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Conceptual Model Architecture and Services

Contribution to the National Science Foundation Report on Research Challenges in Modeling and Simulation for Engineering Complex Systems

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3.3 Conceptual Model Architecture and Services

Many modeling paradigms exist for most kinds of domain problems, applied to knowledge from many engineering disciplines. Understanding complex systems requires integrating these into a common composable reasoning scheme (NATO Research and Technology Organization 2014). The software and the system engineering communities have overcome similar challenges using architecture frameworks (e.g. OMG's Unified Architecture Framework (OMG 2016)), but modeling and simulation does not have a similarly mature integration framework. The first subsection below concerns architectures for conceptual modeling, while the second outlines infrastructure services needed to support those architectures.

Model Architecture

At the foundation of a modeling architecture should be a fundamental theory of models, to enable reusability, composability, and extensibility. What theory of models could support the implementation of a model architecture? An epistemic study of existing modeling and integration paradigms is necessary to develop a theory of models. This should include a taxonomy of modeling paradigms, semantics, syntaxes and their decomposition into primitives that operate under common rules across paradigms, to integrate them as required by complex systems.

Model architecture is needed to unify different classes of models developed using different paradigms. An architecture is the glue specifying interfaces, rules of operation, and properties common across modeling paradigms, enabling models to be interconnected at multiple levels of conceptual abstraction. What is meaningful to connect? What is not? An architecture goes far beyond conventional model transformations and gateways, though these are also essential to comprehension of multi-paradigm modeling processes. An architecture is about persistent co-existence and co-evolution in multiple domains at multiple levels of abstraction. How can a model architecture framework connect models that operate according to different sets of laws? For example, critical infrastructure protection requires connecting country, power grid, internet, economy, command and control, etc. Combat vehicle survivability requires connecting humans, materials, optics, electromagnetics, acoustics, cyber, etc. What mechanisms are required to efficiently interact between different sets of laws (e.g. layered architecture)? What level of detail is required to observe emerging behaviors between different sets of laws when integrated? How should a model architecture be implemented, in which format, using which tools? As a model architecture matures, successful design patterns should emerge for the most common reusable interconnections between disciplines. What are these design patterns in each community of interest?

Model architecture sets the rules to meaningfully interconnect models from different domains. Generalizing and publishing rules for widespread modeling paradigms would allow composing and reusing models that comply with the architecture and complex system simulations will become achievable. As an example of interconnected models across domains, start with a Computer Aided Design (CAD) model representing a physical 3D object in terms of nodes and facets. In the CAD paradigm, objects can be merged to interconnect. A related Finite Element Model (FEM) represents continuous differential equations for physical laws between boundary layers. It can be used to compute the fluid dynamics during combustion. FEM models can interconnect at the level of physical laws to compute the temperature distribution from the combustion products distribution for instance. They also interconnect with a CAD model at the mesh level. A computer graphics model enables display of objects as seen from particular viewpoints. It interconnects with CAD and FEM models to map materials and temperature to facets for the purpose of generating an infrared scene image in the field of view of a sensor. A functional model of a surveillance system can represent discrete events involved in changing a sensor mode as a function of the mission. The functional model interconnects with the computer graphics model at the sensor parameter level. Finally, a business process model can represent a commander's mission planning. It can interconnect with a functional model by changing the mission.

Figures of merit must be developed to demonstrate how well a model architecture facilitates composition of multi-paradigm, multi-physics, multi-resolution models. The performance of a model architecture must be checked against interdisciplinary requirements using metrics for meaningfulness and consistency. How can we test a particular integration for validity? How can it be done efficiently over large-scale complex simulations? How can it be done by a non-expert? What mechanisms should a model architecture framework include to support checking for conceptual consistency?

Integration complexity and coupling between the degrees of freedom of individual components and the degrees of freedom of the integration are yet to be understood. When integrating a model in a complex simulation, what details can be ignored and still ensure a valid use of that model? What details cannot be ignored?

Reliable model integration depends on sufficient formality in the languages used, as described in section 3.1. In particular, formal conceptual models of both the system of interest (referent) and analysis provide a basis for automating much of analysis model creation through model-to-model transformation. As an example, consider the design of a mechanical part or an integrated circuit. The CAD tools for specifying these referents use a standard representation, with a formal semantics and syntax. For particular kinds of analyses—such as response in an integrated circuit—simulations are essentially available at the push of a button. Formalism in the specification of the referent enables automation of certain analyses. This pattern is well-demonstrated, e.g., in the use of BPMN (Business Process Modeling Notation) to define a business process, and then automating the translation of this model into a hardware/software implementation specification. The Object Management Group has developed standard languages for model-to-model transformations. At present, there are only limited demonstrations of applying this approach to systems modeling. Automating this kind of model-to-model transformation captures knowledge about how to create analysis models from referent models, so perhaps the most fundamental question is: where should this knowledge reside—should it be captured in the referent modeling language, in the analysis modeling language, in the transformation, or perhaps spread throughout? Formalization of mappings between conceptual models of a referent and its analysis models is critical to building reliable bridges between descriptions of the referent and specifications of a simulation model and its computational implementation.

Services

The success of large-scale integration of knowledge required by complex systems fundamentally depends on modeling and simulation infrastructure services aggregated into platforms. These enable affordable solutions based on reusing domain-specific models and simulators, as well as integrating them into a multi-model co-simulation. For example, understanding vulnerabilities and resilience of complex engineered systems such as vehicles, manufacturing plants, or electric distribution networks requires the modeling and simulation-based analysis of not only the abstracted dynamics, but also some of the implementation details of networked embedded control systems. Systems of such complexity are too expensive to model and analyze without reuse and synergies between projects.

Services need to enable open model architecture development and sharing of model elements at all levels. How can a common conceptual modeling enterprise be launched involving many stakeholders? How can a conceptual model be augmented with knowledge from different contributors (e.g., wiki)? How does it need to be managed? What structure should the conceptual model have? What base ontologies are required (e.g. ontology of physics)? How can conceptual model components be implemented in executable model repositories and how can components plug and play into simulation architectures? Guiding principles must also be defined and advertised. What guidance should modelers follow to be ready for a collaborative conceptual modeling enterprise in the future? Standard theory of models, architecture, design patterns, consistency tests, modeling processes and tools will arise naturally as the modeling science matures.

Services can be aggregated into three horizontal integration platforms:

- In *Model Integration Platforms*, the key challenge is to understand and model interactions among a wide range of heterogeneous domain models in a semantically sound manner. One of the major challenges is semantic heterogeneity of the constituent systems and the specification of integration models. Model integration languages have become an important tool for integrating complex, multi-modeling design automation and simulation environments. The key idea is to derive opportunistically an integration language that captures only the cross-domain interactions among (possibly highly complex) domain models (Cheng, et al. 2015).
- *Simulation Integration Platforms* for co-simulation have several well-established architectures. The High Level Architecture (HLA) (IEEE Standards Association 2016) is a standardized architecture for distributed computer simulation systems. The Functional Mockup Interface (Modelica Association 2014a) for co-simulation is a relatively new standard targeting the integration of different simulators. In spite of the maturity and acceptance of these standards, there are many open research issues related to scaling, composition, large range of required time resolution, hardware-in-the-loop simulators and increasing automation in simulation integration.
- *Execution Integration Platforms* for distributed co-simulations are shifting toward cloud-based deployment, developing simulation-as-a-service use model via web interfaces and increasing automation in dynamic provisioning of resources as required. More will be said about this in the next chapter.

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