

Berichte aus der Informatik

**Claudia Krull**

**Virtual Stochastic Sensors:  
Formal Background and Example Applications**

Reconstructing the Behavior of Partially Observable Discrete  
and Hybrid Stochastic Systems

Shaker Verlag  
Düren 2021

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Introduction - Complex Technical and Natural Systems . . . . .	1
1.2	Motivation - Partially Observable Complex Systems . . . . .	2
1.3	Are There Existing Solutions to This? . . . . .	4
1.4	Research Goals - Virtual Stochastic Sensors for Stochastic Systems	4
1.5	Technical Requirements . . . . .	6
1.6	Structure of the Thesis . . . . .	7
<b>2</b>	<b>Background and Related Work</b>	<b>9</b>
2.1	Background: Doubly Stochastic Processes as Models of Partially Observable Systems . . . . .	10
2.2	Background: Discrete and Hybrid Stochastic Systems - Models and Their State Spaces . . . . .	13
2.3	Previous Work: State Space-Based Analysis of Discrete Stochas- tic Models Using Proxels . . . . .	19
2.4	Related Work: Machine Learning Methods for Analysis of Parti- ally Observable Systems . . . . .	21
2.5	Scientific Gap . . . . .	23
2.6	Conclusion and Thesis Outlook . . . . .	24
<b>I</b>	<b>Models</b>	<b>27</b>
<b>3</b>	<b>Augmented Stochastic Petri Nets</b>	<b>29</b>
3.1	A User Model for Virtual Stochastic Sensors . . . . .	29
3.2	Discussion of Existing Modeling Paradigms . . . . .	30
3.3	Formal Specification of Augmented Stochastic Petri Nets and Hy- brid ASPN . . . . .	31
3.4	Reviewing Technical Requirements . . . . .	34
3.5	Example ASPN and H-ASPN . . . . .	35
3.6	Discussion and Outlook . . . . .	42
<b>4</b>	<b>Hidden Non-Markovian Models</b>	<b>43</b>
4.1	Combining Hidden Markov Models and Discrete Stochastic Mod- els - What Is the Idea Behind That? . . . . .	43
4.2	Formalization of HnMM - Basic and Variants . . . . .	44
4.3	Proxel-Based HnMM Behavior Reconstruction Algorithm . . . . .	48
4.4	Academic Models and Experiments . . . . .	52

4.5	Discussion of HnMM . . . . .	63
<b>5</b>	<b>Conversive Hidden Non-Markovian Models</b>	<b>65</b>
5.1	Restriction in Modeling Power . . . . .	65
5.2	Formalization - Making HnMM Conversive . . . . .	66
5.3	Fast Behavior Reconstruction Algorithms . . . . .	66
5.4	Academic Models and Experiments . . . . .	75
5.5	Discussion of CHnMM . . . . .	85
<b>6</b>	<b>Hybrid Hidden Non-Markovian Models</b>	<b>87</b>
6.1	Making HnMM Hybrid . . . . .	87
6.2	Formalization - Rewards and Guards . . . . .	88
6.3	Behavior Reconstruction of Hybrid HnMM . . . . .	89
6.4	Academic Models and Experiments . . . . .	97
6.5	Discussion of HHnMM . . . . .	107
<b>II</b>	<b>Applications</b>	<b>109</b>
<b>7</b>	<b>Applications in Engineering</b>	<b>111</b>
7.1	Introduction and Motivation . . . . .	111
7.2	Optibox - Virtual Stochastic Sensors for Tracking in Workshop Environments . . . . .	112
7.3	NIALM - Virtual Stochastic Sensors for Disaggregation of Smart Meter Data . . . . .	121
7.4	Discussion of Applicability in Engineering . . . . .	129
<b>8</b>	<b>Applications in Movement Recognition and Analysis</b>	<b>133</b>
8.1	Introduction and Motivation . . . . .	133
8.2	Existing Approaches for Movement Recognition . . . . .	135
8.3	Wii-Mote and Multi-Touch Table - Preliminary Studies on Vir- tual Stochastic Sensors for Gesture Recognition . . . . .	139
8.4	Stroke Map - Virtual Stochastic Sensors for the Recognition of Freeform Trajectories . . . . .	141
8.5	Discussion of Applicability in Movement Trajectory Recognition	150
<b>9</b>	<b>Conclusion</b>	<b>153</b>
9.1	Summary . . . . .	153
9.2	Contributions and Goal Evaluation . . . . .	154
9.3	Recommendations for Users . . . . .	156
9.4	Benefit and Outlook . . . . .	157
9.5	Further Research . . . . .	157
	<b>List of Acronyms</b>	<b>161</b>
	<b>Bibliography</b>	<b>167</b>