HYBRID SIMULATION FOR CYBER PHYSICAL SYSTEMS – STATE OF THE ART AND A LITERATURE REVIEW

Andreas Tolk
The MITRE Corporation
903 Enterprise Parkway #200
Hampton, VA 23666, USA
atolk@mitre.org

Ernest H. Page, Saurabh Mittal
The MITRE Corporation
7515 Colshire Drive
McLean, VA 22102, USA
smittal@mitre.org; epage@mitre.org

ABSTRACT

This paper evaluates the state of the art of hybrid simulation support for cyber physical systems. The traditional definition for hybrid simulation is expanded to include recent research on multi-paradigm and other multi-faceted modeling approaches. Based on the review of current approaches, the focus of simulation support lies first in providing a virtual environment supporting development and testing, and second on utilizing simulation as part of the cyber physical system. A literature research on support of cyber physical systems within the simulation community shows common trends towards a common formalism, but an aligned research agenda has not been established.

Keywords: hybrid modeling, hybrid simulation, cyber physical systems, modeling paradigms.

1 INTRODUCTION

During the Spring Simulation Multi-Conference 2017, a group of invited experts consisting of Fernando Barros, Andrea D'Ambrogio, Pieter Mosterman, Hans Vangheluwe, and Bernie Zeigler, conducted a panel discussion on *"Challenges in M&S of Cyber-Physical Systems."* Xiaolin Hu moderated the event. This panel was not the only presentation dealing with cyber physical systems (CPS), which are generally defined as a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities (Baheti and Gill 2011). In particular for the computational capabilities, simulation plays an important role. When it comes to providing CPS with forms of computational intelligence, simulation is also one of the options to support the various forms of artificial intelligence (AI), including the idea to provide not only a safe an efficient test-bed, but even to provide an immersive environment in which CPS can learn to adapt and optimize their behavior (Fawkes 2017). As pointed out by Fawkes, a Google artificial intelligence program defeated a Chinese grand master at the ancient board game Go in May 2017 exclusively being trained by playing against itself in a Go environment, so why not think about training the CPS brain in an immersive simulation.

When using simulation as a computational capability for the CPS, the observation that these systems are characterized by many new modalities and domains explains why so many different modeling paradigms and resulting heterogeneous solutions exists. Furthermore, CPS applies computational methods and applications they perceive to be useful without necessarily recognizing that they belong to the field of M&S, e.g., when they use an internal representation of the environment for path discovery or optimization, or when based on status and activities the future resource need is computed. As a result, CPS utilize many diverse M&S methods in support of their computational needs.

The topic of hybrid simulation was recently reintroduced to the M&S community by a series of tracks in the Winter Simulation Conferences. Powell and Mustafee's (2014) paper introduced a taxonomy of hybrid simulation study and hybrid simulation solutions has been widely used to communicate the ideas, and it was recently followed up by an expert panel on the *"Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of its Definition"* (Mustafee et al. 2017), as the growth in interest in such solutions reenergized the discussion about what constitutes a hybrid model and what is new? While the community is still in the process of achieving a convergence of the definition of hybrid simulation, the idea that hybrid simulation holds the promise of allowing to merge two or more components of different categories to generate something new, that combines the characteristics of these components into something more useful. As CPS need many components of different categories, including computational components from the field of M&S, the topic of hybrid simulation for CPS should be of interest for the M&S and the CPS community alike. As already observed by Mustafiz et al. (2016), the reason for such interest is that *"the engineering of a complex CPS involves the creation and simulation of hybrid models often encompassing multiple levels of abstraction and combining different formalisms, often not expressible in any single existing formalisms."*. Similar reasoning is supported by the recent work of Mittal and Zeigler (2017) where they advocated a super-formalism such as *Discrete Event Systems Specification* (DEVS) formalism to bring together various modeling formalisms for a hybrid model.

The MITRE Innovation Program recognized the need for addressing these issues systematically and formally and supported a literature research to be followed by analysis and synthesis of these results. This paper presents the results of the conducted literature research, which are neither complete nor exclusive. We hope much more to support the ongoing discussions to drive the development of this important topic forward by providing an annotated reading list for members of both communities, spawning multi- and interdisciplinary research.

2 WHICH WAY TO HYBRID STREET?

Since this article deals with *hybrid simulation*, at least in part, it behooves us to offer a working definition for the term. As noted in a variety of passages in this paper, the topic of hybrid simulation is experiencing a resurgence in the literature, and a fair bit of exposition has been dedicated to the task of capturing the essential nature of *hybrid* in this context. What does hybrid simulation mean today? What do we think it *should* mean? When did the term originally appear? And what did it mean then? Are today's and past definitions and usage consistent? If there are differences, are they the result of intentional evolution or just accidents of poor scholarship? We will leave it to the reader to sift through those ongoing analyses and debates. For purposes of this paper, we will not attempt to settle the issue, but will take a fairly simple and broad view that a *hybrid thing* (be it a simulation or otherwise) is composed of two (or more) things that are different from each other in some fundamental way and their composition produces something interesting or useful. We also suggest that the hybrid thing should be something which could not be (or could not easily be) created merely by "natively extending" one of the original things. That is, the act of *composition* is fundamentally required.

So, how might we choose to distinguish among simulation "things" in order to say what qualifies as a hybrid? Again, here we recognize there are many modeling taxonomies, and a comprehensive treatment to identify a merged consensus is beyond the scope of this paper. As simulation "old timers", we admit preference for taxonomies rooted in our discipline's foundational literature, but recognize that many useful and widely applied characterizations today do not draw from these same sources.

Firstly, we observe that all digital simulations fall into the class of numerical methods. Although we explicitly limit our consideration to simulation on digital computers with this approach, we recognize that simulation on analog computers has a long history and, in fact, the earliest references to hybrid simulation involved the combination of digital and analog simulation (Burns and Kopp 1961). Numerical solutions all provide *approximate* (rather than *exact*) solutions. Beyond this commonality, there are potentially innumerable ways to differentiate simulations. As early as the 1960s, a distinction between *discrete* and *continuous* simulation methods was commonplace (Teichroew and Lubin 1966). First published in 1976, Zeigler's foundational text (Zeigler 1976) establishes a formal basis for the distinction between discrete and continuous systems and models as well as a framework for their combination, in his revised edition (Zeigler et al. 2000). Shanthikumar and Sargent (1983) classify four types of hybrid simulation/analytic models and observe that even small changes to a model may lead to its reclassification. Nance (1993), in his History of *Discrete Event Simulation Programming Languages*, identifies five predominant types of simulation:

- Continuous – an *equation-based* approach, the underlying model is formulated as a collection of difference, differential and/or partial differential equations which are evaluated using Euler's method or the Runge-Kutta technique.
- Discrete event – an *object-based* approach, the underlying model is comprised of objects and the relationships among objects. An *object* is anything that can be characterized by one or more *attributes* to which *values* are assigned. The model's logic describes the conditions under which attribute value changes occur.
- Monte Carlo – the use of a stochastic process to solve a deterministic problem.
- Combined – a model that includes both continuous and discrete event components.
- Hybrid – the inclusion of an analytical submodel within a discrete event model.

Despite the taxonomy that resulted from Nance's scholarly survey, we observe that today many authors commonly use the terms hybrid and combined interchangeably to describe the combination of discrete event and continuous models/simulations. To be precise, many current articles in hybrid simulation suggest that there are three types of simulation: discrete event simulation, agent-based simulation, and Systems Dynamics. Our view is that agent-based simulation is a member of the discrete event simulation family, and should be viewed as a "world view" closely related to the activity scan and process interaction, and that the family of continuous methods is much broader than System Dynamics.

But is this definition sufficient? Does it capture all, or the majority, of the challenging problems in model composition that we would like to address with hybrid simulation? Perhaps. Perhaps not. For example, as early as the 1960s, the developers of discrete event simulation programming languages were discovering useful variations in the underlying model structures. A discrete event simulation could be organized around the *event*, the *activity* or the *process* (Nance 1981). These *conceptual frameworks* (or *world views*) permit a modeler to think about a given system in fundamentally different ways (Kiviat 1969, Balci 1988). Since each of these formulations are inherently (and obviously) members of the same discrete event family, Overstreet (1982) seeks to define a common specification language to support automated translation between the world views, but finds that such an automated translation falls into the class of *undecidable* computing problems. Yucesan and Schruben (1992) extend Overstreet's findings to the broader consideration of determining equivalence between any two simulation models. Lynch et al. (2014) provide a multi-paradigm modeling framework extending paradigms and methods discussed so far, and Tolk emphasizes the need for conceptual alignment in Mustafee et al. (2017).

Since it is probably non-trivial to navigate between the various discrete event formulations, should we consider their composition to constitute an application of hybrid simulation? It would not seem unreasonable to do so, particularly if we believe (or suggest) that *complexity* of the composition effort is a fundamental characteristic of a hybrid simulation. Similarly, while the authors are unaware of a definitive survey of continuous simulation techniques, it seems evident that the formulations for Systems Dynamics, Finite Element Method, Computational Fluid Dynamics, Transmission Line Matrix, Particle-In-Cell – to name only a few – are sufficiently varied that compositions of these formulations might also require significant mastery and care, and therefore could usefully be included within the hybrid category.

In summary, as we suggest above, for purposes of this article we adopt a broad perspective on the compositions that could be considered within the class of hybrid simulation. We commend this perspective to the community of researchers and practitioners that are reinvigorating the topic.

3 CPS AND SIMULATION

Conducting a literature review on the topic hybrid simulation for CPS can be challenged by the many hardly aligned terms and interpretations used in both communities. Just the recent discussions of the term "hybrid simulation" showed that not even within the M&S community a clear definition exists, and many alternative terms are in use. An overview of terms that are often used synonymously can be found in Balaban et al. (2014a, 2014b, 2015).

Within the CPS communities, the language barrier is often even higher, as they often apply simulation methods without referring to them as such. If a semiautonomous system calculates different route options under various possible near-term developments, it de facto conducts a series of simulations, which are based on the internal model of the route, the environment, and the effects of assumed conditions. However, the terms used come from the domain of sensorics, artificial intelligence, optimization, etc.

Nonetheless, the application of simulation methods in support of CPS can be divided into two categories: the use of simulation for developing and testing by providing a realistic representation of the environment, and the use of simulation within the CPS to support the sense- and decision making processes. The use of simulation-based analysis was not discovered during the literature review.

3.1 Using simulation as an environment for development and testing of CPS

The application of virtual test environments becomes increasingly popular for all kind of systems, but in particular for CPS, as real-world tests rarely provide the necessary stimuli in synchronized form to test all aspects of cyber and physical interactions, as among others observed by Huang et al. (2016) in their review on test methods for autonomous vehicles, which are applicable to a wide array of other CPS solutions.

Li et al. (2006) provide an example for improving the testing of an all-electric ship propulsion systems by real-time simulation. They can emulate a realistic dynamic environment, both mechanically and electrically. They also show how the effort can be used in support of other application domains, as the developed interfaces and well specified functionality allow the reuse of these services, in their example applied for energy research.

Gupta et al. (2016) even go one step further. They observe that the perfect way to perform verification for a CPS is either through experimentation on actual deployment of the system or through accurate simulation thereof. Since in practice, building an experimental test-bed is rarely affordable, they observe that simulation-based testing and verification is likely the way of the future, a vision already presented at the first CPS conference by Huang et al. (2010).

However, many long-time practitioners warn against the exclusive use of simulated environments for testing, following the vision described by Skelley et al. (2004), which integrates M&S as a component into the suite of operational tests, integrating flight and ground testing with simulation-based experiments, brought together using a rigorous data management process to ensure traceability of data and repeatability of observations and experiments to a maximal extend. Even today, the trust in simulation-based virtual environments for operational testing is generally not high enough to justify exclusive virtual testing, but the role of virtual tests is continuously increasing, in particular for CPS systems.

3.2 Using simulation within a CPS for sense- and decision-making

CPS often use means of computational artificial intelligence to provide decision support or even make decisions on their own, in particular when they have to be able to act autonomously. Since 2014, the Modeling and Simulation Center of Excellence of NATO in Rome conducts annual conference on M&S for Autonomous System (MESAS). The proceedings have been published in the lecture notes on theoretical computer science by Springer (Hodicky 2014, 2015, 2016). The use of simulation to support the sense-making process, which means the creation of a perception from the current situational awareness and new reports, information, and observations, is a recurring theme in these proceedings.

Furthermore, the use of simulation optimization methods (Carson and Maria 1997) in support of the decision-making process is often applied, in particular for decisions under uncertainty. Due to the taxonomical similarity of autonomous robots with intelligent software agents (Tolk 2014) many of the research results from the domain of agent-based modeling can be transferred to support CPS as well.

This second application category is still in its infancy in the CPS domain, although some successful applications have been demonstrated within the M&S domain. More collaboration and cross-publication will be necessary to bridge the current gap between CPS and M&S expertise.

3.3 Standardization efforts to support development of CPS

Both application categories need to be integrated, or at least coupled, with CPS. When simulation will be used as a computational capability, it needs to follow the standardized integration principles established by the CPS community. At the same time, the lessons learned by the simulation community, in particular regarding but not limited to interoperability and composability, need to find their way into new standards for CPS. This is the reason to focus on CPS standardization efforts early.

Under the governance of the National Institute of Standards and technology (NIST) National Cybersecurity Center of Excellence (NCCoE) in Rockville, MD, the CPS community is evaluating domains of interest that benefit from common standards. They understand CPS as hybrid systems that incorporate Information Technology and Operational Technology i.e. logical and physical aspects in a single system. While early approaches were characterized by ad-hoc solutions to show the feasibility of solution proposals, recently common solutions for both domains of interest captured in section 3 were addressed in workshops.

Using a virtual environment for development and testing of CPS was part of the topics of the *Universal CPS Environment for Federation Workshop*, Rockville, MD, 27 July 2017. Building a common framework for the integration of IT solutions for a CPS platform itself was on the list of the *CPS Framework Open Source Workshop,* Rockville, MD, 19 September 2017. Both workshops were conducted by the NCCoE in support of the CPS Public Working Group's (PWG) "Framework for Cyber-Physical Systems" (Griffor et al. 2017). As this documents states, NIST established the CPS PWG to bring together a broad range of CPS experts in an open public forum to help define and shape key characteristics of CPS, so as to better manage development and implementation within and across multiple "smart" application domains, including smart manufacturing, transportation, energy, and healthcare. The resulting CPS Framework provides an organized presentation of a CPS analysis methodology based on the CPS Framework core concepts of facets (modes of the system engineering process: conceptualization, realization and assurance) and aspects (clusters of concerns: functional, business, human, trustworthiness, timing, data, composition, boundaries, and life cycle). The results of the supporting workshops are published in volume 2 to support the reproducibility of recommendations proposed in the report.

NIST CPS Framework provides a good conceptual framework (using metamodeling) that is worth taking into consideration when planning a CPS or doing CPS requirements engineering. However, lack of formal rigor in modeling may limit its usage in its current state, which is very much needed when a model is to be simulated. The current document lacks simulation specific considerations. Simulation experts are therefore highly encouraged to not only learn about this effort but to actively support its improvement within the next steps by participating in future workshops, making a strong case for modeling rigor.

4 CURRENT RESEARCH DOMAINS

The following summary of main ideas in important papers addressing issues of hybrid modeling and simulation support for CPS is just the beginning. The list of papers is neither complete nor exclusive, but represents a kernel of expertise contributions to the state of the art in this domain.

Nance (1981) denoted a class of formalism as discrete-event, which started to play a predominant role for digital simulation systems. In the panel discussion at the Spring Simulation Multi-Conference 2017, Zeigler focused on the use of the ***DEVS*** as introduced in (Zeigler 1976). Due to the popularity of DEVS in the academic community, this formalism was used extensively to address the possible combination of different modeling paradigms, such as in (Vangheluwe 2000, Vangheluwe et al. 2002). These papers show that DEVS can express multiple paradigms, helping to make them at least comparable and hopefully ultimately composable into hybrid approaches. Although the DEVS formalism is not without critics, it has been established as the most used simulation formalism and it is worth to consider it in support of CPS support as well. Accordingly, Traoré et al. (2018) are exploring ways to extend DEVS in support of value-based healthcare. The formalism defined in this paper support the multi-perspective modelling and holistic simulation of healthcare systems and are applicable to other forms of CPS as well, as healthcare is used as an application example that doesn't limit the general applicability. Mittal and Martin (2017) discusses the significance of a robust co-simulation environment incorporating super-formalism such as DEVS in the modeling and simulation of complex adaptive systems in cyber domain.

Cuijpers et al. (2008) are among those looking into ***process algebra*** as a formalism to capture multi-paradigm challenges, in particular hybrid processes. They observe that in the CPS domain, models combine behavior on a continuous time scale with discrete state transition behavior at given points in time. They extend therefore the ideas published by Lee (2006) that ***hybrid automata*** are adequate to represent CPS for simulation-based approaches, as they combine finite state machines with ordinary differential equations (ODE), both powerful concepts used in physics modeling. Hybrid automata have non-deterministic finite states, but each states can be described by an ODE. Cuijpers et al. use bond graphs to govern the changes in these models, following the extensions proposed by Mosterman and Biswas (1998) and later generalized for simulation applications towards building hybrid models of physical systems in (Mosterman and Biswas 2002).

Cellier (1977) was among the first to evaluate the possibility to combine continuous and discrete system ***simulation languages*** to allow for hybrid simulation in the sense of combining these two categories, extending the work of Fahrland (1970) and Oren (1977). Although many of the languages evaluated in these contributions are no longer supported, the underlying principles, concepts, and methods are still valid, as shown by Mustafiz et al. (2016) in their work on the modular design of hybrid languages. They do not only address the need for support of discrete and continuous methods, they explicitly mention the general challenge of encompassing multiple levels of abstraction and combining different formalisms, often not expressible in any single existing formalisms. They also address the challenge that the different supporting communities may use different terms to address the same phenomenon, or use the same term to describe different phenomena in their domains. Therefore, they conclude that the creation of new hybrid languages specifically tailored for such supported domains involves not only composition of the syntax but also the semantics. The introduce the idea of Hybrid Timed Finite State Automata (TSFA) – extending the ideas of hybrid automata – and used causal block diagrams for the synchronization and orchestration of process execution. This combination of formalisms from discrete and continuous approaches on various abstraction levels shall ultimately allow the description of ever more complex CPS and allow their simulation in a consistent and comparable form, using the approaches of the CPS community as the basis for their hybrid languages.

A similar philosophy is supported by Bocciarelli et al. (2017), as they use ***business process modeling*** (BPM) as the foundation for their descriptions. Their idea is based on the Industry 4.0 initiative that combines Internet-of-Things (IoT) and cloud computing technologies to obtain increased degrees of cooperation and communication allowing to exploit CPS better, in particular in the context of *smart factories*. Their approach is the use of business processes to analyze complex collaborations. They observe that although languages like the *Business Process Modeling Notation* (BPMN) are the de facto standard for BP specification and have proven to be suitable for formalizing high-level sequences of activities, they often lack structure, expressiveness and flexibility to express the new requirements brought by the integration of CPS as performance enablers for new processes. Bocciarelli et al. introduce therefore, the idea of Performability-enabled BPMN that allows to explicitly address CPS as resource for processes. For readers supporting the military simulation community it may be of interest that this view is consistence with capability-based mission threads used to address the need for increased operational agility in recent approaches.

A more simulationist-specific view is supported by Lin et al. (2011) as well as by Gomes et al. (2017) and Mittal and Martin (2017), namely the idea to use the ***principles of co-simulation*** to address the need for supporting multiples levels of abstraction, different modeling paradigms, or other facets of hybrid simulation. There focus lies on the use of co-simulation to allow an early integration of independently developed part-solutions and test their integrateability in advance. Gomes et al. look in particular at the Functional Mockup Interface (FMI) as a supporting standardized solution, as many tools in the CPS domain are supporting it. While Lin et al. focus on giving a realistic example, Gomes et al. develop a formal framework to address discrete event based co-simulation, continuous time-based co-simulation, and hybrid co-simulation. In each section, they address the challenges and use a common framework to bring the different approaches together. Based on their literature review, they furthermore provide a taxonomy of simulation unit requirements and map them to elements already provided by the FMI standard in the current version 2.0. Mittal and Martin incorporated DEVS as a common denominator to integrate abstraction levels and the underlying simulation engines.

Model-driven approaches are common in the systems engineering domain and have been proven to be applicable in the simulation world as well. It is therefore not surprising that several hybrid simulation approaches take advantage of such approach, among them Vangheluwe and de Lara (2003), Mosterman and Zander (2011), Jensen et al. (2011), Gerostathopoulos (2015), and Djitog et al. (2017a, 2017b), The common denominator of all these approaches is to use a series of models with well-defined model-transformations between these models to allow the consistent solutions supported by all contributing parts. Vangheluwe and de Lara (2003) use graph transformation to show how to evaluate and ensure consistency within the use of multiple meta-models to capture multi-paradigms. Mosterman and Zander (2011) start with the observation that software intensive systems are characterized by an enormous flexibility, but they also come with new challenges, such as a high variety of languages, different levels of abstraction for the hardware used in different levels of software support, and increasing hardware-based requirements for the software, such as response time. They introduce several new layers to the general model-based approaches, including declarative specifications of computational approximations, to address these new challenges. All their findings are directly applicable to hybrid simulation to be used within CPS as well. Jensen et al. (2011) are extending the step-focused model-based approaches into a holistic methodology for CPS. Their focus is the support of complex CPS, especially with heterogeneous subsystems distributed across networks, as it often will be the case with hybrid-simulation supported CPS as well. They introduce a ten step model-based design that starts with stating the problem and ends with verification, validation, and testing. In his PhD thesis, Gerostathopoulos looked at several approaches to use model-driven development of software intensive CPS and comes to the same conclusion: the governance of complex, distributed CPS requires a model-driven approach to ensure success in support of ensemble-based component systems. Djitog et al. (2017a, 2017b) use a healthcare system to show the possible diversity of perspectives that can only be aligned and harmonized by model-driven approaches, extending among many others the ideas published in Aliyu et al. (2016).

Mosterman and Zander (2016) approach the challenge of multi-paradigm support from the ***perspective of the CPS***. They motivate their observations by starting with the National Science Foundation's definition for CPS from the 2012 workshop: "Cyber physical systems are hybrid networked cyber and engineered physical elements co-designed to create adaptive and predictive systems for enhanced performance." Like the idea of Bocciarelli et al. (2017), they postulate that in the era of CPS, the integration of functionality is no longer happening before the deployment of applicable solutions, but after the CPS are already deployed, which requires that CPS must be able to derive a consistent model of operations that needs to be supported by the compositions of various CPS contributors. While Mosterman and Zander focus on the required functional characteristics, they also identify additional challenges regarding maintainability, dependability, security, resilience, certification, and policy for such CPS collaborations. Hybrid simulation plays a double role here: first, it can help to support the collaboration process by providing means and methods for the consistent collaboration model needed, and second, hybrid simulation components themselves are contributing to the complexity of the ensemble of systems.

The recent expert panel on the *"Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of its Definition"* (Mustafee et al. 2017) contributed many good examples for the purpose and benefits of hybrid simulation, with two contributions explicitly addressing the need to broaden the context into a more inclusive framework. First, the definition of hybrid simulation was significantly extended beyond the early view that focused on the combination of discrete and continuous methods. The proposed definition is: *"Hybrid M&S results from using two or more components of different M&S categories to generate something new, that combines the characteristics of these components into something more useful for the underlying M&S effort to be supported that are composable under the constraints of this effort."* These categories comprise all elements captured in this overview of current research, covering various abstraction levels, various aspects on the same abstraction level, all lifecycle phases, and to enable and support multi-, inter-, and transdisciplinarity simulation-based research, including the applicability of domain-specific languages, methods, and models. Two systemically address these challenges, including the alignment with the broader range of operational research practices, Mingers and Brocklesby (1997) ideas were adapted to define qualitative and quantitative paradigms, methods developed within the paradigm, and techniques applying such methods. In combination with the broad support of abstraction levels, facets, and phases, the resulting taxonomy promises to be rich enough to address all the various aspects identified in the literature research, although underlying research is still ongoing.

Numerous additional papers exist that support a further literature review, which are too numerous to include in this paper. If we did not include an aspect the readers perceive to be very important, please make the community aware of the efforts. Some additional ideas are captured in the panel conducted during the workshop (Tolk et al. 2018).

5 DISCUSSION

This paper could only start to scratch on the surface. A recent literature collections on hybrid simulation related efforts conducted in the UK ended up with an initial collection of more than 200 papers. It is the intention of the authors to gain access to this collection for further common research.

One of the main challenges the nearly Babylonian Confusion of Tongues characterizing the field. The need to work on a clearer taxonomy of hybrid modeling and simulation theory, methods, and tools, as started to be discussed in Mustafee et al. (2017), will allow a clearer analysis, comparison, and synthesis of options as identified in this review, supporting modeling and simulation of CPS, for CPS, and within CPS. It will also facilitate the discussion with the CPS community over time.

The common assumptions and constraints of digital simulation system captured in this overview are a challenge, but also support the idea that a common formalism is possible that allows to address all aspects of the recent hybrid approaches. The search for common approaches allowing to address all different facets as summarized at the end of section 5 of this paper is not new, ranging from Vangheluwe (2000) to Barros (2017). Such a common formalism is recommended to have mathematics at its core so that various automation and transformation algorithms can be developed to speed up the integration at both modeling and simulation levels. This will facilitate verification engines to be develop for simulation engine ensuring robustness for hybrid simulation, thereby, limiting the emergent behaviors arising out of computational implementation and integration (Mittal and Martin 2017). However, solution approaches presented so far seem to be focused on communities of interest and often hard to understand outside of this group. Generalization for the broader community of these approaches are needed, hopefully allowing to merge them further into a common framework that will support the better communication of challenges, models, simulation experiments, and results between the different interest groups.

Solutions from the CPS domain are predominantly of technical nature, focusing on the technical integration of solutions of interest. Conceptual challenges are not yet in the spotlight of the reviewed literature.

However, as analog and digital solutions are combined, many of the traditional hybrid simulation solutions are becoming relevant again, and it is very likely that the more recent contributions on conceptual challenges of this topic will be recognized as relevant soon as well. As M&S is just one of many communities supporting CPS, it is of importance to be aware of their standardization efforts and framework. Lessons learned from the military command and control community show that using the interoperability standards and methods provided by the target group facilitate the integration of solutions tremendously, while trying to push simulation specific standards into the application domain has not always been successful. Being aware and application of CPS standards will therefore be pivotal for the successful simulation support of CPS in the future.

This paper shall contribute to help establishing a better foundation for CPS support by simulation methods and applications. The literature review conducted was limited and needs to be extended. The topics are neither exclusive nor do they claim to be complete. It is just a start to systematically collect, analyze, and synthesize our community research and results to make it applicable in the increasingly important context of CPS to help them to avoid pitfalls and dangers we already are aware of. If this paper helps to initialize a deeper discussion between simulation and CPS experts, it is successful.

ACKNOWLEDGMENTS

This effort was supported by the MITRE Innovation Program. We thank our following colleagues for supporting us actively in the literature research by submitting their papers and recommendations to us: Andrea D'Ambrogio, Pieter Mosterman, Navonil Mustafee, Mamadou Traoré, Hans Vangheluwe, and Bernie Zeigler.

REFERENCES

Aliyu, H.O., Maïga, O., and Traoré, M.K. 2016. "The high level language for system specification: A model-driven approach to systems engineering." *Int J Model Simulat Sci Comput* 7(1):1641003.

Baheti, R., and H. Gill. 2011. "Cyber-physical systems." *The impact of control technology* 12: 161-166.

Balaban, M., P. Hester, and S. Diallo. 2014a. "Towards a theory of multi-method M&S approach: part I." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 1652-1663.

Balaban, M., P. Hester, and S. Diallo. 2014b. "Towards a theory of multi-method M&S approach: part II." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 4037-4038.

Balaban, M., P. Hester, and S. Diallo. 2015. "Towards a theory of multi-method M&S approach: part III." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 1633-1644.

Balci, O. 1988. "The Implementation of Four Conceptual Frameworks for Simulation Modeling in High Level Languages." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 287-295.

Barros, F.J. 2017. "Towards a universal formalism for modeling & simulation." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 750-761.

Bocciarelli, P., A. D'Ambrogio, A. Giglio, and E. Paglia. 2017. "A BPMN extension for modeling Cyber-Physical-Production-Systems in the context of Industry 4.0." *14th International Conference on Networking, Sensing and Control (ICNSC)*, IEEE Press, pp. 599-604.

Burns, A.J., and R.E. Kopp. 1961. "Combined Analog-Digital Simulation." *AFIPS 61, Proceedings of the Eastern Joint Computer Conference*, pp. 114-123.

Carson, Y., and A. Maria. 1997. "Simulation optimization: methods and applications." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 118-126.

Cellier, F.E. 1977. "Combined continuous/discrete system simulation languages: usefulness, experiences and future development." *ACM SIGSIM Simulat Dig* 9:18–21.

Cuijpers, P.J.L., J.F. Broenink, and P.J. Mosterman. 2008. "Constitutive hybrid processes: a process-algebraic semantics for hybrid bond graphs." *Simulation* 84(7): 339-358.

Djitog, I., H.O. Aliyu, and M.K. Traoré. 2017a. "Multi-Perspective Modeling of Healthcare Systems." *Privacy and Health Information Management* 5(2):1-20.

Djitog, I., H.O. Aliyu, and M.K. Traoré. 2017b. "A model-driven framework for multi-paradigm modeling and holistic simulation of healthcare systems." *Simulation*, (online first version accessible via DOI) https://doi.org/10.1177/0037549717744888.

Fahrland, D.A. 1970. "Combined Discrete-Event Continuous System Simulation." *Simulation* 14(2):61-72.

Fawkes, A.J. 2017. "Developments in Artificial Intelligence and Opportunities and Challenges for Military Modeling and Simulation." *Proceedings of the 2017 NATO M&S Symposium*, NATO Report STO-MSG-149, pp. 11.1–11.14.

Gerostathopoulos, I. 2015. *Model-Driven Development of Software-Intensive Cyber-Physical Systems.* PhD Thesis at the Faculty of Mathematics and Physics, Charles University, Prague.

Gomes, C., C. Thule, D. Broman, P. Gorm Larsen, and H. Vangheluwe. 2017. "Co-simulation: State of the art." arXiv preprint arXiv:1702.00686.

Griffor, E.R., C. Greer, D.A. Wollman, and M.J. Burns. 2017. *Framework for Cyber-Physical Systems: Volume 1, Overview*. Special Publication (NIST SP) - 1500-201; NIST Rockville, MD. Accessible via https://doi.org/10.6028/NIST.SP.1500-201 (last visited January 2018)

Gupta, S.K.S., T. Mukherjee, G. Varsamopoulos, and A. Banerjee. 2011. "Research directions in energy-sustainable cyber-physical systems." *Sustain. Comput. Inf. Syst.* 1(1),57–74.

Hodicky, J. (Ed.) 2014. *Modeling and Simulation for Autonomous Systems*. Lecture Notes in Computer Science Vol 8906, Springer.

Hodicky, J. (Ed.) 2015. *Modeling and Simulation for Autonomous Systems*. Lecture Notes in Computer Science Vol 9055, Springer.

Hodicky, J. (Ed.) 2016. *Modeling and Simulation for Autonomous Systems*. Lecture Notes in Computer Science Vol 9991, Springer.

Huang, H.M., T. Tidwell, C. Gill, C. Lu, X. Gao, and S. Dyke. 2010. "Cyber-physical systems for real-time hybrid structural testing: a case study." *First International Conference on Cyber-Physical Systems*, ACM press, pp. 69–78.

Huang, W., K. Wang, Y. Lv, and F. Zhu. 2016. "Autonomous vehicles testing methods review." *19th International Conference on Intelligent Transportation Systems (ITSC)*, IEEE press, pp. 163-168.

Jensen, J.C., D.H. Chang, and E.A. Lee. 2011. "A model-based design methodology for cyber-physical systems." *Proceedings of the Wireless Communications and Mobile Computing Conference (IWCMC)*, IEEE Press, pp. 1666-1671.

Kiviat, P.J. 1969. *Digital Computer Simulation: Computer Programming Languages*, RAND Technical Report, RM-5883-PR, January.

Lee, E. A. 2006. "Cyber-physical systems-are computing foundations adequate." *Position Paper for NSF Workshop On Cyber-Physical Systems: Research Motivation, Techniques and Roadmap* (Vol. 2); NSF HQ: Washington, DC.

Li, H., M. Steurer, K.L. Shi, S. Woodruff, and D. Zhang. 2006. "Development of a Unified Design, Test, and Research Platform for Wind Energy Systems Based on Hardware-in-the-Loop Real-Time Simulation," *IEEE Transactions on Industrial Electronics* 53(4):1144-1151.

Lin, H., S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili. 2011. "Power system and communication network co-simulation for smart grid applications." *Proceedings of Innovative Smart Grid Technologies (ISGT)*, IEEE Press, pp. 1-6.

Lynch, C., J.J. Padilla, S.Y. Diallo, J.A. Sokolowski, and C.A. Banks. 2014. "A multi-paradigm modeling framework for modeling and simulating problem situations." *Proceedings of the Winter Simulation Conference*, IEEE press, pp. 1688-1699.

Mingers, J., and J. Brocklesby. 1997. "Multimethodology: Towards a Framework for Mixing Methodologies". *Omega* 25(5):489-509.

Mittal, S., and B.P. Zeigler. 2017. "Theory and Practice of M&S in Cyber Environments", in A. Tolk, T. Oren. (eds.), *The Profession of Modeling and Simulation*, Wiley & Sons.

Mittal, S., and J.L.R. Martin. 2017. "Simulation-based Complex Adaptive Systems", in S. Mittal, U. Durak. T. Oren (eds.) *Guide to Simulation-based Disciplines: Advancing our Computational Future*, Springer, AG

Mosterman, P.J., and G. Biswas. 1998. " A theory of discontinuities in dynamic physical systems." *Journal of the Franklin Institute*, 335B(3):401–439.

Mosterman, P.J., and G. Biswas. 2002. "A hybrid modeling and simulation methodology for dynamic physical systems." *Simulation* 78(1): 5-17.

Mosterman, P.J., and J. Zander. 2011. "Advancing model-based design by modeling approximations of computational semantics." *Proceedings of the 4th International Workshop on Equation-Based Object-Oriented Modeling Languages and Tools*, Zürich, Switzerland, pp. 3–7.

Mosterman, P.J., and J. Zander. 2016. "Cyber-physical systems challenges: a needs analysis for collaborating embedded software systems." *Software & Systems Modeling 15(1): 5-16.*

Mustafee, N., S. Brailsford, A. Djanatliev, T. Eldabi, M. Kunc, and A. Tolk. 2017. "Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of its Definition." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 1631-1645.

Mustafiz, S., C. Gomes, B. Barroca, and H. Vangheluwe. 2016. "Modular design of hybrid languages by explicit modeling of semantic adaptation." *Proceedings of the Symposium on Theory of Modeling & Simulation*, SCS San Diego, pp. 29-36.

Nance, R.E. 1981. "The time and state relationships in simulation modeling." *Communications of the ACM*, 24(4):173-179.

Oren, T.I. 1977. "Software for Simulation of Combined Continuous and Discrete Systems: A State-of-the-Art Review." *Simulation* 28(2):33-45.

Overstreet, C.M. 1982. *Model Specification and Analysis for Discrete Event Simulation.* Ph.D. Thesis, Virginia Polytechnic Institute and State University.

Powell, J.H., and N. Mustafee. 2014. "Soft OR Approaches in Problem Formulations Stage of a Hybrid M&S Study." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 1664-1675.

Shanthikumar, J.G. and Sargent, R.G. 1983. "A unifying view of hybrid simulation/analytic models and modeling." *Operations research* 31(6):1030-1052.

Skelley, M.L., T.F. Langham, and W.L. Peters. 2004. "Integrated test and evaluation for the 21st century." *USAF Developmental Test and Evaluation Summit*, pp. 1-14.

Teichroew, D. and J.F. Lubin. 1966. "Computer Simulation – Discussion of the Technique and Comparison of Languages." *Communications of the ACM*, 9(10):723-741.

Tolk, A. 2014. "Merging two worlds: agent-based simulation methods for autonomous systems." *Autonomous Systems: Issues for Defence Policymakers*, edited by A. P. Williams and P. D. Scharre, Norfolk, VA: NATO ACT HQ, pp. 291-317.

Tolk, A., F. Barros, A. D'Ambrogio, A. Rajhans, P.J. Mosterman, S.S. Shetty, M.M. Traore, H. Vangheluwe, and L. Yilmaz. 2018. "Hybrid Simulation for Cyber Physical Systems – A Panel on Where are We Going regarding Complexity, Intelligence, and Adaptability of CPS Using Simulation." *In these Proceedings of the Spring Simulation Multi-Conference*.

Traoré, M.K., G. Zacharewicz, R. Duboz, and B. Zeigler. 2018. "Modeling and Simulation Framework for Value-based Healthcare Systems." *Proceedings of the Symposium on Theory of Modeling & Simulation*, SCS San Diego, in press.

Vangheluwe, H.L. 2000. "DEVS as a common denominator for multi-formalism hybrid systems modelling." *Proceedings of the IEEE International Symposium on Computer-Aided Control System Design*, IEEE Computer Society Press., pp. 129–134.

Vangheluwe, H.L., and J. de Lara. 2003. "Computer automated multi-paradigm modelling: Meta-modelling and graph transformation." *Proceedings of the Winter Simulation Conference*, IEEE Press, pp. 595-603.

Vangheluwe, H.L., J. de Lara, and P.J. Mosterman. 2002. "An introduction to multi-paradigm modelling and simulation." *Proceedings of the AIS'2002 conference (AI, Simulation and Planning in High Autonomy Systems)*, Lisboa, Portugal, pp. 9-20.

Yucesan, E. and L. Schruben. 1992. "Structural and Behavioral Equivalence of Simulation Models." *ACM Transactions on Modeling and Computer Simulation*, 6(1):82-103.

Zeigler, B.P. 1976. *Theory of Modelling and Simulation.* Wiley-Interscience, New York.

Zeigler, B.P., H. Praehofer, T.G. Kim. 2000. *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems*, Academic Press.

AUTHOR BIOGRAPHIES

ANDREAS TOLK is Technology Integrator for the Modeling, Simulation, Experimentation, and Analytics Division of The MITRE Corporation. He holds a PhD and M.S. in Computer Science from the University of the Federal Armed Forces, Munich, Germany. He is active in the Society of Modeling and Simulation (SCS) as well as the Association for Computing Machinery (ACM) Special Interest Group on Simulation and Modeling (SIGSIM) community, supporting boards, journals, and conferences in various roles. He is a Fellow of SCS and senior member of ACM and IEEE. His email address is atolk@mitre.org.

ERNEST H. PAGE is the Chief Engineer for Technology within the Modeling, Simulation, Experimentation and Analytics Technical Center, and the Director of the Simulation Experimentation and Analytics Lab (SEAL) at the MITRE Corporation. He has a Ph.D. in Computer Science from Virginia Tech. He has served as the Chair of the Association for Computing Machinery (ACM) Special Interest Group on Simulation and Modeling (SIGSIM), the Board of Directors of the Winter Simulation Conference (WSC), and serves on the editorial boards of the *Transactions of the Society for Modeling and Simulation International*, *Journal of Defense Modeling and Simulation* (JDMS), and *Journal of Simulation* (JOS). His email address is epage@mitre.org.

SAURABH MITTAL is Lead Systems Engineer/ Scientist within the Modeling, Simulation, Experimentation and Analysis Technical Center at the MITRE Corporation. He has a Ph.D. in Electrical and Computer Engineering from the University of Arizona, Tucson. He has over 15 years of experience in modeling and simulation-based systems engineering across many disciplines. He serves on the Board of Directors for Society of Modeling and Simulation (SCS) International and on the editorial boards of the *Transactions of the SCS* and *Journal of Defense Modeling and Simulation* (JDMS). His email address is smittal@mitre.org.

DISCLAIMER