Distinguished Dissertations

Springer

London

Berlin

Heidelberg

New York

Barcelona

Hong Kong

Milan

Paris

Singapore

Tokyo

Other titles published in this Series:

Search and Planning Under Incomplete Information: A Study Using Bridge Card Play
Ian Frank

Theorem Proving with the Real Numbers
John Harrison

*Hardware Evolution: Automatic Design of Electronic Circuits in Reconfigurable Hardware
by Artificial Evolution*
Adrian Thompson

User-Developer Cooperation in Software Development
Eamonn O'Neil

*A Combination of Geometry Theorem Proving and Nonstandard Analysis, with Application
to Newton's Principia*
Jacques Fleuriot

Accurate Visual Metrology from Single and Multiple Uncalibrated Images
Antonio Criminisi

Asynchronous System-on-Chip Interconnect
John Bainbridge

John MacCormick

Stochastic Algorithms for Visual Tracking

**Probabilistic Modelling and Stochastic Algorithms
for Visual Localisation and Tracking**

Springer

John MacCormick
Systems Research Center, Compaq Computer Corporation, 130 Lytton Avenue,
Palo Alto, CA 94301-1044, USA

Series Editor

Professor C.J. van Rijsbergen
Department of Computing Science, University of Glasgow, G12 8RZ, UK

British Library Cataloguing in Publication Data

MacCormick, John

Stochastic algorithms for visual tracking. - (Distinguished
dissertations)

1.Computer vision - Mathematical models 2. Algorithms

3.Stochastic processes

I.Title

006.3'7

ISBN-13: 978-1-4471-1176-4

e-ISBN-13: 978-1-4471-0679-1

DOI: 10.1007/978-1-4471-0679-1

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress.

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publishers.

Distinguished Dissertations ISSN 1439-9768

ISBN-13: 978-1-4471-1176-4 Springer-Verlag London Berlin Heidelberg

a member of BertelsmannSpringer Science+Business Media GmbH

<http://www.springer.co.uk>

© Springer-Verlag London Limited 2002

Softcover reprint of the hardcover 1st edition 2002

The use of registered names, trademarks etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant laws and regulations and therefore free for general use.

The publisher makes no representation, express or implied, with regard to the accuracy of the information contained in this book and cannot accept any legal responsibility or liability for any errors or omissions that may be made.

Typesetting: Camera-ready by author

34/3830-543210 Printed on acid-free paper SPIN 10868264

Preface

Computer vision is hard. One way to make progress on hard problems is to develop a coherent mathematical theory which describes them. This book develops one such theory for the field of visual tracking, using probabilistic models and stochastic algorithms. In an applied science like computer vision, however, theory is of little use without practice. Hence, the book also demonstrates the use of this theory in real visual tracking systems.

The stochastic algorithms employed here — variously known as “particle filters”, or the “Condensation algorithm” — are introduced in Chapter 2 via a formulation based on sequences of weighted particles. The properties of the particle filter are proved rigorously, yet presented in a manner intended to be accessible to a general computer vision audience. Chapter 3 introduces the other essential ingredient for visual tracking: a set of probabilistic models for object localisation. These models, called “contour likelihoods”, are based on the statistical properties of image features. Chapter 4 explains the use of contour likelihoods in localisation and tracking problems, and Chapter 5 uses Markov random fields to generalise the contour likelihood for modelling the occlusion of foreground objects. Contour likelihoods can also be derived for collections of more than one object. Chapter 6 shows how such derivations lead to an “exclusion principle” which enables the successful tracking of foreground objects which occlude each other. Finally, Chapter 7 introduces the technique of “partitioned sampling”, which dramatically reduces the computational expense of particle filters in certain problems. As in the previous chapters, I have tried to prove the results in a rigorous yet accessible manner. Readers equipped with a basic knowledge of mathematics, engineering, or computer science will have no difficulty in following the text.

This book arose from my Ph.D. thesis at the University of Oxford. My greatest debt is to Andrew Blake, who was my Ph.D. supervisor; he provided many ideas and much insight. I am also indebted to my colleagues at the Oxford Visual Dynamics Laboratory during the late 1990s: Benedicte Bascle, Colin Davidson, Jonathan Deutscher, Michael Isard, Bob Kaucic, Ben North, Jens Rittscher, Josephine Sullivan, and Andrew Wildenberg. Michael deserves a special vote of thanks because he wrote a lot of the code that I used and was also a very good friend. Many other people helped to keep me sane or were nice to me even when they realised they were failing in this goal; among them are Bear and Christie Bolton, Paul Harvey and his family, Andy Marsham, Jon Scammon, and everyone from OUHC.

For financial support, I am very grateful to the trustees of the Eliot Davis Memorial Scholarship, the trustees of the Jowett Scholarship, and the European Union IMPROOFS grant. Three Oxford colleges — Exeter, Balliol, and Linacre — have assisted me, and I am grateful to each for its generosity. The Systems Research Center of Compaq Computer Corporation supported me during the preparation of the manuscript, and the British Computer Society enabled its publication.

My family all live far away but are close in other ways. In fact they probably helped out much more than they realised, and I would especially like to thank Mum, Dad, Andrew, Jude and G&G, P&B, JGJS&A, RLVSK&L. The book is dedicated to my parents, with love and respect.

John MacCormick
Palo Alto, California
January, 2002

Contents

1	Introduction and background	1
1.1	Overview	2
1.2	Active contours for visual tracking	3
1.2.1	Splines and shape space	4
1.2.2	Dynamical models using auto-regressive processes	5
1.2.3	Measurement methodology	6
2	The Condensation algorithm	8
2.1	The basic idea	8
2.2	Formal definitions	11
2.2.1	Technical detail: convergence of distribution-valued distributions	14
2.2.2	The crucial definition: how a particle set represents a distribution	15
2.3	Operations on particle sets	16
2.3.1	Multiplication by a function	17
2.3.2	Applying dynamics	18
2.3.3	Resampling	20
2.4	The Condensation theorem	24
2.5	The relation to factored sampling, or “where did the proof go?”	25
2.6	“Good” particle sets and the effective sample size	26
2.6.1	The survival diagnostic	28
2.6.2	From effective sample size to survival diagnostic	31
2.6.3	Estimating the weight normalisation	33
2.6.4	Effective sample size of a resampled set	33
2.7	A brief history of Condensation	35
2.8	Some alternatives to Condensation	37
3	Contour likelihoods	38
3.1	A generative model for image features	38
3.1.1	The generic contour likelihood	42
3.1.2	The Poisson likelihood	45
3.1.3	The interior-exterior likelihood	46
3.1.4	The order statistic likelihood	49
3.1.5	The contour likelihood ratio	50
3.1.6	Results and examples	51

3.2	Background models and the selection of measurement lines . . .	54
3.2.1	Discussion of the background model	55
3.2.2	Independence of measurement lines	55
3.2.3	Selection of measurement lines	57
3.3	A continuous analogue of the contour likelihood ratio	60
3.3.1	The continuous model	60
3.3.2	Likelihoods for H_O and H_B	62
3.3.3	Problems with the continuous ARP model	63
4	Object localisation and tracking with contour likelihoods	65
4.1	A brief survey of object localisation	65
4.2	Object localisation by factored sampling	68
4.2.1	Results	70
4.2.2	Interpretation of the gradient threshold	73
4.3	Estimating the number of targets	75
4.4	Learning the prior	79
4.5	Random sampling: some traps for the unwary	80
4.6	Tracker initialisation by factored sampling	84
4.6.1	Kalman filter tracker	85
4.6.2	The Condensation tracker	85
4.7	Tracking using Condensation and the contour likelihoods	86
4.7.1	The robustified colour contour likelihood	86
4.7.2	Implementation of a head tracker	89
5	Modelling occlusions using the Markov likelihood	92
5.1	Detecting occluded objects	92
5.2	The problem with the independence assumption	94
5.3	The Markov generative model	95
5.4	Prior for occlusions	96
5.5	Realistic assessment of multiple targets	99
5.5.1	Explanation of results	99
5.5.2	Experimental details	100
5.6	Improved discrimination with a single target	102
5.7	Faster convergence using importance sampling	103
5.8	Random samples using MCMC	107
5.9	Calculating the partition functions	109
5.10	Further remarks	110
6	A probabilistic exclusion principle for multiple objects	112
6.1	Introduction	112
6.2	A generative model with an exclusion principle	114
6.2.1	Description of the generative model	114
6.2.2	Likelihoods derived from the generative model	115
6.2.3	Where does the “exclusion principle” come from?	116
6.2.4	The full likelihood	118
6.3	Tracking multiple wire-frame objects	118

6.4 Tracking multiple opaque objects	119
7 Partitioned sampling	124
7.1 The need for partitioned sampling	124
7.2 Weighted resampling	127
7.3 Basic partitioned sampling	130
7.4 Branched partitioned sampling	131
7.5 Performance of partitioned sampling	133
7.6 Partitioned sampling for articulated objects	134
7.6.1 Results: a vision-based drawing package	138
8 Conclusion?	144
Appendix A	146
A.1 Measures and metrics on the configuration space	146
A.2 Proof of the interior-exterior likelihood	147
A.3 Del Moral's resampling lemma and its consequences	149
Appendix B	153
B.1 Summary of notation	153
Bibliography	155
Index	165