



Contents

Abstract	i
Zusammenfassung	iii
Nomenclature	xii
Abbreviations	xiv
1 Introduction	1
1.1 Ground Penetrating Radar Data Analysis	1
1.2 Thesis Overview	4
1.3 Contributions	6
1.4 Published Work	7
2 Problem Definition	9
2.1 Radar Data Analysis	10
2.2 Machine Learning	13
2.3 Continuous Real World Measurements	16
2.4 Discretized Formalization of GPR Measurements	19
2.5 The Pipe Identification Task	24
2.6 Chapter Summary	26
3 A Technical Framework for Complex Engineering Raw Data Analysis	29
3.1 Related Work	31
3.2 Use Cases	33
3.3 Analysis of Kinds of Complex Engineering Data	35
3.4 Requirement Analysis for the Analysis of CERD	36
3.5 Conceptual Design	39



3.6	Technical Implementation	45
3.7	Framework Components	53
3.8	End-User Prototypes	56
3.9	Chapter Summary	64
4	Data Preparation	65
4.1	Data Description	66
4.2	Data Preprocessing	68
4.3	Data Analysis	78
4.4	Chapter Summary	84
5	Gathering Accurate Hyperbola Annotations for Applying Machine Learning on GPR Data	85
5.1	Motivation	86
5.2	Related Work on Human Annotations and Inter-Human Annotation Behaviour	89
5.3	Semi-Manual Hyperbola Annotation Process	92
5.4	Qualitative Error Categorization	97
5.5	Advanced Studies on Human Annotation Behaviour on CERD	99
5.6	Technical Integration within our Conceptual Framework	107
5.7	Chapter Summary	109
6	Hyperbola Detection from Sparse Data	111
6.1	Related Work on Hyperbola Detection from Sparse Data	112
6.2	Detecting Single Hyperbolas	114
6.3	Error Shape Analysis for Single Hyperbola Optimization Criteria	117
6.4	Parameter Initialization	120
6.5	Pseudo-Orthogonal Hyperbola Fitting	121
6.6	Multi Hyperbola Estimation	124
6.7	Experimental Results	124
6.8	Chapter Summary	130
7	Unsupervised Object Detection from Dense Data	131
7.1	Related Work on Pipe Detection from Dense Data	132
7.2	Hough Transform	133
7.3	Kirchhoff Migration	138
7.4	Multi Hyperbola Estimation	142
7.5	Experimental Results	144
7.6	Chapter Summary	147
8	Supervised Object Detection by Patch-Based Classification	149
8.1	Related Work on Object Detection from Dense Data (Patch-Based Classification)	150
8.2	Convolutional Neural Networks	152
8.3	Experimental Results	156
8.4	Chapter Summary	161



9	Hyperbola Curvature Inference from Dense Data	163
9.1	Component-wise Radargram Decomposition	164
9.2	Related Work on Parameter Inference for Generative Models	164
9.3	Synthetic Pipe Reflection Pattern	165
9.4	Experimental Results	169
9.5	Chapter Summary	171
10	Conclusion and Future Work	173
10.1	Conclusion	173
10.2	Future Work	175
A	Appendix	179
A.1	GprMax Input Definition	180
A.2	Filter Chain Example	181
A.3	Comparison of Command line Parameter Parsing Libraries	182