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Foreword

The field of computer vision has its sights set on nothing less than enabling computers to see. This monumental challenge has absorbed many creative minds over the course of more than three decades. A basic premise held by the computer vision community is that vision may be understood in precise computational terms, and that doing so raises the possibility of engineering camera-equipped computer systems with human-like perceptual abilities. Once envisioned only in science fiction, powerful machine vision systems are now more than ever poised to become science fact. This is due in part to the advent of increasingly potent microprocessors, as predicted by Moore's law, and in part to the slow but steady unraveling, on multiple scientific fronts, of the mystery that is visual perception in living systems.

Model-based vision is a major trend in the field that approaches computational problems attendant to vision using mathematical models. To see familiar objects as normal people evidently do with ease, computer vision systems must be able to analyze object shape and motion in real time. To this end, in the early 1980s, my colleagues and I introduced a family of mathematical models, known as "deformable models". The motivation was to formulate visual models that unify the representation of shape and motion by combining geometry and physics; in particular, free-form (spline) geometry and the dynamics of elastic curves, surfaces, and solids. We anticipated that deformable models would lead to vision systems capable of interpreting video sequences in terms of rigid and nonrigid objects moving before the camera. Perhaps the simplest deformable model, deformable contours confined to the plane, also known as "active contours" or "snakes", quickly gained popularity following early public demonstrations of these contours actively conforming to the shapes and tracking the motions of object boundaries in video sequences.

I have admired Andrew Blake and his work for many years. His contribution to computer vision is undeniable. A very readable author, Blake's book on *Visual Reconstruction* has become a classic in the field. It gives me great pleasure to see the concept of active contours developed to the remarkable degree evident in this, his latest book, which is authored with his talented student, Michael Isard.

In a characteristically no-nonsense, mathematically solid treatment, Blake and Isard take the subject of active contours to new heights of theoretical sophistication and practical application. The latter addresses the difficult task of visually tracking the motions of a variety of complex objects captured by a video camera feeding a frame-rate video digitizer. The impressive technical achievement of the book is a novel, probabilistic interpretation of active contours built on a geometric substrate that combines B-spline curve bases with shape spaces defined by global deformations. This combination leads to a new class of very fast and highly robust (non-Gaussian) active contour propagation algorithms. Another noteworthy achievement is the ability of these new tracking algorithms to learn the complex motions of specific objects through observation, thereby automatically tuning the tracker with greater selectivity to objects of interest, further enhancing its robustness.

This book defines the state-of-the-art of contour-based object tracking algorithms. It is required reading for anyone interested in computer vision theory and in the design of working computer vision systems.

Demetri Terzopoulos
November, 1997

Preface

In the seventies and eighties, interest in Computer Vision was concentrated on the development of general purpose seeing machines. There was wide agreement on research priorities, developing "bottom-up" computer algorithms that would organise the raw intensity values in images into a more compact form. The purpose of this was not just to compress the data but also to extract its salient features. Salient features could include corners, edges and surface fragments, to be used in identifying objects and deducing their positions. However, experience suggests strongly that general purpose vision is too difficult a goal for the time being.

If general purpose vision is abandoned, what alternative approach could be taken? One answer is that generality can be abated by introducing some "prior" knowledge — knowledge that is specific to the objects that the computer is expected to see. An extreme form of this approach is exemplified by automatic visual inspection machines of the kind used on factory assembly lines. In that context, it is known in advance precisely what objects are to be inspected — it is rare, after all, for potatoes streaming along a conveyor to give way, without notice, to a crop of spanners or chocolate bars. When computer hardware and software are specialised entirely to deal with one object, phenomenal performance can be obtained. A striking example is the "Niagara" machine (Sortex, UK Ltd) for sorting rice grains which "sees" 70,000 grains every second and almost literally spits out the rejects.

It is a commonly held view that it is hard to make progress in research by building such specialised machines because general principles are lost to engineering detail. That is a fair point but by no means, in our view, outlaws the use of prior knowledge about shape in computer vision research. Instead, we would argue, scientific principles for representing prior knowledge need to be developed. Then, when a new problem area is addressed, the principles can be applied to "compile" a new vision system as rapidly as possible. This includes such issues as how to represent classes of shapes that are defined loosely. Potatoes, for instance, might be characterised as roundish but with substantial size variations, with or without knobs. On the other hand, the class of human faces could be represented in terms of a common basic layout, but with considerable variation in the sizes and separations of features. Modelling classes of shapes, their variability and their motion is one of the principal themes of the book. The use of those models to help interpret moving images is the other central theme.

We have tried to present ideas about shape and motion in a way that will be readable not only by specialists, but also by those who are not regularly immersed in the ideas of machine vision. In particular we would hope that those with backgrounds in graphics or signal processing or neural computing would find the book a useful and accessible guide.

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Glossary of notation

SYMBOL	MEANING	see page
$\hat{x}$	an *estimate* for the quantity x	
$\tilde{x}$	a *prediction* of the quantity x	
$\dot{x}$	*temporal derivative* of x	
$\mathbf{x} \cdot \mathbf{y}$	scalar product of vectors $\mathbf{x}$, $\mathbf{y}$	
$\|\cdot\|$	norm for functions/curves	47,58
$\langle \cdot, \cdot \rangle$	inner product for functions/curves	47,58
$A \otimes B$	Kronecker product of matrices A, B	282
^{T}	superscript denoting vector/matrix transpose	
$\mathbf{0}$	vector of zeros, of length N_B	
$\mathbf{1}$	vector of ones, of length N_B	
A	deterministic coefficient matrix in discrete dynamical model	204
A_1, A_2	components of A	204
$\mathbf{B}(s)$	vector of B-spline blending functions	44
B_0	stochastic coefficients in second-order discrete dynamical model	204
B	stochastic coefficient matrix in discrete dynamical model	193, 204
$\mathcal{B}$	metric matrix for B-spline functions	50
$B_m(s)$	mth B-spline blending function	43
C	covariance coefficient $C = BB^T$	242
d	order of spline polynomial	
$\mathcal{E}[Y]$	expectation of a random variable Y	294
H	observation matrix for Kalman filter	216

SYMBOL	MEANING	see page
$\mathcal{H}$	metric matrix for curves in shape-space $\mathcal{S}$	79
$\mathbf{h}(s)$	image measurement matrix for recursive curve-fitting	124
I_r	$r \times r$ identity matrix	
$K(t), \mathcal{K}(t)$	Kalman gain	216
k	index for discrete time $t_k = k\tau$	
κ	length factor for search lines	174
L	no. of spans on B-spline curve	45
M	no. of frames in a training sequence $\mathbf{X}_1, \ldots \mathbf{X}_M$	175
N	no. of sampled image features along a B-spline curve	124
N_B	no. of control points on B-spline curve	43
N_Q	dimension of spline space	66
N_X	dimension of configuration space (shape-space) $\mathcal{S}$	69
$\mathcal{N}(\overline{\mathbf{X}}, P)$	multi-variate Gaussian (normal) distribution	296
$\mathbf{n}(s,t)$	image-curve normal	122
ν_i	innovation due to ith image feature	124
P, P', P''	covariance components for shape $\hat{\mathbf{X}}(t)$	218
$\mathcal{P}(t)$	covariance of state $\hat{\mathcal{X}}(t)$	204, 213
$\tilde{\mathcal{P}}(t_k)$	covariance of predicted state-vector $\tilde{\mathcal{X}}(t_k)$	216
$\mathbf{q}_n$	control points for spline curve	53
$\mathbf{Q}$	vector of control points	58
$\mathbf{Q}^x$	vector of x-coordinates of control points	44, 58
$\mathbf{Q}^y$	vector of y-coordinates of control points	58

SYMBOL	MEANING	see page
$\mathbf{Q}_0$	control points of template curve	74
R	rotation matrix	283
$\mathbf{R}(s)$	space-curve (3D)	81
R_{ij}, R'_{ij}	auto-correlation coefficients of training sequence	244
R_i	training-sequence sums	244
$\mathbf{r}(s)$	image curve (2D)	53
$\rho_0(s)$	root-mean-square displacement at s on a curve	161
$\overline{\rho}_0$	root-mean-square displacement of curve	161
S, S_i	statistical information matrix	127
$\mathcal{S}_Q$	space of spline curves $\mathbf{Q}$	58
$\mathcal{S}$	shape-space	69
s	spatial parameter for curve	
σ	σ^2 is variance of image measurement process	127,169
t	time parameter	
T	duration $T = M\tau$ of an image sequence	
τ	sample interval for image capture	
$U(s)$	matrix mapping control point vector $\mathbf{Q}$ to image curve $\mathbf{r}(s)$	58
$\mathbf{u}$	translation vector	76
$\mathcal{U}$	metric matrix for B-spline parametric curves	58
$\mathcal{V}[Y]$	variance of a random variable Y	294
W	shape-matrix mapping from configuration $\mathbf{X}$ to control point vector $\mathbf{Q}$	74
$W^\dagger$	pseudo-inverse of mapping W	74
$\mathbf{w}_k$	discrete noise: vector of independent standard normal variables	193

SYMBOL	**MEANING**	**see page**
$\mathbf{X}$	curve shape-vector	74
$\overline{\mathbf{X}}$	mean value of curve configuration	160
$\mathcal{X}$	state-vector for image-based dynamics at discrete time k	204
$\hat{\mathcal{X}}(t_k)$	estimated state-vector from a tracker	214
$\tilde{\mathcal{X}}(t_k)$	predicted state-vector in a tracker	216
$\overline{\mathcal{X}}$	mean value of state $\mathcal{X}$	204
$\underline{\mathcal{X}}(t_k)$	history of states $\mathcal{X}(t_1), \ldots, \mathcal{X}(t_k)$	260
$\mathbf{Z}(t_k)$	aggregated vector of visual measurements at time $t = k\tau$	127
$\underline{\mathbf{Z}}(t_k)$	measurement history $\{\mathbf{Z}(t_1), \ldots, \mathbf{Z}(t_k)\}$ up to time $t = k\tau$	213

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