bus computers along with Transputers. Using VME-bus made it possible to install several processor boards on the same bus and Transputer-processors were especially suitable for parallel computing. The initial idea was to rely on inertial navigation and detection of natural beacons for positioning. During the project, the idea of artificial beacons was accepted. The mission planning and navigation systems were implemented on a drilling rig which, during the final demonstration, was able to navigate autonomously to the drilling area and locate itself in proper positions according to plan (Koskinen 1994).

Real life civil applications of outdoor mobile robots are still rare. There are many advanced projects where commercial exploitation is near, but, contrary to many forecasts (see for example Miller, 1988), no mass market exists so far for outdoor robots. There are several reasons for the current situation.

The technology for outdoor robotics is still not mature enough. On board computation power is usually no longer the limiting factor. Reliability, safety aspects, and financial circumstances are the most important factors that slow down acceptance of the technology. All these factors are mostly related to sensor technology and sensor data processing. Finding proper sensors for a specific application is still a problem. In many cases, the price is a problem even when a sensor meets the technical requirements. Reliable safety sensors, which a mobile robot uses for monitoring its environment and detecting potential obstacles, are especially rare. The system must be capable of moving around without running into the surrounding obstructions. In practice, the position,

orientation, and nature of the obstacles are not known in advance but the system must be able to detect a wide variety of obstacle surfaces at varying angles of incidence.

Vision systems are available, but the algorithms for the reliable detection of different types of obstacles in various lighting and environment conditions do not exist. Ultrasonic transducers and, especially, laser scanners give reliable measurements in most conditions. However, the scanners also need good algorithms and software to analyse the 3D-image to detect the obstacles.

Financial profitability is a key issue when deciding whether to invest to automation or to continue with manual machines. In practically all cases, a mobile robot is more expensive than a traditional manual machine performing the same work. In principle, one can save the labour costs of a driver, but a fleet of robots will need some maintenance personnel in any case. In addition, a mobile robot needs more skilled personnel to service it and to solve potential problems. Therefore, the savings in labour costs are often negligible or even negative. So where do the savings come from? The most important factor in most cases is the increased availability of the robot system. For example, automated ore transportation in mines, instead of manual operation may increase the total productive working time from 8-12 hours per day up to 20 hours per day (Transport & Hantering, 2001). This increase may produce a payback time shorter than a year for the extra cost of automation investment. Reaching this type of high availability not only requires reliable realisation of the robots, but also the working conditions of the robots must be carefully planned. This includes planning the operations so that the fleet of robots constantly has work to do.

Further cost savings may arise from the potential decrease of repair needs of an automated machine compared to a manual one. A typical situation with manual machines is that they are overloaded or used against the instructions of the manufacturer. An automatic machine can be programmed to work in such a smooth way that it lengthens the lifetime of the machine itself (de Jong, 1994).

1.2 The scope of the thesis

The overall scope of mobile robotics technology is very wide, comprising a variety of enabling techniques. Designing a mobile robot requires a thorough knowledge of a wide range of technologies including sensors, actuators, computing hardware, electronics, hydraulics, and mechanics. The kinematics of the machine has to be understood and modelled, several types of controllers have to be designed, the data from the sensors has to be processed in an effective way and all this has to be turned into real-time software without too many bugs. The thesis covers many of these topics, but it focuses mainly on the positioning and navigation techniques. Here, the term navigation is understood as a means of driving a machine from one point to another requiring and including both positioning and position control.

A typical navigation system consists of dead reckoning navigation and positioning based on the detection of beacons situated at known locations. The beacons may be either artificial or natural depending on the application. The thesis describes the typical sensors and algorithms needed for realizing a navigation system for a mobile robot based on the

above techniques. Here water, space, and air applications are excluded, the focus being on land vehicles, in particular on outdoor machines. The methods of automatically constructing a model of the environment are especially interesting since they are closely related to navigation in an underground mining environment, which is currently the author's main area of interest. Underground mines do not clearly belong to either indoor or outdoor cases. The space in a mine is confined by the walls of the tunnels (like indoor applications) but the shape of the walls and the topology of the tunnels are irregular and the ground surface is uneven as in outdoor applications.

The annexed publications are organized in chronological order, number VII being the most recent one. The first two Publications (I and II) describe a navigation system consisting of dead reckoning and the visual detection of artificial beacons. The author designed the system and made the practical implementation for the tests.

Publications III, IV and V describe applications which were more practical in nature, since the developed properties of the navigation systems were demonstrated in practice using a tracked vehicle as a test bed. All the navigation systems in these applications consist of a combination of dead reckoning and the detection of artificial beacons. The fusion of dead reckoning position and position produced by beacon detection is, in all cases, done by using an extended Kalman filter with fixed gains. Publication III includes a special feature since it contains a description of a navigation sensor (transponder detection system) developed in the project; in all the other cases, the navigation sensors were commercially available. The author led these development projects, developed and implemented parts of the navigation software and also participated in the field tests.

Publications VI and VII describe the navigation technology for demanding real life applications. In these cases, the practical aspects, such as reliability and cost effectiveness, have been taken into careful consideration. However, the cases have also required development of new algorithms, for example, for position control and positioning using natural features of the environment. The author has developed, implemented, and tested most of the algorithms of the mining application (Publication VII) and also participated in the development and testing of the navigation system in Publication VI.

1.3 Summary of the publications

The publications cover several projects in which the author has participated at VTT (Technical Research Centre of Finland) and the latest achievements of the cases where the research has finally matured into real applications. The time span of the publications is about one decade. Most of the publications deal with a navigation system as a combination of the dead reckoning positioning and some means of correcting the related drift.

Publication I describes an idea to combine dead reckoning positioning and visual detection of landmarks. The application in mind is a forest machine transporting logs from a forest to a road side. The idea is to place easily detectable artificial landmarks along the route of the robot in pairs at proper distances from each other. The robot has a camera connected to the navigation computer and the program analyses the camera's

images. Normally, the robot navigates by dead reckoning which here utilises a ground speed radar as an odometer and a compass to give the heading. When a pair of landmarks is detected a correction is calculated to the position and heading estimate. An algorithm to detect the landmarks is presented, as well as the practical results of the position measurement accuracy using the camera. The method proved to be very reliable and accurate. The beacon detections algorithm was also relatively fast. The operation of the whole concept was verified by simulation which gave encouraging results.

Publication II describes a practical realisation of the navigation principle of Publication I. The shape of the landmarks has been changed from rectangular to round but, otherwise, the detection system has remained the same. The Publication describes the control system for running a test vehicle. Although the components of the navigation system, that is, visual detection of landmarks and dead reckoning, were also generally in use elsewhere, rather few working outdoor demos were built at that time. The control system has matured to a level which has also proven to be applicable in later projects. The division of the control system into logical entities such as positioning and position control, in particular, has been a sound basis for applying the control system for various types of machines and turned out to be of lasting quality. For example, it has been applied to all the applications in Publications III-VII. The isolation of the hardware dependent parts into easily changeable modules has provided another stable feature. Publication II gives some practical test results using a 4-wheel all terrain vehicle as a test bed.

Publication III outlines the first steps of developing a navigation system for a mining machine. The practical application is the LHD (Load, Haul and Dump) machine which is commonly used to transport ore in an underground mine. A combination of dead reckoning and detection of artificial beacons is proposed as the method for positioning. The Publication also mentions the possibility of using a distance measurement sensor as a tool to model the environment of the LHD and to use the model and the distance measurements in automatic mode as the means of correcting the drift of the dead reckoning. The development work later progressed, particularly in this direction, since this approach needs no extra infrastructure in the tunnels. Taking new routes into use, as easily as possible, has become an important advantage compared to using artificial beacons. The Publication describes the sensors and algorithms of building a navigation system for a mining machine and some test results, but does not describe the final demo of the project in which the results were demonstrated in a tunnel. The demonstration was probably the first in the world where, while a machine was driving in a tunnel, the environment was taught to the system and only the tunnel walls were used to correct the drift of dead reckoning.

One of the most viable outdoor navigation methods is based on satellite positioning, especially using GPS (Global Positioning System). Publication IV reports the results of the project using a combination of dead reckoning and GPS positioning to drive a tracked off-road vehicle mainly intended for the applications in agriculture. The project was possibly the first of its kind worldwide, for using real-time kinematic GPS positioning for a mobile robot. Moreover, the whole concept of a PC-based control station with a radio link to the navigation computer along with the mission planning utilities was unique for this type of application. The author's contribution was to lead the project during its starting phase and to participate in the design, implementation, and initial testing phases.

However, the main responsibility and honour for making the system work in practice belongs to the first author of the Publication, Kari Rintanen.

There are applications with the need to use several mobile robots to perform a specific task in a limited working area. Such applications include transporting goods in harbours, removing snow at airports and harvesting peat in peat production areas. Publication V describes the concept of convoy navigation to be used in these cases. The idea is to use one manned machine (a master) that the automatic unmanned slaves follow in a coordinated manner. A test system was built at VTT consisting of one master machine and one slave. Two types of navigation concepts were tested. The first one was based on direct measuring of the relative position and orientation between the master and slave. The ultrasonic positioning system of VTT (Kauppi, 1992 and Järvelä & Mäkelä, 1997) was modified for this purpose. The second concept used an indirect measurement by independently measuring the position of the machines using differential GPS.

The convoy navigation concept of Publication V was not a new one but this was one of the first projects where a working system was built in outdoor conditions. The algorithms for using either GPS or ultrasonic distance measurement and for calculating the speed reference for the slave are the most valuable parts of the Publication. The author's contribution was to lead the project and develop the software and hardware for the master of the latter case using GPS.

Publication VI outlines the navigation and control system for an AGV which transfers heavy steel slabs in a factory yard. The navigation system was a combination of dead reckoning navigation and a transponder detection system. The transponders were passive beacons buried in the ground along the route of the machine. Crossing a transponder, the navigation system got the accurate longitudinal and transverse position of the detection antenna relative to the transponder. Knowing the heading of the machine, the position of the navigation point can be calculated and the drift of dead reckoning removed.

The AGV contained a comprehensive obstacle detection system comprising four laser scanners. Ultimate reliability of the safety system was required since the AGV operated in an area with a lot of other traffic. The AGV got its work orders from a dispatch system via a radio network.

The AGV project was a classical example of the difficulties which will be encountered when making the operation of a mobile robot highly reliable. The safety system especially caused many problems and also the gyro had to be replaced by a better type to make the navigation system reliable.

The navigation system and safety system of Publication VI contains some unique features. The navigation system is capable of localising and driving a vehicle which has a very unconventional kinematic system all wheels being steerable. The kinematic equations and the dead reckoning navigation system for such a vehicle have not been published earlier. In addition, there are few examples of mobile robots which are designed to be used in a non-closed area.

Publication VII describes the navigation system for LHD machines. These machines are used to carry ore in mines. The development work of the navigation system lasted more

than five years and finally reached the stage where the system is available to customers. The navigation system is again based on dead reckoning and a method for correcting the drift. In this case, no artificial beacons are required but the entire environment is used for position and heading estimation. The basic idea is to learn the environment by driving the routes manually in both directions. During learning, the system records not only the route, but also the environment model based on the measurements of two laser scanners. Later on automatic mode, the view of the scanners is matched with the model and the drift can be estimated and corrected.

To be competitive, the navigation system of an LHD must be able to drive the machine at a speed comparable to a human driver. This level has already been achieved and, in some tests, the LHD has been able to reach the maximum speed of 34 km/h on automatic mode with no stability problems. To achieve this speed, the positioning system, and especially the position control system, have required careful planning and realisation. The same navigation system has since been applied to a mining dump truck reaching a speed of 40 km/h, which is the maximum speed of the machine.

The main contribution of the thesis is in presenting a method for constructing a working navigation and control system for a mobile robot for real applications. Although the thesis only describes some applications, many of the methods presented here are general enough to be also utilised for other applications. The most valuable results of the research and development work presented are the structure of the overall control system of a mobile robot in Publication II and later refined in Publication VI and the position control systems for high speed navigation presented in Publication VII.

2 NAVIGATION IN AN OUTDOOR ENVIRONMENT

2.1 Introduction

In order to be useful, an autonomous mobile robot must be able to move from one point to another without human intervention. This requirement means that the control system of the robot has to know its environment. The robot has to have a reference path to follow, and the route must be such that there is no danger of collisions with stationary or moving objects. In addition, the control system needs to know the position and heading (the pose) of the robot in the same reference frame as that of the path. Another obvious requirement is the ability to control the movement of the robot so that the robot follows the path accurately enough. The accuracy requirement naturally depends on the application. In addition, the system must prevent the robot from colliding with humans. Either it has to have sensors to detect humans or access to the working area must somehow be prevented.

In some cases, a mobile robot does not need a specific reference path. For example, a vacuum cleaner robot could just wander randomly around avoiding all obstacles. Gradually it would cover all the area limited by the walls and the furniture. Such cleaning robots are already available on the market. This kind of navigation, where the environment strongly affects the path of the robot, is usually called reactive. However, the emphasis here is on the applications with a preplanned path for the robot to follow.

2.2 Dead reckoning

Dead reckoning is the most widely used pose estimation method for mobile robotics. It provides good short-term accuracy, is inexpensive and allows high sampling rates. In addition, dead reckoning equipment is used onboard the robot which is preferable in most cases. Dead reckoning equipment measures the 2D- or 3D-components of the motion of the robot and deduces its position by integrating the speed vector. The length of the speed vector is the distance travelled and its direction is the direction of motion during the sampling interval. Normally, the interval is short enough so that the assumption of direct motion does not cause too much error.

There are several methods of measuring the distance travelled. One can measure the rotation of the wheels or tracks of the robot or use a ground speed radar, which is based on the Doppler effect or on correlation. Another way to gauge the distance travelled is to double integrate the acceleration of the robot.

The vast majority of land-based mobile robots in use today rely on dead reckoning as the backbone of their navigation system. For example, most of the pose estimation methods to be presented in this thesis assume that the pose of the robot is well enough known to limit the search space of beacon matching. Since the position estimate of dead reckoning rapidly deviates from the real position, the method requires a periodical correction of the accumulated drift with recurring adjustments from various navigational aids. The following gives a brief introduction of the properties of the dead reckoning measurements

and sensors. The subject is described rather briefly since it is of well known basic technology and the given references handle the subject thoroughly.

2.2.1 Odometry

The simplest implementation of dead reckoning is often called odometry, which means that the motion of the robot is directly measured by measuring the rotation of the wheels or tracks of the robot. Odometry requires instrumentation which involves either optical encoders directly coupled to wheel axles or proximity sensors to detect cogs on a wheel. The heading information can be derived from differential odometry, which means calculating the heading based on the distance difference travelled by the left side and right side wheels of the vehicle. In addition to optical encoders potentiometers, synchros, resolvers and other sensors capable of measuring rotation can be used as odometry sensors. (Borenstein *et al.*, 1996) describes thoroughly the various aspects related to odometry including typical error sources:

Systematic errors:

- unequal wheel diameters
- scaling error
- actual wheelbase differs from nominal wheelbase
- misalignment of wheels
- finite encoder resolution
- finite encoder sampling rate

Non-systematic errors

- travel over uneven surfaces
- travel over unexpected objects on the ground
- wheel slippage due to:
 - slippery ground
 - overacceleration
 - fast turning (skidding)
 - external forces
 - internal forces
 - non-point contact with the ground

To minimise the slipping error, it is preferable to couple the odometry sensors to the freely rotating wheels. However, other effects related to the interaction of wheels (or tracks) and the ground surface effect the accuracy (Banta, 1987). In the best case, the error is in the range of 0.1-0.5 % of the distance travelled. Unfortunately, there is no upper limit for the error.

2.2.2 Inertial navigation

Pure inertial navigation is a self-contained navigation system which involves continuous sensing of accelerations in each of the three-directional axes and integration over time to derive velocity, position, and attitude. Inertial navigation uses gyroscopes and accelerometers (inertial sensors) to measure the state of motion of the robot by noting changes in that state caused by accelerations. A good reference of inertial sensors is

given in (Lawrence, 1998). By knowing the starting position of the robot and noting the changes in its direction and speed, one can keep track of the current position of the robot. Inertial navigation seems very appealing at first glance since its accuracy does not depend on ground conditions as is the case with odometry. Since the position determination includes double integration of the accelerations, it is very prone to drift. For example, an uncompensated accelerometer bias of 0.01 m/s^2 in a journey of 1 h starting from standstill gives a distance error of 65 km. The drift of a gyro affects even more the positioning accuracy. A drift of $1^\circ/\text{h}$ gives a position error of 100 m in less than 4 min (Lawrence, 1998).

Despite the sensitivity of inertial navigation, it has been possible to build navigation systems where the drift without external compensation may be within some metres in hour. These systems are very expensive since they require gyros with a drift of less than $0.001^\circ/\text{h}$ and accelerometers to resolve gravity to a few μg . Such systems are used mainly in submarines and some missiles.

Aircraft systems with errors of less than 2 kilometres an hour are found in all civil aircraft that cross the oceans. Ring laser gyros (RLG) are typically used in these systems. Even they are far too expensive to be used in most of the ground applications. In conclusion, sensors and systems which could be used for navigation of mobile robots exist, but at an unreasonable cost. Therefore, the main challenge of inertial navigation is, and will be in the near future, to manufacture sufficiently accurate sensors, both gyros and accelerometers, at a reasonable price.

2.3 Pose estimation fusing dead reckoning and beacon detection

Given the approximate estimate of the pose of a robot based on dead reckoning and given a map of the environment and sufficient means for sensing, it is possible to maintain and update an estimate of the pose of the robot relative to the map. This process is often called positioning or pose estimation. Pose estimation utilises some natural or artificial features of the environment, here referred to as beacons. Knowing the position of the beacons and measuring the distance and bearing to them, the dead reckoning pose estimate can be updated and improved. Chapters 3 and 4 describe the state of the art in the field of pose estimation based on the fusion of dead reckoning and the detection of artificial or natural beacons. A Kalman filter is most commonly used for the fusion.

Figure 1 illustrates the basic structure of a data fusion for pose estimation using a Kalman filter. The next increment for the pose is obtained from the dead reckoning sensors. The increment is added to the latest pose estimate to get the new pose prediction. Every time the pose is obtained by observing one or more beacons, an innovation is calculated by taking the difference of the observed pose and the predicted pose. The innovation is multiplied by the gain matrix to correct the predicted pose, thus, obtaining the new pose estimate. The values of the gain matrix K depend on the statistical properties of the process model and the pose observation (see for example Maybeck, 1982). Very often in practical applications the gain matrix is not updated but steady state values are used instead. This is also the case in all the publications in this thesis.

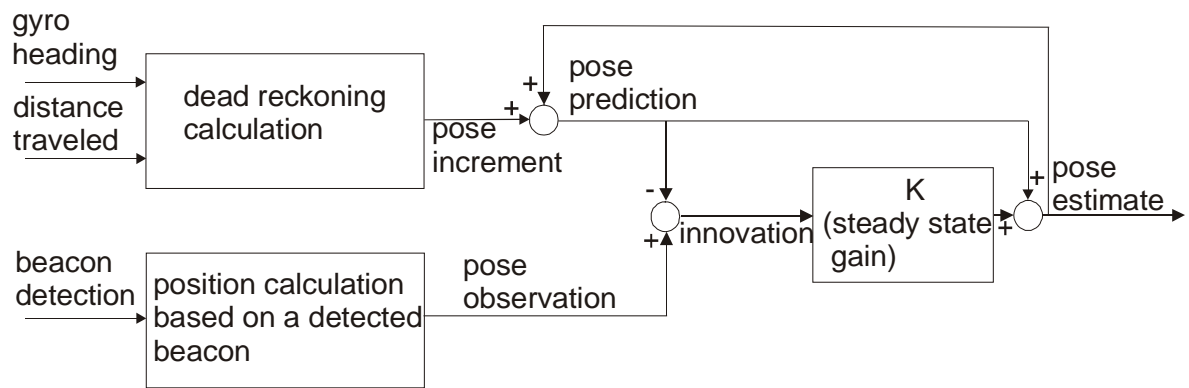


Figure 1. General structure of pose estimation using a Kalman filter.

3 ARTIFICIAL BEACONS

3.1 Introduction

Artificial beacons are objects which are placed at known positions with the main purpose of being used for pose determination. According to this definition, setting up the working environment for a robot using artificial beacons almost always requires a considerable amount of building and maintenance work. In addition, using active beacons requires a power source to be available for each beacon. GPS positioning is one of the major exceptions since the system is constantly available for outdoor navigation. Although the ultimate goal of the research is to develop navigation systems which do not require beacons to be installed in the working environment, artificial beacons are still preferred in many cases. The reason is that artificial beacons can be designed to be detected very reliably which is not always the case when using natural beacons. In the following, only a few examples are given of the techniques relying on artificial beacons, the major emphasis being on natural beacons.

3.2 Pose estimation using artificial beacons

For pose estimation in two dimensions, one can either measure the distances or bearings to at least three beacons and calculate the position and the heading by simple geometry. The calculation is called trilateration if it is based on known distances, and triangulation if it is based on bearings (Everett, 1995). If there are more beacons than required, the system is over-determined and the pose can be solved based on, for example, pseudoinversion, minimizing a least-square criterion (Durieu *et al.*, 1989) or the estimation algorithm by Bettke and Gurvits (Bettke & Gurvits, 1994). Knowing the exact bearing to two beacons gives the solution for the pose of the robot on an arc of a circle according to Figure 2 (Dudec & Jenkin, 2000). An additional beacon restricts the solution to only one point, see Figure 3. Correspondingly, knowing the distances to two beacons gives two solutions for the pose of the robot and three beacons give only one solution.

Usually the measurements include uncertainty. Figure 4 illustrates the pose estimates and the uncertainty with imprecise bearings to two and three beacons. The symbols in Figure 4 are as follows:

α, β	measured bearing in between the beacons
Z_i	vector from observation point to the beacon no. i
D_i	distance between a pair of beacons
P_i	beacon no. i
R	area of position uncertainty

The uncertainty can be further reduced by measuring the bearings to more beacons. It is also possible to discard the measurements which are most contradictory to the average of the measurements. The pose determination becomes more accurate without the outliers.

Everett (Everett, 1995) divides the distance measurement methods in the following groups:

- triangulation
- time of flight
- phase-shift measurement
- frequency modulation
- interferometry
- swept focus
- return signal intensity

The first three methods are the most important types and all of the them are in use, for example, in different types of laser-based distance measurement systems. Triangulation is, in this category, a ranging method although obtaining the range to a beacon is based on angle measurement. A typical triangulation method is stereo vision where two or more cameras in known configuration are pointed at the same scene and an image analysis algorithm tries to find common objects in the image. The displacement of an object in the images is inversely proportional to the distance to the object.

Systems that measure the bearing to several beacons for pose estimation can be divided as follows according to the measurement type:

- rotating laser
- active beacons detected by a camera with special optics
- radio location

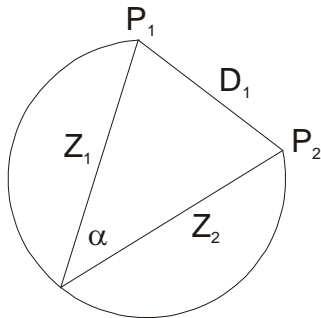


Figure 2. Triangulation based on bearings to two beacons (Dudec & Jenkin, 2000).

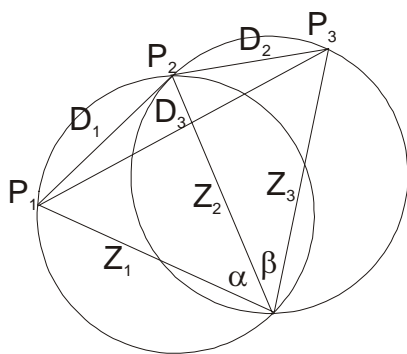


Figure 3. Triangulation based on bearings to three beacons (Dudec & Jenkin, 2000).

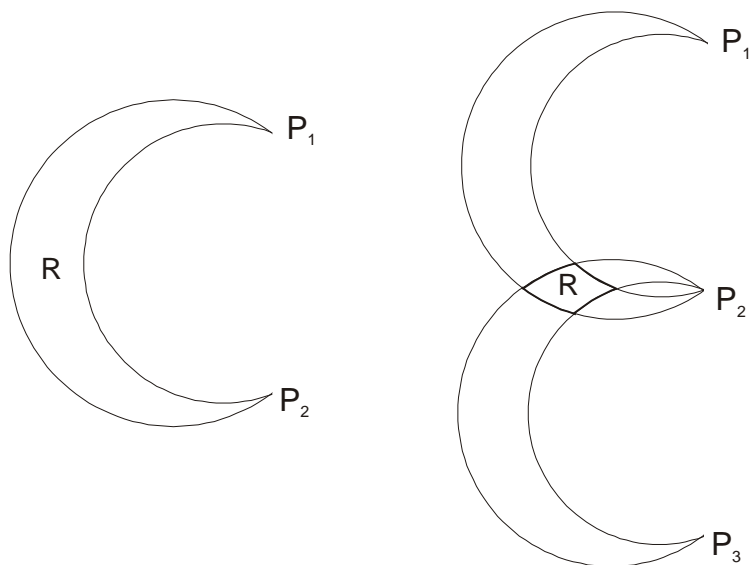


Figure 4. Pose estimates and associated uncertainty based on triangulation using imprecise bearings to two or three beacons (Dudec & Jenkin, 2000).

If the beacons are ground based, the measurement is, in practice, two-dimensional the accuracy of the height coordinate being poor. Anyhow, the accuracy of the pose measurement depends on the accuracy of the distance or bearing measurements, as well as on the geometry of the beacons (McGillem & Rappaport, 1988). The best case is geometry where the lines from the robot to the beacons are mutually orthogonal. The worst case is, correspondingly, the situation where the beacons are spaced closely together in a tight cluster or situated in a colinear fashion relative to the robot.

Active beacon systems typically emit RF energy which is detected by an onboard receiver. RF positioning techniques can be subdivided into ground-based and satellite-based systems. A special subgroup of RF-beacons are the light emitting beacons which

can be detected using a camera (Corre & Garcia, 1992) or a PSD-sensor. Another class of artificial beacons are the passive beacons which are detected by an onboard measurement system. Such techniques include, for example, reflective beacons which are detected by laser-based optical systems (Tsumura, 1993), cameras (Publication I) or radar (Durrant-Whyte, 1996, Clark & Durrant-Whyte, 1998). One particular type of beacon is the passive RF-transponder tags which are activated and detected by onboard antenna systems. The following chapters give an overview of these systems.

Artificial beacons are commonly used in various applications. Pose estimation using artificial beacons may be categorised into two cases depending on whether the beacons are identical without any label, or if they are labelled with their individual identities. The case of identical beacons poses the problem of how to distinguish the beacons from each other for pose determination. This problem has been addressed, for example, by Hyypä (Hyypä, 1993). He has developed an algorithm for deducing the identity of the beacons even without an a priori estimate of the pose of the robot. Beacon detection is usually fused with pose estimation from dead reckoning. (Durrant-Whyte, 1994) gives a short introduction on how to combine a bearing measurement to known beacons with the position estimate of dead reckoning.

3.3 Pose estimation methods

3.3.1 GPS positioning

Global Positioning System (GPS) is the most widely used and known satellite positioning system. It consists of 24 satellites orbiting the earth at a height of 20000 km. The satellites transmit a uniquely coded spread-spectrum radio signal the time-of-flight of which can be measured by the receiver. The times are converted into pseudoranges representing the line-of-sight distances between the satellites and the receiver. The clock offset of the receiver relative to the satellites has to be known in order to correct the pseudoranges to real distances and position in all three coordinates. (Everett, 1995) lists the four major challenges for making the design philosophy of GPS work:

1. Time synchronization between individual satellites and GPS receivers
2. Precise real-time location of satellite positions
3. Accurate measurement of signal propagation time
4. Sufficient signal-to-noise ratio for reliable operation in the presence of interference and possible jamming

Everett also mentions a less obvious challenge of Einstein's theory of general relativity which also has to be taken into account since the motion of the satellites has an effect on the precision of time measurement.

All the challenges mentioned above have been solved as accurately as possible. As a result, the position error of one receiver is in the order of 10-20 m, depending, for example, on the satellite constellation (satellites spaced closely together in a tight cluster or in colinear positions degrade the positioning result). For navigation purposes, this magnitude of error is still too much. The accuracy can be improved to the range of 1-3 m

by a system called differential GPS. It gains in accuracy by improving the measurement of the signal propagation time. A differential GPS system consists of two receivers; one fixed and one movable. While the other receiver is stationary, its calculated position solution can be compared to the known position to generate an error vector representing the prevailing atmospheric conditions. The error vector is sent to the mobile receiver which can then take that into account, thereby reducing its position error by almost an order of magnitude. The accuracy of the differential GPS enables it to be used for some applications of mobile robotics especially where the position is fused together with dead reckoning position estimate (see Publication V).

The most accurate version of GPS positioning is the real time kinematic (RTK) GPS. It utilises the L1 carrier signal (1575.42 MHz) by measuring its phase to within ± 2 millimetres. This results in a positioning accuracy of 1-5 cm. The major drawback of the RTK GPS has been its slow start-up time. This has been a problem especially in cases where the occlusion due to buildings, for example, has caused the receiver to lose the phase tracking. A long recovery time is needed to resolve the entire carrier cycles. Fortunately, recent advances in algorithms and hardware have reduced the start-up time to a few seconds. The RTK GPS requires a fixed base station as does the differential GPS. Despite the price penalty, the accuracy of RTK GPS justifies its use in various applications of outdoor mobile robot positioning (see Publication IV).

Using ground-based satellites called “pseudolites”, it is possible to get rid of the restrictive property of GPS being susceptible to occlusions. The original idea of pseudolites was to extend the satellite coverage by using fixed ground-based beacons which transmit a signal similar to that of the satellites. (Cobb, 1997). Thus, one could use the same receiver which would not necessarily have to know whether the signal comes from a satellite or a pseudolite. The most severe problem, in practice preventing this idea, is the “near/far”-problem. The distance to the pseudolites may vary significantly and, thus, the strength of the signal will vary accordingly preventing simultaneous use of real GPS signals. A pseudolite would also require a very stable clock which would make the manufacturing costs prohibitive for most of the applications. These problems can be circumvented by abandoning the ideal of identical signals of satellites and pseudolites. Although no commercial pseudolite products exist, the topic is still under intensive research and development work (Cobb, 1997, Stone *et al.*, 1999).

3.3.2 Positioning based on transponders

In this context, the transponders are passive devices with an identity that can be remotely detected. The detection system determines the identity of the transponder and also the position relative to it. A typical transponder is a passive device consisting mainly of an LC-oscillator (van Brussel, 1988). An alternating magnetic field is emitted by the antenna frame of the vehicle to supply energy to a transponder. As soon as the energy level is sufficient the transponder transmits its programmed code back to the vehicle. The antenna frame, which can vary in size depending on the application, is both a transmitting and a receiving antenna. The antenna system detects field line fractions in x, y, and z directions. When a transponder is crossed, the system recognises the instantaneous

distance in the direction of travel and also in the crossing direction. This reading process can be repeated as often as desired.

In typical transponder systems, the transponders are buried beneath the ground surface and the detection system is mounted onboard the mobile robot. The transponders are located at a proper distance from each other and the intermediary distance is navigated using dead reckoning. The accuracy of dead reckoning as well as the allowed amount of error determine the distance between the transponders.

The typical reading height of the antenna may vary in the range of 10-30 cm. The positioning accuracy of the system lies within 1-2 cm. The most important merit of the transponders is their reliability. The transponders are passive and there are no moving parts in the whole system. The major disadvantage is that, in between the transponders, the mobile robot is totally dependent on the reliability of the dead reckoning system, that is, it has to find the next transponder along the route with a reasonable safety margin. Being inexpensive, it is possible to install redundant transponders even in a grid covering the whole working area to prevent the robot from getting lost. The main potential of the transponder system lies in applications where GPS cannot be used, for example due to occlusions.

3.3.3 Ground-based RF systems

Various RF systems, such as Loran C, exist for aircraft or marine navigation. They cover large areas and use low frequency signals that propagate beyond the line of sight. However, their accuracy is far too poor for mobile robot positioning. To gain sufficient accuracy, local medium or short range RF positioning systems have been developed.

There are two types of ground-based RF positioning systems: (Borenstein *et al.*, 1996):

1. passive hyperbolic line-of-positioning systems that compare the time-of-arrival phase differences of the incoming signals
2. active radar-like trilateration systems that measure the propagation delays for a number of fixed reference transponders.

Commercial ground-based RF-systems of type 1 have not gained wide acceptance since GPS positioning offers several benefits:

1. no need to build a local infrastructure for transmitters
2. no need to apply for a licence for the radio frequency in use
3. equal or better accuracy (real time kinematic mode)

The most obvious merit of ground-based RF-systems is that the system can be locally designed so that there is no occlusion caused by the buildings, trees or other obstacles. The use of a local positioning system is also sometimes preferred because it is independent of an external system that would be beyond the control of the user.

Type 2 positioning systems are relatively rare but are used, for example, by Durrant-Whyte (Durrant-Whyte, 1996, Clark & Durrant-Whyte, 1998). In these cases, a radar

millimeter wave radar at a frequency of 77 GHz has been used for positioning in the same manner as laser-based systems with passive beacons (see the next chapter). The range of the device is 250 m. The radar beam is mechanically rotated to detect beacons (radar reflectors). The distance and bearing measurements are fused to dead reckoning information by using an extended Kalman filter.

The main advantage, as compared to optical systems, is that a radar-based system is inherently more robust in adverse weather and environmental conditions (Everett, 1995). The main disadvantages are the relatively high price, lower accuracy of range, and the problems of distinguishing the beacons from other objects.

3.3.4 Laser based positioning

Laser based positioning means a system where an onboard laser scanner is used to determine the position of the mobile robot by measuring the distances or bearings or both to a set of known reflective beacons.

Laser range finders are used to measure the distance to the beacons. Mobile robots also can use them for detecting obstacles. Range finders can be classified into the following groups according to their operation principle:

Triangulation uses the geometric relationships between the outgoing light beam and the incoming ray and its position on the sensor surface, for example, a PSD (Photo Sensitive Device).

Time-of-flight systems measure the time the light beam travels to the target and back to the sensor. Since the speed of light is known, the distance is directly proportional to the flight time. This is the most commonly used type of range finders.

Phase shift-based systems measure the phase difference between the emitted and reflected light.

There exist systems where the beacons are identical and the control system determines the identity of each detected beacon. The identity can be determined knowing the current position and heading of the robot and the bearing to the beacon. The reflective beacons can also be coded by using a bar code type of identity (Stephens, 1987). In this case, the identity can be determined in the same manner as reading a normal bar code.

Laser-based positioning was developed in the 1980s. An analysis of the operation of a laser scanner can be found for example in (Hyypä, 1993) or (Adams, 1999). For example, Tsumura (Tsumura *et al.*, 1993) presented a system where the positioning was based on measurement of the bearings and the beacons were reflective corner cubes. Another approach was published by Hyypä, (Hyypä, 1989). He describes a system where the beacons are identical reflective stripes. Hyypä describes an algorithm which determines the initial position and heading when the robot sees a set of identical beacons.

The algorithm deduces which pose best fits the current set of beacons. Naturally, the position of each beacon is defined in advance. The method of using an extended Kalman filter for the association problem of identical beacons is described in (Wernersson *et al.*, 1989) and (Wiklund *et al.*, 1988).

(Åström, 1993) has extended the algorithm so that the position of the beacons has to be known only for the initialisation. When the robot starts to move it extends its known environment by determining the position of each new beacon it detects. This is possible if the same beacon can be seen from several locations and the pose of the robot is known at those locations. When a new beacon is added to the list of the known beacons, it can be used to determine the position at further locations of the robot. An application of this method is described in (www.qnav.se, 2000). Here the beacons are mounted along the path of an LHD machine, which operates in the tunnels of a mine. The position of the beacons can be measured by first performing a position initialisation and then driving the machine through the route.

3.3.5 Ultrasonic positioning

Ultrasonic distance measurement can be used in about the same manner as the laser range finder. The distance measurement is usually based on the time-of-flight principle and is, thus, prone to the variation of the speed of sound in air. The measurement range of ultrasound is relatively limited being dependent, for example, on the frequency of the signal. The relatively slow speed of sound in air also limits the measurement rate below 10-20 Hz depending on the maximum range to be measured. One of the most severe problems of ultrasound is related to the interaction of the sound wave with the surface of the object to be detected. The energy of the sound may be absorbed or reflected by the object surface so that the returning echo is too weak to be detected reliably or a specular reflection is received from secondary objects giving an incorrect measurement for distance (Everett, 1995). To get a strong enough echo, the object should have a sufficiently large surface perpendicular to the direction of propagation of the sound. This can not be guaranteed in practical situations which limits the usability of ultrasound in many of the outdoor cases.

Ultrasound can be used for positioning by the trilateration principle. The accuracy of a sonic positioning system is often limited by the atmospheric disturbances to which the sonic technique is susceptible. Two basic configurations are in use: sound-emitting fixed beacons in the working area are listened for by the robot, or the robot can emit the sound and fixed receivers at known locations listen for the robot. The first principle is best suited for applications where there are several robots working in the same area. In principle, it could also be possible to detect passive beacons in the same manner as bats do. In practice, this alternative is rarely used since distinguishing different types of artificial beacons reliably with ultrasound is a very difficult task.

A basic positioning system is described, for example, by Kleeman (Kleeman, 1992). Here the working area of the robot is surrounded by ultrasonic beacons which are fired consecutively. The propagation time of the sound pulses is measured and fed to a Kalman

filter computation which fuses the dead reckoning information with the beacon positioning.

Other systems have been presented, for example, by (Ziegler & Schlemmer, 1995) and (Kauppi *et al.*, 1992). Ziegler and Schlemmer describe an ultrasonic positioning system which uses the standard time-of-flight technique where the beacons emit the ultrasonic signal and the receiver is mobile. The measurement accuracy of the coordinates is in the range of a few millimetres. The good accuracy has been achieved by modelling the atmospheric conditions using some known fixed distances measured in the working area.

The positioning of Kauppi *et al.* is similar to GPS positioning. The beacons are ultrasonic transducers which emit a repeating sequence of pseudorandom noise. The robot initiates the emitting of the noise sequence by sending a radio command to each beacon. Knowing the structure of the sequence, the robot can deduce the accurate time-of-flight of the sound by correlating the incoming signal with the known sequence. In stable conditions, it is possible to deduce each distance with an accuracy of about one millimetre. The maximum distance which can be measured depends on the choice of the sonic frequency. In practice, the accuracy is limited by the variation of the speed of sound in air. This technique has been applied in Publication V. (Järvelä & Mäkelä, 1997) describe another application of the method. They describe a system where ultrasound is used to measure the dimensions of large concrete blocks in a factory environment. The blocks are stairs and they are measured in three dimensions in order to calculate the path for an industrial robot to polish the surface of the steps. The accuracy requirement for positioning is in the order of 1 mm.

3.3.6 Camera-based positioning

A camera connected to a computer is an obvious choice to be used for detecting both artificial and natural beacons. The most commonly used camera type in computer vision is a CCD (Charge Coupled Device) camera (other options would be a vidicon camera or a camera with a CMOS-chip). Visual navigation offers many desirable potential features, including its passivity, high resolution and long range. In principle, vision could be a very powerful medium, but, at the same time, it is very difficult to use for robotics. Outdoor navigation is especially challenging for several reasons. The visibility to the beacons may be degraded by rain, snowfall or fog, the lighting conditions may be difficult, for example, because of the direct sunlight on the camera or darkness at night or the background of the beacons may vary according to the season or when approaching them from various directions. For example, automatic road following was demonstrated a long time ago both on gravel and asphalt roads (Dickmanns & Mysliwetz, 1992) but when there is snow on the ground the contrast needed for detecting the roadsides is too poor for reliable road detection. Using artificial beacons, one can overcome most of the above-mentioned problems (see Publication I).

A camera must be calibrated for mobile robot positioning. Calibration is needed to compensate for the imperfections of the lens system and the CCD-sensor. Typically, a

camera is calibrated with a geometrically known object which is placed at a known pose relative to the camera (Fischler & Bolles, 1981).

Computer vision is probably the most commonly used method for detecting beacons. Due to the limitations mentioned above, most of the applications of the research projects are of an indoor type. It is relatively easy to make pose estimation, using a camera and artificial beacons, work in an indoor environment. The beacons may be designed so that they are clearly distinguishable from the background. Choosing the proper shape and colour in the case of passive beacons or intensity in the case of active beacons are commonly used methods for achieving reliable detection. The apparent simplicity of using computer vision and artificial landmarks is probably the reason this subject is no longer studied much.

Cameras can be used for positioning based on either trilateration or triangulation. Using two or more cameras makes it possible to adapt stereo vision to obtain the depth information. In practice, stereo vision has several pitfalls, the most severe being how to find the corresponding features from a pair of images (Poggio, 1984). However, for example, Williamson and Thorpe (Williamson & Thorpe, 1999) have reported on a successful highway obstacle detection system based on stereo vision. They claim that their system is capable of detecting objects as small as 14 cm high at ranges in excess of 100 m. The same method could be applied to determine the distance to known beacons.

Most of the researchers have chosen a triangulation approach instead of trilateration. For example, (Feng *et al.*, 1992) present a method for estimating the position of a mobile robot by detecting artificial circular landmarks and combining the pose information obtained by detecting the landmarks with the dead reckoning pose by using a Kalman filter.

Holcombe (Holcombe *et al.*, 1988) has developed a navigation system for indoor use which combines dead reckoning and visual landmark detection. The system is a very basic one using a Kalman filter to combine the dead reckoning pose estimate with visually obtained position updates. In this case, the unconventional feature is that the landmarks are attached in known locations on the ceiling. The landmarks are of a reflective type and they are actively illuminated to achieve a good contrast to the ceiling around a landmark. The method has the same features that are used in Publication I.

(Rathbone *et al.*, 1986) have developed a navigation system comprising active infrared beacons detected by a camera with a fisheye lens (a lens with a wide field of view) and a dead reckoning system. In addition to using the beacons for positioning, they are also used for communication with the robot.

(Cao *et al.*, 1986) have presented an omnidirectional vision navigation technique which uses a fisheye lens to cover the entire scene around the robot. The position of the robot is updated by recognizing artificial beacons with the help of two colour components.

The subject of outdoor navigation with cameras and artificial beacons has been studied for a long time, but so far no major breakthrough has been achieved to move the reported test results into everyday use. A conclusion could be that there are rather few outdoor applications where positioning, using a camera and artificial beacons, would give any

benefit compared to other existing methods. On the other hand, camera-based positioning can be made to work in indoor conditions sufficiently reliably when using artificial landmarks. But here again, using a camera only for this purpose does not offer significant benefits when compared to other methods. Reliable obstacle detection combined with pose estimation would expand the usability of camera systems.

3.4 Summary

Artificial beacons are commonly used for the positioning of mobile robots. In most cases they are inexpensive to use and pose estimation using them is usually rather reliable. Which type of beacons and beacon detection systems should be chosen depends on the application. For example, GPS is available only in rather open areas, but the position can be measured at a high rate whereas transponders buried beneath the surface can be detected only when the robot crosses them.

Artificial beacons have been also used in most of the projects described in Publications I-VII. Publications I and II deal with visually detectable artificial beacons, Publications III, and especially Publication VI, describe navigation with transponders, and Publications IV and V describe GPS-based navigation systems. Publication V also includes ultrasonic measurement for convoy navigation. The relative pose of the master vehicle which is followed by the slave is measured using ultrasonic distance measurement. In this case the beacons are movable, carried onboard the master vehicle.

4 NATURAL BEACONS AND MAP-BASED POSITIONING

4.1 Introduction

Artificial beacons are relatively simple to use and pose estimation based on them is straightforward and reliable. They are useful in many applications where it is possible to install and measure the position of the beacons beforehand. However, there are various applications where artificial beacons can not be used. Many military applications belong to this category. Moreover, in many cases of civil applications, installing and maintaining the beacons is impractical or too expensive. For example, different types of service robots should be able to navigate using only the existing environment.

Natural beacons are objects or features of the environment of the robot that can be used for pose estimation. For example, trees, rocks or terrain shapes could be used as natural beacons. Here the term ‘natural’ has a wide sense meaning that the beacons can also be man-made if they have not been built for pose estimation. For example, buildings, walls, corners of walls, light posts or even the walls of a mine tunnel are examples of natural beacons. In other words, using natural beacons means that setting up a new working environment for the robot does not require installation and maintenance of beacons. This may lower the threshold for taking mobile robots into use by reducing the set-up costs.

Map-based positioning is closely related to natural beacons. A map can be used for pose estimation by comparing the features derived from the sensor data to the features of the map and trying to find the best correspondence. The pose can then be calculated by comparing the position of the common features (see Figure 5). These features could be thought as beacons. However, it is also possible to match raw measurement data directly to the map for pose determination. In this case, it is impossible to say what constitutes the beacons; actually the whole environment around the robot could be seen as a beacon.

4.2 Using natural beacons

Using natural beacons for the pose estimation of the robot involves several phases and related problems:

Set-up phase

1. Select the proper beacons to be used
2. Determine the position of the selected beacons
3. Store the beacons in a database

Pose estimation in automatic mode

4. Extract potential beacons from sensor data
5. Match the beacons to the map
6. Estimate the pose of the robot

The list above is not complete and contains phases that do not exist in all the available methods. For example, there are methods that involve simultaneous teaching and pose

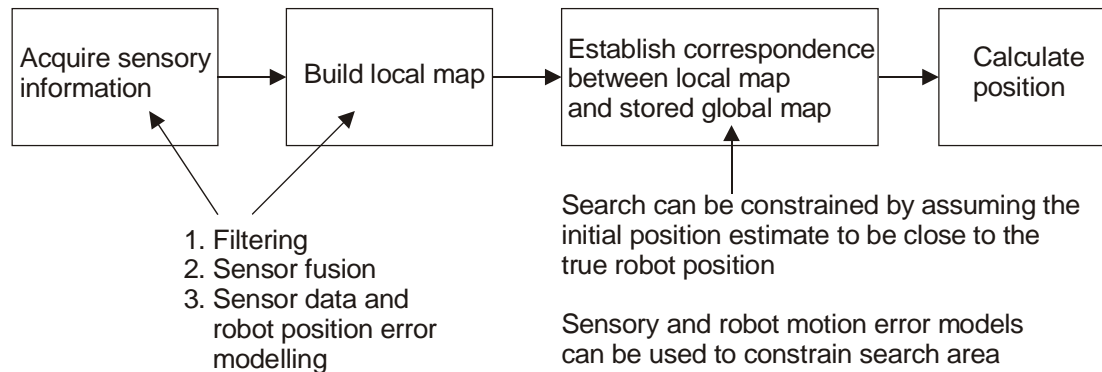


Figure 5. General procedure for map-based positioning (Borenstein *et al.*, 1996).

estimation. On the other hand, in iconic matching method (see Chapter 4.4.2), phases 4 and 5 are combined.

Pose estimation using natural beacons typically requires a great deal of calculation. The calculation workload may depend on the number of beacons ($=N$) as $O(N^3)$ or even $O(N^4)$. Thus, a lot of research work has been invested in further development of the existing methods to make them more effective. More computation power is needed independently of the selected sensor and pose estimation method when using natural beacons compared to using artificial beacons.

4.2.1 Teaching the beacons

To be useful, the setting up of a new working environment for a mobile robot should be as effective as possible. Natural beacons offer the potential for this but using them does not guarantee anything. The key issue is how the beacons are introduced to the robot and how the routes are defined. If the natural beacons have to be defined by measuring their exact position, the preparation work becomes in many cases too slow and laborious. Perhaps the easiest way is to let the robot find the proper beacons by teaching the environment to it. The teaching algorithm analyses the environment, selects the proper beacons, measures their positions, and stores them into a data base (Thrun, 1998). Stereo vision can also be used for selecting and detecting natural beacons (Little *et al.*, 1998)

This approach was introduced as early as the beginning of the 1980s and described, for example, in (Chatila & Laumond, 1985) and (Crowley, 1985). Gonzalez (Gonzalez *et al.*, 1994) describes a method where a robot can extend and modify an existing global map of line segments using rather complicated rules to process the lines. Later this idea was refined by requiring that the robot should be able to build a map of its environment without any a priori knowledge of its position and incrementally expand the map (including the beacons) based on the known beacons which have already been taught. The method is called SLAM (Simultaneous Localization and Map building). The subject has been widely studied, for example, by the research group of Durrant-Whyte (Guivant *et al.*, 2000 and Newman, 1999) and Castellanos (Castellanos *et al.*, 1998).

4.2.2 Detection sensors

So far most of the research related to pose estimation with natural beacons is targeted at indoor applications. The reasons for this are many. Currently, the most important commercial application is industrial transportation handled by automated guided vehicles and great potential is also seen in indoor service robotics. In addition, building a test system is much easier and less expensive for indoor use. Moreover, the problems related to beacon detection are better controlled in a well-structured indoor environment. Although this thesis covers mainly outdoor applications, the following chapters also include indoor research cases. This is because many solutions originally developed for indoor applications are general enough to be also used in some outdoor cases.

A camera is a relatively useful sensor for indoor navigation (see e.g. Krotkov, 1989, Delahoche *et al.*, 1998 or Sim & Dudek, 1999) but complex outdoor environments are typically characterised by uncontrolled lighting, cluttered backgrounds and imprecise control over viewing angles and positions. Thus, the extracted features are always noisy, fragmented, and incomplete. This makes detecting beacons with a camera a very challenging problem in outdoor environments.

Natural beacons can also be detected with the help of various distance sensors. Ultrasonic range sensors are still commonly used for indoor environment mapping and pose estimation. An example of the recent research work is given in (Leonard & Durrant-Whyte, 1991 and Cahut *et al.*, 1998). Laser scanners are becoming more popular especially for outdoor use. Several commercial sensors exist which either scan distances to the nearest objects horizontally or both horizontally and vertically. In most cases, only a horizontal scan is in use. A common approach is to have a map of the environment and base the pose estimation on matching the scans with the map to make a correction to the pose estimate of the robot. Dead reckoning is typically used to maintain the pose in between the scans.

4.2.3 Early research work

The problem of pose estimation using natural beacons has been studied since the beginning of the 1980s. In addition to the work of Chatila, Laumond and Crowley mentioned earlier Bloom (Bloom, 1985), for example, presented a navigation system

using natural beacons to be detected by a camera. The robot has a database of landmarks containing specific parameters of the landmarks in the working area such as colour, shape, texture, and the position of the centre of the mass. The navigation system maintains an error model of the pose of the robot. The model is used to define the areas where the landmarks should be found and the area is modified according to the detected landmarks. Each successful detection gives a measure of the confidence level of the detection which is used to modify the error model of the pose of the robot. Other pioneers of the 1980s included Elfes (Elfes, 1987) and Drumheller (Drumheller, 1987), both studying indoor mapping and navigation using a sonar. Their work will be described in more detail later in Chapters 4.4.1 and 4.4.2.

4.3 Modelling the environment for pose estimation

Most of the tasks to be carried out by an outdoor mobile robot require an internal representation of the environment of the robot. In practice, this means creating a map that describes the environment in a manner needed for the task to be accomplished. The map is typically used for preplanning the mission of the robot or positioning the robot using the information in the map. In this thesis, the subject of path planning is omitted, the focus being on pose estimation.

Dudec and Jenkin (Dudec & Jenkin, 2000) divide map representations into five layers:

1. **Sensorial.** Raw data signals or signal-domain transformations of these signals.
2. **Geometric.** Two- or three-dimensional objects inferred from sensor data.
3. **Local relational.** Functional, structural or semantic relations between geometric objects that are near one another
4. **Topological.** The large-scale relational links that connect objects and locations across the environment as a whole (for example, a subway map).
5. **Semantic.** Functional labels associated with the constituents of the map.

At least map types 1-4 can be used for pose estimation but the most useful representations are types 1 and 2. Typical examples of sensorial maps are occupancy grids which will be described in the next chapter. Geometric maps are described in Chapter 4.3.2.

4.3.1 Spatial decomposition

The idea of spatial decomposition is to represent the environment as a lattice with a resolution depending on the application. This approach precludes the possibility of identifying or discriminating individual objects since the map only tells whether a cell of the lattice is occupied or not. This type of a spatial representation is often called an occupancy grid. The simplest method presents the environment with the cells of a uniform grid. In the case of a binary map, a cell has two possible values indicating whether the cell is free or occupied. A more sophisticated form of the occupancy grid is where the value of the cells indicates the probability of the cell being occupied or not. The value increases when gathering more measurements of a particular cell and decreases in all the cells between the robot and the cell corresponding to the measurement. The idea

of discrete occupancy grids was originally proposed by Elfes (Elfes, 1987) and Moravec (Moravec, 1985, Moravec, 1988).

The main advantage of a regular lattice representation is its generality. The grids can represent any environment, either in two or three dimensions. Another important advantage is related to how easily the presentation can be realised as a computer program. The occupancy grid is a two- or three-dimensional array providing a direct relation from the coordinates of a measured point to a cell of the grid. The coordinates can be directly used as indices to the grid and it is easy to check whether the cell is empty or occupied. It is also easy to determine and access the neighbour cells of a particular cell. The main disadvantage of this type of representation is the large amount of memory required, especially when the grid resolution is fine relative to the size of the space to be represented. Waste of memory is obvious since it is usually the boundaries of occupied and free areas that are interesting, not the areas inside a totally free or occupied area. It is also impractical to change the size of a grid dynamically.

A more advanced version of the grid-based approach for representing the environment is to take advantage of the fact that most of the neighbouring cells have a similar state. Only the cells which form the boundary of objects may have neighbour cells with a different state. One alternative would be to represent space using cells of a non-uniform shape and size. Uniform areas with the same state would be represented by low resolution and the boundary areas by a higher resolution. This approach leads to a complicated programming implementation and is, thus, not widely used. A more simplistic approach is a recursive hierarchical representation. The most common example of this is the quadtree.

A quadtree is a recursive data structure for representing a square two-dimensional region. It is a hierarchical representation that can reduce the memory requirement compared to the ordinary lattice representation. The idea of the quadtree is to represent the interesting areas with higher precision than the other areas. The quadtree can be described as in Figure 6. The original area is divided into uniform cells with coarse fidelity. Cells that are not totally empty or occupied are divided into four equal subcells. The subcells are again divided, according to the same rule, until the desired resolution has been achieved. Thus, the final resolution is high only in those areas which are of special interest. A quadtree is most powerful in cases where the space to be represented is mainly free or occupied. Such is the case, for example, in the mine automation applications.

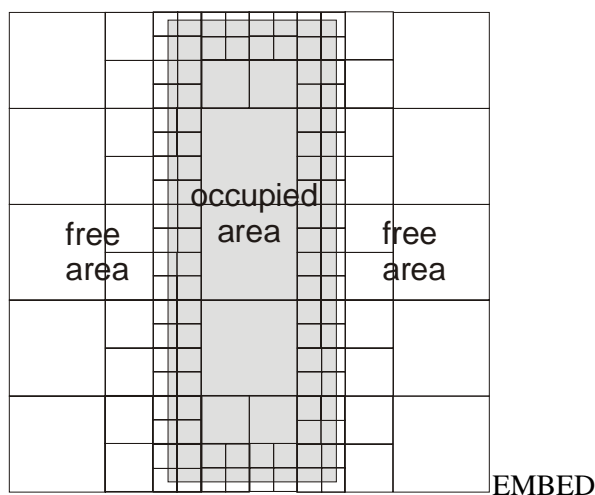


Figure 6. Quadtree representation of an area.

4.3.2 Geometric representation

Geometric maps are made up of discrete geometric primitives: lines, polygons, arcs, polynomial functions, etc. Geometric representation of the environment is highly space-efficient because any part of the space can be represented by a model using only a few numerical parameters. The resolution can also be very high without having to use excessive amounts of memory. Typical 2-D maps are composed of points, lines, circles or arcs, polynomials, polyhedras, and splines. The most commonly used geometric maps consist of lines. By varying the length of lines, one can represent any contour of the environment with the required accuracy. The drawback of using lines to represent a curved contour is the high number of lines which significantly increases the number of calculations for the pose estimation. Generally, if the objects in the map are to be used as landmarks for positioning, the accuracy of their representation must be according to the positioning accuracy requirement.

The obvious shortcoming of geometric model-based representation is related to the fact that it can be extremely difficult to infer the geometric models reliably from sensor data. This is especially true when the sensor data is noisy. However, several publications have introduced methods of building a geometric map with uncertain sensor data. For example, the method of Crowley (Crowley, 1985) is described in more detail in Chapter 4.4.1.

4.4 Pose estimation based on natural beacons

In the simplest case, the environment model only contains information of the beacons which are then detected by a sensor onboard the robot. Knowing the exact position of the beacons and measuring accurately either the bearing or the distance (or both) to them, one can calculate the absolute position of the robot. In some cases, it is also possible to

measure the pose of the robot relative to the beacons without knowing anything about the global coordinates. This is typically the case when using a topological map. However, in most of the real cases the robot has to know its pose in a global coordinate system and, thus, the position of the beacons also has to be known in the same coordinate system.

4.4.1 Pose estimation by feature matching

The feature-based pose estimation method processes the raw sensor data into a small set of geometric features and matches these against the corresponding features in the model. This is probably the most commonly used principle for pose determination with natural beacons. Figure 7 illustrates the basic idea. The environment model is presented as a set of connected line segments. The distance measurements are marked with 'x' and replaced by line segments using a proper fitting method. The main task is to find the rotation and translation by which the measurements match the model in the best way. For example, Crowley (Crowley, 1985) uses a rotating ultrasonic range sensor to integrate a prelearned global world model with information from the sensor to maintain a composite model of the local environment dynamically. The environment is represented as connected line segments in two dimensions. Uncertainty of position and orientation of the line segments is represented by an integer associated with each segment. Information from the global model and the sensor is matched to the local model by determining which line segment in the local model has the best correspondence with a given line segment from either the global model or the sensor. The sensor readings are transformed into line segments using a recursive line fitting algorithm.

The fitting algorithm is often used since it is very general in nature. The algorithm works as follows with a set of measured points. First a line is created between the points which are furthest from each other. The distances from other points to this line are computed. If the maximum distance is below a given limit, all the points belong to the same line. If the maximum distance is too long, the corresponding point is used to divide the points into two groups and two lines are created via this point and the original end points. The procedure is repeated with the new lines until all the points are near enough to a line. The best correspondence between the lines of the measurement and the model is found by performing a sequence of tests based on position, orientation, and length of the line segments relative to each other. The results are then used to update the composite local model by either adding newly perceived line segments to the model or adjusting the confidence value of the existing segments. The update process of the composite local model may also change the length of the line segments or even remove them if the confidence value decays below a given value. Later, Crowley elaborated the method of handling the uncertainty and included Kalman filter update equations to correct the estimated pose of the robot (Crowley, 1989).

Schiele and Crowley (Schiele & Crowley, 1994) have studied the combination of occupancy grids and feature matching. They presented a method for pose determination which basically utilises occupancy grids but extracts line segments out of them by the Hough transform and uses the lines for the matching process. In addition, an extended Kalman filter is used to filter the pose of the robot.

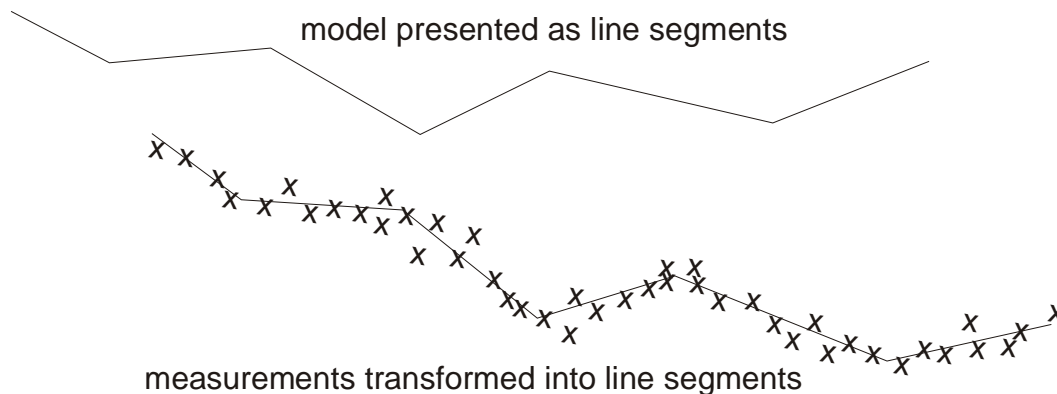


Figure 7. Matching a segmented measurement with a model consisting of line segments.

The curvature of a contour or a surface can be used for matching a scan with the map. Curvature has the desirable property that it is invariant under rotation and translation. For example, Goldgof (Goldgof *et al.*, 1988) has developed a method for matching 3D-images onto an existing surface map. The same idea has been adapted by (Hebert *et al.*, 1989) for the pose determination of a robot. The main drawback of the method is that it is relatively sensitive to measurement noise.

Shaffer presents a modification of feature matching (Shaffer *et al.* 1992) to be used in the mining environment. He uses lines and corners as model features and tries to minimise the error between the features extracted from a laser scanner and the model to find the best pose estimate. (Cox, 1989) presents a method where the world model is based on straight lines and the laser scan readings are matched for the best fit to get the pose of the robot. The dead reckoning pose estimate is corrected by fusing the pose from the scans. The working environment of the test robot is an ordinary office room with a map given a priori. Cox gives an iterative algorithm for finding the rotation and translation to the scan of 360° that minimises the average distance of each scan point to the nearest map line segments. To reduce the computational workload needed Cox has constrained significantly the maximum error that can be corrected in the dead reckoning position estimate. Given M lines in the model and N distance measurements, the complexity of pose determination is relative to $O(N \log M)$.

Drumheller (Drumheller, 1987) presents an algorithm also based on straight lines. The algorithm was adopted from the one represented in (Grimson & Lozano-Pérez, 1985). He uses only a sonar sensor to determine the pose of a robot in a room. The map of the environment is given with straight lines which is a natural choice for a structured indoor case. Drumheller first extracts straight line segments from the sonar data. The algorithm extracts nonoverlapping contiguous subcontours that approximate straight segments. It tries to find the longest subcontours containing at least a minimum amount of points and

having no point farther than a given limit from the line through the endpoints of the subcontours. After extracting the lines, an interpretation tree is created to produce lists of pairings of data features with the map features. Several rules are used to reduce the amount of possible interpretation and finally to get the best one. Drumheller gives experimental results using a Polaroid ultrasonic sensor which gives quite noisy data when used in an indoor environment. The weak points of the method are that it is quite computation intensive and can be used only in an environment which can be modelled accurately enough using straight lines. Unfortunately, the computation work increases as a power of the number of lines in the map.

Shaffer (Shaffer, 1995) has studied the problem of a robot to simultaneously model the workspace and determine its pose. The algorithm was originally applied to the mining environment but it turned out that the tunnels in the mines were too unstructured. The algorithm relies heavily on straight lines and corners which are used as features for pose estimation. Mine tunnels are rarely straight enough and usually there are no sharp corners.

Shaffer uses a rotating laser scanner to record the environment data. He has tested several approaches for pose estimation and made a comparison of their properties. In all the cases, the map is represented as polylines. It is assumed that an estimate of the pose of the robot exists and the pose is used to predict and pick the features that are visible from the pose. A range scan is first transformed into line segments and then a special corner operator searches through the scan to find the potential corners. The pose estimator matches the features of the scan to the predicted features to determine the pose of the robot in the coordinate system of the robot. Several checks are made to verify the correspondence of the map features and the measured features. These checks for line segment features are the orientation of the lines and their distances from each other, and for corners, for example, the position of the corner and the orientation of the lines defining a corner. The process of comparing the measurement and the model is very calculation intensive, being directly proportional to the product of the model features and the measured features. Finding the corresponding features relies heavily on the current pose estimate which must be maintained, for example, by dead reckoning. Only after finding the corresponding features can one calculate the rotation and translation which minimise the error between the sets of features.

A very popular method of positioning a robot in an indoor environment is to use a camera and detect natural vertical beacons (Ayache *et al.*, 1984). Extracting vertical lines from an image representing corners, doors, etc. is relatively simple. For example, (Chenavier & Crowley, 1992) describe a positioning system based on detecting vertical lines and fusing this information with a dead reckoning position estimation. The map of the environment consists, in this case, of only a list of vertical beacons and their 2D positions.

(Forsberg *et al.*, 1993) present a positioning method of a mobile robot using the Hough transform to find straight lines from the data of a laser scanner. Forsberg gives a kinematic model of the robot and uses an extended Kalman filter to combine the dead reckoning pose with the laser measurements. The method only works in a room since the algorithm tries to find the walls of the room to estimate the pose of the robot.

(Riseman *et al.*, 1997) have studied the general problem of finding beacons in camera images, matching the found features with the world model, and calculating the 3D pose of the robot (both position and attitude) based on the found beacons. In the first step, straight lines are extracted from the image. These are then tested against the line segments extracted from the 3D world model to minimise the match error. Taking each possible correspondence, the four parameters (2D position, 2D rotation) are determined to minimise the spatial fit error of the model lines to the data lines. The latter fitting problem is represented as a least-squares one. Solving the minimisation of the least-squares error may produce a local minimum which could be far off the global minimum. This can be avoided by a search strategy presented in the paper. As a result, the presented algorithm works very reliably when the images are good enough. Dealing with 3D computation and iterative solutions make the algorithms very heavy requiring up to one minute to determine the pose.

One basic principle of using natural beacons is to teach the robot the environment and especially the beacons to be used. (Stein & Medioni, 1995) have applied this principle by building a database of panoramic views taken by a camera with the associated pose information. The database is then used to find the best match of the current view to determine the pose of the robot. Comparison does not require any a priori knowledge of the pose of the robot. In this case, the entire horizon is used as a beacon.

4.4.2 Pose estimation by iconic matching

The iconic matching pose estimation method matches the raw sensor data directly to the space map (Gonzalez *et al.*, 1992). No features are extracted from the map or from the measurement. Typically, the map is represented as a lattice and the raw measurement data is converted into the same coordinate system. This method clearly needs an initial guess of the current pose of the robot to reduce the calculation load. If no initial guess is available, all the raw data points should be matched to all the model points which, in most of the real cases, would be extremely time consuming.

4.4.2.1 Pose estimation based on occupancy grids

The basic idea of using occupancy grids for pose estimation is illustrated in Figure 8. The leftmost binary grid presents a wall profile where the cells marked with 'x' contain the surface of the wall. The rightmost grid presents a measurement where the distances are converted into corresponding points on a local map. The problem here is to find the rotation and translation by which the map and the measurement have the best match.

Elfes (Elfes, 1987) presented a pose estimation method based on sonar sensors and a map in the form of an occupancy grid. The map contains a probability for each cell being occupied, empty or unknown. This probability approach is commonly used in sonic sensors to handle the known problems which make the sensor readings unreliable especially in an indoor environment near corners (see Chapter 3.3.5). The scan of 12 sonar sensors produces a scan map around the robot. A measure of the accuracy of the match between the two maps at a specific trial translation and rotation is computed as the

sum of products of the corresponding cells in the two maps. An occupied cell falling on an occupied cell contributes a positive increment to the sum as does an empty cell falling on an empty cell. Other cases have no effect on the sum. This ‘brute force’ correlation approach would be very slow since it requires an order of $O(n^5)$ operations where n is the dimension of the maps to be tested and no a priori information is available about the pose of the robot. Elfes proposes a speedup by taking into account the fact that the real information in the occupancy maps is in the occupied cells. Typically only $O(n)$ cells are occupied in a map of n by n cells. The revised algorithm uses a list of the occupied cells in the maps and a rotation and translation operation for the maps before the same multiplication and summing operation as in the basic method. This procedure reduces the number of operations to $O(n^4)$. Still further speedup is acquired by using multiple resolution maps. A grid with very coarse resolution is first used to get a coarse estimate of the pose of the robot. Using a coarse grid with a doubled grid dimension reduces the number of calculations by four. The pose estimate of the coarser level is then used for testing with maps of a higher resolution. This reduces significantly the search space both for the translation and rotation at each step. In the best case, the number of operations is slightly larger than $O(n)$.

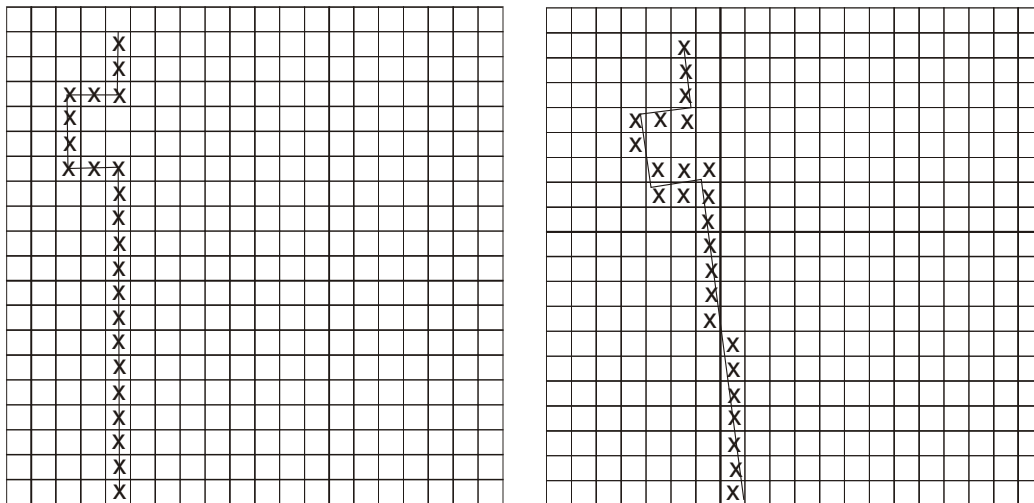


Figure 8. Environment model and measurement as occupancy grids.

Shaffer (Shaffer, 1995) presents a method where the map consists basically of line segments which may be arbitrarily small allowing modelling of irregular surfaces. When determining the pose of a robot, a correspondence determination is made for each point of a scan. This is achieved by measuring the distance to the closest line and to its endpoints. If the distance is too long, the correspondence is discarded. The pairing from a scan point to a model line is accepted for the shortest distance. In principle, the distances should be computed from each scan point to each model line which would require $O(MN)$ operations, where M is the number of lines in the map and N is the number of data points in a scan. To reduce the workload, Shaffer proposes a pre-processed, grid

based map where each grid contains pointers to all those nearest line segments which are closer to the grid cell than a given limit. Thus, a scan point may be compared to only those lines which are close enough. This reduces the complexity to $O(N)$. After determining the correspondence for each scan point, the mean of the distances between the scan points and the corresponding map lines is minimised. This gives the pose of the robot relative to the map.

(Gonzalez *et al.*, 1995) describe a hybrid map to speed up the matching process. A cell map with a proper resolution covers the whole working area of a robot. Each cell has a link to those lines of a line map which are, at least partially, inside the cell. The purpose of the hierarchical representation of the environment is to speed up the matching process. To find the corresponding lines of a scanned point, one finds first the correct cell based on the coordinates of the point. The lines which actually describe the environment can be easily found using the links associated to the cell. Actually, Gonzalez checks several cells based on the uncertainty related to the scanner measurements and the pose estimate of the robot. After finding the lines related to each scan such a pose for the robot is calculated which minimises the sum of the distances between the scanned points and the nearest lines.

Schulz and Adams (Schulz & Adams, 1998) have studied different types of matching techniques using occupancy grids. They give quantitative results and, according to their tests, the best combination of matching and search procedure gives an average position error which is about the size of a cell in the grid. The basic approach is the same as that of (Elfes, 1987).

4.4.2.2 Pose estimation based on iterative closest point algorithm

One of the most advanced matching methods was described by Zhang (Zhang, 1994). The method is called *iterative closest point algorithm* (ICP). The work of Zhang is based on the work of many researchers, for example, Besl and McKay (Besl & McKay, 1992). The idea here is also to match each point of a scan to the map directly without trying to find any corresponding features. The closest map point is searched for each measured point, and the rotation and translation between the map and the measurements is computed based on the group of closest point pairs. It is assumed that a fairly good estimate of the pose of the robot exists. In the worst case, this requires $O(N)$ comparisons, where N is the number of points in the map. To speed up the search Zhang uses a binary search tree, where the points of the map are classified into a binary tree according to their coordinates. In the search phase, the maximum acceptable distance between a point and the closest point in the map is limited to a given value. If this limit is exceeded, the point is discarded. Another constraint is the orientation of the surface at a point which should be about the same as that of the closest point in the map. Figure 9 gives the initial situation of a match indicating the pairs. The final translation and rotation are calculated after several iterations. The iteration of the algorithm is as follows. When each point of a scan is analysed, a distance D is calculated based on the statistical properties of the distances between the closest points. All the pairs whose distance exceeds D are discarded and a rotation and translation component is calculated between

the scan and the map applying a least-squares estimation. The whole procedure is repeated until the rotation and translation are in the given limits. If the maximum acceptable number of iterations is exceeded, the correspondence of the scan and the map is not good enough.

The ICP algorithm has been used for LHD navigation in mines. Madhavan (Madhavan *et al.*, 1998) states that the algorithm is robust in the presence of occlusions, as well as gross outliers in the data. However, the algorithm does not sufficiently tolerate uncertainty of the range data and does not always give a reliable motion estimate. To overcome this shortcoming, Madhavan proposes a combination of ICP and EKF (Extended Kalman Filter). The Kalman filter exploits a non-linear kinematic model of the LHD, a non-linear observation model based on the vertices of a poly-line map and the bearing of the laser scans. The practical results are significantly better with this combination than when using the ICP algorithm alone.

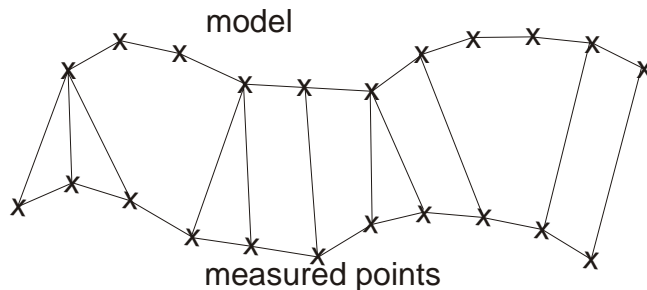


Figure 9. Finding the closest point for each measured point.

4.4.2.3 Pose estimation based on cross correlation

The basic problem of pose estimation using natural beacons is to find the rotation and translation between a scan and the map which minimises the total error at the points. Weiss and Puttkamer (Weiss & Puttkamer, 1995) have developed a pose estimation method based on matching two scans with the same number of points. The algorithm consists of three steps:

1. The scans are transformed into a representation that is invariant against rotation.
2. The relative rotation of a new scan and the reference scan is solved and removed.
3. The shift between the scans is resolved.

In order to match two scans, the scans are transformed into a representation that is invariant against the measurement place and orientation. Such a representation can be formed by calculating the directions of the lines connecting each pair of consecutive scan points (see Figure 10). The angles of the lines are rounded to a discrete value and a histogram is created giving the distribution of the angles in a scan. Assuming a robot is in a rectangular room, the histogram would contain four clear peaks. The shape of the histogram is independent of the position where the scan was taken but not of the orientation. If the robot rotated for example 45° the peaks in the histogram would also shift 45° (see Figure 11). Defining the relative orientation of two scans is, thus, transformed into a task of calculating the cross-correlation of the two histograms. The

cross-correlation function shows a local maximum at the phase-shift between the two angle-histograms.

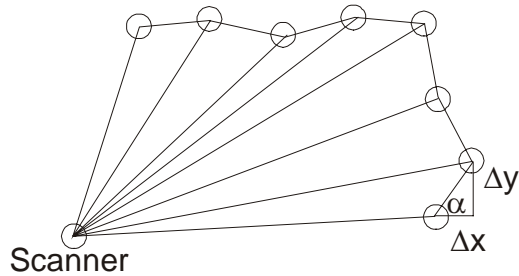


Figure 10. Calculating angles for angle-histogram.

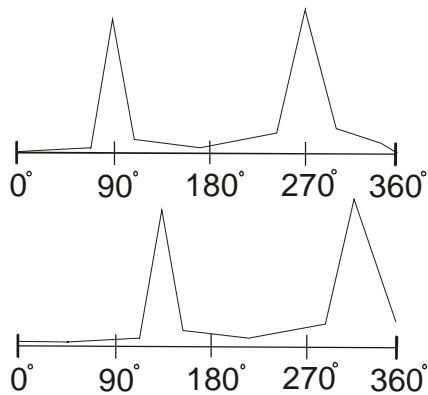


Figure 11. Angle-histogram showing a rotation of 45° .

After the relative orientation difference of the two scans is found the translation is calculated also based on histograms. Two histograms are calculated indicating the distribution of the scan-points in x- and y-direction of the coordinate system. The coordinate system to calculate the x-histogram is chosen so that its x-axis is along the most common direction of the lines between the scanned points, that is, the direction corresponding to the highest peak of the angle-histogram. The coordinate system is correspondingly chosen for calculations in the y-direction. The x- or y-histograms of the two scans have a phase-shift indicating the displacement in the corresponding direction and can be found by cross-correlation.

In order to use the method described above for navigation, the robot needs a map of its environment. Weiss and Puttkamer propose a method where the working area is divided into square cells forming a grid. A scan is assigned to each cell that the route of the robot crosses and the scan is then used for pose estimation when the robot comes near that cell. The map can also be updated automatically when the robot arrives at a cell that does not contain a scan. In that case, a new scan is stored and assigned to that particular cell. The algorithm also relies on dead reckoning which gives a rather accurate pose estimation. When travelling in an unknown area, the map can be slightly distorted because of the

drift of dead reckoning. In many cases (as in the mine application of Publication VII), the global distortion of the map does not cause any harm for navigation since, as long as the map is locally consistent, the robot knows its pose relative to the local environment.

Dubrawski and Siemiatkowska (Dubrawski & Siemiatkowska, 1998) have modified the ideas of Weiss and Puttkamer by introducing a neural network for producing a more robust position estimate especially in the presence of noise in the measurement. In this case as well, the algorithm searches for dominant orientations related to the scanned points and forms a histogram of the orientation. The relative orientation of two scans can be determined in the same manner as Weiss and Puttkamer introduced. Dubrawski and Siemiatkowska present results based on a rather large set of test scans and compare the results to those of Weiss and Puttkamer. According to the experiments, the proposed method is more robust against sensory noise.

4.4.3 Pose estimation by principal components

The pose estimation methods based on feature matching and iconic matching transform the sensor signal into a 2D or 3D cartesian coordinate frame. However, alternative coordinate spaces are possible. (Crowley *et al.*, 1998) presents a method where the map of the environment is formed of a large set of range scans taken from different positions. The range data is not converted into x- and y-coordinates, but into the principal components forming an eigenspace. The structure of the environment is represented as a family of surfaces in this space. The same idea was earlier applied to computer vision (Jones *et al.*, 1997). A range scan for pose estimation is transformed into a point in this space. When this point is associated into a family of surfaces, a set of candidate poses is retrieved. These candidates correspond to poses where the range scans fit in a similar way into the environment. A Kalman filter is then used to select the most probable pose.

Each individual range measurement can be considered an independent dimension for a range scan. In practice, there would be correlation between adjacent measurements, the dimensions of the space would not be orthogonal, and the space would not be minimal. The analysis of the principal components provides a method for determining a linear subspace with the minimal number of dimensions. The principal component vectors from a covariance matrix of range data form an orthogonal basic set providing the eigen-modes of the range sensor in that environment. The dimension of the eigenspace can be significantly reduced by using only the most important eigen-vectors. By removing the dimensions with small eigenvalues, an approximation is made and the transformation from range data into the eigenspace is no longer reversible. The practical number of dimensions in the eigenspace depends on the shape of the object in the environment. For instance, only two or three dimensions are required for describing a rectangular room.

Pose estimation using the principal components converts the problem of associating a range profile to possible poses into a table lookup. This means that the scan is converted into a point in eigenspace and listing all sample points within a given distance of the observed point gives a list of candidate poses. In principle, the pose estimation phase is simple but the method requires a thorough set-up phase. The entire working area of the robot should be travelled through and the range scan must be taken from a dense grid of

poses. Crowley (Crowley *et al.*, 1998) suggests a method for avoiding this problem by actually measuring with only a sparse grid and calculating the intermediary poses and the related range scans based on the real measurements.

Although the pose estimation by principal components has some appealing features, its operation is uncertain in an environment with complicated structures. If the walls are not straight but very curved, as is the case in tunnels, either the dimension of the eigenspace or the error of the transformation increases.

4.5 Summary

To use natural beacons and map matching, one has to choose a proper method of representing the environment as well as an algorithm for pose estimation. An overview of the research results in the literature has been given in this chapter. Most of the algorithms have been tested in laboratories and no data is generally available on how reliably they work in various environments. Thus, it is difficult to estimate the merits or weaknesses of the algorithms without actually implementing and testing them.

In addition to being robust, the environment model of the selected method should be simple and use the computer memory sparingly. Furthermore, the pose estimation algorithm should be fast. Using these criteria the ICP algorithm with Kalman filter described in Chapter 4.4.2.2 seems to be a good choice. One of its merits is that it has been tested in a real mine environment. The cross correlation algorithm of Weiss and Puttkamer in Chapter 4.4.2.3 also has potential since it is relatively simple and seems to be also robust. The pose estimation algorithm of Publication VII has also proven to be very robust in mine conditions. It has been successfully tested in several mines and tunnels. The environment model is stored simply as a sorted list of coordinates of the points in the model. The pose estimation algorithm is a modification of the ICP algorithm.

5 PATH TRACKING CONTROL

5.1 Introduction

The objective of path tracking control is to make a mobile robot follow the given path with the accuracy that is required by the application. Usually, one point of a robot is selected for the point to be maintained on the reference path. Here, this point is called the navigation point. Usually, the point is selected so that it moves into the direction of the body of the robot. For a car-type kinematic system, the middle point of the rear axle is selected as this point.

Path tracking includes detecting the error in the pose compared to the reference path, calculating the amount of corrective action, and adjusting the steering to decrease the error. The error in the pose consists of the heading error and the lateral perpendicular distance to the path. The error in the direction of the path is usually omitted since, in most cases, the robot does not have to follow an accurate time-table. Speed is rather adjusted according to some higher level events, such as curves in the path, obstacles or properties of the road surface.

Path tracking controllers can be divided into two main classes:

1. The pose of the robot is controlled based on direct measurement of the deviation from the path. The pose of the robot in any coordinate system does not have to be known.
2. The robot has a preplanned path in its memory consisting of a sequence of points and it continuously measures its pose and tries to minimise the deviation between the measured pose and the reference pose. The nearest point to the navigation point of the robot is selected as the reference point, or a point at some distance ahead of the robot.

Class 1 path tracking is typically used by AGVs that follow an inductive wire buried in the floor. The robot does not have to know its pose since it measures its transversal deviation from the nominal path defined by the cable. The same concept applies, for example, to optical path tracking, where the robot tries to follow a white lane on the floor by measuring the lateral deviation by optical means, or to a wall-following case where a robot tries to maintain a constant distance from a wall beside the robot. A common feature in all the cases in this category is that the navigation concept does not allow both high speed and good accuracy. This path tracking method has no practical means of preparing for a curve in the path in front of the robot. Since the tracking control reacts only to the measured deviation it is always late. This does not necessarily cause problems at a relatively slow speed but increasing the speed will inevitably also increase the lateral position error.

Path tracking methods belonging to the second category provide much better chances of maintaining both high navigation speed and good tracking accuracy. This is because, in this case, the path is known in advance by the path tracking controller and it can take into

account the curves in advance. However, high speed navigation requires that the reference path of the robot is sufficiently smooth so that following the path accurately enough is physically possible. In this chapter, path planning and tracking methods are brought under a closer look, the focus being on high speed navigation, especially on navigation of robots with articulated steering. The tracking methods belonging to class 1 in the above are omitted.

5.2 Path planning

In order to make accurate high speed navigation feasible, the reference path of a robot must be suitable for that purpose. The process of creating a reference path is called path planning. This may take place both as an off-line process or as an on-line process while the robot is moving. The path consists of a set of points, usually in two dimensions. The distance between the points is selected, for example, by taking into account the speed of the robot, the control rate of the path tracking controller and the shape of the path. A path with tight curves requires more points than a straight path.

The main requirement for a good reference path is that its curvature is adjusted according to the capabilities of the robot. Curvature is defined as the inverse of the radius of a curve of a path or it can be expressed as the rate of the heading change along the path (dh/ds). The heading of a point on a path is defined as the direction of the tangent of the path at that point.

Paths can be classified into the following groups according to their smoothness (Kanayama *et al.*, 1988), see Figure 12:

1. class0: A path with lateral discontinuity. This means that there is a significant sideways jump between successive points.
2. class1: A continuous path with discontinuous curvature κ .
3. class2: A path with continuous tangent direction (heading). For example, connecting a straight line and a circular arc produces continuous heading.
4. class3: A path with continuous curvature and heading.

The path planning problem has been studied widely. A typical path planning task can be reduced to the following problem: any given two points with a heading attached to them create a path between the points starting and ending with the specified heading. In practice, the generated path has to fulfil the following constraints:

$$|\kappa| \leq \kappa_{\max} \quad (1)$$

$$|d\kappa/ds| \leq \sigma_{\max} \quad (2)$$

The first constraint implies that the radius of the path at any point may not be less than the minimum turning radius of the robot. The latter constraint limits the change rate of the curvature due to the limited turning rate of the steering actuator of the robot. The limit σ_{\max} is also a function of the speed of the robot.

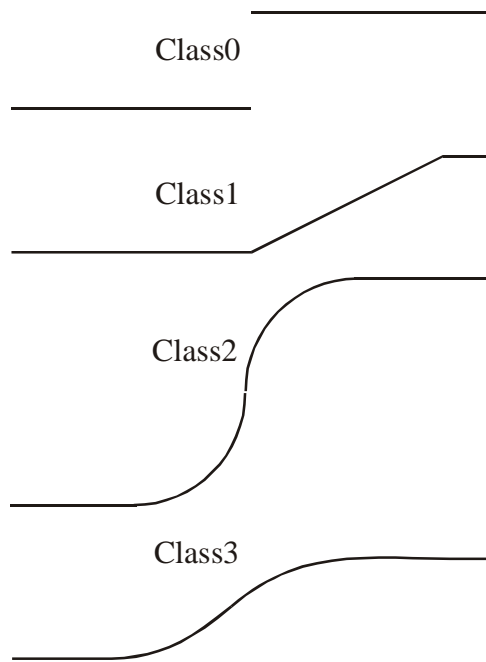


Figure 12. Path classification.

The simplest strategy is to compose the path using straight lines and circular arcs (Bochereau *et al.*, 1987). Using these components, one can always design a path for connecting two points with a specified heading, but the result is not generally suitable for high speed navigation since the type of the path created is class 2.

A more advanced method is to use splines for interpolating a path with continuous curvature between two points. Cubic splines are commonly used but, unfortunately, they create a path with unlimited derivative of the curvature (Komoriya, Tanie, 1989). (Andersson *et al.*, 1997) propose a method where the path consists of special X4Y4 curves, connecting lines, and circular arcs. A property of the X4Y4 curve is that the derivative of the curvature is continuous. This reduces the dynamical constraints of the steering actuator of the robot. The idea is to adjust the length of the X4Y4 curve so that when connecting a line and a circular arc the curvature increases smoothly from zero to the value of the circular arc.

Other approaches for path planning include composing the path of circular arcs, line segments, and clothoids (Scheuer & Laugier, 1998), clothoids only (Shin & Singh, 1990), cubic spirals (Kanayama & Hartman, 1989), using optimal control theory (Reuter, 1998) and neural networks (Rintanen, 1993). A common feature of all these techniques except that of (Shin & Singh, 1990) is that they try to optimise the created path. A usual cost function to optimise is the length of the path, maximum curvature, variation of curvature or a combination of these. The result is a path of class3 type. Since no analytical method of finding the optimal solution has been found and the path equations can not be solved in closed form, iterative numerical methods have to be used or, in the case of (Rintanen, 1993), the optimal solution is taught to a neural network.

5.3 Path tracking control

A path tracking controller compares the measured pose of a robot to the reference pose on the reference trajectory and as an output calculates such a steering value that reduces the pose error. Usually, the path tracking controller and the steering controller can be thought of as nested feedback control loops according to Figure 13. In this context, the task of the steering controller is to maintain the steering angle as close to the reference value as possible.

The path tracking controller of Figure 13 may give an optimistic idea of how to realise a working controller. In reality, a robot seldom obeys the kinematic equations accurately. The reference value to the steering angle controller is calculated supposing certain behaviour of the robot according to the theoretical kinematic model which is actually an approximation. Thus, the path tracking controller must be able to compensate for the errors caused by the real behaviour of the machine. These errors can be caused, for example, by the disturbances of the ground surface, wheel skidding, and the dynamics of the steering controller. Another source of disturbances for a path tracking controller are the errors in position measurement. The controller must be able to handle random position errors of several centimetres depending on the measurement principle. Also the dynamics of the robot have to be taken into account at least when the driving speed is high relative to the speed of the steering actuators.

5.3.1 Path tracking control algorithms for car-type robots

Path tracking controllers can be categorised according to which information they utilise as a feedback (Shin *et al.*, 1992). The simplest type of path tracking control is a feedback control comparing the position of the navigation point and the nearest point at the reference path. The steering angle is corrected relative to the position error. This type of control is analogous to the AGV control where the AGV follows a buried inductive wire. The controller reacts only to the error and does not take into account the path in front of the robot. Thus, the highest attainable driving speed is low. This type of controllers have been presented, for example, by (Nelson & Cox, 1988) and (Kanayama *et al.*, 1988). In many cases, the performance of the controller is adequate and more advanced controllers are justified only if the robot is to follow the route at high speed or if the steering of the robot is slow compared to the driving speed. The latter condition is the justification for the controller described in the Publication VI.

Road following using computer vision is a typical example of path tracking using direct measurement of transverse position error. The error is detected by analysing the image of a camera connected to the navigation computer. In the simplest cases, the image processing algorithm detects the white lane marking lines at certain distances in front of the robot. Jurie (*et al.*, 1993) describes a navigation system for a car by which a

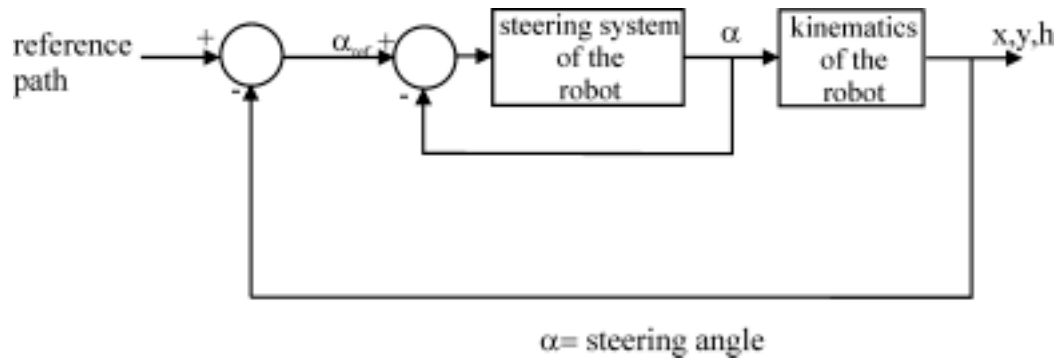


Figure 13. Path tracking controller.

speed of 100 km/h has been achieved when driving in a straight line. In addition to the smooth path, the kinematics and steering system were modelled rather carefully and the controller tuned accordingly. On a circular test circuit, the lateral position error was up to 3.8 m at 70 km/h. This error could be decreased significantly if the curvature of the test circuit was given as a parameter to the path tracking controller. In this case, the controller is no longer purely class 1 but rather class 2. A more sophisticated algorithm can estimate the curvature of the road in front of the robot based on image analysis only. Dickmanns (Dickmanns, 1997) reports driving speeds up to 130 km/h on highways.

In the second category, the controller is a combination of the feedback controller and a feed forward controller. The control scheme is called preview control by Shin (Shin *et al.*, 1992). The feed forward control takes into account the delay of the steering actuator of the robot. It also utilises the knowledge of the shape of the reference path. In the simplest case, the reference point is selected as the nearest point on the reference trajectory. However, this does not necessarily produce an acceptable performance of the controller, since the dynamics of the steering actuator are always limited. The performance of the controller can be easily improved by not picking the nearest reference point but selecting it at some distance in front of the robot. Shin models the steering dynamics as a first order lag system. The distance to the reference point is relative to the driving speed and the delay of the steering actuator. This approach has a clear analogy to a human car driver looking at the road sufficiently far ahead of the car.

The corrective steering action suggested by Shin is calculated as follows. A reference point with a reference heading is selected at a proper distance in front of the robot. A path from the current pose of the robot to the reference point is calculated as a quintic polynomial. This path is recalculated at every control loop and the proper steering angle is calculated according to the initial curvature of the corrected path. Shin has simulated the properties of the controller and also tested it using a van (the CMU NavLab) as a test bed. The research group has been able to reach a driving speed of up to 32 km/h.

Many authors have studied path tracking algorithms which can be proved to be stable. Samson (Samson, 1993) presents a control algorithm where the feedback of the controller is time-varying. Although the controller is proven to be stable, Samson states that the parameters are difficult to determine in such a way that the performance of the controller

would be satisfactory. The simulation results show significant oscillation of the steering angle.

Kanayama and Fahroo (Kanayama & Fahroo, 1997) present a control algorithm which resembles the one of (Shin *et al.*, 1992) The control rule is a sum of the current path curvature, heading error, and distance error:

$$d\kappa/ds = -a\kappa - b\Delta\theta - c\Delta d, \quad (3)$$

where a, b, and c are positive constants.

Kanayama and Fahroo prove that the controller is asymptotically stable if $a=3k$, $b=3k^2$ and $c=k^3$, where k is a positive constant. Varying the constant k, one can change how strongly the controller tries to return the robot to the reference path. The results were verified by simulation and with a small scale robot, the results being satisfactory. However, the authors give no indication of how the controller would behave at high speeds when the dynamics of the robot (which have been totally omitted) play a significant role.

5.3.2 Path tracking control algorithms for articulated robots

Path tracking control of articulated robots has recently become a relatively common research topic. This is mainly due to the increasing interest in automating the operation of LHD machines in the mining industry. These machines are usually of the articulated type. Path tracking control of articulated robots is more challenging than controlling car-type robots due to the more complicated kinematics. The body of the robot consists of two parts with the articulation link between them. Steering is achieved by changing the relative orientation of the parts of the machine. The kinematic equation of an articulated vehicle is as follows:

$$d\theta_f/dt = (v_f \sin\alpha + R_f \cos\alpha d\alpha/dt) / (R_f + R_r \cos\alpha) \quad (4)$$

where

θ_f is the orientation of the front part

v_f is the speed of the front part

α is the steering angle (articulation angle)

R_f is the distance from the front axle to the articulation link

R_r is the distance from the rear axle to the articulation link

The equation implies that the rate of change of the heading of the front part of the robot is proportional not only to the steering angle α , but also to the speed of the machine and the change rate of the steering angle. Choosing the navigation point is very critical. The articulation link has been considered an improper choice by many authors. If the navigation point is beside the reference path, a correction will temporarily deviate the point even further. This makes it very difficult to stabilise the controller. Another choice is the middle point of the rear axle (Polotski *et al.*, 2000). Choosing this point only for

calculating the deviation from the reference path will certainly produce an unstable controller. Polotski has added the orientation error as a term in the error criteria, as well as the error in the steering angle. The latter term requires the reference steering angle to be calculated for each point on the reference path.

Choosing the middle point of the front axle as the navigation point is a good choice when driving forward. When reversing, the position controller becomes unstable (Jannok & Petersen, 1992). Consequently, Altafani (Altafani, 1999) has chosen both the middle point of the front axle and the rear axle to be controlled simultaneously. In this case, the controller tries to minimise the transversal distance error to the reference path of both navigation points simultaneously. The headings of the parts of the robot are included in the control law.

Ishimoto (Ishimoto *et al.*, 1997) present a typical path tracking controller. The control law is a sum of the lateral position error, heading error, steering angle error, and steering angle velocity. All these terms have their own coefficients as tuning parameters and the sum of the terms is used to correct the speed of the steering actuator. One of the drawbacks of this controller is that the reference values are obtained using the nearest path point to the navigation point. Choosing the articulation link as the navigation point is not justified by Ishimoto. Testing, using a slow, small-scale robot, indicates that the controller at least works moderately well.

DeSantis has published a proposal for a path tracking controller resembling that of Ishimoto (DeSantis, 1997). He models an articulated robot taking into account not only the basic kinematics, but also dynamics. The dynamical equations model the inertial properties of the mass of the robot. Using the model, DeSantis calculates almost the same error terms as Ishimoto, namely lateral, heading, and steering angle errors which are multiplied with proper gains and added to the nominal turning rate to get the corrected turning rate for the robot. The navigation point is selected to be in the middle of the front axle of the machine. DeSantis analytically derives rules on how to determine the gains so that the controller becomes stable. The proposed controller, unlike most of the others presented in the literature, also includes a speed controller. The performance of the controller is verified by simulation driving straight and circular paths where the position and heading errors have been small. The author believes that the controller would also behave well when the errors are large or the shape of the reference path is more complicated. The possible weaknesses of the proposed controller include that it does not take into account the lag of the steering actuator and the nearest point to the navigation point is picked as the reference point, not a point in front of the robot.

The position controller of Publication VII also selects the middle point of the axle, which is ahead in the direction of motion, as the navigation point. This means the point is changed when the direction of motion changes. The controller takes into account the current curvature of the reference path and adds a corrective term to it. The correction includes not only heading and position error, but also the predicted position error after certain time interval t . The time interval is chosen according to the latency of the steering actuator. In the case of heavy mining machines, it may be up to 0.5 seconds. The predicted position error is calculated based on the current heading and curvature; that is the error is the distance of the navigation point from the reference path assuming the

robot maintains its current heading or steering angle. This type of prediction reacts early enough not only to the shape of the path in front of the machine, but also to the current state of the robot, to make the corrections in time. The results using the controller have been satisfactory allowing the test machines to drive accurately and at full speed along reference paths containing several curves.

SUMMARY

Mobile robots are gradually emerging from research laboratories into real civil applications. Only lately has the technology matured to a level that enables various cost effective outdoor applications. The first commercial applications have been made for the mining environment and for various transporting tasks in harbours and factory areas. The author's work in the area of mobile robotics reflects this same trend during the past decade. The focus of everyday work has shifted from publicly-funded applied research at VTT to commercial product development in a company. The same progress also applies to the publications forming this thesis. The two latest publications cover real life applications, the rest describing mainly the results of projects where only prototypes have been developed to prove that the proposed technology works.

Experience has proven that the last step from a working prototype to a commercial product is surprisingly long. This is caused, especially, by the fact that a mobile robot consists of so many subsystems and sensors that making them work in a reliable manner according to the specifications and at a reasonable cost is extremely challenging.

In many cases, it is practical to automate only part of the whole operation of a mobile robot and handle the most difficult parts by teleoperation. In many cases, this lowers the threshold to apply mobile robots to real work. This is also the case in the mining application of Publication VII where filling the bucket of the LHD is handled by teleoperation.

One of the most important subsystems of a mobile robot is the pose estimation system, which is also the focus of this thesis. The fusion of dead reckoning and beacon detection, in particular, has proven to give good results in various applications from small-scale test machines to heavy mining machines. Various combinations of this technology are described in Publications I - VII. The applications cover the cases of using both artificial and natural beacons. In either case, the environment of the robot has to be modelled. The basic sensors, methods, and algorithms for using a map for pose estimation are covered by this thesis. Publication VII gives an example of the design of a navigation system where the natural environment of the robot is modelled and used for pose estimation.

Once the pose estimation problem is solved, the robot has to be able to follow the required path to the target position. To design a position controller, one has to model the kinematics of the robot. In many cases, a relatively simple position controller is enough to maintain the position and heading error within the required limits (see Publication IV) but, in some cases, the dynamics of the steering have to be taken into account. The literature states very few examples of designing a position controller for high speed navigation. Publication VII contains an outline of a position controller which takes the dynamics of the steering mechanism into account enabling a heavy mining machine to drive autonomously at full speed and follow a predetermined path with high accuracy.

Although real applications of outdoor mobile robots are reaching the commercialisation phase a great deal of research and development work is still going on. The technology for mobile robotics is far from mature. One of the most demanding subsystems required in

most of the cases is a reliable obstacle detection system which is still lacking. Improvement here would require both better sensors and better algorithms for processing sensor data. Another topic would be to increase the intelligence of robots to react in a sensible and predictable way to various situations which the robot has not encountered earlier. For example, if a robot could be able to analyse the nature of an earlier unknown obstacle it could decide whether to cross the obstacle, travel around it or retreat. This type of behaviour would be required for a robot which is exploring an unknown area. In a similar way, a robot could react according to the condition of the ground surface (hard, soft, even, uneven, slippery, etc.). Such ability would be useful in most of the potential applications.

REFERENCES

- Adams, M. (1999) *Sensor Modelling, Design and Data Processing for Autonomous Navigation*. World Scientific, Singapore, 232 p.
- Altafini, C. (1999) A Path-Tracking Criterion for an LHD Articulated Vehicle. *The International Journal of Robotics Research*, vol. 18, no. 5, p. 435-441.
- Andersson, U., Mrozek, K., Hyypä, K., Åström, K. (1997) Path Design and Control Algorithms for Articulated Mobile Robots. *International Conference on Field and Service Robotics (FSR)*, 7-10 December 1997, Canberra Australia, pp. 405-411.
- Ayache, N., Faugeras, O., Faverjon, B. (1984) A Geometrical Matcher for Recognizing and Positioning 3-D Rigid Objects. *SPIE vol. 521, Intelligent Robots and Computer Vision*, pp. 152-159.
- Banta, L. (1987) *Advanced Dead Reckoning Navigation for Mobile Robots*. Ph.D. Dissertation, MHRC Report TD-86-16, Atlanta, Georgia Institute of Technology.
- Besl, P., McKay, N. (1992) A Method for Registration of 3-D Shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 14, no. 2.
- Bettke, M., and Gurvits, L. (1994) Mobile Robot Localization Using Landmarks. *1994 International Conference on Intelligent Robots and Systems (IROS'94)*, pp. 135-142.
- Bloom, B. (1985) Use of Landmarks for Mobile Robot navigation. *SPIE vol. 579 Intelligent Robots and Computer Vision*.
- Bochereau, L., Wolfstein, D., Kanayama, Y. (1987) Simulation of Model-Based Path Planning for a Mobile Robot. *IECON 1987*, pp.137-141.
- Borenstein, J., Everett, H., Feng, L. (1996) *Where am I? Sensors and Methods for Mobile Robot Positioning*. University of Michigan, Technical Report, 282 p.
- Van Brussel, H., Van Helsdingen, C., Machiels, K. (1988) FROG, Free Ranging on Grid: New Perspectives in Automated Transport. *Proceedings, 6th International Conference on Automated Guided Vehicle Systems, Brussels, Belgium*, pp. 223-232.
- Cahut, L., Valavanis, K., Delic, H. (1998) Sonar Resolution-Based Environment Mapping. *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp. 2541-2547.
- Cao, Z., Röning, J., Hall, E. (1986) Omnidirectional Vision Navigation Integrating Beacon Recognition with Positioning. *Proceedings of Mobile Robotics Conference (SPIE Proceedings vol. 727)*, Cambridge, USA, pp. 213-220.

Castellanos, J., Martinez, J., Neira, J., Tardos, J. (1998) Simultaneous Map Building and Localization for Mobile Robots: A Multisensor Fusion Approach. Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 1244-1249.

Chatila, R., Laumond, J-P. (1985) Position Referencing and Consistent World Modeling for Mobile Robots. Proceedings of the 1985 IEEE International Conference on Robotics and Automation, pp. 138-145.

Chenavier, F., Crowley, J. (1992) Position Estimation for a Mobile Robot Using Vision and Odometry. Proceedings of the 1992 IEEE International Conference on Robotics and Automation, pp.2588-2593.

Clark, S., Durrant-Whyte, H. (1998) Autonomous Land Vehicle Navigation Using Millimeter Wave Radar. Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 3697-3702.

Cobb, S. (1997) GPS Pseudolites: Theory, Design, and Applications. Doctoral Dissertation, Stanford University, 166 p.

Corre, J., Garcia, G. (1992) Real Time Determination of the Location and Speed of Mobile Robotics Running on Non-Planar Surfaces. Proceedings of the 1992 IEEE International Conference on Robotics and Automation, pp. 2594-2599.

Cox, I. (1989) Blance: Position Estimation for an Autonomous Robot Vehicle. IEEE/RJS International Workshop on Intelligent Robots and Systems, pp. 223-240.

Crowley, J. (1985) Navigation for an Intelligent Mobile Robot. IEEE Journal of Robotics and Automation, vol. RA-1, no. 1, pp. 31-41.

Crowley, J. (1989) World Modelling and Position Estimation for a Mobile Robot Using Ultrasonic Ranging. Proceedings of the 1989 IEEE International Conference on Robotics and Automation, pp. 674-680.

Crowley, J., Wallner, F., Schiele, B. (1998) Position Estimation Using Principal Components of Range Data. Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 3121-3128.

de Jong, T. (1994) Developing Driverless Straddle Carriers. Terminal operations 94 Conference, Amsterdam, May 1994, London: CS Publications Ltd. 14 p.

Delahoche, L., Pegard, C., Mouaddib, M., Vasseur, P. (1998) Incremental Map Building for Mobile Robot navigation in an Indoor Environment. Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 2560-2565.

DeSantis, R. (1997) Modeling and Path-Tracking for a Load-Haul-Dump Mining Vehicle. Transactions of the ASME, vol 119, March 1997, pp. 40-47.

Dickmanns, E., Mysliwetz, B. (1992) Recursive 3-D Road and Relative Ego-State Recognition. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 14, no. 2, pp. 199-213.

Dickmanns, E. (1997) Improvements in Visual Autonomous Vehicle Guidance 1987-94. Aloimonos, Y. (editor), *Visual Navigation*, LEA, 1997 Mahwah, New Jersey, pp. 375-404.

Drumheller, M. (1987) Mobile Robot Localization Using Sonar. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. Pami-9, no. 2, pp. 325-332.

Dubrawski, A., Siemiatkowska, B. (1998) A Method for Tracking Pose of a Mobile Robot Equipped with a Scanning Laser Range Finder. *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp. 2518-2523.

Dudec, G., Jenkin, M. (2000) *Computational Principles of Mobile Robotics*. Cambridge University Press, 280 p.

Durieu, C., Clergeot, H., Monteil, F. (1989) Localization of a Mobile Robot with Beacons Taking Erroneous Data into Account. *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, pp.1062-1068.

Durrant-Whyte, H. (1994) Where Am I? *Industrial Robot*, vol. 21, no. 2, pp. 11-16.

Durrant-Whyte, H. (1996) An Autonomous Guided Vehicle for Cargo Handling Applications. *International Journal of Robotics Research*, vol. 15, no. 5, pp. 407-441.

Elfes, A. (1987) Sonar-based Real-World Mapping and Navigation. *IEEE Journal of Robotics and Automation*, vol. 3, no 3, pp. 249-265.

Everett, H. (1995) *Sensors for Mobile Robots*, A. K. Peters, Ltd., 528 p.

Everett, H. (1998) Breaking down the Barriers. *Unmanned Vehicles*, vol. 3, no. 1, pp. 18-20.

Feng, L., Fainman, Y., Koren, Y. (1992) Estimation of the Absolute Position of Mobile Systems by an Optoelectronic Processor. *IEEE Transactions on Systems, Man and Cybernetics*, vol. 22, no 5, pp. 953-963.

Fischler, M., Bolles, R. (1981) Random Sample Consensus: A Paradigm for Model Fitting with Application to Image Analysis and Automated Cartography. *Communication AMC*, vol. 24, no. 6, pp. 381-395.

Forsberg, J., Larsson, U., Åhman, P., Wernersson, Å. (1993) The Hough Transform Inside the Feedback Loop of a Mobile Robot. *Proceedings of the 1993 IEEE International Conference on Robotics and Automation*, pp.791-798.

Giralt, G., Chatila, R., Vaisset, M. (1984) An Integrated Navigation and Motion Control System for Autonomous Multisensory Mobile Robots. In Brady, M. and Paul, R.

(editors), 1st International Symposium of Robotics Research, MIT Press, Cambridge, MA, pp. 191-214.

Goldgof, D., Huang, T., Lee, H. (1988) Feature Extraction and Terrain Matching. Proceedings of the 1988 IEEE International Conference on Robotics and Automation, pp. 899-904.

Gonzalez, J., Stentz, A., Ollero, A. (1992) An Iconic Position Estimator for a 2D Laser Rangefinder. Proceedings of the 1992 IEEE International Conference on Robotics and Automation, pp. 2646-2651.

Gonzalez, J., Ollero, A., Reina, A. (1994) Map Building for a Mobile Robot Equipped with a 2D Laser Rangefinder. Proceedings of the 1994 IEEE International Conference on Robotics and Automation, pp. 1904-1909.

Gonzalez, J., Stentz, A., Ollero, A. (1995) A Mobile Robot Iconic Position Estimation Using a Radial Laser Scanner. Journal of Intelligent and Robotic Systems, no. 13, pp. 161-179.

Grimson, W., Lozano-Pérez, T. (1985) Recognition and Localization of Overlapping Parts from Sparse Data in Two and Three Dimensions. Proceedings of International Conference of Robotics and Automation, pp. 61-66.

Guivant J., Nebot E., Durrant-Whyte H. (2000) Simultaneous Localization and Map Building Using Natural Features in Outdoor Environments. IAS-6 Intelligent Autonomous Systems 6, Italy, pp. 581-588.

Hebert, M., Caillas, C., Krotkov, E., Kweon, I., Kanade, T. (1989) Terrain Mapping for a Roving Planetary Explorer. Proceedings of the 1989 IEEE International Conference on Robotics and Automation, pp.997-1002.

Hebert, M., Thorpe, C., Stentz, A. (1997) Intelligent Unmanned Ground Vehicles, Autonomous Navigation Research at Carnegie Mellon. Kluwer Academic Publishers, 309 p.

Holcombe, W., Dickerson, S., Larsen, J., Bohlander, R. (1988) Advances in Guidance Systems for Industrial Automated Guided Vehicles. Proceedings SPIE Mobile Robots III, pp. 288-297.

Hyypä, K. (1989) Method of navigating an automated guided vehicle. US Patent 4811228, March 1989.

Hyypä, K. (1993) On a laser anglemeter for mobile robot navigation. Doctoral thesis, Luleå University of Technology.

Ishimoto, H., Tsubouchi, T., Sarata, S., Yuta, S. (1997) Practical Trajectory Following or an Articulated Steering Type Vehicle. International Conference on Field and Service Robotics (FSR), 7-10 December 1997, Canberra Australia, pp. 412-419.

- Jannok, D., Petersen, M. (1992) Lasernavigering av Midjestyrd Gruvlastare. Examenarbete, Tekniska Högskolan i Luleå, 129 p.
- Jones, S., Andersen, C., Crowley, J. (1997) Appearance Based Processes for Visual Navigation. IROS'97, IEEE/RJS Conference on Intelligent Robotics Systems, pp. 551-557.
- Jurie, F., Rives, P., Gallice, J., Brame, J. (1993) High Speed Vehicle Guidance Based on Vision. Intelligent Autonomous Vehicles (IAV'93), 1993, pp. 203-208.
- Järvelä, V., Mäkelä, H. (1997) Sonic-based 3-D digitizer. Automation Technology Review 1997, VTT Automation, Finland.
- Kanayama, Y., Fahroo, F. (1997) A New Line Tracking Method for Nonholonomic Vehicles. Proceedings of the 1997 IEEE International Conference on Robotics and Automation, pp. 2908-2913.
- Kanayama, Y., Nilipour, A., Lelm, C. (1988) A Locomotion Control Method for Autonomous Vehicles. Proceedings of the 1988 IEEE International Conference on Robotics and Automation, pp. 1315-1317.
- Kanayama, Y., Hartman, B. (1989) Smooth Local Path Planning for Autonomous Vehicles. Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1265-1270.
- Kauppi, I., Seppä, H., Koskinen, K. (1992) Sonic Localization System Using Pseudo Random Noise and Cross-correlation Technique. Second International Conference on Automation, Robotics and computer Vision, ICARV'92, pp. RO-11.3.1-RO-11.3.4.
- Kleeman, L. (1992) Optimal Estimation of Position and Heading for Mobile Robots Using Ultrasonic Beacons and Dead-reckoning. Proceedings of the 1992 IEEE International Conference on Robotics and Automation, pp. 2582-2587.
- Komoriya, K., Tanie, K (1989) Trajectory Design and Control of a Wheel-type Mobile Robot Using B-spline Curve. Proceedings of the IEEE-RJS International Conference on Intelligent Robots and Systems (IROS'89), pp. 398-405.
- Koskinen, K., Halme, A., Tuunanen, A. (1994) Perception and Navigation System for Autonomous Mobile Applications (The Panorama project) – Experiences and Results. Proceedings of the Tampere international conference on machine automation, Tampere, Finland, February 1994, pp. 111-126.
- Krotkov, E. (1989) Mobile Robot Localization Using a Single Image. Proceedings of the 1989 IEEE International Conference on Robotics and Automation, pp. 978-983.
- Lawrence, A. (1998) Modern Inertial Technology, Navigation, Guidance, and Control. Second Edition, Springer Verlag, New York, 280 p.

- Leonard, J., Durrant-Whyte, H. (1991) Mobile Robot Localization by Tracking Geometric Beacons. *IEEE Transaction on Robotics and Automation*, vol. 7, no. 3, pp. 376-382.
- Little, J., Lu, J., Murray, D. (1998) Selecting Stable Image Features for Robot Localization Using Stereo. *Proceedings of the IEEE-RJS International Conference on Intelligent Robots and Systems (IROS)*, pp. 1072-1077.
- Madhavan, R., Dissanayake, M., Durrant-Whyte, H. (1998) Autonomous Underground Navigation of an LHD Using a Combined ICP-EKF Approach. *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp.3703-3708.
- Maybeck, P. (1982) *Stochastic Models, Estimation, and Control. Volume 1*, Academic Press, New York, 423 p.
- McGillem, C., Rappaport, T. (1988) Infra-red Location System for Navigation of Autonomous Vehicles. *Proceedings of the 1988 IEEE International Conference on Robotics and Automation*, pp. 1236-1238.
- Miller, R. (1988) *Mobile Robots, Emerging Industries*, no. 1. Technical Insights Inc., New York, USA, 283 p.
- Moravec, H. (1977) Towards Automatic Visual Obstacle Avoidance. *Proceedings of 5th International Joint Conference on Artificial Intelligence (IJCAI)*, Cambridge, MA, p. 584.
- Moravec, H., Elfes, A. (1985) High Resolution Maps from Wide-Angle Sonar. *Proceedings of the 1985 IEEE International Conference on Robotics and Automation*, pp. 116-121.
- Moravec, H. (1988) Sensor Fusion in Certainty Grids for Mobile Robots. *AI Magazine* 9 (2), pp. 61-74.
- Nelson, W., Cox, I. (1988) Local Path Control for an Autonomous Vehicle. *Proceedings of the 1988 IEEE International Conference on Robotics and Automation*, pp. 1504-1510.
- Newman, P. (1999) *On the Structure and Solution of the Simultaneous Localisation and Map Building Problem*. PhD Thesis, Australian Centre of Field Robotics, The University of Sydney, March 1999.
- Nilsson, N. (1969) *A Mobile Automation: An Application of Artificial Intelligence Techniques*. *Proceedings IJCAI*, pp. 509-520.
- Poggio, T. (1984) Vision by Man and Machine. *Scientific America*, vol. 250, no. 4, pp. 106-116.
- Polotski, V., Bakambu, J., Wu, W., Cohen, P. (2000) Guideless Navigation System for Underground Mining Vehicles: Architecture and Experimental Setup. *International Symposium on Robotics (ISR 2000)*, pp. 380-385.

- Rathbone, R., Valley, R., Kindlmann, P. (1986) Beacon-Referenced Dead Reckoning: A Versatile Guidance System. *Robotics Engineering*, December 1986, pp. 11-16.
- Rintanen, K. (1993) Curvature-Optimal Path Planning and Servoing for Autonomous Vehicles. A Neural Net Implementation, 1st IFAC International Workshop on Intelligent Autonomous Systems, Southampton, England, pp. 571-476.
- Riseman, E., Hanson, A., Beveridge, J., Kumar, R., Sawhney, H. (1997) Landmark-Based Navigation and the Acquisition of Environmental Models. In Aloimonos, Y. (editor), *Visual Navigation*, Lawrence Erlbaum Associates, New Jersey, USA, pp. 317-374.
- Samson, C. (1993) Time-varying Feedback Stabilization of Car-like Wheeled Mobile Robots. *The International Journal of Robotics Research*, vol. 12, no 1, pp. 55-64.
- Scheuer, A., Laugier, C. (1998) Planning Sub-Optimal and Continuous-Curvature Paths for Car-Like Robots. *Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Victoria, Canada, pp. 25-31.
- Schiele, B., Crowley, J. (1994) A Comparison of Position Estimation techniques Using Occupancy Grids. *Proceeding of the IEEE International Conference on Robotics and Automation*, pp. 1628-1634.
- Schulz, A., Adams, W. (1998) Continuous Localization Using Evidence Grids. *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp. 2833-2839.
- Shaffer, G. (1995) Two-Dimensional mapping of Expansive Unknown Areas. *Doctoral Thesis*, The Robotics Institute, Carnegie Mellon University, Pittsburgh, USA, 114 p.
- Shaffer, G., Stentz, A., Whittaker, W., Fitzpatrick, K. (1992) Position Estimator for Underground Mine Equipment. *IEEE Transactions on Industry Applications*, vol. 28, no. 5.
- Shin, D., Singh, S., Lee, J. (1990) Path Generation for Robot Vehicles Using Composite Clothoid Segments. *CMU, The Robotics Institute, Technical Report*, 29 p.
- Shin, D., Singh, S., Lee, J. (1992) Explicit Path Tracking by Autonomous Vehicles. *Robotica*, vol. 10, pp 539-554.
- Sim, R., Dudek, G. (1999) Learning Visual Landmarks for Pose Estimation. *Proceeding of the 1999 IEEE International Conference on Robotics and Automation*, pp. 1972-1978.
- Stein, F., Medioni, G. (1995) Map-Based Localization Using the Panoramic Horizon. *IEEE Transaction on Robotics and Automation*, 11(6), pp. 892-896.
- Stephens, P. (1987) Vehicle Guidance and Control System. U.S. Pat. no. 4,647,784, dated Mar. 3, 1987, General Electric Company p.l.c. of England.

Stone, J., LeMaster, E., Powell, J., Rock, S. (1999) GPS Pseudolite Transceivers and their Applications. ION National Technical Meeting, San Diego, CA, USA, January 25-27, 12 p.

Thorpe, C. E. (ed.) (1990) Vision and Navigation for the Carnegie Mellon Navlab. Kluwer Academic Publishers, Boston, USA, 370 p.

Thrun, S. (1998) Finding Landmarks for Mobile Robot Navigation. Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 958-963.

Transport & Hantering (2001) no. 8, pp. 44-46.

Tsumura, T., Okubo, H., Komatsu, N. (1993) A 3-D Positioning and Attitude Measurement System Using Laser Scanners and Corner Cubes. IEEE International Conference on Intelligent Robots and Systems, Yokohama, Japan, pp. 604-611.

Zhang, Z. (1994) Iterative Point Matching for Registration of Free-Form Curves and Surfaces. International Journal of Computer Vision, vol. 12, no. 2, pp. 119-152.

Ziegler, C., Schlemmer, H. (1995) Static and Kinematic 3D-Point-Determination with a Local Positioning System. The Role of Models in Automated Scene Analysis Joint Workshop of ISPRS WG III/2 and IC WG II/III, August 30 - September 1, 1995, Stockholm, Sweden, pp. 343-351.

Åström, K. (1993) Automatic Mapmaking. Intelligent Autonomous Vehicles (IAV), IFAC Workshop, Southampton, pp. 179-184.

Weiss, G., Puttkamer, E. (1995) A Map Based on Laserscans Without Geometric Interpretation. Intelligent Autonomous Systems, U. Rembold et al. (Eds.). IOS Press, pp. 405-407.

Wernersson, Å., Wiklund, U., Andersson, U., Hyypä, K. (1989) Vehicle Navigation Using "Image Information". Intelligent Autonomous Systems 2, An International Conference, Amsterdam, pp. 814-822.

Wiklund, U., Andersson, U., Hyypä, K. (1988) AGV Navigation by Angle Measurements. Proceedings of 6th International Conference on Automated Guided Vehicle Systems, pp. 199-212.

Wilcox, B., Gennery, D., Mishkin, A., Cooper, B., Lawton, T., Lay, K., Katzmann, S. (1987) A Vision System for a Mars Rover. Proceedings SPIE Mobile Robots II, pp. 172-179.

Williamson, T., Thorpe, C. (1999) A Trinocular Stereo System for Highway Obstacle Detection. Proceedings of the 1999 IEEE International Conference on Robotics and Automation, pp. 2267-2273.

Wolfe, W., Marquina, N. (editors) (1986), Proceedings SPIE Mobile Robots II, vol. 852.

www.qnav.se, Q-Navigator www-pages, 16.4.2000.

Publication I

Publication II

Publication III

Publication IV

Publication V

Publication VI

Publication VII