

FINDING COLOR AND SHAPE PATTERNS IN IMAGES

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF COMPUTER SCIENCE
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

By
Scott Cohen
May 1999

Contents

Abstract	v
Acknowledgements	vii
1 Introduction	1
1.1 The Pattern Problem	4
1.2 Thesis Overview	6
2 Background	9
2.1 The 1D Shape Pattern Problem	9
2.2 Focused Color Searching	12
2.3 From Histogram Intersection to the Earth Mover’s Distance	16
2.4 The Earth Mover’s Distance	18
2.5 Matching under Transformation Groups	22
2.5.1 The Hausdorff Distance	22
2.5.2 The ICP Iteration	26
2.6 The FOCUS Image Retrieval System	29
3 The Polyline Shape Search Problem	33
3.1 Problem Setup	35
3.2 The Best Rotation	38
3.3 The 2D Search Problem	39
3.3.1 Faces	43
3.3.2 Edges and Vertices	46
3.4 The Algorithm	47
3.5 Results	50
3.6 Summary and Suggestions for Future Work	53

4	The Earth Mover's Distance (EMD)	59
4.1	Basic Definitions and Notation	62
4.2	Connection to the Transportation Problem	67
4.3	Special Cases	69
4.3.1	Point Set Matching using the EMD	69
4.3.2	The EMD in One Dimension	71
4.4	Modifications	80
4.4.1	The Partial Earth Mover's Distance	80
4.4.2	The Restricted Earth Mover's Distance	83
4.5	Use in Scale Estimation	85
4.5.1	Experiments with the Color Pattern Problem	91
5	Lower Bounds on the EMD	97
5.1	Centroid-based Lower Bounds	98
5.1.1	Equal-Weight Distributions	98
5.1.2	Unequal-Weight Distributions	100
5.1.2.1	The Centroid Lower Bound	101
5.1.2.2	The Centroid Bounding Box Lower Bound	103
5.2	Projection-based Lower Bounds	104
5.3	Experiments in Color-based Retrieval	110
6	The EMD under Transformation Sets	123
6.1	Definitions and Notation	125
6.2	A Direct Algorithm	128
6.3	The FT Iteration	128
6.3.1	Similar Work	131
6.3.2	Convergence Properties	133
6.4	The Optimal Transformation Problem	135
6.4.1	Translation	135
6.4.1.1	Minimizing a Weighted Sum of Squared L_2 Distances	137
6.4.1.2	Minimizing a Weighted Sum of L_1 Distances	137
6.4.1.3	Minimizing a Weighted Sum of L_2 Distances	141
6.4.1.4	Minimizing a Weighted Sum of Cyclic L_1 Distances	142
6.4.2	Euclidean and Similarity Transformations	147
6.4.3	Linear and Affine Transformations	147
6.5	Allowing Weight-Altering Transformations	148

6.6	Some Specific Cases	151
6.6.1	The Equal-Weight EMD under Translation with $d = L_2^2$	152
6.6.2	The Equal-Weight EMD under Translation on the Real Line	152
6.6.3	The Equal-Weight EMD under \mathcal{G} with $m = n = 2$	154
6.7	Global Convergence in $\mathcal{F} \times \mathcal{G}$?	156
6.7.1	Partial Matching	157
6.7.2	One Optimal Flow or Transformation	160
6.7.3	A Perfect Match under Translation	161
6.7.4	Equal-Weight Comparisons with Local Minima	163
6.8	Odds and Ends	169
6.8.1	L_2^2 versus L_2	171
6.8.2	Sensitivity and Growth Rate	172
6.9	Some Applications	175
6.9.1	Lighting-Invariant Object Recognition	175
6.9.2	Feature Matching in Stereo Images	177
7	The SEDL Image Retrieval System	181
7.1	SEDL's Image Signatures and Distance Function	185
7.2	The Scale Estimation Phase	188
7.3	The Initial Placement Phase	189
7.3.1	Experiments with the Color Pattern Problem	194
7.4	The Verification and Refinement Phase	195
7.5	Results	205
7.5.1	The Product Advertisement Color Database	205
7.5.1.1	Creating Signatures	205
7.5.1.2	Query Results	212
7.5.1.3	SEDL versus FOCUS	217
7.5.2	The Chinese Character Shape Database	217
7.5.2.1	Creating Signatures	230
7.5.2.2	Query Results	230
7.5.2.3	Possible Modifications	231
8	Conclusion	241
8.1	Thesis Summary and Discussion	241
8.2	Future Work	244
8.3	Final Thoughts	247

