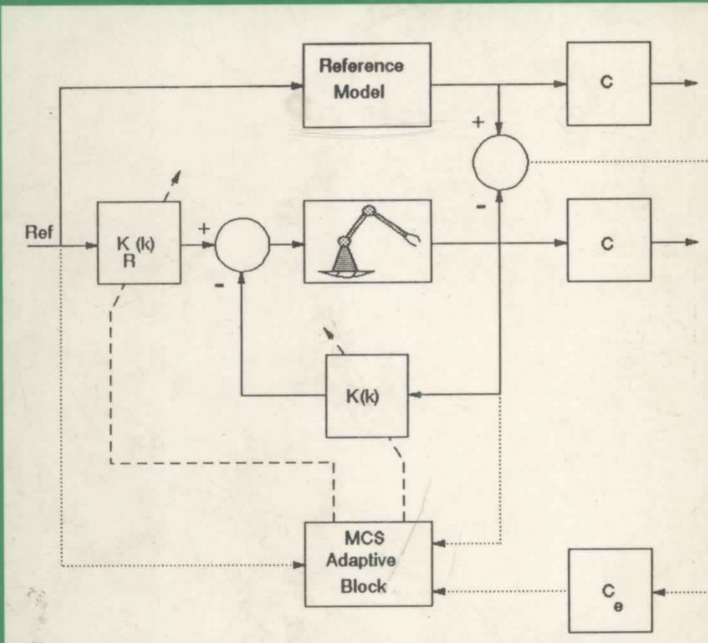
Model Reference Adaptive Control of Manipulators

D. P. STOTEN



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RESEARCH STUDIES PRESS LTD.
Taunton, Somerset, England

JOHN WILEY & SONS INC.
New York · Chichester · Toronto · Brisbane · Singapore

RESEARCH STUDIES PRESS LTD.
24 Belvedere Road, Taunton, Somerset, England TA1 1HD

Marketing and Distribution:

Australia and New Zealand:
Jacaranda-Wiley Ltd.
GPO Box 859, Brisbane, Queensland 4001, Australia

Canada:
JOHN WILEY & SONS CANADA LIMITED
22 Worcester Road, Rexdale, Ontario, Canada

Europe, Africa, Middle East and Japan:
JOHN WILEY & SONS LIMITED
Baffins Lane, Chichester, West Sussex, England

North and South America:
JOHN WILEY & SONS INC.
605 Third Avenue, New York, NY 10158, USA

South East Asia:
JOHN WILEY & SONS (SEA) PTE LTD.
37 Jalan Pemimpin 05-04
Block B Union Industrial Building, Singapore 2057

Library of Congress Cataloging-in-Publication Data

Stoten, D. P., 1952–
Model reference adaptive control of manipulators / D. P. Stoten.
p. cm.—(Mechanical engineering research studies.
Engineering control series : 5)
Includes bibliographical references.
ISBN 0-86380-097-1.—ISBN 0-471-92623-X (Wiley)
1. Manipulators (Mechanism) 2. Adaptive control systems.
I. Title. II. Series.
TJ211.35.S76 1990
629.8′36—dc20 89-24263
CIP

British Library Cataloguing in Publication Data

Stoten, D. P. (David Paul), *1952–*
Model reference adaptive control of manipulators.
1. Industral robots. Manipulators. Control. Applications
of computer systems
I. Title II. Series
629.8′92

ISBN 0 86380 097 1
ISBN 0 471 92623 X U.S.

ISBN 0 86380 097 1 (Research Studies Press Ltd.)
ISBN 0 471 92623 X (John Wiley & Sons Inc.)

Printed in Great Britain by Galliard (Printers) Ltd., Great Yarmouth

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To Cristina and Chiara

Series Editor's Preface

Problems generated by the automation of machines and process plant, especially during the last decade, have stimulated widespread interest in the modelling and control of robotic devices. Many of the control algorithms which have been presented in learned journals and conference proceedings have failed to gain acceptance because of the difficulty, and in some cases impossibility, of implementation. These practical limitations are frequently associated with too stringent sensor requirements or the need for excessive computation: therein lies the motivation for the author's work.

The last decade has seen significant advances in the theory and application of adaptive control systems. Dr Stoten has played a significant role in this activity, particularly on Model Reference Adaptive Control (MRAC) where he has been concerned with developing the Minimal Controller Synthesis (MCS) algorithm and applying it to the problem of manipulator control. This book represents a snapshot, taken at the beginning of 1989, of a research programme which is still progressing. The themes running throughout the book are: is the control algorithm robust?; is it pragmatic?; does it solve engineering problems?; is it easy to implement?

A unified modelling technique for MRAC design of manipulators is presented, together with detailed applications of MRAC and MCS algorithms on a number of devices. Realistic simulation results indicate that the algorithms show substantial improvements over conventional control designs, as predicted by the theoretical results of Chapter 6.

Dr Stoten has adopted a continuous-time framework for control system and plant analysis and synthesis. However, virtually all control implementations are considered to be of a discrete-time nature, which are derived from the original continuous-time approach. He is not alone in believing that the most efficient analysis and synthesis techniques are naturally in continuous-time!

Professor C R Burrows
University of Bath
November 1989

Foreword

The purpose of this monograph is to convey some of my recent research on the control of mechanical manipulators. The work is complete to the stage of confirming the robustness of the Model Reference Adaptive Control (MRAC) and Minimal Controller Synthesis (MCS) algorithms applied to manipulators. Robustness is confirmed analytically, and by realistic non-linear simulation techniques. However, the work is not entirely complete, in the sense that the MRAC and MCS algorithms have yet to be implemented on real manipulators (although very successful implementations have been reported, by myself and co-workers, on other machines). Such are the problematical features of research - when to publish? I believe that this monograph is complete to the point indicated and the *intention* of paving the way to novel, implementable, and powerful controllers, is satisfied.

I would particularly wish to emphasise the robustness proofs of MRAC and MCS in Chapter 6, and the excellent results from the closed-loop simulation studies of Chapter 5. The MCS algorithm can be viewed as a significant extension to the MRAC algorithm, and has been developed by the author over the last year.

The dynamic modelling of manipulators takes second place to the concepts of adaptive control; this is intentional. Some of the dynamic models are quite complicated, in an algebraic sense, and I would not be surprised to have errors (in proof-reading!) reported back to me. If Mathematica was available at the time of writing, I would have used it to generate the model dynamics. No doubt this package would have helped me with some of the tedious expansions in Chapter 6, too. I am not concerned with 'high-level' controls in this monograph - such as trajectory planning, machine intelligence and so on. The prime motive is to present 'low-level' direct controller algorithms which have the potential of providing very robust closed-loop control of manipulator motions. If this 'low-level' (*sic*) control is inadequate, then I am of the opinion that 'high-level' control strategies are worthless.

The word 'robot' has been virtually unused in this monograph, since I believe it to be a too emotive term, and perhaps evocative of fictitious devices. The word 'manipulator', which is used extensively here, is a precise description of the type of machine under investigation.

As for the readership, I believe that some of the chapters have a tutorial content which would be of use to undergraduates on mechanical, electrical and associated engineering degree courses. However, my main objective is to provide a research monograph for those intent on the study of MRAC and MCS algorithms, in the field of manipulator control. If any of the ideas are taken up and used in practice, then my objectives in writing this monograph will have been satisfied.

I am indebted to the Department of Mechanical Engineering, University of Bristol, for providing resources (of many kinds) which culminated in this monograph. Professor Clifford Burrows of Bath University deserves special thanks for ensuring that something was written in the first place! I also wish to thank my research student, Hacine Benchoubane, for many fruitful discussions on MRAC/MCS robustness. Finally, I am particularly grateful to Maggie Watts for her patient use of ChiWriter, and all the shift key-strokes required, in processing this material.

D P Stoten
University of Bristol
June 1989

Notation

The following is a list of the main symbols used in this text, together with a brief description of their significance. I have tried to maintain a conventional use of symbols, but I am aware that, at times, the use of super- and sub-scripts has led to rather cumbersome formulations. Normally, subscripts (in general, i) refer to a particular link of a manipulator, whereas superscripts refer to certain sub-blocks within matrix descriptions of dynamical systems.

a: entry in matrix A

b: entry in matrix B

c: viscous friction coefficient

e: state error

f: force; disturbance

f_o: observer estimate of disturbances

g: gravity constant

g_c: gravity compensation

k: motor gain; sampling instant (integer)

k_D: derivative gain

k_m: motor/amplifier/gearbox gain

k_p: proportional gain

l: length

m: mass

m_e: external disturbance mass

q: generalised force

r: reference signal

s: Laplace (complex) variable

t: time

t_s: settling time

u: control signal

w: adaptive loop signal; angular velocity vector

w_e: $w_e = -w$

x: state vector

x_I: integral of output error

x_L: generalised coordinate vector

x_m: reference model state

y: output (controlled) variable

y_m: reference model output

z: z-transform (complex) variable

A: plant matrix

A_m: reference model plant matrix

B: plant input matrix; term in general Lyapunov equation

B_m: reference model input matrix

C: plant output matrix; viscous friction matrix

C_e: state error output matrix

D: 'centrifugal' force matrix; term in general Lyapunov equation

E: Coriolis force matrix; term in general Lyapunov equation

F: gravity force matrix; general positive-definite matrix; non-linear function of state

F': general positive semi-definite matrix

G: transfer function; general positive-definite matrix; Luenberger observer gain matrix

G_c: controller transfer function

G_p: plant transfer function

H: controller feedback transfer function

I: identity matrix

J: inertia

K: feedback gain matrix

K_I: integral gain matrix

K_L: external force matrix

K_R: feedforward gain matrix

L: length; Lagrangian

M: inertia matrix; general positive-definite matrix

M': general positive semi-definite matrix

N: number of links; general positive-definite matrix

P: positive-definite solution to Lyapunov equation

Q: positive-definite, right-hand side term in Lyapunov equation

T: kinetic energy

U: potential energy

X: parameter matrix

α: integral adaptive algorithm gain

β: proportional adaptive algorithm gain

γ: Popov constant

δ: change (in parameters, gains)

ε: output error

ζ: damping ratio

θ: angle

λ: eigenvalue

ρ: ratio of entries in A and B matrices

σ: term in adaptive algorithm

ϕ_1: integral term in adaption laws

ϕ_2: proportional term in adaption laws

χ: nonlinear state vector

ψ_1: integral term in adaption laws

ψ_2: proportional term in adaption laws

ω_n: natural frequency

Γ: term in solution to Lyapunov equation

Δ: sampling interval

Θ: term in solution to Lyapunov equation

Ψ: term in solution to Lyapunov equation

$\mathcal{Z}$: z-transform operator

$||x||$: Frobenius norm of x

$\wedge$: (superscript): estimate

T: (superscript): transpose

$\dagger$: (superscript): pseudo-inverse

-: (superscript): steady-state value

-: (subscript): vector in 3-dimensional, orthogonal, space

Abbreviations

CLCE: closed-loop characteristic equation

LMRC: linear model reference control

LO: Luenberger observer

MCS: minimal controller synthesis

MRAC: model reference adaptive controller

OFC: output-feedback control

OFCIE: output-feedback control with integral of error

PID: proportional-plus-integral-plus-derivative

P+DFB: proportional-plus-derivative feedback

P+I: proportional-plus-integral

SFC: state-feedback control

SFCIE: state-feedback control with integral of error

STC: self-tuning control

Contents