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Reggie Davidrajuh

Petri Nets for Modeling of Large Discrete Systems

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Reggie Davidrajuh

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Reggie Davidrajuh
Department of Electrical Engineering
and Computer Science
University of Stavanger
Stavanger, Norway

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This book is dedicated to my family:

my wife Ruglin

and

my daughter Ada

Foreword

It gives me great pleasure to write a "foreword" for this wonderful book on Petri nets and an innovative approach to handling huge Petri net models using distributed computing so as to enable them to be fast enough for real-time control applications. Petri nets are handy for modeling discrete event systems. However, they suffer from some weaknesses, e.g., massive size, huge state space, and slow simulation. Due to the enormous state space, model checking a Petri net is difficult. Also, Petri nets are difficult to be used for real-time applications due to the slowness in simulation. Thus, this book suggests modular Petri nets as a way of overcoming these difficulties.

In modular Petri nets, modules are designed, developed, and run independently. Also, the modules communicate with each other via inter-modular connectors. Hence, the bottom-up approach is suggested (starting with the modules and then combining them after thorough testing) for developing newer Petri net models. However, many Petri net models of real-life systems exist (legacy models), which are enormous and non-modular. These legacy models cannot be discarded as large amounts of time, effort, and money were spent developing these legacy models. In this case, the top-down approach is the only solution, which starts with the existing legacy models, decomposing them into modules, and then joining them together after testing them individually. This book presents both approaches centering around modules (known as "Petri modules"). Petri modules are well defined for inter-modular collaboration.

This book aims to introduce a methodology in which Petri nets are moved to a new level. In this new level, large Petri net models are made of Petri modules that are independent and run on different computers. Also, Petri modules communicate with each other using the inter-modular components (e.g., TCP/IP sockets). Thereby, the compact Petri modules run faster and, thus, become suitable for supervisory control of real-time systems.

This book focuses on Petri modules. This book presents the literature study on modular Petri nets and definitions for the newer Petri modules. Also, algorithms for extracting Petri modules and algorithms for connecting Petri modules and applications are given in this book. The ideas and algorithms proposed in this book are implemented in the software General-purpose Petri net Simulator (GPenSIM, developed by the author of this book). Hence, real-life discrete event systems could be modeled, analyzed, and performance-optimized with GPenSIM.

I congratulate Prof. Davidrajuh for bringing out this highly technical book in a very lucid manner and welcome this book as a valuable addition to the Springer series on "Asset Analytics".

Ajit Kumar Verma
Professor (Technical Safety) and Series Editor,
Asset Analytics-Performance and Safety
Management, Western Norway University
of Applied Sciences, Haugesund, Norway

Preface

Cyber-physical systems involve hardware and software that are highly interconnected and complex. Unexpected failures in these systems can cause material damages, cost a lot of money and reputation, and can risk human lives too. The correct way of avoiding unexpected failures is to make a mathematical model of the system and to perform exhaustive analysis on it. Also, mathematical models are inevitable for performance analysis of the systems (e.g., finding throughput and bottlenecks) and to plan for extensions (e.g., measuring cost over performance factor).

Petri net, since its inception in 1962, has been used for modeling and performance analysis of discrete event systems. In the 1970s and 80s, Petri net was tried out on modeling smaller discrete manufacturing systems like flexible manufacturing systems with a handful of CNC machines and robots. Very soon, it became apparent that even for smaller systems, the Petri net models become huge. Also, the state spaces generated from the models become too big to handle (the problem of state explosion). Of course, for a large Petri net model of a real-life discrete system, the state space is enormous, and analysis of it is not a possibility.

Also, simulations take too much time, as the simulation of a Petri net means tracking the movement of tokens as they pass through places and transitions. For a large Petri net with hundreds of places and transitions, monitoring the movements of all those tokens makes the simulations slower. The slow simulations also make Petri net not suitable for real-time control. If faster execution of Petri net is possible, then Petri net could become an ideal candidate for supervisory control of real-time systems.

Finally, researchers and engineers agree that model checking is the only systematic way of finding and fixing errors in industrial systems before they go into production. For Petri net models of discrete event system, model checking verifies whether the state space satisfies a given property specification. Here too, due to the enormous size of the state space, model checking is either difficult or not possible at all.

Some Petri net slicing methods are proposed in the literature to make the Petri net smaller so that the resulting state space also becomes smaller. However, for real-life discrete even systems (especially for manufacturing systems), the proposed Petri net slicing methods fail to produce any slice at all, as the systems are strongly connected.

In some cases, the slicing methods provide slices; however, the resulting state spaces remain as huge as before.

For all these problems mentioned above (massive Petri net models resulting in enormous state spaces, slowness in simulation, and unsuitability for real-time control), this book presents the modular Petri net as the solution. Although in the literature, modular Petri net has been proposed as a solution, this is the first time modular Petri net is given a full focus. In this book, starting with a historical perspective (literature study), a clear and well-defined Petri module is designed and analyzed. Also, the toolbox of the General-purpose Petri net Simulator (GPenSIM) is extended to support modules, so that modular Petri net models of real-life discrete event systems can be developed and tested.

It is must be emphasized that the modular Petri net presented in this book is designed and developed as a general solution to many problems that are discussed above. In particular, the theory, design, and implementation of modular Petri net presented in this book provide four benefits:

1. Fast and Flexible model development: Modelers can independently design, develop, and test modules that make up a modular Petri net model.
2. Faster simulation: The modules can be hosted on different computers so that they can run faster, and these modules can communicate through TCP/IP sockets, exchanging tokens (messages, status, and control policies as tokens).
3. Real-time control: A module can receive data from sensors that are attached to the computer that is hosting the module. Also, a module can control actuators that are also attached to the computer.
4. Departmental cost calculation: Since GPenSIM supports cost calculation, activity-based departmental cost calculation is possible as modules represent different departments of a manufacturing system and the transitions inside a module represent different activities of a department.

The Structure of This Book

This book consists of four parts. Part-I "Petri nets and GPenSIM" is the introductory part consisting of four chapters:

- Chapter 1 "Introduction to Petri nets" starts with formal definitions of the key terms used in this book.
- Chapter 2 "Introduction to GPenSIM" introduces the software known as the General-purpose Petri net Simulator (GPenSIM). Only the basics of GPenSIM are given in this chapter. GPenSIM defines a Petri net language on the MATLAB platform. GPenSIM is also a simulator with which Petri net models can be developed, simulated, and analyzed. GPenSIM is developed by the author of this book.
- Chapter 3 "Models of Real-Life Systems" presents some Petri net models of typical manufacturing systems. The reason behind this chapter is to clearly show

the major difficulties in using Petri nets for modeling of real-life discrete event systems generally and manufacturing systems especially.
- Chapter 4 "GPenSIM for Monolithic Petri nets" presents the software GPenSIM, focusing on the transitions and their visibility. Chapter 4 is essential as the knowledge of how GPenSIM supported the development of monolithic Petri nets will help understand the extensions that are added to GPenSIM to support modules.

Part-II "Design of Modular Petri Nets" consists of the following four chapters:

- Chapter 5 "Literature Review on Modular Petri Nets" presents an extensive literature study on modular Petri nets. The conclusions drawn from the literature study are the basis for the new design of Petri net modules presented in this book.
- With the conclusion from the literature study, Chap. 6 "Toward Developing a New Modular Petri net" takes the first attempt to design a modular Petri net. This chapter introduces the main elements of a modular Petri net (such as Petri modules and Inter-Modular Connectors (IMC)) and also the input and out ports (IO ports) of a module.
- Chapter 7 "Design of a New Modular Petri Nets" presents complete details about modular Petri nets, providing the formal definitions to all the elements. An application example on modular Petri net is also given.
- Chapter 8 "GPenSIM support for Petri Modules" presents the extension to GPenSIM to support developing modular Petri nets. This chapter discusses the programming constructs provided by GPenSIM for the development.

Part-III "*Legacy* Petri Nets" is about transforming legacy models into Modular Petri nets. Part-III consists of the following two chapters:

- Chapter 9 "Module Extraction": Modularization of a monolithic model starts with identifying the modules (or segments or groups of elements) of the model that can decompose the model into a set of connected independent modules. Once the modules are identified, how can the modules be carved out of the model so that these modules individually adhere to the formal definition of modules? The module extraction algorithm is described in this chapter. Also, this chapter presents an analysis of the preservation of structural properties by modularization.
- Chapter 10 "Activity-Oriented Petri nets (AOPN)": Sometimes, it may not be possible to modularize a legacy model, due to its crisscrossing connections. For example, the modularization techniques described in Chap. 9 may not be successful. In this case, AOPN could be a remedy.

The final part (Part-IV) is about "Collaborating Modules", allowing the modules to collaborate to perform larger jobs. Part-IV consists of the following five chapters:

- Chapter 11 "Discrete Systems as Petri Modules" is about putting the modules together in a modular Petri net. This chapter consists of three groups of sections. In the first group of sections, nine blocks are introduced as the basic building blocks of a discrete system. The second group of sections introduces five matrices, such as adjacency, reachability, Rader's, connection, and component matrices. The third group of sections introduces the spanning tree and connected components of a graph. All the material introduced in this chapter will be used in the newer algorithms developed in Chap. 12.

- Chapter 12 “Algorithms for Modular Connectivity” presents five new algorithms for analyzing the network connectivity in the modular Petri net models. The algorithms are designed with Industry 4.0 in mind; this means the modules are intelligent enough to choose with whom they may communicate, in case some of the modules are not collaborating.
- Chapter 13 “Model Checking for Collaborativeness” focuses on the property of collaborativeness. Collaborativeness is a property of a module, indicating whether the module is willing or be able to participate in collaboration with the other modules. This chapter applies the theories and techniques developed in this book to solve the problem of model checking for collaborativeness. The literature study suggests the use of external tools, off-line, for model checking of collaborativeness. However, Chap. 13 proposes using a novel online technique that is tailor-made for the GPenSIM environment.
- Chapter 14 “Generic Petri Module” presents a generic three-layered architecture for Petri modules that can participate in collaboration while performing some useful functions on their own. This chapter starts with a crude structure for Petri modules and discusses the necessity of using colored Petri net. Finally, the generic architecture is presented.

Companion Website

Companion Website for this book is
http://www.davidrajuh.net/gpensim/book-II/.

This Companion website presents the GPenSIM code for some of the examples given in this book.

Acknowledgement

The book is a result of my teaching and research at two institutions. I work as a Professor of informatics at the Department of Electrical Engineering and Computer Science (IDE), University of Stavanger. I give two courses for master students in Computer Science, “DAT530 Discrete Simulations” and “DAT600 Algorithm Theory”. My experiences from these two courses are instrumental in writing this book. I am also a Visiting Professor at the Department of Engineering Processes Automation and Integrated Manufacturing Systems (RMT2), Silesian University of Technology, Gliwice, Poland. In Gliwice, I give a variety of short courses to master students in Mechanical Engineering. A part of the book is written during my stays in Gliwice, benefiting from my discussions with my colleagues there. My sincere thanks go to these two institutions (IDE and RMT2) for offering me ample time and research facilities to complete this book.

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From the publisher Springer's side, I would like to thank the "Asset Analytics" series editor Prof. Ajit Verma Kumar, for encouraging me to submit the book to the series and for the speedy and qualitative review process. Prof. Ajit Verma was also kind enough to write the foreword of this book. My thanks also go to Ms. Kamiya Khatter—the receiving editor at Springer Nature India. Ms. Kamiya patiently answered my numerous emails to her.

I am also thankful to my wife Ruglin and my daughter Ada for tolerating my frequent absence in their daily lives.

Stavanger, Norway Reggie Davidrajuh
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About the Author

Reggie Davidrajuh has a Bachelor's study in Physics, a Master's degree in Control Systems, and a Ph.D. in Industrial Engineering (awarded by the Norwegian University of Science and Technology). Also, he has a D.Sc. (habilitation) degree in Information Science (AGH University of Science and Technology) and one more Ph.D. in Mechanical Engineering (Silesian University of Technology). He is presently a professor of Informatics at the University of Stavanger, Norway, and holds a visiting professor position at the Silesian University of Technology, Poland.

Dr. Davidrajuh is an editor of the journal "International Journal of Business and Systems Research". Also, he serves on the editorial committees of many journals that include "Expert Systems with Applications" (Elsevier) and "Archives of Control Sciences" (a Quarterly of Polish Academy of Sciences). Dr. Davidrajuh has published over 150 publications in diverse areas such as supply chain, e-commerce, e-government, modeling and simulation, discrete event systems, green power generation, etc. His three papers won the best paper awards: "Modeling humanoid robot as a discrete event system" at the IEEE Third International Conference on Artificial Intelligence, Modeling, and Simulation (AIMS2015), in December 2015, in Kuala Lumpur; "GPenSIM for Performance Evaluation of Event Graphs" at the International Scientific and Technical Conference on Manufacturing (Manufacturing 2017), in October 2017, in Poznan, Poland; "Measuring Network Centrality in Petri Nets" at the 2018 IEEE International Conference on Advanced Manufacturing (ICAM), in November 2018, in Yunlin, Taiwan.

He has organized over 60 international conferences and has given keynote speeches in four conferences. His current research interests are "Modeling, simulation, and performance analysis of discrete-event systems", Algorithms, and Graph Theory. He is a senior member of IEEE and a Fellow of the British Computer Society. He is also a member of the Norwegian Academy of Technical Sciences.

Nomenclature

λ_2	Algebraic Connectivity: the second eigenvalue of a Laplacian matrix
β	Self-loop strength (arc weight of an arc that is directed from a node to itself)
$\bullet p$	Input transitions of place p
$\bullet t$	Input places of transitions t
δ	Value for step-wise reduction of the self-loop strength
$\overrightarrow{t_i}$	Firing transition t_i
Φ	State formula (in CTL)
ϕ	Path formula (in CTL)
Φ_i	Petri module
Ψ_i	Inter-Modular Connector
A	Adjacency Matrix (N, N) of a graph, consisting of N nodes
A	CTL path quantifier for "all paths"
A	Incidence Matrix (m, n) of a Petri Net, m places and n transitions
A	Set of arcs (directed connections) of a Petri Net
AOPN	Activity-Oriented Petri Nets
a or a_i	Arc of a Petri Net
a or a_{ij}	Element of an adjacency matrix or incidence matrix
C	Connection Matrix
C_{m_i}	Collaborativeness of a Petri module
CTL	Computation Tree Logic
D	Rader's Matrix, Diagonal matrix
E	(Number of) edges of a graph $G = (V, E)$
E	CTL path quantifier for "there exist some paths"
F	CTL temporal modality for "in future" or "eventually"
FMS	Flexible Manufacturing System
G	CTL temporal modality for "always" or "globally"
GPenSIM	General-purpose Petri Net Simulator
IMC	Inter-Modular Connector
L	Laplacian Matrix
LFN	Leader-Followers Networking
LTS	Labeled Transition System (*aka* the Kripke Structure)

M	Marking (state) of a Petri Net
$M(p)$	Marking of (the number of tokens in) place p
$M[t_i\rangle$	Enabled transition t_i in the marking M
M_0	Initial marking (initial state) of a Petri Net
$M_\dashv$	Terminal state of a state space
$M_0[\rangle$	All the markings that are reachable from M_0
$M_0[t_1\rangle M_1$	M_1 is directly reachable from M_0 due to the firing of t_1
MPN	Modular Petri Net, consisting of one or more Petri modules and zero or more Inter-Modular Connectors
MSF	Main Simulation File (in GPenSIM)
N	CTL temporal operator for "Next"
N	Natural numbers
N^+	Natural numbers, excluding zero
NPN	Negotiating-Peers Networking
P	Set of Places of a Petri Net
p	Atomic property (in CTL)
$p\bullet$	Output transitions of place p
PDF	Petri net Definition File (in GPenSIM)
PTN	Place–Transition (P/T) Petri Net
p or p_i	Place of a Petri Net
R	Reachability Matrix
R	Real numbers
R^+	Positive real numbers, greater than zero
RG	Reachability Graph (State Space)
$SCEG$	Strongly Connected Event Graph
SMN	Steiner-Mode Networking
T	Set of Transitions of a Petri Net
$t\bullet$	Output places of transitions t
$t_\dashv$	Terminal transition of a state space
$t_i\rangle$	Enabled transition t_i
T_{m_i}	Timing of a Petri module
tI	Input port(s) of a Petri module
$tINV$	Transition for inviting the other modules for collaboration
$tMCC$	Transition for model checking for collaborativeness
tO	Output port(s) of a Petri module
TPN	Timed Petri Net
t or t_i	Transition of a Petri Net
U	CTL temporal operator for "Until"
V	(Number of) vertices of a graph $G = (V, E)$
$W(p_i, t_j)$	Weight of the arc between the place p_i and the transition t_j
Z	Integers

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