

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative Evaluation

David Lee

Frontmatter

[More information](#)

**The Map-Building and Exploration Strategies of a  
Simple Sonar-Equipped Mobile Robot**

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative Evaluation

David Lee

Frontmatter

[More information](#)

## Distinguished Dissertations in Computer Science

Edited by

C.J. van Rijsbergen, University of Glasgow

The Conference of Professors of Computer Science (CPCS), in conjunction with the British Computer Society (BCS), selects annually for publication up to four of the best British PhD dissertations in computer science. The scheme began in 1990. Its aim is to make more visible the significant contribution made by Britain – in particular by students – to computer science, and to provide a model for future students. Dissertations are selected on behalf of CPCS by a panel whose members are:

C.B. Jones, Manchester University (Chairman)

S. Abramsky, Imperial College, London

D.A. Duce, Rutherford Appleton Laboratory

M.E. Dyer, University of Leeds

G. Nudd, University of Warwick

V.J. Rayward-Smith, University of East Anglia

Ian Wand, University of York

M.H. Williams, Heriot-Watt University

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative Evaluation

David Lee

Frontmatter

[More information](#)

---

## THE MAP-BUILDING AND EXPLORATION STRATEGIES OF A SIMPLE SONAR-EQUIPPED ROBOT

---

An Experimental, Quantitative Evaluation

DAVID LEE

*Department of Engineering Science  
University of Oxford*



**CAMBRIDGE**  
UNIVERSITY PRESS

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative Evaluation

David Lee

Frontmatter

[More information](#)

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE  
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS

The Edinburgh Building, Cambridge CB2 2RU, UK  
40 West 20th Street, New York NY 10011-4211, USA  
477 Williamstown Road, Port Melbourne, VIC 3207, Australia  
Ruiz de Alarcón 13, 28014 Madrid, Spain  
Dock House, The Waterfront, Cape Town 8001, South Africa

<http://www.cambridge.org>

© Cambridge University Press 1996

This book is in copyright. Subject to statutory exception  
and to the provisions of relevant collective licensing agreements,  
no reproduction of any part may take place without  
the written permission of Cambridge University Press.

First published 1996

First paperback edition 2003

*A catalogue record for this book is available from the British Library*

ISBN 0 521 57331 9 hardback

ISBN 0 521 54215 4 paperback

# Contents

Preface	xi
<b>1 Question, Context and Method</b>	<b>1</b>
1.1 The Question - What is This Thesis About? . . . . .	1
1.2 The Context - Why Make Maps? . . . . .	1
1.3 The Method - How Will the Question be Addressed? . . . . .	6
1.4 Contributions . . . . .	9
<b>I Starting Points</b>	<b>11</b>
<b>2 Maps Used in Previous Research</b>	<b>13</b>
2.1 Is an Environment Model Necessary? . . . . .	14
2.1.1 What is a model? . . . . .	14
2.1.2 The Significance of State . . . . .	14
2.1.3 Robustness and Flexibility . . . . .	16
2.2 Model Types - The Strength Hierarchy . . . . .	17
2.2.1 Recognisable Locations . . . . .	18
2.2.2 Topological Maps . . . . .	19
2.2.3 Metric Topological Maps . . . . .	20
2.2.4 Full Metric Maps . . . . .	21
2.3 Biologically-Inspired Models . . . . .	24
2.4 Conclusions . . . . .	26
<b>3 The Maps Used in This Research</b>	<b>27</b>
3.1 The Application . . . . .	27
3.2 The Impact of the Application on the Choice of Map . . . . .	28
3.2.1 The Robot <i>Does</i> Need a World Model . . . . .	28
3.2.2 The Robot Needs a Metric Map . . . . .	29
3.2.3 The Robot Needs a Free-Space Map . . . . .	29
3.2.4 The Robot Will Use a 2-Dimensional Map . . . . .	29
3.2.5 The Free-Space Map Will Use a Regular Grid . . . . .	29

3.2.6	The Grid-Based Map will be Derived from a Feature-Based Map . . . . .	30
3.3	Probabilistic Grid Maps and Feature Maps . . . . .	30
3.3.1	Ambiguity About The Use of Probability . . . . .	30
3.3.2	Premature Use of Probability . . . . .	31
3.3.3	No Modelling of Data Dependence . . . . .	33
3.3.4	Premature Loss of Precision . . . . .	34
3.4	Why Build Maps? . . . . .	34
<b>4</b>	<b>Approaches to Exploration</b>	<b>37</b>
4.1	The Wall-Following Boom . . . . .	38
4.2	Go Where It's Interesting . . . . .	40
4.3	The Approach in this Thesis . . . . .	45
<b>II</b>	<b>System Components</b>	<b>47</b>
<b>5</b>	<b>The Robot</b>	<b>49</b>
5.1	Hardware . . . . .	50
5.2	Software . . . . .	51
5.2.1	Communications Controller . . . . .	51
5.2.2	Sonar Controller . . . . .	52
5.2.3	Movement Controller . . . . .	52
5.2.4	Memory-Mapped Interface . . . . .	54
5.2.5	Collision Detection . . . . .	54
<b>6</b>	<b>Modelling the Sonar Sensor</b>	<b>55</b>
6.1	The Polaroid Ultrasonic Sensor . . . . .	56
6.2	Experimental Evaluation . . . . .	57
6.3	Proposed Sonar Model . . . . .	59
6.4	Other Types of Object . . . . .	61
6.5	Summary . . . . .	69
<b>7</b>	<b>Map Construction</b>	<b>71</b>
7.1	Detecting Potential Features . . . . .	72
7.2	Clustering Potential Features . . . . .	76
7.3	Updating Existing Features . . . . .	78
7.4	Free Space . . . . .	79
7.4.1	Unknown Cells . . . . .	79
7.4.2	Occupied Cells . . . . .	79
7.4.3	Free Cells . . . . .	80
7.4.4	Dangerous Cells . . . . .	82
7.5	Map Construction in Practice . . . . .	83
7.6	Conclusion . . . . .	83

*Contents*

vii

<b>8 Path Planning</b>	<b>87</b>
8.1 The Basic Idea . . . . .	88
8.2 Implementation . . . . .	90
8.3 Path Smoothing . . . . .	93
8.4 Conclusion . . . . .	94
<b>9 Localisation</b>	<b>97</b>
9.1 An Outline of the Process . . . . .	98
9.2 The Plant Model . . . . .	99
9.3 The Measurement Model . . . . .	100
9.4 Applying the Extended Kalman Filter . . . . .	102
9.5 Conclusion . . . . .	103
<b>10 Map Quality Metrics</b>	<b>105</b>
10.1 Requirements of a Metric . . . . .	106
10.1.1 The Metric Must Be Clearly-Defined . . . . .	106
10.1.2 The Metric Must Be Multi-Valued . . . . .	107
10.1.3 The Metric Must Reflect the Purpose of the Map . . . . .	107
10.1.4 The Metric Must be Applicable <i>During</i> Exploration . . . . .	107
10.1.5 The Metric Must Balance Coverage and Detail . . . . .	108
10.2 Do We Need an Omniscient Observer? . . . . .	108
10.3 Quality Metrics used In Previous Research . . . . .	109
10.4 The Measure to Be Used in This Work . . . . .	111
10.4.1 How Are The Test Journeys Selected? . . . . .	111
10.4.2 How Are The Paths Evaluated? . . . . .	112
10.4.3 How Are The Results Summarised And Used? . . . . .	113
10.5 How Good Is This Metric? . . . . .	114
10.5.1 Does This Metric Satisfy Our Criteria? . . . . .	114
10.5.2 Why Not Just Measure Free Space? . . . . .	114
10.5.3 What About False Positives? . . . . .	116
10.6 Conclusion . . . . .	117
<b>III Experiments</b>	<b>119</b>
<b>11 Experimental Evaluation</b>	<b>121</b>
11.1 The Choice of Exploration Cost Measure . . . . .	122
11.2 Tests for Statistical Significance . . . . .	124
11.2.1 Paired Readings . . . . .	124
11.2.2 Unpaired Readings . . . . .	125
<b>12 Wall-Following</b>	<b>127</b>
12.1 Implementation . . . . .	127

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative

Evaluation

David Lee

Frontmatter

[More information](#)

12.2 Experiments . . . . .	130
12.3 Conclusions . . . . .	133
<b>13 The Results of Localisation</b>	<b>135</b>
13.1 Setting the Uncertainty Parameters . . . . .	136
13.2 Experimental Results . . . . .	138
13.3 Wall-Following in More Cluttered Environments . . . . .	140
13.3.1 Map Quality and Environmental Complexity . . . . .	142
13.4 Tuning the Confirmation Threshold . . . . .	145
13.5 Conclusion . . . . .	145
<b>14 Supervised Wall-Following</b>	<b>147</b>
14.1 Shortcomings of Wall-Following . . . . .	147
14.2 Implementation . . . . .	150
14.2.1 Avoiding Traps . . . . .	150
14.2.2 Skipping Past Known Objects . . . . .	151
14.2.3 Avoiding Fruitless Examinations . . . . .	151
14.2.4 The Algorithm . . . . .	153
14.3 Experiments . . . . .	153
14.4 Conclusions . . . . .	158
<b>15 Can a Human Do Any Better?</b>	<b>159</b>
15.1 Motivation . . . . .	159
15.2 Procedure . . . . .	159
15.3 Experiments . . . . .	160
15.4 Conclusions . . . . .	162
<b>16 Longest Lines of Sight</b>	<b>163</b>
16.1 Motivation . . . . .	163
16.2 Implementation . . . . .	163
16.3 Experiments . . . . .	164
16.4 Conclusions . . . . .	171
<b>17 Free Space Boundaries</b>	<b>173</b>
17.1 Motivation . . . . .	173
17.2 Implementation . . . . .	173
17.3 Experiments . . . . .	176
17.4 Conclusions . . . . .	184
<b>18 Summary of Experimental Results</b>	<b>187</b>
18.1 The Sensor Model . . . . .	187
18.2 The Feature Map . . . . .	188
18.3 Exploration Strategies . . . . .	189

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative Evaluation  
David Lee  
Frontmatter  
[More information](#)

*Contents*

ix

<b>19 Conclusions</b>	<b>197</b>
19.1 The Ultrasonic Sensor Model . . . . .	197
19.2 The Feature-Based and Area-Based Maps . . . . .	198
19.3 Localisation . . . . .	198
19.4 The Map Quality Metric . . . . .	198
19.5 Model-Based and Sensor-Based Navigation . . . . .	199
<b>20 Directions for Further Research</b>	<b>201</b>
20.1 Mixing Planning and Reactive Navigation . . . . .	201
20.2 An Evolving Exploration Strategy . . . . .	202
20.3 Different Sensors . . . . .	202
20.4 Eliminating Ambiguities and Inconsistencies . . . . .	204
<b>A The Feature-Map Data Structure</b>	<b>205</b>
<b>B Test Rooms</b>	<b>210</b>
<b>C Finding the Best-Fit Line</b>	<b>215</b>
<b>D ARNE's Standard Dialogue</b>	<b>217</b>
<b>Bibliography</b>	<b>219</b>
<b>Index</b>	<b>226</b>

Cambridge University Press

0521542154 - The Map-Building and Exploration Strategies of a Simple Sonar-Equipped Robot: An Experimental, Quantitative Evaluation

David Lee

Frontmatter

[More information](#)

## Preface

This book is the product of my PhD research at University College London. I am grateful to the many people and organisations that have made my research both possible and enjoyable. I have benefited greatly from the companionship and support of all of my colleagues in the Computer Science and Anatomy departments during the course of this work. The following paragraphs can only recognise some of the more direct contributions.

Many thanks are due to Michael Recce for his enthusiastic and constructive supervision. Michael has been generous with his time, his ideas, and his lab space. I am also indebted to Michael for his careful reading of draft versions of this document and his valuable suggestions about its style and content.

Jim Donnett has made many much-appreciated contributions to this work, ranging from hardware design and debugging through to a detailed reading of the thesis. Jim's breadth and depth of knowledge have been invaluable, and his friendship and sense of humour have helped me through some trying moments.

I owe a great deal to Clive Parker for the construction of my robot, ARNE. Thanks to Clive's electronic and mechanical skills, a loose collection of components was transformed into an effective research tool.

David Brown of the Statistics Department kindly took the time to advise me about the statistical analysis of my results, despite having been 'volunteered' for the job. His insight and suggestions were most welcome.

John Greenwood contributed greatly to this work by forcing me to set deadlines during my writing-up and then carefully reading the chapters I produced.

Financial support is, of course, always welcome and I would like to thank the Engineering and Physical Sciences Research Council for their funding during this work.

This thesis is being published as part of the 1995 Distinguished Dissertations Scheme. I am very grateful to all of the judges for making this possible. My thanks are also due to Professor Keith van Rijsbergen, the series editor, and to David Tranah at Cambridge University Press for leading me by the hand through the preparations for publication.

Above all, I thank Melanie for more types of support and encouragement than I could possibly list here. Without her, this work would never have happened.