

Contents

Certificate	ii
Acknowledgments	v
Preface	vii
List of Publications	ix
Contents	x
List of Figures	xiii
List of Tables	xv
Abbreviations	xvi
Symbols	xviii
1 Introduction	1
1.1 Research Goal and Problem Statement	6
1.2 Motivation	7
1.3 Contribution	10
1.4 Scope of Research	11
1.5 Thesis Outline	11
2 Preliminaries and Literature Review	14
2.1 Preliminaries	14
2.1.1 System Requirements	14
2.1.2 Security Related Concepts	15
2.1.3 Model Based System Engineering (MBSE)	16
2.1.4 Threat modeling	17
2.1.4.1 Markov Model	17

2.1.4.2	Petri Net	22
2.1.4.3	Stochastic Petri Net	23
2.1.4.4	GSPN	24
2.2	Literature Review	26
2.2.1	Modeling and Analysis Methods for CPS Security	26
2.2.1.1	Organization and Management of Distributed Secure CPS	32
3	Model based Security Verification of Cyber-Physical System Based on Petrinet: A Case Study of Nuclear Power Plant	38
3.1	Formal Description of CPS	39
3.2	Proposed Methodology	40
3.2.1	Requirement Analysis	40
3.2.2	Functional Model Generation	40
3.2.3	Threat Model Generation	40
3.2.4	Mitigation Model Generation	42
3.2.5	Security Validation	42
3.2.5.1	Qualitative Analysis	43
3.2.5.2	Quantitative Analysis	45
3.3	Case study	46
3.3.1	Requirement identification and analysis:	47
3.3.2	Functional Model Generation	49
3.3.3	Threat Model Generation	52
3.3.4	Mitigation Model Generation	55
3.3.5	Security Metrics Validation	56
3.3.5.1	Qualitative Analysis	56
3.3.5.2	Quantitative Analysis	58
3.4	Discussion	61
3.5	Summary	61
4	Towards Analyzing the Impact of Intrusion Prevention and Response on Cyber-Physical System Availability: A case study of NPP	62
4.1	A roadmap to research solution	63
4.1.1	Intrusion-Disruption Model	64
4.1.2	Security Measures	66
4.2	Formal Specification of Applied Security Measures	67
4.2.1	Preventive Measures	67
4.2.1.1	Perimeter Protection Layers	68
4.2.1.2	Authentication Layer	69
4.2.1.3	Access Control Layer	70
4.2.2	Responsive Measures	71
4.2.2.1	Intrusion Detection and Response Layer	71

4.3	Proof of Concept	72
4.3.1	DFWCS Security Modeling	74
4.3.2	Quantitative Evaluation	78
4.3.3	Comparative Evaluation	92
4.4	Summary	92
5	An Integrated Approach to Design Functionality with Security for Cyber-Physical Systems	93
5.1	Attack scenarios	95
5.2	The proposed architectural model	96
5.2.1	Formal description	96
5.2.2	Layers responsibilities	96
5.2.3	Role of functionality and security leaders	99
5.2.4	The proposed leader election algorithm	101
5.2.4.1	Message type	103
5.2.4.2	Leader election method	103
5.2.4.3	Complexity analysis	107
5.2.5	Resilience against cyber attacks	109
5.3	Performance evaluation of the proposed architectural model	110
5.3.1	Case study	110
5.3.2	Performance evaluation	112
5.4	Summary	118
6	Conclusion and Future Direction	120
6.1	Conclusion	120
6.2	Future Research Directions	123
	Bibliography	125

List of Figures

1.1	Holistic view of a CPS	2
1.2	Major responsibilities of CPS architecture layers [78]	2
1.3	Thesis Structure	12
2.1	Security ontology	15
2.2	Simplex system model example	21
2.3	Elementary SPN models	24
2.4	Transformation of SPN model	24
2.5	GSPN model and its reachability graph	25
3.1	Proposed security modeling and analysis methodology	40
3.2	Architectural view of feed water controller [4]	47
3.3	Functional model of DFWCS (FMA)	48
3.4	Integrity attack on sensor data (FMIT)	48
3.5	DoS attack on communication channel (FMDT)	48
3.6	Functional model of DFWCS with security measure (FMM)	49
3.7	Reachability graph of FMA	49
3.8	Reachability graph of FMIT	50
3.9	Reachability graph of FMDT	50
3.10	Reachability Graph of FMM	51
3.11	Markov chain corresponding to FMM reachability graph	51
3.12	Transition rate matrix corresponding to FMM	52
3.13	Effect of readjustment of mitigation strategy	53
4.1	General underline framework of CPS security	68
4.2	Applied preventive and responsive defense measures on DFWCS	73
4.3	GSPN model of DFWCS functionality	74
4.4	GSPN model of DFWCS under attack and defense	74
4.5	Reachability graph of FIGURE 4.4	77
4.6	EMC generated from reachability graph of FIGURE 4.4	77
4.7	Integrity Attack (IA) on level sensor	79
4.8	DoS Attack on level sensor	80
4.9	Impact of adjusting defense strength on security evaluation metrics	84
5.1	Layered representation of CPS architecture	97

5.2	Clustered view of the proposed distributed CPS architectural model	97
5.3	Clustered view of cyber layer and decision support layer of the proposed distributed CPS architectural model with functionality and security leaders	97
5.4	Cluster arrangement of a distributed hospital network with functionality and security leaders	111
5.5	Comparison of the proposed system management manner with other possible system management manners based on the number of exchanged messages to complete the task.	114
5.6	Comparison of the proposed system management manner with other possible system management manners based on the time required to complete the task.	115
5.7	Comparison of the proposed system management manner with the distributed manner with a single leader based on the average response time of the task.	116
5.8	Comparison of the proposed system management manner with the distributed manner with a single leader based on the success ratio of real time tasks completion within deadline	117
5.9	Quantile-Quantile plot (Q-Q plot) on the average response time of the tasks getting through the proposed system management manner.	117
5.10	Quantile-Quantile plot (Q-Q plot) on the completion ratio of real-time tasks getting through the proposed system management manner.	118

List of Tables

1.1	Cyber Attacks on cyber physical systems	8
2.1	Related work	31
2.2	Comparative analysis with existing works	36
3.1	Operational mode of DFWCS	47
3.2	Place Description of FMA	52
3.3	Transition Description of FMA	52
3.4	Security metrics evaluation table of FMA, FMIT, FMDT	57
3.5	Effect of readjustment of mitigation strength on steady-state probabilities λ_9	60
4.1	IDRS responses	72
4.2	Place Description of Figure 4.3	73
4.3	Transition Description of Figure 4.3	73
4.4	Place Description of Figure 4.4	75
4.5	Transition Description of Figure 4.4	76
4.6	Impact of attack	78
4.7	Effect of readjustment of mitigation strength on performance metrics	85
4.8	Effect of readjustment of mitigation strength on performance metrics	86
4.9	Comparative study	87
5.1	Details of the networks considered for the experiments	112