

Table of Contents

Kurzfassung	v
Abstract	vii
List of Abbreviations and Chemical Symbols	xiii
List of Symbols	xv
1 Introduction	1
1.1 Motivation	1
1.2 Problem Statement	2
1.3 Objectives	4
1.4 Thesis Outline	5
1.5 Contributions and Publications	6
1.5.1 Contributions	6
1.5.2 Publications and Patents	6
1.6 State of the Art	7
1.6.1 Measurement Techniques for Gas Detection, Localization and Quantification	7
1.6.2 Computer Vision Techniques for Scene Flow Computation of Gaseous Structures	11
2 Theoretical Background	13
2.1 Basic Concepts and Principles in Radiometry	13
2.1.1 Radiant Energy	13
2.1.2 Spectral Radiance	14
2.1.3 Blackbody Radiation	16
2.1.4 Radiant Energy Propagation through Participating Media ...	18
2.1.5 Radiative Properties at Interfaces	19
2.2 Concepts of Industrial IR-based Gas Leak Detection	21
2.2.1 Infrared Gas Absorption Spectroscopy	21
2.2.2 Gas Leaks	23
2.3 Image Formation	28
2.3.1 Radiometric Model	28
2.3.2 Geometric Model	30
2.4 Image Processing and Computer Vision Concepts	37
2.4.1 Image Denoising	37

2.4.2	Contrast Enhancement	38
2.4.3	Image Segmentation.....	39
2.4.4	Optical Flow	40
2.4.5	Disparity and Stereo Reconstruction	42
2.4.6	Scene Flow	43
2.4.7	Variational Methods in Computer Vision	45
2.5	Section Summary	46
3	Obtaining Spatio-Temporal Information on Gas Structures with Stereo Gas Camera Systems.....	49
3.1	IR Optical Gas Imaging Cameras	49
3.1.1	Radiometric Image Formation	50
3.1.2	Geometric Image Formation.....	52
3.1.3	Differential Images	54
3.1.4	Brightness Constancy Assumption in Differential Images of OGI Cameras	55
3.2	Scene Flow of Gas Structures from Stereo OGI Systems and Differential Images	56
3.2.1	Measurement Model for Scene Flow Computation.....	56
3.2.2	Image Processing Pipeline for Scene Flow Computation.....	58
3.2.3	Optical Flow	64
3.2.4	Disparity and Disparity Change	68
3.2.5	Image Segmentation.....	70
3.3	Uncertainty Propagation and Confidence Measure.....	73
3.4	Time Offset Compensation Method	74
3.5	Section Summary and Discussion	75
4	Validation with Synthetic Data.....	77
4.1	Synthetic Gas Image Generation Framework	77
4.2	Datasets for 3D Fluid Density and 3D Fluid Velocity	79
4.3	Testing of Measurement Model	81
4.3.1	Path-averaged and Concentration Weighted Gas Position	83
4.3.2	Path-averaged and Concentration Weighted Gas Velocity	85
4.4	Effect of Error Sources on Scene Flow Computation of Gas Structures	88
4.4.1	Image Contrast-to-Noise Ratio	88
4.4.2	Main Flow Direction	90
4.4.3	Gas Distance	90
4.5	Section Summary and Discussion	92

5	Measurement System Setup and Calibration	95
5.1	System Description	95
5.1.1	Gas Imaging Camera FLIR GF320	95
5.1.2	Two-camera Stereo System	98
5.1.3	Catadioptric Stereo System	99
5.1.4	Tri-Camera System	102
5.2	System Calibration	102
5.2.1	Jitter Effect	102
5.2.2	Geometric Calibration	104
5.2.3	Radiometric Calibration, Image Noise and Radiometric Correction	109
5.3	Temporal Offset	115
5.4	Section Summary and Discussion	116
6	Experimental Analysis	119
6.1	Laboratory Measurements	119
6.1.1	Test Bench	120
6.1.2	Effect of Radiation Difference	122
6.1.3	Temporal Offset	124
6.1.4	Jet Flow Velocity and Orientation	125
6.2	Field Measurements with Simulated Methane Leak in Biogas Plant	128
6.3	Field Measurement of Real Leakage in Biogas Plant	132
6.4	Simulated Butane/Propane Leak in Petroleum Refinery	134
6.5	Main Technical System Limitations	138
6.6	Section Summary and Discussion	139
7	Summary and Outlook	141
7.1	Summary	141
7.2	Outlook	145
8	Appendix	149
8.1	Refractive Index n of some common Gases	149
8.2	Derivation of generic camera radiometric model	149
8.3	Euler-Lagrange equations of the used scene flow functional	150
8.4	Proposed local contrast enhancement approach	152
8.5	Mirror Reflectivity and Depth of Field in Catadioptric Stereo Systems	153
8.6	Sensor Specifications	155
8.7	Results of Intrinsic Camera Calibration	156
8.8	Datasets for optical and scene flow computation in the visual range	157

References 159