

## ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Marc P. Christensen for his relentless support and advise during the course of my Ph.D. study. His vision and experience influenced my work to a large degree. This is the end of Acknowledgement section.

Sinharoy, Indranil

BE in Electronics & Communication Engineering, VTU, India, 2003  
MS in Electrical Engineering, Southern Methodist University, 2006

Computational Scheimpflug Imaging for Improving  
the Depth of Field of Iris Recognition Systems

Advisor: Professor Marc P. Christensen

Doctor of Philosophy    December 17, 2016

Dissertation completed    October 12, 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 severe 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.....	iv
LIST OF TABLES.....	xv
LIST OF FIGURES.....	xvii

## Chapter

1. INTRODUCTION.....	10
1.1. Introduction.....	10
1.2. The Problem.....	12
2. BACKGROUND ON IRIS RECOGNITION.....	20
3. MODEL OF SCHEIMPFLUG IMAGING – I: PROPERTIES OF IMAGE.....	30
3.1. Introduction.....	30
3.2. Notations.....	31
3.3. Relation between pupil magnification and chief ray angle.....	32
3.4. Transfer of chief ray's direction cosines between the pupils.....	33
3.5. Image formation for arbitrary orientation of the lens and image plane.....	35
3.6. Verification of imaging equation in Zemax.....	36
3.7. Geometric properties of images under lens and image plane rotation.....	38
3.7.1. Properties of image field induced by sensor rotation ( $\alpha_x, \alpha_y = 0, \beta_x, \beta_y \in \mathbb{R}$ ).....	38
3.7.2. Properties of image field induced by lens rotation away from center of the entrance pupil ( $\alpha_x, \alpha_y \in \mathbb{R}, \beta_x, \beta_y = 0; d_e \neq 0$ ) .....	38

3.7.3.	Properties of image field induced by lens rotation about the center of the entrance pupil ( $\alpha_x, \alpha_y \in \mathbb{R}, \beta_x, \beta_y = 0; d_e = 0$ ).....	39
3.8.	Summary.....	39
4.	MODEL OF SCHEIMPFLUG IMAGING – II: FOCUSING.....	40
4.1.	Introduction.....	40
4.2.	Relationship between the object, lens, and image planes for focusing.....	41
4.3.	Examples of typical Scheimpflug imaging configurations.....	45
4.3.1.	Example: Focusing in frontoparallel configuration.....	45
4.3.2.	Example: Focusing on tilted object plane by tilting the image plane.....	46
4.3.3.	Example: Focusing on a tilted object plane by tilting a lens using thin lens model.....	48
4.3.4.	Example: Focusing on a tilted object plane by tilting a lens using thick lens model.....	50
	○ Verification of formulae for focusing on a tilted object plane by tilting the lens.....	55
	○ Consequences and analysis of the focusing equation.....	60
	○ Condition for monotonicity of $g(\alpha, m_p, f, z_o)$ .....	65
	○ Algorithm for finding $\alpha$ for known $\beta$ .....	70
4.4.	Summary.....	75
5.	ANALYSIS OF DEPTH OF FIELD.....	80
6.	OMNIFOCUS IMAGE SYNTHESIS.....	120
	APPENDIX.....	130
A.	Appendix A.....	131
B.	Appendix B.....	135

C. Appendix C.....	136
REFERENCES.....	138

## LIST OF FIGURES

### Figure

1.1	Depth of field (DOF) problem.....	10
1.2	Incoherent impulse response and DOF.....	11
1.3	First order simulation of Iris Acquisition at multiple depths.....	12
1.4	Complexity and uniqueness of human iris.....	13
1.5	The iris recognition as a binary classification problem.....	14
1.6	Overview of Iris biometric code generation.....	15
1.7	Schematic of the normalization process using a spoke pattern.....	16
1.8	Number of publications in (Eng.) journals on iris recognition between 1990 & 2013....	17
1.9	Maximum optical spatial frequency vs. F-number for different modulation transfer functions calculated for a wavelength of 850 nm at the image plane.....	18
1.10	Focal length vs. standoff distance for maintaining 200 pixels across the iris for different pixel pitch.....	19
1.11	Geometric depth-of-field vs. system F-number for various object distances.....	20
1.12	Diffraction depth-of-field vs. system F-number for various object distances.....	21
1.13	Effect of aperture size on DOF and lateral resolution.....	22
2.1	A visual representation of the capture volumes of some systems.....	30
3.1	Scheimpflug camera movements.....	35
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 $\{C\}$ .....	46
3.6	Schematic of geometric image formation.....	47
3.7	Schematic of the image plane.....	48
3.8	Ray tracing for verifying Eq. (3.27).....	49
3.9	“Image points” corresponding to two object planes—a far plane twice the size of the near plane.....	50
3.10	Geometric image under image plane (sensor) rotation for varying pupil magnifications.	60
3.11	Comparison of geometric distortion induced by sensor rotation for varying object plane distances.....	61
3.12	Geometric image under lens rotation away from the entrance pupil for varying pupil magnifications.....	62
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.....	64
3.14	Geometric image under lens rotation away from the entrance pupil for varying pupil magnifications.....	65
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.....	66
4.1	Schematic of Scheimpflug imaging.....	68
4.2	Object and image plane tilt.....	72



## LIST OF TABLES

### Tables

1.1	Comparison of numerically computed image points with ray traced (in Zemax) image points for the optical system shown in Figure 3.8.....	20
1.2	Next table title.....	21

## DEDICATION

Dedicated to my wife, parents, parents-in-law, brother, sister, and friends.