Contents

Part I Methods of 3D Computer Vision

1	Geometric Approaches to Three-dimensional Scene Reconstruction			
	1.1	The P	inhole Camera Model	3
	1.2	Bundl	e Adjustment Methods	7
	1.3	Geom	etric Aspects of Stereo Image Analysis	9
		1.3.1	Euclidean Formulation of Stereo Image Analysis	9
		1.3.2	Stereo Image Analysis in Terms of Projective Geometry	12
	1.4	Geom	etric Calibration of Single and Multiple Cameras	17
		1.4.1	Methods for Intrinsic Camera Calibration	17
		1.4.2	The Direct Linear Transform (DLT) Method	18
		1.4.3	The Camera Calibration Method by Tsai (1987)	21
		1.4.4	The Camera Calibration Method by Zhang (1999a)	25
		1.4.5	The Camera Calibration Method by Bouguet (2007)	27
		1.4.6	Self-calibration of Camera Systems from Multiple Views	
			of a Static Scene	28
		1.4.7	Semi-automatic Calibration of Multiocular Camera Systems	41
		1.4.8	Accurate Localisation of Chequerboard Corners	51
	1.5	Stereo	Image Analysis in Standard Geometry	62
		1.5.1	Image Rectification According to Standard Geometry	62
		1.5.2	The Determination of Corresponding Points	66
	1.6	Three-	-dimensional Pose Estimation and Segmentation Methods	87
		1.6.1	Pose Estimation of Rigid Objects	88
		1.6.2	Pose Estimation of Non-rigid and Articulated Objects	95
		1.6.3	Point Cloud Segmentation Approaches	113
2	Photometric Approaches to Three-dimensional Scene Reconstruction			
	2.1	Shape	from Shadow	127
		2.1.1	Extraction of Shadows from Image Pairs	128
		2.1.2	Shadow-based Surface Reconstruction	
			from Dense Sets of Images	130

xiii



xiv Contents

2.2.2 Determination of Surface Gradients 2.2.3 Reconstruction of Height from Gradients 2.2.4 Surface Reconstruction Based on Eikonal Equations 2.3 Photometric Stereo 2.3.1 Classical Photometric Stereo Approaches 2.3.2 Photometric Stereo Approaches Based on Ratio Images 2.4 Shape from Polarisation 2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data		2.2	Shape	from Shading	132
2.2.3 Reconstruction of Height from Gradients 2.2.4 Surface Reconstruction Based on Eikonal Equations 2.3 Photometric Stereo 2.3.1 Classical Photometric Stereo Approaches 2.3.2 Photometric Stereo Approaches Based on Ratio Images 2.4 Shape from Polarisation 2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes 3 Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.2.1	The Bidirectional Reflectance Distribution Function (BRDF)	132
2.2.4 Surface Reconstruction Based on Eikonal Equations 2.3 Photometric Stereo 2.3.1 Classical Photometric Stereo Approaches 2.3.2 Photometric Stereo Approaches Based on Ratio Images 2.4 Shape from Polarisation 2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes 3 Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Focus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Small Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstructio at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 4.3.5 Estimation of the Surface Albedo			2.2.2	Determination of Surface Gradients	. 137
2.3.1 Classical Photometric Stereo Approaches 2.3.2 Photometric Stereo Approaches Based on Ratio Images 2.4 Shape from Polarisation 2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstructio 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.2.3	Reconstruction of Height from Gradients	142
2.3.1 Classical Photometric Stereo Approaches 2.3.2 Photometric Stereo Approaches Based on Ratio Images 2.4 Shape from Polarisation 2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes 3 Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstructio at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.2.4	Surface Reconstruction Based on Eikonal Equations	144
2.3.2 Photometric Stereo Approaches Based on Ratio Images . 2.4.1 Surface Orientation from Dielectric Polarisation Models . 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes . 3 Real-aperture Approaches to Three-dimensional Scene Reconstruction . 3.1 Depth from Focus . 3.2.1 Basic Principles . 3.2.2 Determination of Small Depth Differences . 3.2.3 Determination of Absolute Depth Across Broad Ranges . 4 Integrated Frameworks for Three-dimensional Scene Reconstructio . 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale . 4.1.1 Combining Motion, Structure, and Defocus . 4.1.2 Online Version of the Algorithm . 4.1.3 Experimental Evaluation Based on Tabletop Scenes . 4.1.4 Discussion . 4.2 Self-consistent Combination of Shadow and Shading Features . 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis . 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism . 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis . 4.2.4 Experimental Evaluation Based on Synthetic Data . 4.2.5 Discussion . 4.3 Shape from Photopolarimetric Reflectance and Depth . 4.3.1 Shape from Photopolarimetric Reflectance . 4.3.2 Estimation of the Surface Albedo . 4.3.3 Integration of Depth Information . 4.3.4 Experimental Evaluation Based on Synthetic Data . 4.3.5 Experimental Evaluation Based on Synthetic Data . 4.3.6 Experimental Evaluation Based on Synthetic Data . 4.3.7 Experimental Evaluation Based on Synthetic Data . 4.3.8 Experimental Evaluation Based on Synthetic Data . 4.3.9 Experimental Evaluation Based on Synthetic Data . 4.3.1 Experimental Evaluation Based on Synthetic Data . 4.3.2 Experimental Evaluation Based on Synthetic Data .		2.3	Photo	metric Stereo	146
2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes 3. Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Small Depth Differences 3.2.3 Determination of Small Depth Across Broad Ranges 4. Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of Depth Information 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.3.1	Classical Photometric Stereo Approaches	147
2.4.1 Surface Orientation from Dielectric Polarisation Models 2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes 3 Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.3.2	Photometric Stereo Approaches Based on Ratio Images	. 148
2.4.2 Determination of Polarimetric Properties of Rough Metallic Surfaces for Three-dimensional Reconstruction Purposes Real-aperture Approaches to Three-dimensional Scene Reconstruction. 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data		2.4	Shape	from Polarisation	151
Metallic Surfaces for Three-dimensional Reconstruction Purposes Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.4.1	Surface Orientation from Dielectric Polarisation Models	. 151
Purposes Real-aperture Approaches to Three-dimensional Scene Reconstruction. 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm. 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			2.4.2	Determination of Polarimetric Properties of Rough	
Real-aperture Approaches to Three-dimensional Scene Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data					
Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data				Purposes	. 154
Reconstruction 3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data	_	_			
3.1 Depth from Focus 3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data	3				1.00
3.2 Depth from Defocus 3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data					
3.2.1 Basic Principles 3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges 4 Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			-		
3.2.2 Determination of Small Depth Differences 3.2.3 Determination of Absolute Depth Across Broad Ranges Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data		3.2	-		
Integrated Frameworks for Three-dimensional Scene Reconstructio 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data					
4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data					
 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 			3.2.3	Determination of Absolute Depth Across Broad Ranges	. 170
 4.1 Monocular Three-dimensional Scene Reconstruction at Absolute Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 	4	Inte	grated	Frameworks for Three-dimensional Scene Reconstruction	181
Scale 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data	•		_		
 4.1.1 Combining Motion, Structure, and Defocus 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 		-			182
 4.1.2 Online Version of the Algorithm 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 					
 4.1.3 Experimental Evaluation Based on Tabletop Scenes 4.1.4 Discussion 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 			4.1.2		
 4.1.4 Discussion. 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 			4.1.3		
 4.2 Self-consistent Combination of Shadow and Shading Features 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 				-	
 4.2.1 Selection of a Shape from Shading Solution Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 		4.2	Self-c		
Based on Shadow Analysis 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data					
 4.2.2 Accounting for the Detailed Shadow Structure in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 					. 197
in the Shape from Shading Formalism 4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data			4.2.2	Accounting for the Detailed Shadow Structure	
4.2.3 Initialisation of the Shape from Shading Algorithm Based on Shadow Analysis 4.2.4 Experimental Evaluation Based on Synthetic Data 4.2.5 Discussion 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data				in the Shape from Shading Formalism	200
4.2.4 Experimental Evaluation Based on Synthetic Data			4.2.3	Initialisation of the Shape from Shading Algorithm	
4.2.4 Experimental Evaluation Based on Synthetic Data				Based on Shadow Analysis	202
4.2.5 Discussion			4.2.4		
 4.3 Shape from Photopolarimetric Reflectance and Depth 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 			4.2.5	Discussion	
 4.3.1 Shape from Photopolarimetric Reflectance 4.3.2 Estimation of the Surface Albedo 4.3.3 Integration of Depth Information 4.3.4 Experimental Evaluation Based on Synthetic Data 		4.3	Shape		
 4.3.2 Estimation of the Surface Albedo					
4.3.3 Integration of Depth Information			4.3.1		207
4.3.4 Experimental Evaluation Based on Synthetic Data				Shape from Photopolarimetric Reflectance	
			4.3.2	Shape from Photopolarimetric Reflectance	211
4.3.5 Discussion			4.3.2 4.3.3	Shape from Photopolarimetric Reflectance	. 211 . 212
4.4 Stereo Image Analysis of Non-Lambertian Surfaces			4.3.2 4.3.3 4.3.4 4.3.5	Shape from Photopolarimetric Reflectance Estimation of the Surface Albedo Integration of Depth Information Experimental Evaluation Based on Synthetic Data Discussion	. 211 . 212 . 217 . 222

Contents

		4.4.1	Iterative Scheme for Disparity Estimation	
		4.4.2	Qualitative Behaviour of the Specular Stereo Algorithm	. 229
	4.5	Three-	-dimensional Pose Estimation Based on Combinations of	
		Mono	cular Cues	. 230
		4.5.1	Appearance-based Pose Estimation	
			Relying on Multiple Monocular Cues	. 231
		4.5.2	Contour-based Pose Estimation Using Depth from Defocus	. 236
Par	rt II	Applica	tion Scenarios	
5	Ann	dication	ns to Industrial Quality Inspection	243
	5.1		etion of Rigid Parts	
	0.1	5.1.1	Object Detection by Pose Estimation	
		5.1.2	Pose Refinement	
	5.2		etion of Non-rigid Parts	
	5.3	-	etion of Metallic Surfaces	
	3.3	5.3.1	Inspection Based on Integration of Shadow	. 250
		3.3.1	and Shading Features	256
		5.3.2	Inspection of Surfaces with Non-uniform Albedo	
		5.3.3	Inspection Based on SfPR and SfPRD	
		5.3.4	Inspection Based on Specular Stereo	
		5.3.5	Discussion	
		3.3.5	23000000	. 2,3
6	App	lication	s to Safe Human–Robot Interaction	. 277
	6.1	Vision	-based Human-Robot Interaction	. 277
		6.1.1	The Role of Gestures in Human-Robot Interaction	. 278
		6.1.2	Safe Human-Robot Interaction	. 279
		6.1.3	Pose Estimation of Articulated Objects in the Context	
			of Human-Robot Interaction	. 282
	6.2	Object	t Detection and Tracking in Three-dimensional Point Clouds	. 291
	6.3		ion and Spatio-temporal Pose Estimation of Human Body	
			• • • • • • • • • • • • • • • • • • • •	. 293
	6.4		dimensional Tracking of Human Body Parts	
			·	
7	App		s to Lunar Remote Sensing	. 303
	7.1		dimensional Surface Reconstruction Methods for Planetary	
		Remot	te Sensing	
		7.1.1	Topographic Mapping of Solar System Bodies	
		7.1.2	Reflectance Behaviour of Planetary Regolith Surfaces	. 307
	7.2	Three-	dimensional Reconstruction of Lunar Impact Craters	. 311
		7.2.1	Shadow-based Measurement of Crater Depth	. 311
		7.2.2	Three-dimensional Reconstruction of Lunar Impact	
			Craters	
			at High Resolution	. 314
	7.3	Three-	dimensional Reconstruction	
		of Lun	nar Wrinkle Ridges and Faults	. 322

xvi	Contents
AVI	Contents

	7.4 Three	e-dimensional Reconstruction of Lunar Domes		
	7.4.1	General Overview of Lunar Mare Domes		
	7.4.2	Observations of Lunar Mare Domes		
	7.4.3	Image-based Determination of Morphometric Data		
	7.4.4	Geophysical Insights Gained from Topographic Data 343		
8	Conclusion	1		
Re	ferences			