Complexity Challenges in Cyber Physical Systems
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Using Modeling and Simulation (M&S) to Support Intelligence, Adaptation and Autonomy

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To the Infinite Intelligence that created things simple, just, and accommodating enough, which manifests itself in complex universes, both within and without, that we all share, enjoy, and strive to understand.

Saurabh Mittal

To all scientists and researchers who dare to leave the comfort of their home discipline and seek collaboration with like-minded partners to create transdisciplinary teams inspiring progress in our complex work.

Andreas Tolk
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The various definitions for Cyber Physical Systems (CPSes) all focus on their computational and physical components, integrating sensors, networks, motors, and more. But we often overlook that CPS will significantly change the way we access systems and our environment. They are ubiquitous: cars self-park, recognize street signs and react accordingly, know the distance to other cars and keep the correct distance, and more. CPS allows a new family of medical devices, from surgical assisting tools to smart prostheses. Smart houses observe the comfort level of people and control the air conditioning accordingly. They are learning when people are home, can prepare their meals and keep the meals warm in case of a traffic jam. If the house were part of the smart city, sensors would have learned about the jam and diverted the traffic, automatically reconfiguring the traffic lights and communicating the news to the smart cars. First responders as well as soldiers are getting accustomed to their colleague CPS in human cyber teams, where the CPS can assess regions too dangerous or otherwise not reachable for the human team partners. However, all this support comes with a price: growing complexity! How can we either manage or govern such intelligent, adaptive, and autonomous systems? How can we take advantage of positive emergence, and avoid the major consequences of negative ones?

We went through a similar dramatic change before, namely when the Internet changed our view on searching for and gaining access to information. Many CPSes are using the Internet to gather and change information as well; and again, it comes with a price. Before the Internet era, many complex systems had both the software and hardware components, but they were shielded from cyberattacks due to a lack of network access. Due to the additional capability of connectedness of these components across varied networks (both within and without the organization that own the CPS), new challenges have emerged. Some of the challenges include cyber security, control, test, degree of connectivity, constant vigilance and operation, degree of autonomy, intelligence-based behavior, resilience, and impact on the socioeconomic fabric.
As is the case in many current publications, CPS and Internet of Things (IoT) are used interchangeably but there are some subtle differences between the two. We understand CPS as domain-specific versions of IoT, so the difference lies in terms of scale, societal impact and the propagation of effects. CPS are more focused towards a specific domain such as aviation, health, military, defense, manufacturing, etc. Due to the domain-specific nature, CPS can be studied in more detail at both the operational technology and information technology levels. However, the resulting danger is that CPS within their domains share neither their insights nor benefit from insights of other CPS from other domains. A domain-agnostic common theory providing common methods that lead to domain specific solutions would be advantageous, and some candidates exist and will be discussed, but no common formalism in support of this idea has been widely accepted yet.

Modeling and Simulation (M&S) has emerged as a mechanism by which various CPS challenges can be studied in a virtual environment. Model-based engineering (MBE) and simulation-based engineering are two distinct activities, even though the simulation activity subsumes the modeling activity. A model is an abstract representation of the system and is evaluated in an environment that may be a live (people using real systems), a virtual (people using simulated systems), or a constructive (simulated people and systems) environment. The simulation infrastructure ensures the model system is provided the right environment for evaluating the capabilities, which are essentially the system’s capabilities that need to be tested and evaluated.

We started our journey in Fall 2017, when we gratefully received some internal MITRE research funding to research the challenges of hybrid simulation in support of CPS. We allocated part of the funding to bring experts to a panel discussion. The experts belonged to disparate domains who employ M&S to address the CPS challenges and conduct CPS engineering together. Interestingly, this spawned some collaboration, as we discovered similarities in our challenges and solutions, from which this book ultimately emerged. This book tries to organize the obtained insights and report the latest in the use of M&S for CPS engineering. We address the subject in five parts: Introduction, Modeling Support to CPS Engineering, Simulation-Based CPS Engineering, The Cyber Element, and The Way Forward.

The Part I begins with a chapter from us and provides an overview of complexities associated with the application of M&S to CPS Engineering. Castro et al. in the second chapter, provide a more detailed description of the challenges in the operation and design of intelligent CPS. The third chapter by Mazal et al. discusses M&S in the context of autonomous systems involvement within the North Atlantic Treaty Organization (NATO). Part II begins with a chapter from Traoré on multi-perspective modeling and holistic simulation for very complex systems analysis. The next chapter by Barros describes a unifying framework for hierarchical co-simulation of CPS. This is followed by model-based system of systems engineering tradeoff analytics by Markina-Khusid et al. The next chapter by Mittal
et al. considers a larger version of CPS, i.e. IoT, and the complexities associated
with developing a risk assessment framework. Part III begins with a chapter from
Castrol et al. on simulation model continuity for efficient development of embed-
ded controllers in CPS. This is followed by another practical application by
Henares et al. on CPS design methodology for prediction of symptomatic events
in chronic diseases. In this chapter they present the entire lifecycle methodology
for CPS engineering from concept to cloud deployment and execution. The next
chapter by Bhadani et al. applies model-based engineering to the subject of auton-
omy in CPS. Part IV begins with a chapter by Furness on providing various per-
spectives on securing CPS. This is supported by the next chapter by Haque et al.
on CPS resilience and discusses frameworks, complexities, and future directions
on resilient systems engineering. The next chapter by Suarez and Demareth dis-
cusses the creation of social structures employing CPS. The Part V incorporates
another chapter by the editors on the way forward and provides a research agenda
for addressing complexity in application of M&S for CPS engineering.

Editing this book was a rewarding journey that offered plenty of opportunities
to learn and discover. We invite you to share the exciting journey of CPS engineer-
ing that offers a wealth of opportunities for advancement at various levels. CPS
are going to shape our lives: observing the well-being of the elderly, observing our
health, observing and optimizing our production systems, and many more oppor-
tunities. Just as our children can hardly imagine finding information on certain
topics of interest – mainly due to homework or college projects – before Internet
and Google, the new generation may no longer imagine how often we had to prac-
tice parallel parking, or how parcels were delivered only once a day. We hope to
contribute to the efficient development of future CPS solutions with this compen-
dium, and hopefully generate some ideas for scholars and researchers as well.

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Foreword

Several important global trends are occurring with regards to the advancement of cyber physical systems. Worldwide, significant technology-driven advances are being pursued that address increasing cyber physical system performance, safety, and security while achieving design, development, and operational efficiencies that reduce cost. These trends include:

- Significant investment in higher levels of automation for physical systems, including autonomous systems.
- Increasing research and early applications of Artificial Intelligence to physical systems (AI), including addressing “Dependable AI” for high assurance AI-software design and development.
- Development of advanced static and dynamic analysis tools by the Modeling and Simulation community. The resulting Model-based Systems Engineering (MBSE) analysis tools and methods address considerations related to the growing complexity of highly integrated System-of-System architectures.
- Development of cyberattack resilient system architectures that can restore acceptable system operation in response to a real-time detection of a functionally disabling cyberattack.

These initiatives bring with them increased complexity of system designs, with a corresponding set of risks that need to be addressed when designing new or significantly upgraded systems. These risks include:

- Cyberattacks that include supply chain and insider attacks that can directly impact the application layer of physical systems and, in the worst case, can potentially result in operator or user injuries or loss of life.
- Safety-related incidents due to undetected deficiencies in system design.
- Operator errors due to uncertainties related to human–machine roles under anomalous circumstances.

But, perhaps the most concerning risk is the recognized shortage of engineers and scientists who can contribute to the development of these new technologies and
tools, as well as the shortage of the workforce that can productively employ the analysis tools that are designed to enable high productivity in the development and evaluation of new cyber physical system designs. This book helps to address this risk by providing a well-constructed, selective set of articles that together offer the reader an integrated view of the state-of-the-art in addressing complex cyber physical system design and development. By integrating the diverse set of articles, the book serves to compliment the education curriculums at Universities, which tends to separate the subjects discussed above into the curriculums of different departments (e.g. Mechanical Engineering for physical systems, Computer Science for AI and cybersecurity, Systems Engineering for complex system design analysis, etc.). As a result, I believe that books of this kind can play a significant role in enabling engineers to build on their formal education and prior experience in a manner that supports the greatly needed enhanced design and evaluation skills that the trends in cyber physical systems are calling for.

Reading this book is something that I highly recommend for engineers and scientists who are interested in becoming important participants in the global trends related to advancing the automation levels of cyber physical systems!

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