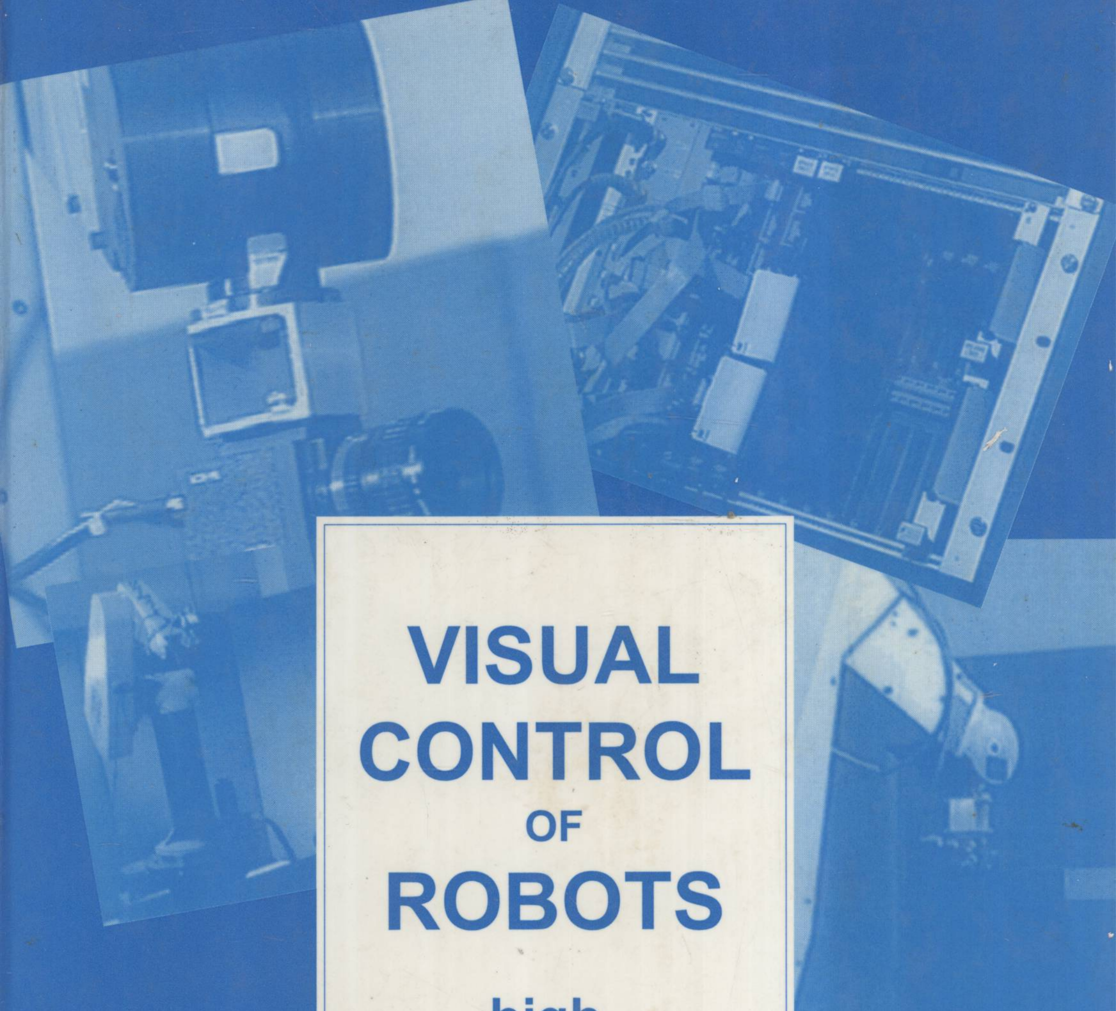

VISUAL CONTROL OF ROBOTS

high-performance visual servoing

Peter I. Corke

Visual Control of Robots:

high-performance visual servoing

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Visual Control of Robots: high-performance visual servoing

ROBOTICS AND MECHATRONICS SERIES

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1. Making Complex Machinery Move: automatic programming and motion planning
   David A. Sanders

2. Visual Control of Robots: high-performance visual servoing
   Peter I. Corke

To my family, Phillipa, Lucy and Madeline.

Editorial foreword

It is no longer necessary to explain the word 'mechatronics'. The world has become accustomed to the blending of mechanics, electronics and computer control. That does not mean that mechatronics has lost its 'art'.

The addition of vision sensing to assist in the solution of a variety of problems is still very much a 'cutting edge' topic of research. Peter Corke has written a very clear exposition which embraces both the theory and the practical problems encountered in adding vision sensing to a robot arm.

There is great value in this book, both for advanced undergraduate reading and for the researcher or designer in industry who wishes to add vision-based control.

We will one day come to expect vision sensing and control to be a regular feature of mechatronic devices from machine tools to domestic appliances. It is research such as this which will bring that day about.

John Billingsley
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Toowoomba, QLD4350
August 1996

Author's Preface

Outline

This book is about the application of high-speed machine vision for closed-loop position control, or visual servoing, of a robot manipulator. The book aims to provide a comprehensive coverage of all aspects of the visual servoing problem: robotics, vision, control, technology and implementation issues. While much of the discussion is quite general the experimental work described is based on the use of a high-speed binary vision system with a monocular 'eye-in-hand' camera.

The particular focus is on accurate high-speed motion, where in this context 'high speed' is taken to mean approaching, or exceeding, the performance limits stated by the robot manufacturer. In order to achieve such high-performance I argue that it is necessary to have accurate dynamical models of the system to be controlled (the robot) and the sensor (the camera and vision system). Despite the long history of research in the constituent topics of robotics and computer vision, the system dynamics of closed-loop visually guided robot systems has not been well addressed in the literature to date.

I am a confirmed experimentalist and therefore this book has a strong theme of experimentation. Experiments are used to build and verify models of the physical system components such as robots, cameras and vision systems. These models are then used for controller synthesis, and the controllers are verified experimentally and compared with results obtained by simulation.

Finally, the book has a World Wide Web home page which serves as a virtual appendix. It contains links to the software and models discussed within the book as well as pointers to other useful sources of information. A video tape, showing many of the experiments, can be ordered via the home page.

Background

My interest in the area of visual servoing dates back to 1984 when I was involved in two research projects; video-rate feature extraction[1], and sensor-based robot control. At that time it became apparent that machine vision could be used for closed-loop control of robot position, since the video-field rate of 50 Hz exceeded the position setpoint rate of the Puma robot which is only 36 Hz. Around the same period Weiss and Sanderson published a number of papers on this topic [224–226,273] in particular concentrating on control strategies and the direct use of image features — but only in simulation. I was interested in actually building a system based on the feature-extractor and robot controller, but for a number of reasons this was not possible at that time.

[1] This work resulted in a commercial unit — the APA-512 [261], and its successor the APA-512+ [25]. Both devices are manufactured by Atlantek Microsystems Ltd. of Adelaide, Australia.

In the period 1988–89 I was fortunate in being able to spend 11 months at the GRASP Laboratory, University of Pennsylvania on a CSIRO Overseas Fellowship. There I was able to demonstrate a 60 Hz visual feedback system [65]. Whilst the sample rate was high, the actual closed-loop bandwidth was quite low. Clearly there was a need to more closely model the system dynamics so as to be able to achieve better control performance. On return to Australia this became the subject of my PhD research [52].

Nomenclature

The most commonly used symbols used in this book, and their units are listed below. Note that some symbols are overloaded in which case their context must be used to disambiguate them.

$\underline{v}$	a vector	
$\underline{v}_x$	a component of a vector	
$\mathbf{A}$	a matrix	
$\hat{x}$	an estimate of x	
x	error in x	
x_d	demanded value of x	
$\mathbf{A}^T$	transpose of A	
α_x, α_y	pixel pitch	pixels/mm
B	viscous friction coefficient	N.m.s/rad
$\mathbf{C}$	camera calibration matrix (3×4)	
$\mathbf{C}(\underline{q}, \dot{\underline{q}})$	manipulator centripetal and Coriolis term	kg.m^2/s
ceil(x)	returns n, the smallest integer such that $n \geq x$	
E	illuminance (lux)	lx
f	force	N
f	focal length	m
F	f-number	
$F(\dot{q})$	friction torque	N.m
floor(x)	returns n, the largest integer such that $n \leq x$	
G	gear ratio	
ϕ	luminous flux (lumens)	lm
ϕ	magnetic flux (Webers)	Wb
$\mathbf{G}$	gear ratio matrix	
$\mathbf{G}(\underline{q})$	manipulator gravity loading term	N.m
i	current	A
$\mathbf{I}_n$	$n \times n$ identity matrix	
j	$\sqrt{-1}$	
J	scalar inertia	kg.m^2

$\mathbf{J}$	inertia tensor, 3×3 matrix	$kg.m^2$
$^A\mathbf{J}_B$	Jacobian transforming velocities in frame A to frame B	
k, K	constant	
K_i	amplifier gain (transconductance)	A/V
K_m	motor torque constant	N.m/A
$\mathcal{K}\{\}$	forward kinematics	
$\mathcal{K}^{-1}\{\}$	inverse kinematics	
L	inductance	H
L	luminance (nit)	nt
m_i	mass of link i	kg
$\mathbf{M}(\underline{q})$	manipulator inertia matrix	$kg.m^2$
Ord()	order of polynomial	
$\underline{q}$	generalized joint coordinates	
$\underline{Q}$	generalized joint torque/force	
R	resistance	Ω
θ	angle	rad
$\underline{\theta}$	vector of angles, generally robot joint angles	rad
s	Laplace transform operator	
$\underline{s}_i$	COM of link i with respect to the link i coordinate frame	m
$\underline{S}_i$	first moment of link i. $\underline{S}_i = m_i \underline{s}_i$	kg.m
σ	standard deviation	
t	time	s
T	sample interval	s
T	lens transmission constant	
T_e	camera exposure interval	s
$\mathbf{T}$	homogeneous transformation	
$^A\mathbf{T}_B$	homogeneous transform of point B with respect to the frame A. If A is not given then assumed relative to world coordinate frame 0. Note that $^A\mathbf{T}_B = \left(^B\mathbf{T}_A\right)^{-1}$.	
τ	torque	N.m
τ_C	Coulomb friction torque	N.m
v	voltage	V
ω	frequency	rad/s
$\underline{x}$	3-D pose, $\underline{x} = [x\ y\ z\ r_x\ r_y\ r_z]^T$ comprising translation along, and rotation about the X, Y and Z axes.	
x, y, z	Cartesian coordinates	
X_0, Y_0	coordinates of the principal point	pixels
$^ix, {}^iy$	camera image plane coordinates	m
$^iX, {}^iY$	camera image plane coordinates	pixels
$^i\underline{X}$	camera image plane coordinates $^i\underline{X} = ({}^iX, {}^iY)$	pixels
^iX	image plane error	

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

The following conventions have also been adopted:

- Time domain variables are in lower case, frequency domain in upper case.
- Transfer functions will frequently be written using the notation

$$K(a)[\zeta, \omega_n] = K\left(\frac{s}{a}+1\right)\left[\frac{1}{\omega_n^2}s^2+\frac{2\zeta}{\omega_n}s+1\right]$$

  A free integrator is an exception, and (0) is used to represent s.

- When specifying motor motion, inertia and friction parameters it is important that a consistent reference is used, usually either the motor or the load, denoted by the subscripts m or l respectively.

  For numeric quantities the units radm and radl are used to indicate the reference frame.

- In order to clearly distinguish results that were experimentally determined from simulated or derived results, the former will always be designated as 'measured' in the caption and index entry.
- A comprehensive glossary of terms and abbreviations is provided in Appendix A.

Acknowledgements

The work described in this book is largely based on my PhD research [52] which was carried out, part time, at the University of Melbourne over the period 1991–94. My supervisors Professor Malcolm Good at the University of Melbourne, and Dr. Paul Dunn at CSIRO provided much valuable discussion and guidance over the course of the research, and critical comments on the draft text.

That work could not have occurred without the generosity and support of my employer, CSIRO. I am indebted to Dr. Bob Brown and Dr. S. Ramakrishnan for supporting me in the Overseas Fellowship and PhD study, and making available the necessary time and laboratory facilities. I would like to thank my CSIRO colleagues for their support of this work, in particular: Dr. Paul Dunn, Dr. Patrick Kearney, Robin Kirkham, Dennis Mills, and Vaughan Roberts for technical advice and much valuable discussion; Murray Jensen and Geoff Lamb for keeping the computer systems running; Jannis Young and Karyn Gee, the librarians, for tracking down all manner of references; Les Ewbank for mechanical design and drafting; Ian Brittle's Research Support Group for mechanical construction; and Terry Harvey and Steve Hogan for electronic construction. The PhD work was partially supported by a University of Melbourne/ARC small grant. Writing this book was partially supported by the Cooperative Research Centre for Mining Technology and Equipment (CMTE), a joint venture between AMIRA, CSIRO, and the University of Queensland.

Many others helped as well. Professor Richard (Lou) Paul, University of Pennsylvania, was there at the beginning and made facilities at the GRASP laboratory available to me. Dr. Kim Ng of Monash University and Dr. Rick Alexander helped in discussions on camera calibration and lens distortion, and also loaned me the SHAPE system calibration target used in Chapter 4. Vision Systems Ltd. of Adelaide, through their then US distributor Tom Seitzler of Vision International, loaned me an APA-512 video-rate feature extractor unit for use while I was at the GRASP Laboratory. David Hoadley proof read the original thesis, and my next door neighbour, Jack Davies, fixed lots of things around my house that I didn't get around to doing.

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