ACKNOWLEDGEMENTS

I am greatly indebted to Dr. Marc P. Christensen, my advisor, for his unyielding support and astute guidance during my Ph.D. I sincerely admire his inexhaustible patience, and his ability to deconstruct complex problems and illuminate the essence in simple terms. I have tried my best to learn these valuable skills by observing him. I thank him for masterfully shaping my thoughts through critical questioning, helpful discussions, insightful suggestions, and at the same time giving me the freedom to define and pursue the research in my own way.

I am very grateful to my friend and colleague Dr. Prasanna Rangarajan. I have spent several years collaborating with him on a multitude of Optics and Imaging research. I have grown as a researcher seeing and admiring his tenacious work ethics, math wizardry, and problem-solving methods. I thank him for the endless stimulating whiteboard discussions, for sharing his knowledge and ideas, and for helping me refine the mathematical model in this thesis.

I express my sincere gratitude to Dr. Panos Papamichalis, Dr. Dinesh Rajan and Dr. Predrag Milojkovic for shaping my research through hard questioning, vocational guidance, perceptive comments, encouragement and help without question whenever I required.

I thank Dr. Delores M. Etter and Dr. Yunkai Zhou for serving on my dissertation committee and giving meaningful feedback on the research work despite their busy schedule. They have always been most sympathetic and accommodating to all my needs.

I am very grateful to Dr. Duncan MacFarlane for providing critical feedback on my work and giving valuable suggestions on improving as a researcher.

I will forever be grateful to my Master’s thesis advisor Dr. Scott Douglas for initiating me to research. Without that opportunity, my life would have inevitably carved out a different path.

I have been very fortunate to be part of a highly motivated and talented group of researchers during my time at SMU: Dr. Manjunath Somayaji, Dr. Vikrant Bhakta, Dr. Esmaeil Faramarzi, Ting Li, Nick Saulnier, Jack Ho, Muralidhar Balaji, Aparna Viswanath and Ashwini Subramanian. I have learned a lot from each of them, and I will always cherish their friendship. I will always be indebted to Dr. Manjunath Somayaji for thoughtfully guiding me both on technical and non-technical matters whenever I needed. I am thankful to Dr. Vikrant Bhakta for being a supportive friend and collaborator. It was Dr. Bhakta and Dr. Somayaji who had initiated the groundwork for examining various techniques for solving the limited capture volume problem in iris recognition.

I would like to thank Jack Strobel of Harwin Camera, Inc. for going out of his way to help with issues related to the view camera we bought from Sinar. I also thank Senior Lecturer Charles DeBus for being kind enough to teach me the basics of view camera photography and allowing me to use his film development lab for my experimentation with a view camera.

Life could have been difficult during my time at SMU without all the help, support and care I received from Susan Bailey, Jay Kirk, Mitzi Hennessey, Julie Bednar, Misti Compton, Kristine R. Reiley, Elizabeth Van Dyken, Lorna Runge and Jim Dees. Susan is very thoughtful and compassionate. I will always be grateful for the generosity Susan, Mitzi, Julie, Misti, and Kristine have shown towards me. Jim's attention to details has ensured the quality of the dissertation. He has also been very kind and helpful with issues related to admission when I needed.

I would like to thank my friends outside the sphere of my research who have motivated me to achieve whatever little I have till now—Sid Choraria, Kiran Tatiparthi, Ruan Chimata, Srinivas Bandi, Arun Hegde, Dipto Mukherjee, Zahid Najam and Nithin Mohandas. I will always be grateful for their generosity and encouragement.

I have been blessed to have a beautiful family. I thank my parents for the immense personal sacrifices they have made for providing me the best education, incommensurable love and care, and constant inspiration. I am grateful for the gift of a wonderful brother and sweet sister. I highly cherish their boundless love and warmest affection. I am very fortunate to have kindhearted and understanding parents-in-law. I can’t thank them enough for their immense love, tiresome patience, and unceasing words of encouragement. Any listing of gratitude would be utterly incomplete without acknowledging the immense love and delicate care I have always received from my *dadu,* *didun*, and *borthakuma*, my grandparents.

Last but not the least, I thank my wife and best friend, Vibha, for her steadfast support, unfathomable patience, and unconditional love for me through the vicissitudes of our life. Time just seems to fly in her presence.

Sinharoy, Indranil BE in Electronics & Communication Engineering, VTU, India, 2003

MS in Electrical Engineering, Southern Methodist University, 2006

Scheimpflug with Computational Imaging to Extend the Depth of

Field of Iris Recognition Systems

Advisor: Professor Marc P. Christensen

Doctor of Philosophy December 17, 2016

Dissertation completed November 28, 2016

Despite the enormous success of iris recognition in close-range and well-regulated spaces for biometric authentication, it has hitherto failed to gain wide-scale adoption in less controlled, public environments. The problem arises from a limitation in imaging called the depth of field (DOF): the limited range of distances beyond which subjects appear blurry in the image. The loss of spatial details in the iris image outside the small DOF limits the iris image capture to a small volume--the capture volume. Existing techniques to extend the capture volume are usually expensive, computationally intensive, or afflicted by noise. Is there a way to combine the classical Scheimpflug principle with the modern computational imaging techniques to extend the capture volume? The solution we found is, surprisingly, simple; yet, it provides several key advantages over existing approaches.

Our method, called Angular Focus Stacking (AFS), consists of capturing a set of images while rotating the lens, followed by registration, and blending of the in-focus regions from the images in the stack. The theoretical underpinnings of AFS arose from a pair of new and general imaging models we developed for Scheimpflug imaging that directly incorporates the pupil parameters. The model revealed that we could register the images in the stack analytically if we pivot the lens at the center of its entrance pupil, rendering the registration process exact. Additionally, we found that a specific lens design further reduces the complexity of image registration making AFS suitable for real-time performance. We have demonstrated up to an order of magnitude improvement in the axial capture volume over conventional image capture without sacrificing optical resolution and signal-to-noise ratio. The total time required for capturing the set of images for AFS is less than the time needed for a single-exposure, conventional image for the same DOF and brightness level. The net reduction in capture time can significantly relax the constraints on subject movement during iris acquisition, making it less restrictive.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS……………………………………………………………………… iii

ABSTRACT……………………………………………………………………………………… vi

LIST OF FIGURES……………………………………………………………………………… xii

LIST OF TABLES……………………………………………………………………………… xvi

Chapter

1. BACKGROUND...……………………………………………………………………….. 1
   1. The depth of field problem illustrated………………..……………………………. 3
   2. Understanding optical resolution and depth of field..…………………………….... 4
   3. Primer on iris recognition………………………………………………………….. 9
   4. Desirable properties of iris recognition systems………………………………….. 15
   5. Scheimpflug imaging……………………………………………………………... 23
   6. Computational imaging…………………………………………………………… 25
   7. Summary…………………………………………………………………………. 26
2. STATE-OF-THE-ART…………………………………………...................................... 27
   1. State-of-the-art large standoff iris acquisition…………………………………… 27
   2. State-of-the-art iris acquisition with large capture volume………………………. 29
   3. State-of-the-art iris acquisition with large instantaneous capture volume……….. 31
      1. Extending capture volume using image processing…………………….. 31
      2. Extending capture volume using wavefront coded systems…………….. 31
3. MODEL OF SCHEIMPFLUG IMAGING – I: PROPERTIES OF IMAGE…………... 36
   1. Background.……………………………………………………………………… 39
   2. Notations…………………………………………………………………………. 41
   3. Relation between pupil magnification and chief ray angle………………………. 42
   4. Transfer of chief ray’s direction cosines between the pupils…………………….. 44
   5. Image formation for arbitrary orientation of the lens and image plane………….. 50
   6. Verification of imaging equation in Zemax……………………………………… 57
   7. Geometric properties of images under lens and image plane rotation…………… 58
      1. Properties of image field induced by sensor rotation ………………………………………………………………………... 60
      2. Properties of image field induced by lens rotation away from center of the entrance pupil …………………...... 61
      3. Properties of image field induced by lens rotation about the center of the entrance pupil …………..…………. 62
   8. Summary…………………………………………………………………………. 70
4. MODEL OF SCHEIMPFLUG IMAGING – II: FOCUSING………………………….. 71
   1. Relationship between the object, lens, and image planes for focusing…………... 72
   2. Examples of typical Scheimpflug imaging configurations………………………. 80
      1. Example: Focusing in frontoparallel configuration……………………... 80
      2. Example: Focusing on tilted object plane by tilting the image plane…… 82
      3. Example: Focusing on a tilted object plane by tilting a lens using thin lens model…………………………………………………………………….. 87
      4. Example: Focusing on a tilted object plane by tilting a lens using thick lens model…………………………………………………………………….. 89
      * Verification of formulae for focusing on a tilted object plane by tilting the lens……………………………………………………………….. 93
      * Consequences and analysis of the focusing equation………………... 95
      * Condition for monotonicity of ……………………... 102
      * Algorithm for finding for known ………………………………. 106
   3. Summary………………………………………………………………………... 111
5. SYNTHESIZING EXTENDED DEPTH OF FIELD…………………………………. 113
   1. Extending depth of field using frontoparallel focus stacking…………………... 114
      1. Advantages of focus stacking for extended depth of field……………... 116
   2. Extending depth of field using angular focus stacking (AFS)…..……………… 118
      1. Inter-image homography for lens of unit pupil magnification, tilted about entrance pupil…………………………………………………………... 120
      2. Image registration using the inter-image homography………………… 124
   3. Simulation of extended DOF image synthesis using angular focus stacking…... 125
   4. Advantages of angular focus stacking for extending the DOF of iris acquisition systems………………………………………………………………………….. 132
   5. Demonstration of capture volume extension for iris acquisition………………... 132
   6. Summary………………………………………………………………………... 141
6. DISCUSSION…………………………………………………………………………. 143
   1. Summary of the work…………………………………………………………… 143
   2. Conclusions…………………………………………………………………… 146
   3. Limitations……………………………………………………………………… 148
   4. Directions of future research……...…………………………………………….. 150

APPENDIX……………………………………………………………………………………... 152

1. Appendix A…………………………………………………………………………….. 152

A.1 Transfer of chief ray’s direction cosine for arbitrary orientation of the optical axis………………………………………………………………………….. 152

A.2 The direction cosine, originating from exit pupil, has unit -Norm………. 156

1. Appendix B…………………………………………………………………………….. 158

B.1 Derivation of Gaussian imaging equation with pupil magnification……….. 158

B.2 A brief account on the significance of pupil magnification………………... 158

1. Appendix C…………………………………………………………………………….. 165

C.1 Distribution of light near focus (3D PSF) for imaging between parallel planes……………………………………………………………………….. 165

REFERENCES…………………………………………………………………………………. 167

LIST OF FIGURES

Figure

* 1. The depth of field (DOF) problem……………………………………………………...... 3
  2. Incoherent impulse response and DOF…………………………………………………… 5
  3. First order simulation of iris acquisition at multiple depths……………………………… 7
  4. Complexity and uniqueness of human iris……………………………………………….. 9
  5. The iris recognition as a binary classification problem…………………………………. 10
  6. Schematic of the normalization process using a spoke pattern ………………………… 13
  7. Overview of iris biometric code generation ……………………………………………. 14
  8. Number of publications in (English) journals on iris recognition between 1990 & 2013……………………………………………………………………………………… 15
  9. Maximum optical spatial frequency vs. F-number (F/#) for different modulation transfer functions for a wavelength of 850 *nm* at the image plane…………….………………… 17
  10. Focal length vs. standoff distance for maintaining 200 pixels across the iris for different pixel pitches…………………………………………………………………………….. 19
  11. Geometric depth of field vs. system F-number (F/#) for various object distances……… 20
  12. Diffraction depth of field vs. system F-number (F/#) for various object distances……... 21
  13. Effect of aperture size on DOF and lateral resolution…………………………………... 23
  14. Frontoparallel vs Scheimpflug imaging………………………………………………… 25
  15. A visual representation of the capture volumes of selected systems from Table 2.1…… 35
  16. Scheimpflug camera movements………………………………………………………... 38
  17. Fundamental rays (contained within the meridional place) and pupils in a Double Gauss lens for an object at infinity……………………………………………………………... 40
  18. Schematic of chief and marginal rays…………………………………………………... 42
  19. Specific problem—optical axis coincides with reference frame’s z-axis………………. 45
  20. Configuration of the general problem—optical axis pivots freely about the origin of camera frame ………………………………………………………………………………... 48
  21. Schematic of geometric image formation………..……………………………………... 52
  22. Schematic of the image plane…………………………………………………………... 53
  23. Ray tracing for verifying Eq. (3.27)…………………………………………………….. 56
  24. “Image points” corresponding to two object planes—a far plane twice the size of the near plane……………………………………………………………………………………... 60
  25. Geometric image under image plane (sensor) rotation for varying pupil magnifications. 64
  26. Comparison of geometric distortion induced by sensor rotation for varying object plane distances…………………………………………………………………………………. 65
  27. Geometric image under lens rotation away from the entrance pupil for varying pupil magnifications…………………………………………………………………………… 66
  28. Variation of geometric distortion of image field induced by lens rotation away from the entrance pupil as a function of object distance and pupil magnification………………... 67
  29. Geometric image under lens rotation away from the entrance pupil for varying pupil magnifications…………………………………………………………………………… 68
  30. Variation of geometric distortion of images induced by lens rotation about the entrance pupil as a function of object distance and pupil magnification…………………………. 69
  31. Schematic of Scheimpflug imaging……………………………………………………... 73
  32. Object and image plane tilt……………………………………………………………… 83
  33. Object and image plane tilt (distances measured from principal planes)………………. 86
  34. Object and lens (thin lens model) plane tilt …………………………………………….. 89
  35. Object and lens (thick lens model) plane tilt …………………………………………… 90
  36. Variation of (y-axis) with respect to lens pivot position for (a) , (b) , and (c) …………………………………………………………………………… 93
  37. Object plane angle and versus lens tilt angle if a lens is rotated about a point away from the entrance pupil…………………………………….. 96
  38. Determination of lens tilt angle for known object tilt angle using point of intersection of *quartic plane curve* with the unit circle……………………………………………… 98
  39. Object plane angle and versus lens tilt angle if a lens is rotated about the entrance pupil……………………………………………………………….. 101
  40. Plots of the first derivative of …………………………………………. 103
  41. Determination of lens tilt for known object plane tilt using point of intersection of *quadratic plane curve* with the unit circle……………………………………………... 107
  42. Example determination of lens tilt angle …………………………………………….. 109
  43. Inner workings of the iterative algorithm for determining given …………………. 111
  44. Schematic of frontoparallel focus stacking…………………………………………….. 114
  45. Example of extend DOF in macro photography using frontoparallel focus stacking…. 116
  46. Schematic of angular focus stacking…………………………………………………… 119
  47. Schematic of simulation setup…………………………………………………………. 127
  48. Integrated sensor images (simulated) in the angular focus stack………………………. 129
  49. Analytic registration of images in the focal stack……………………………………… 130
  50. Result of the angular focus stacking simulation in Zemax…………………………….. 131
  51. Setup for demonstrating capture volume extension…………………………………… 133
  52. Single-shot traditional image capture at F/8…………………………………………… 136
  53. In-focus regions in the registered images in the angular focus stack…….……………. 137
  54. Synthetic image showing extended capture volume using angular focus stacking……. 139
  55. Magnified view of regions near the eyes in the composite (Figure 5.11)…………….... 138
  56. Comparison of magnified patches near the eye between the conventional and composite image obtained using angular focus stacking………………………………………….. 141

B1.1 Schematic of imaging through a lens…………………………………………………... 159

B2.1 Pupil magnification in a wide variety of lenses that form *real* images……………. 162

LIST OF TABLES

Tables

* 1. Comparison of features in the state-of-the-art iris acquisition systems………………… 33
  2. Comparison of numerically computed image points with ray traced (in Zemax) image points for the optical system shown in Figure 3.8……………………………………… 58
  3. Verification of imaging equations Eq. (4.59) and Eq. (4.63) for focusing on a tilted object plane by tilting a lens about a point away from the entrance pupil…………………….. 94
  4. Verification of imaging equations Eq. (4.65) and Eq. (4.66) for focusing on a tilted object plane by tilting a lens about the entrance pupil………………………………………… 100
  5. Algorithm for finding lens tilt required to focus on an object plane tilted by ……. 110

To Vibha.