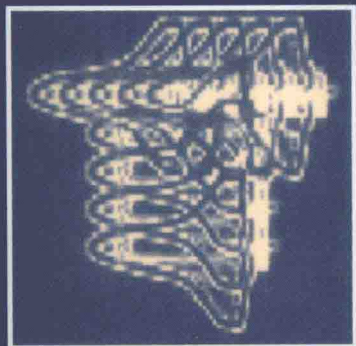
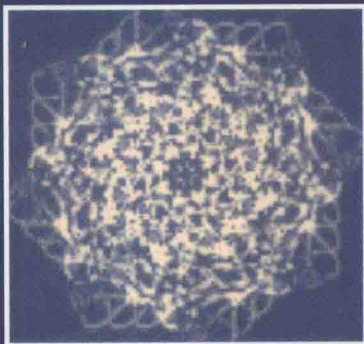

OPTICAL



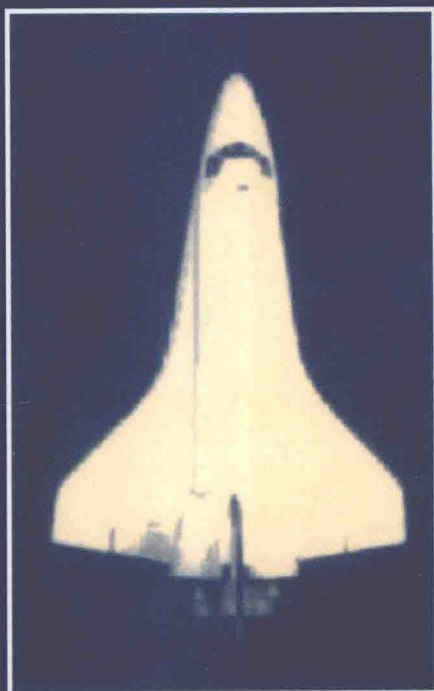
PATTERN

RECOGNITION

EDITED BY

FRANCIS T. S. YU

SUGANDA JUTAMULIA



Optical pattern recognition

Edited by
FRANCIS T. S. YU
and
SUGANDA JUTAMULIA



CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521465175

© Cambridge University Press 1998

This publication 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 1998
This digitally printed version 2008

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Optical pattern recognition / edited by Francis T. S. Yu, Suganda
Jutamulia.

p. cm.

ISBN 0-521-46517-6

1. Optical pattern recognition. I. Yu, Francis T. S., 1932- .

II. Jutamulia, Suganda.

TA1650.0655 1998
621.39'9 - dc21

97-36651
CIP

ISBN 978-0-521-46517-5 hardback
ISBN 978-0-521-08862-6 paperback

Contributors

Dr. Tien-Hsin Chao

Jet Propulsion Lab
4800 Oak Grove Drive
Pasadena, CA 91109-8099

Prof. Robert W. Cohn

Department of Electrical Engineering
University of Louisville
Louisville, KY 40292

Dr. Gregory Gheen

KLA Instrument Corporation
160 Rio Robles
San Jose, CA 95161

Prof. Don A. Gregory

Physics Department
University of Alabama in Huntsville
Huntsville, AL 35899

Prof. Laurence G. Hassebrook

Department of Electrical Engineering
University of Kentucky
Lexington, KY 40506

Dr. Suganda Jutamulia

In-Harmony Technology Corp.
101 South Antonio Road
Petaluma, CA 94952

Dr. Yao Li

NEC Research Institute
Physical Science Division
Princeton, NJ 08540

Dr. Guowen Lu

Applied Research laboratory
The Pennsylvania State University
University Park, PA 16802

Dr. Taiwei Lu

In-Harmony Technology Corp.
101 South Antonio Road
Petaluma, CA 94954

Dr. Mingzhe Lu

Institute of Modern Optics
Nankai University
Tianjin, 300071, P.R. China

Prof. David Mendlovic

Faculty of Engineering
Tel-Aviv University
Tel-Aviv, Israel 69978

Prof. Guoguang Mu

Institute of Modern Optics
Nankai University
Tianjin, 300071, P.R. China

Prof. Haldun M. Ozaktas

Faculty of Electrical Engineering
Bilkent University
Ankara, Turkey

Dr. Eung-Gi Paek

National Institute of Standards and
Technology
Gaithersburg, MD 20899

Prof. Joseph Shamir

Department of Electrical
Engineering
Technion-Israel Institute of
Technology
Technion City
Haifa, Israel 32000

Prof. Yunlong Sheng

Physics Department
Laval University
Sainte-Foy 61K7P4, Canada

Prof. Q. Wang Song

Department of Electrical and Computer
Engineering
Syracuse University
Syracuse, NY 13244-1240

Prof. Yin Sun

Institute of Modern Optics
Nankai University
Tianjin, 300071, P.R. China

Dr. Aris Tanone

JAYA Corporation
University Square
Huntsville, AL 35816

Prof. Xiangyang Yang

Department of Electrical
Engineering
University of New Orleans
New Orleans, LA 70148

Prof. Leonid Yaroslavsky

Department of Interdisciplinary Studies
Engineering Faculty
Tel-Aviv University
Tel-Aviv 69978, Israel

Prof. Shizhuo Yin

Department of Electrical Engineering
The Pennsylvania State University
University Park, PA 16802

Prof. Francis T. S. Yu

The Pennsylvania State University
University Park, PA 16802

Dr. Zeev Zalevsky

Faculty of Engineering
Tel-Aviv University
Tel-Aviv, Israel 69978

Dr. Yu-He Zhang

Department of Electrical and Computer
Engineering
Syracuse University
Syracuse, NY 13244-1240

Preface

Smart automatic machines that may reduce our working load and minimize risk in work have been sought for a long time. This suggests supplementing rather than supplanting, and extending rather than denying, our human capabilities to work. To be smart, the machine must understand a scene as a human does. In other words, the machine must be able to recognize the scene by comparing the present scene and the past scenes. The machine operates based more on the scene it views, and it is less controlled by a set of thousands of instructions. For these smart machines, a picture is, indeed, worth a thousand words. Pattern recognition is the primary task of any smart automatic machine. Because the pattern to be recognized is often received optically, it is perhaps most natural and straightforward to recognize an optical pattern by using optics. This book reviews in depth the recent progress in optical pattern recognition, although no attempt has been made to give an encyclopedic presentation.

The book was designed to incorporate multiple facets and approaches essential for today's optical pattern recognition research enterprise to proceed. To this end, we have brought together leading researchers worldwide, all focusing their efforts on selected aspects of optical pattern recognition issues in 15 chapters. The first chapter overviews pattern recognition that is performed mainly with an optical correlator. The following four chapters describe new approaches to optical pattern recognition: neural networks, wavelet transform, fractional Fourier transform, and mathematical morphology. Nonlinear methods are discussed in the following three chapters. One method employs a nonlinear device in a Fourier plane. The other two methods apply nonlinear-quadratic and composite filters, respectively. These nonlinear filters are implemented in a conventional linear optical system. The next two chapters describe optoelectronic hybrid systems that use an optical system and a digital computer in recognizing an input pattern. The remaining five chapters present devices and materials used in an optical pattern recognition system: photorefractive crystals, microlasers, bacteriorhodopsin, liquid-crystal spatial light modulators, and complex-function spatial light modulators.

We thank all the authors for their excellent contributions, and we are honored to have had an opportunity to work with them. It is early yet to estimate the magnitude of the contribution optical pattern recognition will make to the extension of human capabilities and the corresponding convenience in human life, and it would be more than a little reckless to rank it now along with optical disk and fiber communication. But the contribution will be in that class and will indeed be profound.

*Francis T. S. Yu
Suganda Jutamulia*

Contents

<i>Contributors</i>	xiii
<i>Preface</i>	xv
1 Pattern recognition with optics	1
1.1 Introduction	1
1.2 Optical correlators	1
1.3 Hybrid optical correlators	3
1.4 Autonomous target tracking	7
1.5 Optical-disk-based joint transform correlator	9
1.6 Photorefractive-crystal-based correlator	12
1.7 Optical neural networks	14
1.8 Scale- and rotational-invariant correlation	15
1.9 Wavelet transform filtering	17
1.10 Discriminant filtering	17
1.11 Phase-only filtering	19
1.12 Pattern recognition with neural networks	20
1.13 Position-encoding joint transform correlator	24
1.14 Phase-representation joint transform correlator	25
1.15 Composite filtering with the joint transform correlator	27
1.16 Non-zero-order joint transform correlator	28
1.17 Summary and conclusions	31
References	31
2 Hybrid neural networks for nonlinear pattern recognition	40
2.1 Introduction	40
2.2 Neural network background	41
2.2.1 Neural networks for nonlinear transformation	41
2.2.2 Black box versus transparent box	44
2.2.3 Hidden neurons	45
2.2.4 Hybrid neural networks	45
2.3 Hybrid optical neural networks	46
2.3.1 Basic architecture of the holographic optical neural network system	47
2.3.2 Construction of an automatic recording system	49

2.4	Construction of holographic optical neural network systems	51
2.4.1	Benchtop demonstration system	51
2.4.2	Portable demonstration system	51
2.4.3	Compact lunchbox demonstration system	52
2.5	Holographic optical neural network for pattern recognition	53
2.5.1	Hybrid holographic optical neural network hybrid for distortion-invariant pattern recognition	53
2.5.2	Lunchbox demonstration of shift-, scale-, and rotation-invariant automatic target recognition	58
2.6	Conclusions	61
	Acknowledgments	62
	References	62
3	Wavelets, optics, and pattern recognition	64
3.1	Introduction	64
3.2	Historical background	64
3.3	Wavelet transforms: definitions and properties	66
3.3.1	Continuous wavelet transform	66
3.3.2	Discrete wavelet transform and the frame	67
3.3.3	Other important wavelet-related concepts	68
3.4	Wavelets in general optics	69
3.4.1	Wavelets in diffraction	69
3.4.2	Wavelets in early vision interpretation	70
3.4.3	Wavelets in binocular vision	71
3.5	Optical wavelet transforms	72
3.5.1	Coherent optical wavelet transforms	73
3.5.2	Coherent optical inverse wavelet transforms	76
3.5.3	Incoherent optical wavelet transforms	77
3.5.4	Other modified wavelet or waveletlike optical transforms	78
3.5.5	Advantages and limitations of optical wavelet transforms	78
3.6	Optical wavelet transforms for pattern recognition	81
3.6.1	Wavelet matched filters	81
3.6.2	Adaptive composite wavelet matched filters	82
3.6.3	Scale-invariant data classifications	85
3.6.4	Feature-based neural wavelet pattern classifier	86
3.7	Concluding remarks	86
	References	86
4	Applications of the fractional Fourier transform to optical pattern recognition	89
4.1	Preface	89
4.2	Introduction	89
4.3	Fractional correlator performance analysis	92
4.3.1	Performance criteria	92
4.3.2	Performance optimization in conventional correlators	93
4.3.3	Performance optimization in fractional correlators	93

4.3.4	Signal-to-noise ratio comparison between a fractional correlator and a conventional correlator	95
4.3.5	Fractional correlator performance with additive colored noise	96
4.3.6	Fractional Fourier transform of white noise	98
4.4	Fractional correlator with real-time control of the space-invariance property	100
4.4.1	Mathematical analysis	100
4.4.2	Interpretations	102
4.5	Localized fractional processor	103
4.5.1	Mathematical definitions	103
4.5.2	General applications	106
4.5.3	Application for pattern recognition	107
4.6	Anamorphic fractional Fourier transform for pattern recognition	110
4.6.1	Anamorphic fractional Fourier transform	110
4.6.2	Multiple fractional-Fourier-transform filters	112
4.6.3	Optical implementation	113
4.6.4	Results	114
4.7	Fractional joint transform correlator	117
4.7.1	Wigner distribution function	117
4.7.2	Concept of the joint fractional correlator	118
4.7.3	Removal of the extraneous terms	119
4.8	Concluding remarks	123
	Acknowledgments	124
	References	124
5	Optical implementation of mathematical morphology	126
5.1	Introduction	126
5.1.1	Binary morphology	127
5.1.2	Gray-scale morphology	129
5.2	Optical morphological processor	130
5.2.1	Shadow-cast optical morphological processor	133
5.2.2	Reconfigurable optical morphological processor	134
5.2.3	Optical morphological processor with a diffraction grating and a shutter spatial light modulator	135
5.2.4	Optical morphological processor with a laser source array	136
5.3	Miniature system architecture	136
5.4	Gray-scale optical morphological processor	139
	Acknowledgments	139
	References	140
6	Nonlinear optical correlators with improved discrimination capability for object location and recognition	141
6.1	Introduction: a review of the theory	141
6.2	Nonlinear optical correlators	144
6.3	Nonlinear optical correlators with $(-k)$ th-law nonlinearity in the Fourier plane	145

6.3.1	Optimal adaptive correlator	149
6.3.2	Suboptimal correlators with $(-k)$ th-law nonlinearity and empirical estimation of the image power spectrum	149
6.3.3	Phase-only filters and phase-only correlators	159
6.4	Nonlinear joint transform correlators	159
6.4.1	Logarithmic joint transform correlators	159
6.4.2	Nonlinear joint transform correlators with $(1/k)$ th-law nonlinearity	164
6.4.3	Binary joint transform correlators	167
6.5	Conclusion	169
	Acknowledgments	169
	References	169
7	Distortion-invariant quadratic filters	171
7.1	Introduction	171
7.2	Technical background	172
7.2.1	Notation	172
7.2.2	Bayes decision theory and discriminant functions	172
7.2.3	Quadratic filters and their optical implementation	174
7.2.4	Normalization of input signals	177
7.3	Invariant quadratic filters	179
7.3.1	Quadratic filters invariant to a training set	180
7.3.2	Quadratic filters invariant to a linear transformation group	182
7.3.3	Principal component analysis and invariant feature extraction	185
7.4	Performance analysis of invariant quadratic filters	187
7.4.1	Assumptions and models for target and clutter	187
7.4.2	Fisher ratio of filters	189
7.4.3	Relationship between filter performance and key parameters	189
	References	192
8	Composite filter synthesis as applied to pattern recognition	193
8.1	Introduction	193
8.2	Bipolar composite filter synthesis by simulated annealing	194
8.2.1	Simulated annealing algorithm	194
8.2.2	Bipolar composite filter synthesis	194
8.2.3	Target detection with a bipolar composite filter	197
8.2.4	Pattern discrimination capability of a bipolar composite filter	197
8.2.5	Noise performance of bipolar composite filter	200
8.3	Multilevel composite filter synthesis by simulated annealing	204
8.4	Multitarget composite filter synthesis	206
8.5	Optical implementation of a bipolar composite filter by a photorefractive crystal hologram	207
8.6	Implementation in a joint transform correlator	210
8.6.1	Position encoding	211
8.6.2	Position-encoding joint transform correlator	215
8.6.3	Experimental demonstration	217

8.7	Summary	218
	References	218
9	Iterative procedures in electro-optical pattern recognition	221
9.1	Introduction	221
9.2	Pattern recognition and optimization	222
9.3	Iterative optimization algorithms: an overview	224
9.3.1	Gradient-descent algorithm	224
9.3.2	Hill-climbing procedure	225
9.3.3	Simulated annealing	225
9.3.4	Genetic algorithms	226
9.3.5	Projections-onto-constraint-sets algorithms	227
9.3.6	Discussion	230
9.4	Detection criteria: information theoretical approach	231
9.4.1	Generalized information function	234
9.4.2	Performance comparison of different cost functions	235
9.5	Hybrid electro-optical implementation	238
9.5.1	Performance comparison for various algorithms	241
9.6	Applications of projection algorithms	244
9.6.1	Class discrimination by a linear correlator	245
9.6.2	Class discrimination by the phase-extraction correlator	247
9.7	Adaptive procedures for distortion invariance	249
9.7.1	Scale measurement procedure	250
9.7.2	Filter design	253
9.8	Conclusions	258
	Acknowledgments	258
	References	258
10	Optoelectronic hybrid system for three-dimensional object pattern recognition	262
10.1	Introduction	262
10.2	Fresnel holographic filter	263
10.2.1	Principle of the Fresnel holographic filter	263
10.2.2	Experimental demonstrations of a lensless intensity correlator	266
10.2.3	White-light intensity correlator with a volume Fresnel holographic filter	267
10.2.4	Lensless intensity correlator with high discrimination	272
10.2.5	Multiplex intensity correlator with a Fourier-transform holographic filter	274
10.3	Serial-code filters	274
10.3.1	Principle of serial-code filters	274
10.3.2	Digital simulations	276
10.4	Cascaded model of neural networks suitable for optical implementation	277
10.4.1	Structure and features of the cascaded model	277
10.4.2	Learning algorithm of the cascaded model of neural networks	279
10.4.3	Gray-level compression of the mask	281

10.4.4	Property analysis of the model	282
10.4.5	Optoelectronic hybrid system for three-dimensional pattern recognition	284
10.5	Conclusion	285
	References	285
11	Applications of photorefractive devices in optical pattern recognition	287
11.1	Introduction	287
11.2	Fundamentals of the photorefractive effect	287
11.2.1	Photorefractive effect	287
11.2.2	Two-wave mixing and four-wave mixing	289
11.2.3	Multiplexing schemes	291
11.2.4	Commonly used photorefractive materials	292
11.3	Photorefractive correlators for two-dimensional pattern recognition	293
11.3.1	VanderLugt-type correlator	293
11.3.2	Joint transform correlator	299
11.3.3	Optical wavelet transform correlator	301
11.4	Photorefractive processors for radio frequency signal processing	303
11.4.1	Photorefractive time-integrating correlator	303
11.4.2	Photorefractive radio frequency notch filter	304
11.5	Photorefractive novelty filters	307
11.6	Implementation of artificial neural networks by photorefractive media	310
11.7	Summary	313
	References	314
12	Optical pattern recognition with microlasers	319
12.1	Introduction: microlasers, surface-emitting laser diode arrays, or vertical-cavity surface-emitting lasers	319
12.1.1	What is a surface-emitting laser?	319
12.1.2	What is a microlaser?	320
12.1.3	Why microlasers?	321
12.2	Status of microlasers	321
12.2.1	Low threshold current	321
12.2.2	Coherence	322
12.2.3	Visible microlasers	323
12.2.4	Two-dimensional addressing schemes	324
12.2.5	Polarization control	324
12.2.6	Multiple wavelengths	324
12.2.7	Wavelength tuning	325
12.2.8	Efficiency	326
12.2.9	Modulation speed	327
12.2.10	High-power output	328
12.3	Optical correlators with microlasers	328
12.3.1	Introduction	328
12.3.2	Classification of optical pattern recognition systems	329

12.3.3	Multichannel optical correlator based on a mutually incoherent microlaser array	331
12.3.4	Compact and robust incoherent correlator	332
12.4	Holographic memory readout with microlasers	333
12.4.1	Introduction	333
12.4.2	Compact and ultrafast holographic memory with a SELDA	333
12.4.3	Combined angular and wavelength multiplexing with a two-dimensional MC-SELDA	334
12.4.4	Incoherent-coherent multiplexing with a SELDA	335
12.5	Microlasers for holographic associative memory	335
12.5.1	Introduction	335
12.5.2	Holographic neurons	336
12.5.3	Microlaser-based holographic associative memory	336
12.5.4	Holographic associative memory with time-division multiplexing	337
12.6	Integration and packaging	338
12.7	Conclusion	340
13	Optical properties and applications of bacteriorhodopsin	345
13.1	Introduction	345
13.2	Optical characterization	345
13.3	Wave mixing and phase conjugation	350
13.4	Real-time holography	352
13.5	Spatial light modulators	354
13.6	Optical correlation and pattern recognition	357
13.7	Holographic switching and optical interconnection	359
13.8	Photoreceptor/artificial retina	359
13.9	Optical memory	362
13.10	Other applications	362
13.11	Conclusions	364
	Acknowledgment	364
	References	364
14	Liquid-crystal spatial light modulators	367
14.1	Introduction	367
14.1.1	Building blocks of an optical processor	367
14.1.2	Spatial light modulator	368
14.2	Liquid crystals	370
14.2.1	Liquid-crystal classifications	370
14.2.2	Optical and electro-optical properties of twisted nematic liquid crystals	371
14.3	Electrically addressed spatial light modulators	373
14.3.1	Background	373
14.3.2	Liquid-crystal television spatial light modulators	376
14.4	Optically addressed spatial light modulators	377

14.4.1	Liquid-crystal light valves	378
14.4.2	Ferroelectric liquid-crystal spatial light modulators	379
14.5	Implementations of a liquid-crystal television in real-time optical processing	380
14.5.1	Programmable joint transform correlators	380
14.5.2	Real-time phase modulators	383
14.5.3	Application in camera	388
14.6	The applications, the problems, and the future of liquid-crystal spatial light modulators	390
	References	392
15	Representations of fully complex functions on real-time spatial light modulators	396
15.1	Introduction	396
15.2	Early methods of complex-valued representation	398
15.2.1	Holographic encoding	398
15.2.2	Detour-phase-encoding methods	399
15.2.3	Multiple spatial light modulators	402
15.3	Methods of representing complex values on current spatial light modulators	402
15.3.1	Synthesis of Fourier transforms by use of time-integrated spectrum analyzers	402
15.3.2	Full-bandwidth methods of encoding: encoding by global optimization	405
15.3.3	Full-bandwidth methods of encoding: point-oriented encoding	406
15.3.4	Optimality	420
15.4	Discussion: scenarios for fully complex representations	423
15.4.1	Optical security	424
15.4.2	Arbitrary multispot scanning and beam shaping	424
15.4.3	Hybrid optoelectronic correlators for autonomous recognition and tracking	424
15.5	Summary and conclusion	428
	References	429
	<i>Index</i>	433

Pattern recognition with optics

Francis T. S. Yu and Don A. Gregory

1.1 Introduction

The roots of optical pattern recognition can be traced back to Abbé's work in 1873 [1], when he developed a method that led to the discovery of spatial filtering to improve the resolution of microscopes. However, optical pattern recognition was not actually appreciated until the complex spatial filtering work of VanderLugt in 1964 [2]. Since then, techniques, architectures, and algorithms have been developed to construct efficient optical correlators for pattern recognition application.

Our objective in this chapter is to discuss the optical architectures and techniques as applied to recent advances in pattern recognition. Basically there are two approaches in the optical implementation of pattern recognition, namely, the correlation approach and the neural net approach. In the correlation approach, there are two frequently used architectures: the VanderLugt correlator (VLC) and the joint transform correlator (JTC). The first JTC architecture was demonstrated by Weaver and Goodman in 1966 [3] and independently by Rau [4]. Because of a lack of interface devices, the JTC was virtually stagnant until 1984, when a real-time programmable JTC was reported by Yu and Lu [5]. Since then the JTC has assumed a major role in various processing applications.

Aside from correlation applications to pattern recognition, artificial neural networks (NN's) are also well suited. The first optical NN is attributed to Psaltis and Farhat in 1985 [6], who showed that pattern retrieval can be achieved with a lenslet array interconnection network.

In this chapter, advances in this rapidly growing field are reviewed and the basic optical architectures and techniques addressed. The pros and cons of each approach are discussed. Because of recent technical advances in interface devices [such as electronically addressable spatial light modulators (SLM's), nonlinear optical devices, etc.], new philosophies and new algorithms have been developed for the design of better pattern recognition systems.

1.2 Optical correlators

The optical implementation of pattern recognition can be accomplished with either Fourier-domain complex matched filtering or spatial-domain filtering. Correlators that use Fourier-domain matched filtering are commonly known as VLC's [2], and an example of spatial-domain filtering is the JTC [3–5]. The basic distinctions between them are that the VLC depends on Fourier-domain spatial filter synthesis (e.g., Fourier hologram), whereas the JTC depends on spatial-domain (impulse-response) filter synthesis. In other words,

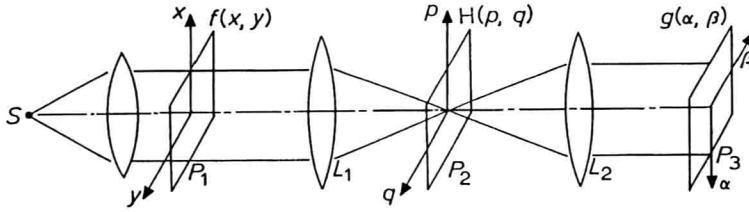


Fig. 1.1. VLC.

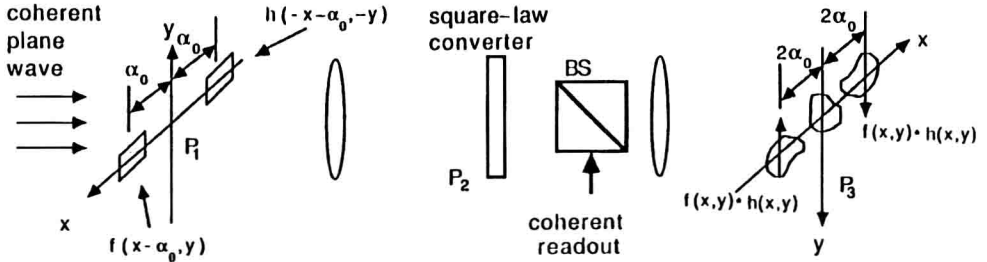


Fig. 1.2. JTC.

the complex spatial detection of the VanderLugt arrangement is input scene *independent*, whereas the joint transform method is input scene *dependent* [7]. The basic optical setups of these two types of correlator are depicted in Figs. 1.1 and 1.2. A prefabricated Fourier-domain matched filter $H(p, q)$ is needed in the VLC, whereas a matched filter is not required in the JTC but a spatial-domain impulse response $h(x, y)$ is needed. Although the JTC avoids spatial filter synthesis problems, it generally suffers lower detection efficiency, particularly when applied to multitarget recognition or targets embedded in intense background noise [8]. Nonetheless, the JTC has many merits, particularly when interfaced with electronically addressable SLM's.

The JTC has other advantages, such as higher space-bandwidth products, lower carrier frequency, higher index modulation, and suitability for real-time implementation. Disadvantages include inefficient use of illuminating light, a large transform lens, stringent spatial coherence requirements, and the overall small size of the joint transform spectrum. A quasi-Fourier-transform JTC (QFJTC) that can alleviate some of these limitations is shown in Fig. 1.3 [9, 10]. The depth of focus is given by [10]

$$\delta \leq 2\lambda(f/b)^2. \quad (1.1)$$

To illustrate the shift-invariant property of the QFJTC, an input object such as that shown in Fig. 1.4(a) is used. The joint transform power spectrum (JTPS) is recorded as a photographic transparency, which could be thought of as a joint transform hologram (JTH). When the recorded JTH is simply illuminated with coherent light, the cross-correlation distribution can be viewed in the output plane [shown in Fig. 1.4(b)], where autocorrelation peaks indicating the location of the input character, G, are detected.

Representative experimental results were obtained with the QFJTC with the input object and the reference functions of Fig. 1.5(a). Three JTHs – for $\delta = 0$, $\delta = f/10 = 50$ mm, and $\delta = f/5 = 100$ mm – are shown in Fig. 1.5(b), which shows that the size of the JTPS enlarges as δ increases. Figure 1.6 illustrates that the correlation peak intensity increases as δ

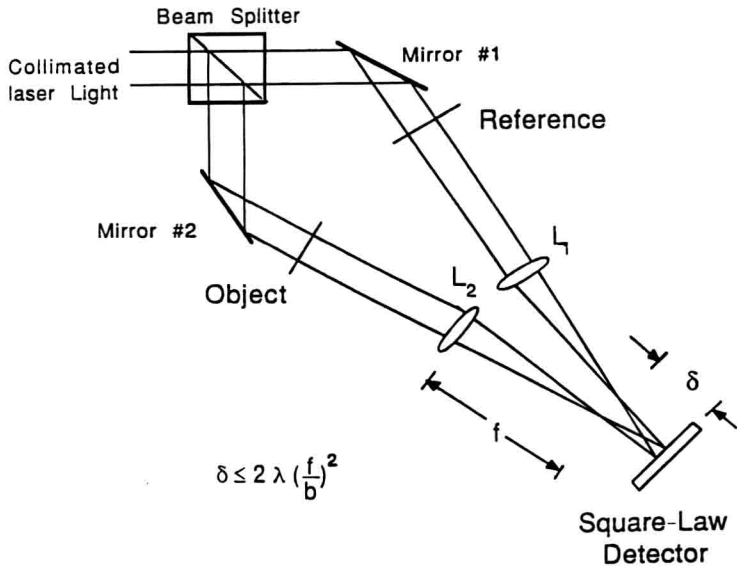


Fig. 1.3. QFJTC.

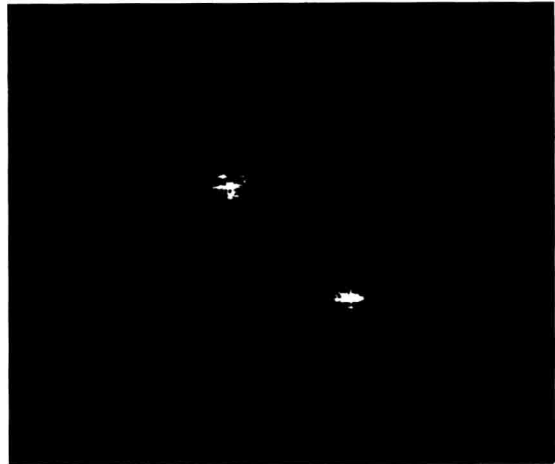
G A
B G

Input Object

G

Reference

(a)



(b)

Fig. 1.4. (a) Input object and reference function, (b) output correlator distribution.

increases, whereas the size of the correlation spot decreases as δ increases. Thus the QFJTC architecture can improve the signal-to-noise ratio (SNR) and the accuracy of detection.

1.3 Hybrid optical correlators

It is apparent that a purely optical correlator has drawbacks that make certain tasks difficult or impossible to perform. The first problem is that optical systems are difficult to program, in the sense of programming general-purpose digital-electronic computers. A purely optical system can be designed to perform specific tasks (analogous to a hard-wired electronic computer), but it cannot be used when more flexibility is required. A second problem is that