

Contents

1	Introduction	1
1.1	Objectives	2
1.2	Challenges	4
1.3	Contributions	6
1.4	Outline	8
2	Related Work	9
2.1	3D acquisition for outdoor urban modelling	9
2.1.1	3D laser scanning	10
2.1.2	Multi-view airborne imagery	13
2.1.3	Multi-view satellite imagery	15
2.1.4	Mobile Mapping Systems (MMS)	17
2.1.5	Comparison between LiDAR and 3D vision	19
2.2	Fundamentals of computational 3D vision	22
2.2.1	Feature detectors and descriptors	22
2.2.2	Camera models and calibration	24
2.2.3	Fundamentals of computational stereo	27
2.2.4	Dense stereo matching	29
2.2.5	Structure-from-Motion	35
2.2.6	Multi-View Stereo	38
2.3	Urban 3D modelling and semantic analysis	41
2.3.1	Semantic segmentation of images	41
2.3.2	Semantics and 3D	43
2.3.3	Street-level 3D modelling of architecture	45
2.3.4	Procedural and inverse procedural modelling	47
2.3.5	Facade parsing	49
2.3.6	Urban 3D modelling from airborne data	51
3	Efficient preprocessing for image-based street-side modelling	55

3.1	Sparse point clouds from street-side sequences	56
3.2	Image over-segmentation for 3D modelling	61
3.2.1	Unsupervised image segmentation methods	62
3.2.2	Hierarchical Unregularized Superpixels (HUNS)	64
3.2.3	Evaluation	68
3.3	Conclusions	77
4	Street-side reconstruction from sparse SfM data and superpixels	79
4.1	Multi-view piecewise-planar modelling	80
4.1.1	Generating plane hypotheses from multiple views . . .	82
4.1.2	Energy formulation for piecewise-planar segmentation	84
4.1.3	Optimization of the support regions	88
4.1.4	Experiments	89
4.1.5	Conclusions	94
4.2	Fast 2.5D mesh modelling over SfM points	97
4.2.1	Overview of the proposed method	99
4.2.2	2D base mesh extraction from an image	100
4.2.3	Depth reconstruction	101
4.2.4	Handling discontinuities and occlusions	104
4.2.5	Qualitative results	106
4.2.6	Evaluation of depth accuracy	112
4.2.7	Evaluation of rendering quality	113
4.2.8	Conclusions	114
5	Compact 2.5D modelling of large urban areas from airborne data	117
5.1	Problem formulation	118
5.2	Overview of our approach	121
5.3	Base mesh extraction from dense height maps	123
5.3.1	Piecewise-planar partitioning of a dense height map . .	123
5.3.2	Region merging with quality control	124
5.4	2.5D surface reconstruction by mesh lifting	127
5.4.1	Depth data association	127
5.4.2	Initial baseline reconstruction via planes	128
5.4.3	Vertex depth optimization with connectivity	129
5.4.4	Handling discontinuities	131
5.4.5	Base mesh splitting and component analysis	133
5.4.6	Hole filling driven by the topology of the base mesh .	134
5.5	Experiments	135

5.5.1	Results on DSM from airborne imagery	135
5.5.2	Comparison to other methods	140
5.5.3	Results from LiDAR data	141
5.6	Conclusions	143
6	Fusing airborne and street-side 3D data	145
6.1	Generic 3D data fusion	147
6.2	The proposed surface reconstruction method	148
6.2.1	Volumetric reconstruction based on visibility constraints	148
6.2.2	Airborne and street-side point cloud blending	151
6.2.3	Data reduction techniques for large scenes	153
6.3	Experiments	154
6.4	Multi-view texturing of large urban meshes	161
6.4.1	Image-based texturing of 3D meshes	161
6.4.2	The proposed multi-view texturing pipeline	162
6.4.3	Textured results	166
6.5	Conclusions	170
7	Multi-class semantic analysis of urban 3D models	173
7.1	Semantic segmentation of large-scale models	174
7.1.1	Unsupervised semantic segmentation of a compact urban mesh based on geometric features	175
7.1.2	Supervised segmentation of urban DSMs with defects	179
7.2	Semantic segmentation of street-side meshes	190
7.2.1	Baseline street-side mesh segmentation	191
7.2.2	Reducing the workload of semantic segmentation . . .	193
7.2.3	Experimental evaluation	197
7.3	Summary and discussion	203
8	Conclusions	207