

Risk Management in Intelligent Agents

Xun Wang



A Thesis submitted for the degree of Doctor of Philosophy

Faculty of Engineering and Information Technology

University of Technology, Sydney

2012

Certificate of Authorship and Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student

Acknowledgements

Working on my doctoral research has been one of the most memorable experiences of my life. I would like to thank all people who have helped and inspired me during the past five years of my study.

First and foremost, I would like to thank my supervisor, Professor Mary-Anne Williams. Without your inspiration and encouragement, I would not even contemplate working on my Ph.D research project. Throughout my Ph.D career, you have shown me what would be possible and steer me towards my research goals. You have given me great support in developing my main research ideas; challenged me on many of my immature thoughts. You have pushed me to reach a level of scientific standards that I would not be able to achieve alone. In addition to my main research project, you have also encouraged me to explore new technologies and supported me on fun and challenging projects such as RoboCup. These “side” projects have kept me sane when my main research topic overwhelmed me at times. “Research should be fun” is what I have learned from you. You are a great mentor and a friend. I am deeply grateful for what you have done for me.

Second, I would like to thank many of my colleagues for reviewing my thesis and collaborating with me on many projects. Birger Johansson was the first person who read my thesis draft while it was still an incoherent piece of text. Your suggestions were very useful. I enjoyed many insightful discussions with you while you were visiting our laboratory. I also had the great opportunity working with Chris Stanton on the RoboCup project which I enjoyed enormously. Thanks for correcting many of my grammatical errors in my thesis. Your comments on how to structure my work

has greatly helped me. Sajjad Haider taught me a great deal on machine learning and Bayesian inference techniques. Your inputs on my thesis have further improved some of my research ideas. I would also like to thank Benjamin Johnston for his great effort going through my final thesis draft in details. Many of your comments were invaluable. I am also in debt to Shan Chen for keeping my spirit up when I was exhausted at times. I also had pleasure working with Jebrin Al-Sharawneh. Our discussions on what is risk were challenging and insightful.

Third, I would like to thank Thierry Denoeux for our discussion on Belief Functions and Transferable Belief Model during KSEM 2010 conference and many anonymous reviewers for their comments and suggestions on the ideas presented in my research papers. My thesis examiners Didier Dubois and Pavlos Peppas have given me valuable critiques and insightful suggestions. I am forever grateful for your helps! I would also like to thank IBM for their financial support during the fourth year of my Ph.D career.

Finally, I would like to thank my parents, my wife Lily and my daughter Alison for putting up with me for such a long time. Without your support and understanding, this thesis would not be possible.

Table of Contents

Table of Contents	iv
Abstract	xiv
1 Introduction	1
2 An Analysis of Risk Related Concepts	8
2.1 Definitions of Risk	9
2.2 Conceptualising Risk for Intelligent Agents	11
2.3 Uncertainties, Probabilities, Belief and Possible Worlds	13
2.3.1 Possible Worlds Paradigm	14
2.3.2 Encoding Uncertainty in a Likelihood Order	15
2.3.3 Encoding Uncertainty in Probability	16
2.4 Measuring Consequence	18
2.4.1 Qualitative Consequence	18
2.4.2 Quantitative Consequence	19
2.5 Combining Uncertainty and Consequence	19
2.5.1 Risk Matrix for Qualitative Risk Representation	20
2.5.2 Quantitative Risk Measure	21
2.5.2.1 Expected Utility	22
2.5.2.2 Probability-EU Space	22
2.5.3 Application of the Risk Measure	25
2.5.3.1 Value at Risk	25
2.6 Summary	26
3 Requirements for a Generalised Risk Management Framework	29
3.1 Benchmark Problems for Risk Modelling	30
3.1.1 Benchmark Problem 1 - Ball Passing Problem	30
3.1.2 Benchmark Problem 2 - Foreign Exchange (FX)	31
3.2 Framework Requirements	32

3.3	Existing Risk Management Methodologies	35
3.3.1	Fault Tree Analysis (FTA)	35
3.3.2	Event Tree Analysis (ETA)	37
3.3.3	Failure Mode and Effects Analysis (FMEA)	38
3.3.4	Probabilistic Models	39
3.3.5	Hierarchical Holographic Models	40
3.3.6	Dealing with Uncertainty under Partial Ignorance	40
3.3.7	A Comparison with the Framework Requirements	41
4	Knowledge Representations and Management in Complex and Un-	
	certain Environments	43
4.1	Classical Logic	45
4.1.1	Propositional Logic	46
4.1.1.1	Interpretation and Knowledge Base	46
4.1.1.2	Forms of Propositional Formula	47
4.1.2	First Order Logic	48
4.1.3	Second Order Logic	49
4.2	Non-Classical Logic	50
4.2.1	Default Logic	51
4.2.1.1	Syntax of Default Logic	51
4.2.1.2	Semantics of Default Logic	52
4.2.1.3	Operational Semantics of Default Logic	52
4.2.1.4	Variations of Extensions	53
4.2.1.5	*Applicability of Default Logic	54
4.2.2	Autoepistemic Logic	54
4.2.2.1	Semantics of Autoepistemic Logic	55
4.2.2.2	Computation of Expansions	56
4.2.2.3	*Relation with Default Logic	57
4.2.3	Circumscription	57
4.2.3.1	Syntax of Circumscription	58
4.2.3.2	Semantics of Circumscription	59
4.2.3.3	Applicability of Circumscription	60
4.2.4	*Incomplete Knowledge and Changing Information	60
4.3	Belief Revision	61
4.3.1	AGM Paradigm	62
4.3.1.1	Preliminaries	62
4.3.1.2	Postulates for Expansion	63
4.3.1.3	Postulates for Revision	63
4.3.1.4	Postulates for Contraction	64
4.3.1.5	Belief Contraction versus Belief Revision	65

4.3.2	Belief Operator Selection	65
4.3.2.1	Epistemic Entrenchment	66
4.3.2.2	System of Spheres	67
4.3.3	Belief Base Change	69
4.3.4	Iterative Belief Revision	70
4.3.4.1	Ordinal Conditional Functions (OCF)	70
4.3.4.2	Transmutations	71
4.3.4.3	Ordinal Epistemic Functions	71
4.4	Bayesian Probabilistic Model	75
4.4.1	Conditional Probability	75
4.4.2	Conditional Independence	76
4.4.3	Bayesian Networks	77
4.4.4	Bayesian Network Construction	79
4.4.4.1	Learning Network Parameters from Complete Data .	81
4.4.4.2	Learning Network Parameters from Incomplete Data	83
4.4.4.3	Learning Network Structures	86
4.4.5	Inferences in Bayesian Networks	90
4.4.5.1	Exact Inference	90
4.4.5.2	Approximate Inference	98
4.4.6	*Limitations of Bayesian Networks	103
4.5	Transferable Belief Model	105
4.5.1	Belief Function	106
4.5.2	Simple Support Function	108
4.5.3	Vacuous Belief Function	108
4.5.4	Latent Belief Structure	108
4.5.5	The Λ Operator and Apparent Belief	109
4.5.6	Rules of Combination	109
4.5.7	Conditional Belief Function and Rules of Conditioning	111
4.5.8	Generalised Bayesian Theorem	112
4.5.9	Evidential Network	113
4.5.10	Pignistic Transformation	114
4.5.11	*TBM versus Probabilistic Model	115
4.6	Possibility Theory	116
4.6.1	Possibility Distributions	117
4.6.2	Possibility and Necessity Measures	118
4.6.2.1	Comparative Possibility Relation	119
4.6.2.2	Conditioning and Combination in Qualitative Possibility	121
4.6.2.3	Quantitative Possibility Measure	122
4.6.2.4	Conditioning and Combination in Quantitative Possi- bility	123

4.6.3	*Connecting Qualitative and Quantitative Uncertainty	124
4.7	Capturing Causal Connections	125
4.7.1	Ramsey Test	125
4.7.1.1	Compatibility with Belief Revision	126
4.7.2	Inductive Causation	128
4.8	*Summary	129
5	An Overview of HiRMA	132
5.1	Three-level Framework Architecture	133
5.2	Iterative Risk Modelling Process	136
5.3	A Knowledge Description Template for Risk Analysis	138
5.4	Theoretical Assumptions	142
6	Risk Management with Qualitative Knowledge	143
6.1	Qualitative Epistemic Reasoning Model	144
6.1.1	Epistemic Reasoning Model Schema	144
6.2	Qualitative Graphical Risk Model	149
6.2.1	Capturing Knowledge in the Ball Passing Problem	150
6.2.2	Risk Modelling in a System of Spheres	152
6.2.2.1	Epistemic Reasoning Models within a Sphere	153
6.3	Risk Model Construction and Revision	154
6.3.1	Revision of Domain Variables	154
6.3.1.1	Semantics of Variable Addition	155
6.3.1.2	Removal of a Domain Variable	156
6.3.2	Revision of Reasons	157
6.3.3	Model Construction and Revision Algorithms	158
6.3.3.1	Modelling with the Ball Passing Problem	163
6.4	Decision Making under Qualitative Risk Model	164
6.5	Discussion	167
7	Risk Management with Quantitative Knowledge	172
7.1	Quantitative Graphical Risk Model	174
7.1.1	Model Quantified Epistemic Reasons	175
7.1.1.1	Lead – Quantified Epistemic Reason	176
7.1.1.2	Frame of Discernment Ω_X	177
7.1.1.3	Data Fusion in Lead	178
7.1.1.4	Latent Lead	179
7.1.1.5	The $\dot{\Lambda}$ Operator and Causal Strength	180
7.1.1.6	The Ranking Structure RS	181
7.2	Risk Model Construction and Revision	182
7.2.1	Revision of Domain Variables	182

7.2.2	Revision of Leads	185
7.2.3	Model Construction and Revision Algorithms	186
7.2.4	Graphical Probabilistic Model Generation	187
7.2.5	Modelling with Ball Passing Problem	189
7.3	Discussion	190
8	A Unified Multi-level Iterative Framework	195
8.1	Bridging the Qualitative and Quantitative Divide in Risk Management	196
8.2	Framework Evaluation	199
8.3	Risk Modelling Strategies	201
8.4	A Generic Software Architecture	203
9	Conclusions	207
A	An Extended FX Example	214
A.1	Initial Risk Analysis	214
A.2	Analysis and Selection of Modelling Process	216
A.3	Knowledge Databases for Modelling FX risk	216
A.3.1	Database Structure for \mathbb{K}	216
A.3.2	Database Structure for \mathbb{K}^c	218
A.3.3	Populated Knowledge Database \mathbb{K}	219
A.4	Functional Code Snippets	221
A.4.1	add_variable	222
A.4.2	add_metavariable	223
A.4.3	remove_variable	224
A.4.4	remove_reason	224
A.4.5	revise_reason	225
A.4.6	consolidate_reason	227
B	Published Conference Papers	228
	Bibliography	229

List of Figures

1.1	An intelligent agent as a black box, adapted from Poole et al. (1998).	3
2.1	Possible worlds in a likelihood preorder.	16
2.2	Probability-EU space and Probability-Consequence space.	23
2.3	VaR in Probability-Consequence space.	27
3.1	Ball passing between robots	30
3.2	An example of a fault tree (Stephans 2005).	36
3.3	An example of an event tree (Andrews & Dunnett 2000).	37
3.4	An example of a FMEA table (Aven 2008).	38
3.5	An example of a Hierarchical Holographic Model (Liu & Jiang 2012).	39
4.1	A System of Spheres	67
4.2	A Directed Acyclic Graph for the Ball Passing Problem.	77
4.3	A (nonminimal) jointree for the Bayesian network shown in Figure 4.2.	94
4.4	Conversion of a Bayesian network (left) to a likelihood weighting network (right) based on evidence on variables B and E . The CPTs for B and E are modified such that, for example, if $B = b$ and $E = \bar{e}$, then $\theta_b = 1$, $\theta_{\bar{b}} = 0$ and $\theta_e = 0$, $\theta_{\bar{e}} = 1$. This figure is taken from Darwiche (2009).	103
5.1	High level theoretical relationships between qualitative and quantitative modelling approach for risk modelling and management.	135

5.2	A typical risk modelling and management process in HiRMA (at medium domain knowledge abstraction).	137
6.1	Epistemic reasoning models for ball-passing under two initial domain contexts.	151
6.2	A ball passing risk model with all possible epistemic reasoning models captured in a System of Spheres.	153
6.3	Revised ball passing risk model after adjustment with $E(\text{ReasonFor}(D, S_1) \wedge \text{ReasonFor}(D, S_2)) = 1$	158
6.4	Evolution of a simple risk model for ball passing problem. '+' means addition and '-' means contraction. Vacuous reasons are shown in steps in which new variables are added for illustration purpose.	171
7.1	Evolution of a quantitative epistemic reasoning model for risk: initial model setup (a) and corresponding ranking structure (b).	175
7.2	Evolution of a quantitative epistemic reasoning model for risk: Fuse additional lead information from another source with $m(L_{D \rightarrow S_1}) = 0.5$, $m(L_{D \rightarrow S_2}) = 0.3$ and $m(\Omega_D) = 0.2$	178
7.3	Evolution of a quantitative epistemic reasoning model for risk: addition of a risk factor NR (Nearby Robot).	184
7.4	Evolution of a quantitative epistemic reasoning model for risk: update lead $L_{NR \rightarrow S_2}^{0.7}$	185
7.5	Evolution of a simple risk model for ball passing problem. '+' means addition and '-' means contraction. \oplus means data fusion with TBM conjunctive combination rule. Vacuous leads are shown in steps in which new variables are added for illustration purpose.	194
8.1	A flowchart for selecting appropriate risk modelling and management process.	202
8.2	A schematic diagram of a generic software architecture for implementation of the HiRMA framework.	204

A.1 Database schema for a FX risk model at credal level. 216

A.2 Database schema for a consolidated FX risk model. 219

A.3 A snapshot of the quantitative epistemic reasoning model for FX risks. 222

List of Tables

2.1	A conventional risk matrix.	20
2.2	A risk matrix with possible world preorder structure.	21
3.1	A feature comparison of the existing risk management methodologies.	41
4.1	Truth-valued function associated with unary connective.	47
4.2	Truth-valued function associated with the binary connectives.	48
4.3	Conditional Probability Tables (CPT) for $Pr(p k, o)$ and $Pr(i k, o)$. .	78
4.4	A complete set of data samples and empirical distribution for ball passing BN.	81
4.5	Examples of incomplete dataset.	83
4.6	A set of samples generated from network Figure 4.2.	99
4.7	An example of a conditional belief function represented in a table of bbms.	113
5.1	A high-level theoretical architecture of HiRMA.	133
5.2	A domain knowledge description template for knowledge engineer un- dertaking risk analysis.	139
5.3	A simplified analysis of possible scenarios.	140
5.4	A simplified analysis of possible scenarios for FX risk in Australian Dollars.	141
6.1	Graphical symbols and their corresponding meanings.	150

8.1	A high-level theoretical architecture of HiRMA.	197
8.2	A feature comparison between HiRMA and the existing risk management methodologies.	201
A.1	An analysis of possible scenarios for FX risk in Australian Dollars (AUD).	215

Abstract

This thesis presents the development of a generalised risk analysis, modelling and management framework for intelligent agents based on the state-of-art techniques from knowledge representation and uncertainty management in the field of Artificial Intelligence (AI). Assessment and management of risk are well established common practices in human society. However, formal recognition and treatment of risk are not usually considered in the design and implementation of (most existing) intelligent agents and information systems. This thesis aims to fill this gap and improve the overall performance of an intelligent agent. By providing a formal framework that can be easily implemented in practice, my work enables an agent to assess and manage relevant domain risks in a consistent, systematic and intelligent manner.

In this thesis, I canvas a wide range of theories and techniques in AI research that deal with uncertainty representation and management. I formulated a generalised concept of risk for intelligent agents and developed formal qualitative and quantitative representations of risk based on the Possible Worlds paradigm. By adapting a selection of mature knowledge modelling and reasoning techniques, I develop a qualitative and a quantitative approach of modelling domains for risk assessment and management. Both approaches are developed under the same theoretical assumptions and use the same domain analysis procedure; both share a similar iterative process to maintain and improve domain knowledge base continuously over time. Most importantly, the knowledge modelling and reasoning techniques used in both approaches share the same underlying paradigm of Possible Worlds. The close connection between

the two risk modelling and reasoning approaches leads us to combine them into a hybrid, multi-level, iterative risk modelling and management framework for intelligent agents, or HiRMA, that is generalised for risk modelling and management in many disparate problem domains and environments. Finally, I provide a top-level guide on how HiRMA can be implemented in a practical domain and a software architecture for such an implementation. My work lays a solid foundation for building better decision support tools (with respect to risk management) that can be integrated into existing or future intelligent agents.