STUDIES IN *FUZZINESS*
AND *SOFT COMPUTING*

Studies in Fuzziness and Soft Computing

Nick Barnes
Zhi-Qiang Liu

# Knowledge-Based Vision-Guided Robots

Physica-Verlag
A Springer-Verlag Company

Nick Barnes
Zhi-Qiang Liu

# Knowledge-Based Vision-Guided Robots

With 99 Figures
and 3 Tables





Physica-Verlag
A Springer-Verlag Company

Dr. Nick Barnes
University of Melbourne
Department of Computer Science
and Software Engineering
3010 Victoria
Australia
nmb@cs.mu.oz.au

Professor Zhi-Qiang Liu
City University of Hong-Kong
School of Creative Media
Tat Chee Ave., Kowloon
Hong Kong
P. R. China
zliu@cs.mu.oz.au

ISSN 1434-9922
ISBN 3-7908-1494-6 Physica-Verlag Heidelberg New York

Library of Congress Cataloging-in-Publication Data applied for
Die Deutsche Bibliothek – CIP-Einheitsaufnahme
Barnes, Nick: Knowledge based vision guided robots: with 3 tables / Nick Barnes; Zhi-Qiang Liu. – Heidelberg; New York: Physica-Verl., 2002
(Studies in fuzziness and soft computing; Vol. 103)
ISBN 3-7908-1494-6



Physica-Verlag Heidelberg New York
a member of BertelsmannSpringer Science+Business Media GmbH


Printed in Germany



Hardcover Design: Erich Kirchner, Heidelberg

SPIN 10876877 88/2202-5 4 3 2 1 0 – Printed on acid-free paper

Knowledge-Based
Vision-Guided Robots

# Studies in Fuzziness and Soft Computing

**Editor-in-chief**
Prof. Janusz Kacprzyk
Systems Research Institute
Polish Academy of Sciences
ul. Newelska 6
01-447 Warsaw, Poland
E-mail: kacprzyk@ibspan.waw.pl
http://www.springer.de/cgi-bin/search_book.pl?series=2941

---

Further volumes of this series can be found at our homepage.

Vol. 83. S. Barro and R. Marín (Eds.)
*Fuzzy Logic in Medicine, 2002*
ISBN 3-7908-1429-6

Vol. 84. L.C. Jain and J. Kacprzyk (Eds.)
*New Learning Paradigms in Soft Computing, 2002*
ISBN 3-7908-1436-9

Vol. 85. D. Rutkowska
*Neuro-Fuzzy Architectures and Hybrid Learning, 2002*
ISBN 3-7908-1438-5

Vol. 86. M.B. Gorzałczany
*Computational Intelligence Systems and Applications, 2002*
ISBN 3-7908-1439-3

Vol. 87. C. Bertoluzza, M.Á. Gil and D.A. Ralescu (Eds.)
*Statistical Modeling, Analysis and Management of Fuzzy Data, 2002*
ISBN 3-7908-1440-7

Vol. 88. R.P. Srivastava and T.J. Mock (Eds.)
*Belief Functions in Business Decisions, 2002*
ISBN 3-7908-1451-2

Vol. 89. B. Bouchon-Meunier, J. Gutiérrez-Ríos, L. Magdalena and R.R. Yager (Eds.)
*Technologies for Constructing Intelligent Systems 1, 2002*
ISBN 3-7908-1454-7

Vol. 90. B. Bouchon-Meunier, J. Gutiérrez-Ríos, L. Magdalena and R.R. Yager (Eds.)
*Technologies for Constructing Intelligent Systems 2, 2002*
ISBN 3-7908-1455-5

Vol. 91. J.J. Buckley, E. Eslami and T. Feuring
*Fuzzy Mathematics in Economics and Engineering, 2002*
ISBN 3-7908-1456-3

Vol. 92. P.P. Angelov
*Evolving Rule-Based Models, 2002*
ISBN 3-7908-1457-1

Vol. 93. V.V. Cross and T.A. Sudkamp
*Similarity and Compatibility in Fuzzy Set Theory, 2002*
ISBN 3-7908-1458-X

Vol. 94. M. MacCrimmon and P. Tillers (Eds.)
*The Dynamics of Judicial Proof, 2002*
ISBN 3-7908-1459-8

Vol. 95. T.Y. Lin, Y.Y. Yao and L.A. Zadeh (Eds.)
*Data Mining, Rough Sets and Granular Computing, 2002*
ISBN 3-7908-1461-X

Vol. 96. M. Schmitt, H.-N. Teodorescu, A. Jain, A. Jain, S. Jain and L.C. Jain (Eds.)
*Computational Intelligence Processing in Medical Diagnosis, 2002*
ISBN 3-7908-1463-6

Vol. 97. T. Calvo, G. Mayor and R. Mesiar (Eds.)
*Aggregation Operators, 2002*
ISBN 3-7908-1468-7

Vol. 98. L.C. Jain, Z. Chen and N. Ichalkaranje (Eds.)
*Intelligent Agents and Their Applications, 2002*
ISBN 3-7908-1469-5

Vol. 99. C. Huang and Y. Shi
*Towards Efficient Fuzzy Information Processing, 2002*
ISBN 3-7908-1475-X

Vol. 100. S.-H. Chen (Ed.)
*Evolutionary Computation in Economics and Finance, 2002*
ISBN 3-7908-1476-8

Vol. 101. S.J. Ovaska and L.M. Sztandera (Eds.)
*Soft Computing in Industrial Electronics, 2002*
ISBN 3-7908-1477-6

Vol. 102. B. Liu
*Theory and Praxis of Uncertain Programming, 2002*
ISBN 3-7908-1490-3

# Acknowledgements

The authors would like to thank members of technical services of the department, particularly, John Horvath, Andrew Peel, Thomas Weichert, and David Hornsby, for keeping robots and cameras going, despite our best efforts to burn, crash, and destroy them in anyway possible.

Nick Barnes would also like to thank Andrew Howard, Sandy Dance, and Les Kitchen for the challenging research discussions. Thank-you to my family, Betty, Barry, Lisa and Dale for supporting me in this strange enterprise called research. Also, my other family John and Wendy for support, encouragement and Sunday dinners. Finally to Nina, the greatest person whom I know. Her inspiration is a great source of strength to me. Her support of everything that I do makes challenges seem easy. Her company makes problems seem trivial. Her smile makes everything else seem unimportant. Her writing and editing skills have improved this book beyond recognition. Without her help this book would never be completed.

*. . . if there were machines which bore a resemblance to our body and imitated our actions as far as it was morally possible to do so, we should always have two very certain tests by which to recognise that, for all that, they were not real men.*
R. Descarte. circa 1628. [95][1]

*I possessed the capacity of bestowing animation, yet to prepare a frame for the reception of it, with all its intricacies of fibres, muscles, and veins, still remained a work of inconceivable difficulty and labour.*
Frankenstein. Mary Shelley, 1818. [201]

*. . . to manufacture artificial workers is the same thing as to manufacture motors. The process must be of the simplest, and the product of the best from a practical point of view.*
R. U. R. (Rossum's Universal Robots). (English translation) Karel Capek, 1923. [39]

[1] See conclusion full text.

# Contents

# Chapter 1

# Introduction

Robots have been a subject of philosophical inquiry and a source of literary inspiration for hundreds of years. It is only since this century that robots have emerged out of fiction and philosophy into the real world. Today robots are common-place, for instance, fixed-location robotic arms now tirelessly perform precise repetitive tasks for industry. However, robots still have significant limitations. Specifically, most industrial robots require the parts they operate on to be precisely aligned, and mobile robots that move around in an environment are still largely confined to academic research laboratories. Clearly, there is a need for a more advanced generation of robots that can react to unexpected events, and can complete complex tasks under less controlled conditions. To facilitate the advancement, systems must be developed that enable robots to perceive and understand their environment.

Perhaps the greatest potential benefit to humanity that robots can provide is to alleviate the need for humans to regularly perform tasks in dangerous environments, such as underground mines, underwater, in space, and in hazardous industrial environments. In such applications, robots can perform not only the tasks that humans currently undertake, but also handle operations that are too dangerous for individuals. The Soujourner Mars robot [158] gathered valuable information from the surface of Mars. This mission could not be carried out by humans as the craft was never to return to earth. As well, anti-personnel mines kill and maim civilians, but removing them is dangerous, hence robots could play an invaluable role in demining [168]. Finally, cleaning up in the aftermath of natural and human-made disasters (e.g., Chernobyl [159]) create highly dangerous environments for humans; these are environments where robots could excel.

In order to facilitate more advanced applications, robots need to be capable of more flexible autonomy than is currently possible. Robots need to be able to seek out and operate on target objects. This will enable tasks such as finding and removing dangerous objects (e.g., mines and nuclear material) returning to base stations and docking, and performing operations on objects that are dangerous for humans to access.

As a basis for such operations, robots require means for identifying and operating on specific objects. This book aims to take an initial step along this path, by constructing a framework to enable the robot to identify particular objects, when other similar objects may be present, and then navigate around the required objects. Importantly, the robot must have a knowledge of its approximate position with respect to the object. We call this task *circumnavigation*. This research is primarily concerned with autonomous robot navigation applications that require high-level perception to support their operation.

## 1.1 Background

Autonomous mobile robots are machines that are able to move around freely in a manner appropriate for their environment, with respect to some general goals. Control of the robot's movement in an environment is generally referred to as navigation. The earliest autonomous mobile robot was built by Dr. Grey Walter in the 1940's [230]. However, research in developing mobile robots as an end in itself began in earnest in the late 1960's with the development of vision-based robots such as 'Shakey' [169]. Recently, decreases in hardware costs have led to a flourish of research in robotics.

### 1.1.1 A vision-guided approach

Many types of sensors have been used by researchers as a basis for mobile robot perception. This book focuses almost exclusively on *vision-based sensors* that produce an image of light intensity values. Extensive discussion of other forms of sensors can be found in [75].

This book is directed at autonomous robot navigation applications that require high-level perception, for tasks such as uniquely identifying an object, when other similar objects are also visible. For such tasks, vision offers advantages in the type and amount of information it recovers in good lighting conditions. Sensors such as sonar are insensitive at a fine resolution, laser-range finders, and radar-like sensors can extract structural detail at a finer resolution, but cannot recover non-structural data, such as regions of different colour or reflective properties. Also, tactile sensors restrict operations by requiring physical contact.

### 1.1.2 Computer vision and vision-guided mobile robots

At present, research on *Computer Vision* and on *Vision-Guided Robot Navigation* forms an inadequate basis for the tasks required. When vision is used to guide robots, researchers often emphasise the use of techniques that are specialised to a particular application. Other more general vision techniques developed by the computer vision community, on the other hand, are too slow to be practically useful for mobile robot navigation.

Current research on vision guided-robotics often applies specific techniques for particular problems. For example, in road-following vehicles, systems such as that in [45] make assumptions [129] which are highly specific to road following. Some other mobile robot systems use only low-level features directly from the image, such as colour [196]. Little use has been made of high-level aspects of computer vision, such as three-dimensional (3D) object recognition, that are appropriate for large classes of problems and situations.

Computer vision methods are generally considered to be too cumbersome for real-world applications. This is a serious problem with most high-level techniques from traditional computer vision, where systems may often take minutes to complete processing a single image. This is clearly untenable for navigation where the robot has to move continuously. To maintain a speed of 10 cm/sec, a robot will often need to process a single image in a few seconds at most, and often multiple frames need to be processed per second. Slow processing may be acceptable only in exceptional circumstances.

Historically, most research in computer vision has been aimed at off-line systems, where an image is taken of an object or scene, from an unexpected, arbitrary angle that may be close to or far from the object. In particular, high-level vision often focuses mainly on the extraction of symbolic descriptions, and pays little attention to the speed of processing. The emphasis has been on exhaustive exploration of available image data. In many cases, researchers assume human intervention at stages that are impossible for an autonomous robotic system. For example, the shape-from-shading techniques assume that reflectance and lighting models are given, or that some of the surface normals are preset by manual intervention to offer boundary conditions [24].

### 1.1.3 Applying high-level computer vision to guide mobile robots

In order to apply high-level computer vision to robot navigation, methods that have fast response time, and can be used autonomously, are required. The methods must not rely on human intervention during operation. However, navigation does not require *general* computer vision. There are also additional constraints which follow from the fundamental differences between what is required in traditional computer vision, and what is required for robotic vision. Many differences follow from the fact that the camera is physically mounted on the robot, and the robot moves in a constrained way under its own control. This is referred to as *embodiment* [137]. Rather than having an isolated image from a random point in space, typically, a series of images are taken as the robot moves deliberately in continuous space. Systems utilising such differences need not be *ad-hoc*, but may be valid for a class of mobile robots.

This book aims to apply techniques from high-level vision for the purpose of mobile robot navigation. It is not adequate to take traditional high-level vision techniques and apply them to images from the camera of a mobile robot. Particular attention must be paid to reformulating the traditional vision methods to be appropriate for applications in mobile robot navigation. This book presents an operational robot system for navigating around objects. It also presents versions of high-level computer vision methods such as object recognition and shape-from-shading that have been designed specifically for robot navigation.

## 1.2 Aims of the Research Presented in this Book: A Problem in Robot Vision

The aim of this book is to develop computer vision methods that enable the robot to perform the following tasks:

1. The robot is required to be able to uniquely identify a single, specific known object placed randomly in an indoor environment

in which there may be other objects.

2. The robot must be able to move around the object maintaining a constant knowledge of its position relative to the object.

3. The robot is expected to be able to identify an object that cannot be uniquely distinguished from surrounding objects by simple features such as colour.

4. The robot is expected to be able to distinguish objects that have similar structure.

5. Edge-based matching of an object may not always be adequate; the robot must be able to distinguish objects based on surface shape.

6. The robot must be able to move around a corner of an object, so that all the object features that are initially visible become occluded, and new object surfaces are visible.

7. The robot cannot assume any prior knowledge of the object's position in the environment. It may not assume that it is facing any particular object surface. However, it may assume that the object is in the camera field of view.

8. The system should process each image of the scene within a few seconds, except in exceptional circumstances, such as recognising the object for the first time.

9. The system should be able to initially recognise the object from a large range of locations around it, although it is acceptable for the robot to misidentify based on a single view, as long this error is corrected once the robot has moved.

10. The robot is assumed to be ground-based, however, the methodology applied should not preclude extension into full 3D robot motion.

## 1.3 The Approach of this Book

In order to uniquely identify objects in the environment, it is necessary to compare robot sensor data to some form of object model. This book uses knowledge-based and model-based approaches to perception for mobile robots. The approach uses a model of required objects, and knowledge of the robot and camera, environment, and task required.

The system presented uses high order features, particularly edges and shapes, for object recognition. Such features are necessary to give the robot the discriminating power required. The approach here does not preclude supplementing these features with additional features such as colour and texture where necessary. However, these additional features are not used in the experiments in this book.

Vision is used primarily, as active sensors may not be adequate for distinguishing structurally similar objects. Also, to overcome the difficulties of discriminating objects with similar wire-frames, this book presents a method for verification of shape for candidate edge-based matches.

The proposed approach does not use methods of active vision, such as optical flow or visual servoing. Such methods are currently unable to handle occlusion of all visible surfaces. It is the author's belief that some form of model is required to allow the robot to recognise new surfaces that appear as part of the object.

Although, the approach assumes to know properties of the environment, it does not require a map of the environment in any form. Further, this book is concerned with the problems of navigation given an object model. It does not consider the problem of learning object models.

Finally, a vision-guided mobile robot must be able to translate perceptions to actions via motors. We examine the use of fuzzy control for this task.