ACKNOWLEDGEMENTS

I would like to thank my dissertation advisor Dr. Marc P. Christensen for his unyielding support and guidance during my Ph.D. work. His invaluable insights influenced my scientific thinking and research work to a significant degree. I admire his ability to deconstruct complex problems quickly and illuminate the essence in simple terms.

I would like to thank my dear friend and colleague Dr. Prasanna Rangarajan. I have spent well over seven years collaborating with him in our Photonics Architecture Laboratory on a multitude of Optics and Imaging problems. I have grown as a researcher seeing and admiring his method of working. He is a math wizard and very talented researcher. I am indebted to him not only for not suggesting me to derive a model more general than required for solving the problem specific to my thesis but also for helping me with the math when I got stuck.

I would like to express my gratitude to Dr. Panos Papamichalis, Dr. Dinesh Rajan and Dr. Predrag Milojkovic for shaping my education, giving advice and for helping me without question whenever I required.

I thank Dr. Delores M. Etter and Dr. Yunkai Zhou for agreeing to serve on my dissertation committee and giving valuable inputs on the research work despite their busy schedule. I am grateful to Dr. Duncan MacFarlane for providing valuable feedback on my work and giving critical suggestions on improving as a researcher.

I have been very fortunate to be part of a highly motivated and talented group of researchers during my time at SMU from whom I have learned a lot and will always cherish their friendship. They are Dr. Vikrant Bhakta, Dr. Manjunath Somayaji, Dr. Esmaeil Faramarzi, and Ting Li.

I will always be indebted to Dr. Manjunath Somayaji who has been both a friend and a professor to me and has thoughtfully guided me whenever I needed. I am thankful to Dr. Vikrant Bhakta being supportive friend and collaborator.

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

I would like to thank my family and friends especially to my wife, Vibha, for her steadfast support, unfathomable patience, and eternal love; our parents for their love, blessings, and constant encouragement; my brother and sister for their love and wishes; Kiran and Runa; Srinivas Bandi; Arun Hegde; and Zahid.

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

Iris recognition is a promising biometric surveillance technology. However, the inability of an iris camera to operate across a large range severely restricts its use. For example, subjects are required to either stand still at a fixed standoff distance or move slowly through a pre-defined and narrow zone during the capture. Such restrictions pose sever challenges for scaling iris recognition systems that can be used with multiple subjects and in crowded areas.

Two main methods for improving the imaging volume of current iris cameras have been proposed recently: By making the imaging system's response insensitive to focusing errors using wavefront coding. Or by aggregating a large imaging volume using multiple cameras juxtaposed in time or space. While the wavefront coding systems improve the imaging volume by a few folds at close standoff distances, they generally entail high computational cost and are plagued by low SNR. The second method, which requires multiple synchronized cameras for tracking and capturing subjects with the specified volume, has significant system complexity and incur high system cost.

To extend the imaging volume of iris acquisition systems by multiple folds while using a single camera, I propose to use a combination of classical Scheimpflug photography with modern computational imaging. Using Scheimpflug imaging techniques, the plane of sharp focus and the associated DOF can be oriented within a prescribed imaging volume. An optimal orientation of the DOF will be found that maximizes the ability to capture in-focus iris images from multiple subjects positioned within the volume. Computational imaging techniques will be used to address the space variance associated with Scheimpflug imaging, and for further improving the spatial resolution of the camera.

The complexity of such a system is minimal as it will not require multiple cameras and sophisticated tracking mechanism. This system can be scaled simply by using a lens with higher magnification and/ or a sensor with larger area which can be highly cost effective and efficient for installment in public places.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS…… iii

ABSTRACT…… v

LIST OF FIGURES…… xi

LIST OF TABLES…… xiv

Chapter

1. BACKGROUND…… 1

1.1. The depth of field problem illustrated…… 3

1.2. Understanding optical resolution and depth of field…… 4

1.3. Primer on iris recognition…… 9

1.4. Desirable properties of iris recognition systems…… 15

1.5. Scheimpflug imaging…… 24

1.6. Computational imaging…… 25

1.7. Summary…… 26

2. STATE-OF-THE-ART…… 27

2.1. State-of-the-art large standoff iris acquisition…… 27

2.2. State-of-the-art iris acquisition with large capture volume…… 29

2.3. State-of-the-art iris acquisition with large instantaneous capture volume…… 31

2.3.1. Extending capture volume using image processing…… 31

2.3.2. Extending capture volume using wavefront coded systems…… 31

3. MODEL OF SCHEIMPFLUG IMAGING – I: PROPERTIES OF IMAGE…… 36

3.1. Background…… 39

3.2. Notations…… 41

3.3. Relation between pupil magnification and chief ray angle…… 42

3.4. Transfer of chief ray's direction cosines between the pupils…….. 44

3.5. Image formation for arbitrary orientation of the lens and image plane…….. 50

3.6. Verification of imaging equation in Zemax…….…….…….…….… 57

3.7. Geometric properties of images under lens and image plane rotation…… 58

3.7.1. Properties of image field induced by sensor rotation $(\alpha_x, \alpha_y = 0,\ \beta_x,\ \beta_y \in \mathbb{R})$……..……..……..

4.3. Summary……..…….…….…….

C. Appendix C……..……..……..……..……..……..……..…….. 152

C.1 Distribution of light near focus (3D PSF) for imaging between parallel planes……..……..……..……..……..……..……... 152

REFERENCES…….……..……..……..……..……..……..……..…… 154

LIST OF FIGURES

Figure

1.1 The depth of field (DOF) problem……..... 3

1.2 Incoherent impulse response and DOF……5

1.3 First order simulation of iris acquisition at multiple depths…… 7

1.4 Complexity and uniqueness of human iris…….. 9

1.5 The iris recognition as a binary classification problem…… 10

1.6 Schematic of the normalization process using a spoke pattern …… 13

1.7 Overview of iris biometric code generation …… 14

1.8 Number of publications in (English) journals on iris recognition between 1990 & 2013……15

1.9 Maximum optical spatial frequency vs. F-number (F/#) for different modulation transfer functions for a wavelength of 850 *nm* at the image plane…… 17

1.10 Focal length vs. standoff distance for maintaining 200 pixels across the iris for different pixel pitches…….. 19

1.11 Geometric depth of field vs. system F-number (F/#) for various object distances……20

1.12 Diffraction depth of field vs. system F-number (F/#) for various object distances……... 21

1.13 Effect of aperture size on DOF and lateral resolution……... 23

1.14 Frontoparallel vs Scheimpflug imaging…… 25

2.1 A visual representation of the capture volumes of selected systems from Table 2.1…… 35

3.1 Scheimpflug camera movements…….. 38

3.2 Fundamental rays (contained within the meridional place) and pupils in a Double Gauss lens for an object at infinity……... 40

3.3 Schematic of chief and marginal rays……..... 42

3.4 Specific problem—optical axis coincides with reference frame's z-axis…… 45

3.5 Configuration of the general problem—optical axis pivots freely about the origin of camera frame $\{C\}$……... 48

3.6 Schematic of geometric image formation…….. 52

3.7 Schematic of the image plane…….. 53

3.8 Ray tracing for verifying Eq. (3.27)……... 56

3.9 "Image points" corresponding to two object planes—a far plane twice the size of the near plane……...60

3.10 Geometric image under image plane (sensor) rotation for varying pupil magnifications. 64

3.11 Comparison of geometric distortion induced by sensor rotation for varying object plane distances……..65

3.12 Geometric image under lens rotation away from the entrance pupil for varying pupil magnifications……66

3.13 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

3.14 Geometric image under lens rotation away from the entrance pupil for varying pupil magnifications……68

3.15 Variation of geometric distortion of images induced by lens rotation about the entrance pupil as a function of object distance and pupil magnification…….. 69

4.1 Schematic of Scheimpflug imaging……...73

4.2 Object and image plane tilt…… 83

4.3 Object and image plane tilt (distances measured from principal planes)…… 86

4.4 Object and lens (thin lens model) plane tilt 89

4.5 Object and lens (thick lens model) plane tilt 90

4.6 Variation of β (y-axis) with respect to lens pivot position for (a) $\alpha = 0^o$, (b) $\alpha = -5^o$, and (c) $\alpha = -10^o$ 93

4.7 Object plane angle β and $\tan\beta = g(\alpha, m_p, f, d_e, z_o)$ versus lens tilt angle α if a lens is rotated about a point away from the entrance pupil..... 96

4.8 Determination of lens tilt angle α for known object tilt angle β using point of intersection of *quartic plane curve* with the unit circle..... 98

4.9 Object plane angle β and $\tan\beta = g(\alpha, m_p, f, z_o)$ versus lens tilt angle α if a lens is rotated about the entrance pupil..... 101

4.10 Plots of the first derivative of $g(\alpha, m_p, f, z_o)$..... 103

4.11 Determination of lens tilt α for known object plane tilt β using point of intersection of *quadratic plane curve* with the unit circle..... 107

4.12 Example determination of lens tilt angle α..... 109

4.13 Inner workings of the iterative algorithm for determining α given β..... 111

5.1 Schematic of frontoparallel focus stacking..... 114

5.2 Example of extend DOF in macro photography using frontoparallel focus stacking.... 116

5.3 Schematic of angular focus stacking..... 119

5.4 Schematic of simulation setup..... 125

5.5 Integrated sensor images (simulated) in the angular focus stack..... 128

5.6 Analytic registration of images in the focal stack..... 129

5.7 Result of the angular focus stacking simulation in Zemax..... 130

B1.1 Schematic of imaging through a lens..... 146

B2.1 Pupil magnification m_p in a wide variety of lenses that form *real* images..... 149

LIST OF TABLES

Tables

2.1 Comparison of features in the state-of-the-art iris acquisition systems……. 33

3.1 Comparison of numerically computed image points with ray traced (in Zemax) image points for the optical system shown in Figure 3.8…….……..……..…… 58

4.1 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

4.2 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

4.3 Algorithm for finding lens tilt α required to focus on an object plane tilted by β……. 110

To Vibha.