

Optical Flow Estimation in the Presence of Fast or Discontinuous Motion

by

Yan Niu

Thesis submitted for the degree of

Doctor of Philosophy

in

Computer Science and Mathematics
University of Adelaide

2010

© 2010
Yan Niu
All Rights Reserved



Contents

Contents	iii
Abstract	vii
Statement of Originality	ix
Acknowledgments	xi
	xii
Bibliography	xiii
List of Figures	xv
List of Tables	xvii
Notations	xix
Chapter 1. Introduction	1
1.1 Problem Overview	1
1.1.1 Problem Statement	1
1.1.2 Why Would We Want To Do This?	2
1.1.3 Why Is This A Difficult Problem?	3
1.2 Thesis Overview	4
1.2.1 Contributions of This Thesis	4
1.2.2 Thesis Outline	4
Chapter 2. Differential Optical Flow Techniques for Motion Estimation	7
2.1 Problem Statement	8
2.2 Local Computation	10
2.2.1 Extension of the Invariant Features	10

2.2.2	Affine or Higher-Order Prior Assumption	11
2.2.3	Handling the Aperture Problem of $A\vec{X} = \vec{b}$	13
2.2.4	Handling the Inconsistency of $A\vec{X} = \vec{b}$	13
2.3	Global Computation	14
2.3.1	Variational Flow Techniques	15
2.3.2	Rigid Motion Constraints	21
2.4	Local and Global Computation in Tandem	21
2.5	Summary	24
Chapter 3. Measuring Local Motion Inconsistency		25
3.1	Motion Inconsistency of One Pixel	26
3.2	Motion Inconsistency Between Two Pixels	28
3.3	Motion Consistency among a Group of Pixels	30
3.3.1	An Inconsistency Measure for Linear Systems	30
3.3.2	An Example of the Lucas-Kanade System	33
3.3.3	Measuring flow confidence and motion boundary by COIN	34
3.4	Experimental Results	37
3.4.1	Measuring Flow Confidence	37
3.4.2	Motion Boundary Detection	38
3.5	Summary	42
Chapter 4. Discontinuity-Preserving Local Flow Computation		43
4.1	The Linear System Model	44
4.2	Weighting Functions for the Local Model	46
4.2.1	Spatial Proximity Term	46
4.2.2	Pairwise Intensity Affinity Term	46
4.2.3	Dynamic Occlusion and Boundary Detection	47
4.3	Performance Evaluation	49
4.4	Summary	54
Chapter 5. Complementary Combination of Local and Global Constraints		55
5.1	Motion Outlier Inhibited Local Flow Computation	56

5.2	Flow Field Segmentation	59
5.3	Global Regularization	60
5.3.1	Global Subspace Constraint	62
5.3.2	Spatial Smoothness Constraint	64
5.4	Experimental Results	66
5.5	Summary	70
Chapter 6. Optical Flow Computation for Fast Rotation		71
6.1	Fast Rotation and Large Displacement	72
6.2	Local Adaptive Coordinate System	73
6.2.1	Isophote Direction Detection	73
6.2.2	Constructing the Local Reference Frame	76
6.3	Flow Formulation in the Local Coordinates	79
6.3.1	The Brightness Constancy Constraint	79
6.3.2	The Edge-Normal Derivative Invariance Constraint	80
6.3.3	The Regularity Constraints in Edge and Normal Directions	80
6.3.4	The Balanced Combination of the Constraints	81
6.4	Multi-Scale Multi-Stage Numerical Solution	83
6.4.1	Multi-Scale Pyramidal Implementation	84
6.4.2	Multi-stage Refinement	85
6.4.3	Removal of the Nonlinearity and Its Relation to Iteratively Re-weighted Least Squares	86
6.4.4	Jacobi Iteration	88
6.5	Experimental Results	89
6.5.1	Comparison with Existing Methods	89
6.5.2	Numerical Evaluation of Each Step	89
6.5.3	Real Sequences	92
6.6	Summary	92
Chapter 7. Optical Flow Computation by Expectation-Maximization		97
7.1	Combine Local and Global Computation by EM	98

Contents

7.2	Generalization to Fast Rotation	100
7.2.1	The Quantization of the 2D plane by Integer Vectors	100
7.2.2	E-Step for Rotation	103
7.2.3	M-Step for Rotation	103
7.3	Experimental Results	106
7.3.1	Experiments on Real Sequences	106
7.3.2	Quantitative Evaluation	107
7.4	Summary	108
Chapter 8. Summary and Discussion		117
8.1	Summary	117
8.2	Future Research	118
8.3	Conclusion	120
Appendix A. List of Test Sequences		121
A.1	MiddleBury Training Dataset	121
A.1.1	Hidden Fluorescent Texture Sequences	122
A.1.2	Computer Graphics Synthetic Sequences	122
A.1.3	Modified Stereo Sequence	122
A.1.4	Real Sequence	123
A.2	McCane et al. Dataset	124
A.2.1	Computer Graphics Synthetic Sequences	124
A.3	Miscellaneous	126
Bibliography		131

Abstract

This thesis focuses on the computation of optical flow, i.e., the motion perceived from a sequence of gradually changing images, as an estimate for the 2D velocity of the scene. Due to the large variety and high complexity of the motion types existing in practice, motion recovery requires the estimation process to be highly adaptive. This thesis investigates how to select and combine the reasoning rules, namely the optical flow constraints, according to the type of motion information detected. Moreover, the thesis extends optical flow computation to fast rotation, an important, frequent and challenging motion type, which has not been addressed much in the literature.

The thesis starts by proposing various measures, based on theory as well as heuristics, for motion inconsistency detection. This facilitates selecting only the optical flow constraints that are valid for each pixel. While this selection benefits pixels affected by inconsistent motion, the combination of different constraints also enhances flow recovery for pixels that have consistent motion.

Two frameworks are designed for the combination of flow constraints. One utilizes motion segmentation; and the other is close in spirit to Expectation-Maximization. Within these frameworks, new constraints are formulated and tested. Furthermore, the adaptive reasoning is generalized from translational motion to motion that includes fast rotation. The key concept that enables this generalization is the use of intrinsic directions in differential geometry.

Experimental results on a variety of benchmark sequences have demonstrated the ability of the proposed methods to improve the performance of existing techniques in several situations, including strong motion discontinuities and fast rotational motion.

Statement of Originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published written by another person, except where due reference has been made in the text.

I give consent to this copy of the thesis, when deposited in the University Library, being available for loan, photocopying and dissemination through the library digital thesis collection.

Signed

Date

Acknowledgments

In Adelaide, I have had 3 very happy years in my life. I have concentrated on my study well; I have improved my research skills; I have learned a lot about Computer Vision and Graphics; And I have seen more of the world; I have made many good friends from different countries; I know I could not have had them done just by myself. Therefore I am more than grateful to those people who have brought the happiness to my life.

One happiest thing here is to work with my supervisor Dr. Anthony Dick. I believe Anthony deserves the world's sincerest thanks. If my Ph.D study is an exploration of a terrain, Anthony is the one who leads my way through the journey, giving me maps, telescopes and the compass. He watches my steps, lifts me up and encourages me to keep going. He constructively gives me the confidence to do things that I was scared of. Following him, the exploration is very pleasant and joyful. It saddens me to think that sooner or later Anthony won't teach me any more.

And I sincerely appreciate my supervisor Professor Mike Brooks for his guidance, support, giving me chances and being warm to me, which makes me feel home and protected when I pursue my study as a foreigner.

Truly and really I am very proud to be Anthony and Mike's student.

Many thanks to the head of school Professor David Suter for always being nice to me; and our administrative manager Ms. Tracey Young for looking after me; and Ms. Sharon Liersch and Kathy Cooper for their kind assistance to make things easier. And I am very grateful to Dr. Chris Madden for doing the proof reading of my thesis - I know it is not fun. Thanks to Professor Wojciech Chojnacki, Professor Garry Newsam and Dr. Anders Eriksson for discussing optical flow with me and teaching me mathematics. Thanks to my colleague and close friend Alex Cichowski for patiently and promptly rescuing me from debugging every time when I need help.

Sincere thanks to the Australian IPRS scholarship, without which I would not have been able to study here with so much fun. I am also grateful for the Horald Scholarship and Cowan scholarship from Kathleen Lumley College and the conference funding, which allows me to see more and learn more. Thanks to Kathleen Lumley College, a wonderful place where I enjoy the leisure time with so many friends and have learned

Acknowledgments

a lot from them. Especially I am thankful to the master Felix, secretary Allyson and chef John.

I appreciate the university security staff members for always being so nice to me. They are Kym, Francisca, Tony, Bruce, Jeff and David. When I work at uni late at night, they even walk me back home. I still remember the Easter Eggs that David secretly left at my office table. I still keep the warping papers. I am also thankful to the shuttle bus drivers Bob and Michael, who drive me home warmly and safely when I work after office hours and remember my Birthday.

Thanks to Professor Wang ZhengXuan, my close friends Dr. Wang Xin and Dr. Guo XiaoXin back home, who help me a lot with the jobs I left in China so to let me concentrate better on my study overseas. Thanks to my closest friend Ms Yao ZhiYun, who has given me many tips about daily life from Japan.

And I also hope to take the chance to thank my International Bridging Program lecturer Michelle Picard and the Manager of the International Student Center Patricia Anderson.

I probably have forgotten to mention some people who helped me here and there at the time of writing. I am full of gratitude to those who have said “leave this to me for now” or “don’t worry about that” or “I will be there to have a look”...; and those who made me feel the world is gentle.

Most of all, I thank my parents. To me, their love, care, support, encouragement, understanding, patience and confidence in me are the whole world. Although research is rewarding, only being loved and supported during research allows me to truly enjoy what I am doing. Baba and Mama, I love You!

I dedicate this thesis to my parents

Bibliography

- Niu, Y., Dick, A. & Brooks, M. (2009). A new inconsistency measure for linear systems and two applications in motion analysis, *International Conference on Image and Vision Computing New Zealand*. **Receiver of Best Paper Award.**
- Niu, Y., Dick, A. & Brooks, M. (2008). A new combination of local and global constraints for optical flow computation, *International Conference on Image and Vision Computing New Zealand*.
- Niu, Y., Dick, A. & Brooks, M. (2007). Discontinuity-preserving optical flow computation by a dynamic overdetermined system, *Digital Image Computing: Techniques and Applications*, Australia.

List of Figures

1.1	Geometry of Projection	2
<hr/>		
3.1	Comparison of various confidence measures on RubberWhale etc.	39
3.2	Comparison of various confidence measures on Grove2 etc.	40
3.3	The recall-precision curves of the motion boundary detection	41
<hr/>		
4.1	The visual performance on RubberWhale	51
4.2	The visual performance on Grove2	52
<hr/>		
5.1	Weighted local computation by 4 weighting functions	57
5.2	Weighted by 6 weighting functions	58
5.3	A motion segmentation example	61
5.4	Visual results on sequence Long Street	67
5.5	Visual results on sequence Office	68
<hr/>		
6.1	An illustration of pixels uses in the directional convolution	76
6.2	Isophote direction detection on Barbara	77
6.3	Isophote direction detection on a structural image	78
6.4	Pyramidal implementation	84
6.5	Multi-stage refinement	85
6.6	Multi-step linearization	86
6.7	Jacobi iteration	88
6.8	Visual results on Middlebury sequences	93
6.9	The interpolation error	94

List of Figures

6.10	Qualitative performance comparison on HumanEva-II	95
<hr/>		
7.1	Integer Quantization Vectors	101
7.2	Group the quantization vectors to 5 sets	102
7.3	Visual results on HumanEva-II	110
7.4	A zoom-in comparison	111
7.5	Visual results on Walking	112
7.6	Visual results on MiniCooper	113
7.7	Visual results on Moving	114
7.8	Performance difference on Grove2	114
7.9	The strength and weakness of the two methods	115
<hr/>		
A.1	The Middlebury colorwheel	121
A.2	Middlebury hidden fluorescent texture sequences	123
A.3	Middlebury computer graphics synthetic sequences	124
A.4	Middlebury stereo sequences	125
A.5	Middlebury real sequences	126
A.6	McCane et al. synthetic sequences	128
A.7	Yosemite	129
A.8	Miscellaneous test sequences	129

List of Tables

4.1	Performance evaluation on benchmark sequences	53
5.1	Analysis of the error statistics of sequence Long Street	69
5.2	Analysis of the error statistics of sequence Office	69
6.1	Comparison with other methods	90
6.2	Numerical evaluation of each step.	91
7.1	Quantitative comparison	108

Notations

Image Intensity and Geometry

X, Y, Z	the world coordinate of a 3D point
x, y	spatial coordinates in the image plane
t	temporal coordinate in an image sequence
$E(x, y, t)$	image intensity function
\vec{d}	a general direction or the isophote (edge) direction, depending on the context
\vec{n}	the edge normal direction
$\mathcal{N}()$	the set of neighbours of a pixel
k	the k th pixel in a local patch, unless otherwise specified
$a^{(k)}$	the “a” of the k th pixel in the local patch
$a^{(c)}$	the “a” of the patch center
u	the horizontal component of the flow vector
v	the vertical component of the flow vector
\vec{v}	the flow vector, i.e., $\vec{v} = \begin{bmatrix} u & v \end{bmatrix}^T$
\vec{V}	the homogeneous flow vector, i.e., $\vec{V} = \begin{bmatrix} u & v & 1 \end{bmatrix}^T$

Derivatives

E_x	first order partial derivatives of $E(x, y, t)$ with respect to variable x
E_{xx}	second order partial derivatives of $E(x, y, t)$ with respect to variable x
\dot{E}	total temporal derivative when compact notation is needed, $\dot{E} = \frac{dE}{dt}$
∇	spatial gradient vector
∇_3	spatial-temporal gradient vector
∇_d	gradient vector in an oriented coordinate system
Δ	Laplacian, $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$
$\text{div}\left(\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}\right)$	divergence $\text{div}\left(\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}\right) = \frac{\partial}{\partial x}(a_1) + \frac{\partial}{\partial y}(a_2)$
$\text{div}_d\left(\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}\right)$	directional divergence $\text{div}_d\left(\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}\right) = \frac{\partial}{\partial \vec{d}}(a_1) + \frac{\partial}{\partial \vec{n}}(a_2)$
$\partial_{\vec{d}}$	directional derivative in direction \vec{d} , i.e., $\frac{\partial}{\partial \vec{d}}$

Notations

H_{2D}	the spatial Hessian matrix	$\begin{bmatrix} E_{xx} & E_{xy} \\ E_{xy} & E_{yy} \end{bmatrix}$
H_{3D}	the spatio-temporal Hessian matrix	$\begin{bmatrix} E_{xx} & E_{xy} & E_{xt} \\ E_{xy} & E_{yy} & E_{yt} \\ E_{xt} & E_{yt} & E_{tt} \end{bmatrix}$
S_{2D}	the spatial Structure tensor	$\begin{bmatrix} \sum E_x^2 & \sum E_x E_y \\ \sum E_x E_y & \sum E_y^2 \end{bmatrix}$
S_{3D}	the spatio-temporal Structure tensor	$\begin{bmatrix} \sum E_x^2 & \sum E_x E_y & \sum E_x E_t \\ \sum E_x E_y & \sum E_y^2 & \sum E_y E_t \\ \sum E_x E_t & \sum E_y E_t & \sum E_t E_t \end{bmatrix}$

Vector and Matrix Operation

$\mathbf{0}$	a matrix whose elements are all zeros
\vec{a}	"a" is a vector
\vec{X}	the motion parameter vector in the local system $A\vec{X} = \vec{b}$
$\ \cdot \ _1$	the l_1 norm of a vector
$\ \cdot \ _2$	the l_2 norm of a vector
$[\cdot]^T$	the transpose of a vector or a matrix
$\langle \vec{a}, \vec{b} \rangle$	inner product of vector \vec{a} and \vec{b}
$A * B$	the convolution of A and B
A^+	the pseudo-inverse of matrix A
$N(A)$	the null space of matrix A
$col()$	the column space
$span(\vec{a}_1, \dots, \vec{a}_n)$	the space spanned by basis vectors $\vec{a}_1, \dots, \vec{a}_n$
\perp	orthogonal
G_σ	Gaussian smoothing kernel of standard deviation σ
$K_{\frac{\partial}{\partial \vec{a}}}$	directional differencing filter
$A \sim B$	matrix A can be transformed to B by elementary matrix operations

Miscellaneous

\mathcal{E}	the error functional
$\alpha_1, \dots, \alpha_6$	affine motion model parameters
ϵ	a small positive number to prevent the denominator from being 0
λ	Lagrange multiplier
λ_i	the i th eigenvalue or singular value of a matrix
ω	weight
τ	index of the iteration stage, unless otherwise specified
ζ, η	the axes of the locally oriented coordinate frame
T	threshold, unless otherwise specified
δa	the refinement or increase of a in an iteration process
R	the set of real numbers
R^+	the set of positive real numbers