

# Contents

<b>Abstract</b>	<b>V</b>
<b>List of Figures</b>	<b>XII</b>
<b>List of Tables</b>	<b>XIII</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Research Context . . . . .	2
1.2 Socially Aware Navigation . . . . .	2
1.3 Research Challenges in Socially Aware Navigation . . . . .	3
1.4 Contributions and Outline . . . . .	4
<b>2 Related Work</b>	<b>7</b>
2.1 Survey Works on SAN . . . . .	7
2.2 Motion Planning Methods for Social Navigation . . . . .	9
2.3 Integrating Social Awareness into Motion Planning . . . . .	15
2.4 Evaluation Methodologies in SAN . . . . .	19
2.5 Summary and Discussion . . . . .	20
<b>3 Background</b>	<b>23</b>
3.1 Core Concepts and Factors of Socially Aware Navigation . . . . .	23
3.1.1 Proxemics and Human Comfort . . . . .	24
3.1.2 Speed Adaptation in Socially Aware Navigation . . . . .	24
3.1.3 Proactive Planning and Human Intention Inference . . . . .	26
3.2 Collision Avoidance using Dynamical System Modulation . . . . .	26
3.2.1 Notations . . . . .	27
3.2.2 Fundamentals of Dynamical System Modulation . . . . .	27
3.2.3 DSM with additional Dynamics . . . . .	31
3.3 An Analytical View of DSM for Socially Aware Navigation . . . . .	33
3.3.1 State-Space Interpretation: Shaping System Equilibria . . . . .	34
3.3.2 Dynamic Interpretation: Governing Acceleration . . . . .	34
3.3.3 Comparative Analysis: DSM and Social Force Model . . . . .	35
3.3.4 Analytic Properties of the DSM Framework . . . . .	36
3.4 Summary . . . . .	40

<b>4</b>	<b>Framework 1: Social Inference Modulated DSM (SIM-DSM)</b>	<b>41</b>
4.1	Social Inference Model for Intent-Aware Planning . . . . .	41
4.1.1	Background: Social Force Model for Robot Navigation . . . . .	42
4.1.2	Probabilistic Human Navigation Intent Inference . . . . .	43
4.1.3	Formulation of the Social Inference Model . . . . .	44
4.2	The SIM-DSM Framework . . . . .	48
4.2.1	Modeling of Human Proxemics Zone in DSM . . . . .	49
4.2.2	Socially-Aware Eigenvalue Design for Velocity Scaling . . . . .	51
4.3	Simulation Study . . . . .	53
4.3.1	Simulation Setups and Scenarios . . . . .	53
4.3.2	Evaluation Metrics . . . . .	55
4.3.3	Simulation Result: Corridor . . . . .	56
4.3.4	Simulation Results: Four Agent Position Swapping . . . . .	61
4.4	Summary . . . . .	62
<b>5</b>	<b>Experimental Validation and Evaluation of SIM-DSM</b>	<b>69</b>
5.1	Introduction . . . . .	69
5.2	Experiment Setup . . . . .	70
5.2.1	Study Context: Environment and Participants . . . . .	70
5.2.2	Experimental Design and Conditions . . . . .	71
5.2.3	Experimental Procedure . . . . .	72
5.2.4	Evaluation Methodology . . . . .	74
5.3	Validation of the SIM-DSM Framework . . . . .	75
5.3.1	Validation of Proxemics Zone Model . . . . .	75
5.3.2	Online Human Intent Estimation . . . . .	76
5.3.3	Proactive Behavior . . . . .	78
5.3.4	Objective Validation and Analysis . . . . .	78
5.4	Subjective Participant Feedback . . . . .	82
5.4.1	Analysis of Social Factors . . . . .	82
5.4.2	The Influence of the Experimental Environment . . . . .	86
5.5	Discussion . . . . .	86
5.5.1	Limitations of the Human Intent Estimation . . . . .	86
5.5.2	Summary and Outlook . . . . .	87
<b>6</b>	<b>Framework 2: Opinion Dynamics-based DSM (OD-DSM)</b>	<b>93</b>
6.1	Basic Idea of Opinion Dynamics . . . . .	93
6.2	The OD-DSM Framework . . . . .	95
6.2.1	Modeling Robot Passing-Side Intention with Opinion Dynamics . . . . .	96
6.2.2	Socially-Aware Eigenvalue Design . . . . .	99
6.2.3	The Algorithmic Implementation of OD-DSM . . . . .	102
6.3	Simulation Study . . . . .	103
6.3.1	Simulation Scenarios and Setups . . . . .	103

6.3.2	Metrics for Evaluation . . . . .	103
6.3.3	Head-On Scenario Simulation . . . . .	104
6.3.4	Results of Multi-Agent Simulation . . . . .	107
6.4	Summary . . . . .	114
<b>7</b>	<b>Experimental Validation and Evaluation of OD-DSM</b>	<b>117</b>
7.1	Experiment Setup . . . . .	117
7.2	Objective Validation of OD-DSM Framework . . . . .	118
7.2.1	Validation of the Controller Framework . . . . .	118
7.2.2	Proactive Behavior . . . . .	121
7.3	Subjective Participant Feedback . . . . .	121
7.4	Comparison of SIM-DSM and OD-DSM . . . . .	123
7.5	Summary . . . . .	124
<b>8</b>	<b>Conclusions and Future Work</b>	<b>131</b>
8.1	Conclusions . . . . .	131
8.2	Limitations and Future Work . . . . .	132
8.2.1	Limitations . . . . .	132
8.2.2	Future Work . . . . .	133
<b>A</b>	<b>Appendix</b>	<b>135</b>
A.1	Statistics of the Participant Feedback . . . . .	135
A.1.1	Statistics of SIM-DSM Experiment . . . . .	135
A.1.2	Statistics of SIM-DSM in 2 Environments . . . . .	135
A.1.3	Statistics of OD-DSM . . . . .	136
A.2	Mobile Platform for Experimental Validation . . . . .	136
A.3	Software Architecture . . . . .	138
A.4	Human Motion Tracking . . . . .	139
A.4.1	General Structure . . . . .	139
A.4.2	Human Heading and Speed Estimation using EKF . . . . .	140
A.5	Participant Demographics . . . . .	142
A.6	Image Credits . . . . .	142
	<b>Bibliography</b>	<b>156</b>
	<b>Zusammenfassung</b>	<b>157</b>
	<b>Publications and Supervised Theses</b>	<b>161</b>
	<b>Curriculum Vitae</b>	<b>163</b>