

Contents

Contents	I
Abbreviations	IV
Symbols	VII
1 Introduction	1
1.1 Problem statement	1
1.2 Research objective	2
1.3 Structuring questions	3
1.4 Structure of the thesis	3
2 Fundamentals	4
2.1 Visual inspection in remanufacturing	4
2.1.1 The remanufacturing process	4
2.1.2 Challenges for initial visual inspection	7
2.1.3 Automated visual inspection	9
2.1.4 Summary and conclusion: View planning tasks for the initial visual inspection	10
2.2 View planning for visual inspection systems	11
2.2.1 Robot active vision and the view planning problem (VPP)	12
2.2.2 Object representation alternatives for the solution of the VPP	15
2.2.3 Analytical solution methods for VPP	18
2.2.4 Algorithmic requirements, acquisition goal, and evaluation metrics	20
2.2.5 Fundamentals of coordinate systems and pose transformations	22
2.2.6 Summary and conclusion: View planning in Remanufacturing	23
2.3 Machine learning and deep learning	24
2.3.1 Overview of machine learning categories	24
2.3.2 Neural networks (NNs) as universal function approximators	26
2.3.3 Advanced machine learning using deep learning	29
2.3.4 Summary and conclusion: View planning enabled by machine learning	34
3 State-of-the-art literature review	36
3.1 Approaches for visual inspection in remanufacturing	36
3.1.1 Works using image-based defect detection in remanufacturing	36

3.1.2	Interim conclusion to existing works on image-based defect detection in remanufacturing	38
3.2	Derivation of delimitation criteria	39
3.3	Approaches using analytical methods	41
3.4	Approaches using machine learning	43
3.4.1	Approaches using supervised learning	44
3.4.2	Approaches using reinforcement learning	46
3.5	Derivation of the research deficit	50
4	Overview of the solution approach	54
5	Autonomous view planning for visual inspection in Remanufacturing	58
5.1	Setup, modeling, and control of the inspection station and 3D reconstruction of the inspection object	58
5.1.1	Hardware setup of the inspection station and acquisition process	58
5.1.2	Virtual model and control approach of the inspection station	61
5.1.3	Kinematic modeling and calibration of the inspection station	63
5.1.4	3D reconstruction of the inspection object	65
5.2	Approach for semantic 3D reconstruction of the inspection object	67
5.2.1	Dataset generation and data preprocessing	68
5.2.2	Semantic and instance segmentation with deep learning	71
5.2.3	Uncertainty estimation for segmentation results	78
5.2.4	Semantic 3D reconstruction of the inspection object	80
5.3	View planning using reinforcement learning	81
5.3.1	Formalization of view planning goals	82
5.3.2	Overview of the simulation framework using a reinforcement learning agent $A_{Plan,RL}$	83
5.3.3	Modelling of the scan simulation environment S_{Sim}	84
5.3.4	Modelling of the agent interface I_{Agent}	89
5.3.5	Modeling of the reinforcement learning agent $A_{Plan,RL}$	106
6	Evaluation and computational results	109
6.1	Results for the approaches of 3D reconstruction and semantic 3D reconstruction	109
6.1.1	Validation of the 3D Reconstruction approach	109
6.1.2	Results of the semantic segmentation and instance segmentation approaches	111
6.1.3	Evaluation of the semantic 3D reconstruction approach	118

6.2	RL for the solution of VPPs in remanufacturing	121
6.2.1	Dataset description	121
6.2.2	Evaluation approach	123
6.2.3	Results of the RL agent training using the proposed simulation frame- work for the NBV problem	128
6.2.4	Results of the RL agent training using the proposed simulation frame- work for the RPP problem	131
6.2.5	Results of the RL agent training using the proposed simulation frame- work for the IPP problem	152
7	Discussion and outlook	158
7.1	Critical appraisal	158
7.2	Outlook	160
8	Conclusion	162
	Bibliography	165
	List of Figures	186
	List of Tables	191
	Own Publications	194
	Anhang	XII
A1	General solution approach for SCP, CM and NBV approaches	XII
A2	In-depth basics of coordinate transformations	XV
A3	Basics of the perceptron, multi-layer perceptron and backpropagation algorithm	XVII
A4	Details on point cloud transformation using $\mathbf{T}^{A/RT'}$ and determination of $\mathbf{T}^{E/A}$ and $\mathbf{T}^{R/RT}$	XX
A5	In-depth details and foundations on the segmentation model architectures and training procedure	XXIII
A6	T-Scan system product information	XXX
A7	Evaluation metrics for the 3D reconstruction approach	XXXI
A8	Result tables for training the U-Net, UD-Net, M-Net and MD-Net configurations	XXXII
A9	Evaluation metrics for the semantic segmentation approach using uncertainty- based filtering	XXXVIII
A10	Details on the SCP benchmark algorithms used in this work	XL