CAREER: Domain-Specific Modeling Techniques for Cyber-Physical Systems

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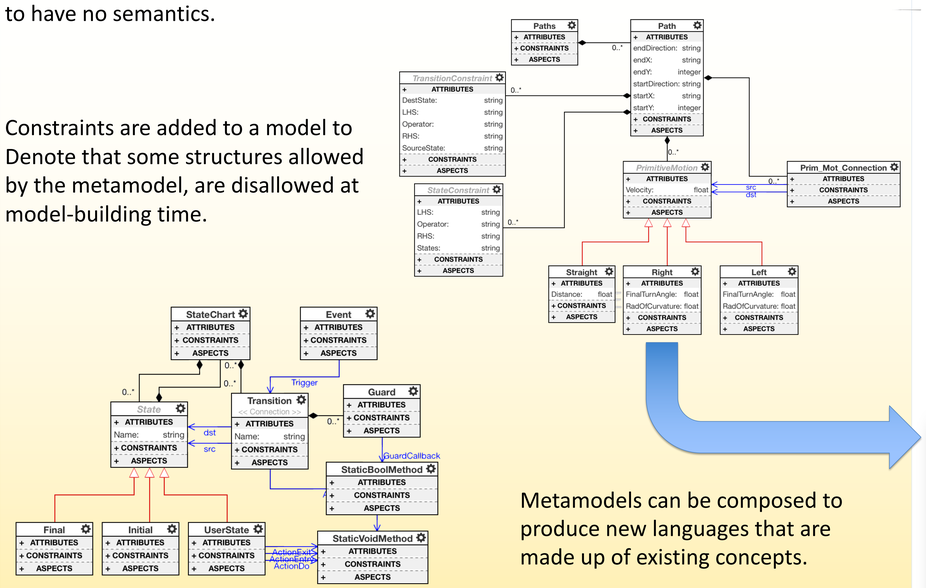
Abstract

The objective of this research is an injection of new modeling techniques into the area of Cyber-Physical Systems (CPSs). The approach is to design new architectures for domain-specific modeling tools in order to permit feedback from analysis, validation, and verification engines to influence how CPSs are designed. This project outlines new research into the integration of existing, heterogeneous modeling languages in order to address problems in CPS design, rather than a single language used to design any CPS.

Models (Structurally) Correct by Construction

Metamodels are used in domain-specific modeling to develop constraints for how models can be constructed. Metamodels prevent the assembly of structures that are *known a priori* to have no semantics.

Constraints are added to a model to Denote that some structures allowed by the metamodel, are disallowed at model-building time.



Metamodels can be composed to produce new languages that are made up of existing concepts.

Closing the Loop

The research in this work addresses the synthesis of model transformations, based on a model's output artifacts, and whether those artifacts fail to meet the CPS constraints.

This work will demonstrate the feasibility of model-transforming *feedback loops*. Like feedback in control theory, there will be conditions for the stability and convergence of the proposed approaches, based on the structure of the models (and CPS domain).

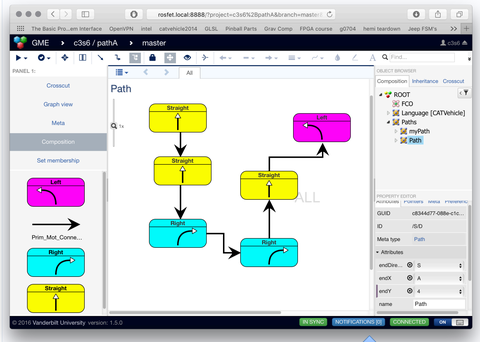
CPS Constraints

For domain-specific models of CPSs, the structure of the model is important, but also important are the behavior of the output artifacts once synthesized from the model.
Fundamentally, "correct" for the CPS requires correctness for the software artifacts, as well as their behavior in the continuous domain.

Ex: changing controller structure to meet constraints.
This is a well-understood problem for control experts, but software experts may not understand it as well. Should I add new structure, or just change attribute values of my existing structure, in order to meet these constraints?

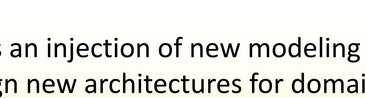
Example: Elementary School Students

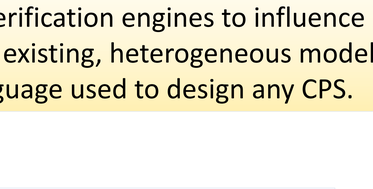
WebGME Model Builder



Model Transformations

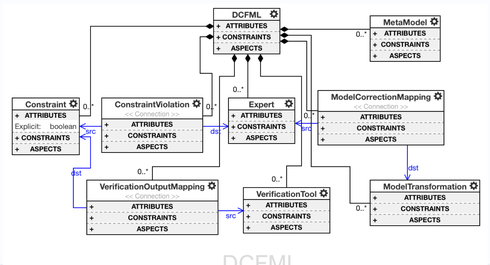
Verification Tool





Constraint Violation Feedback

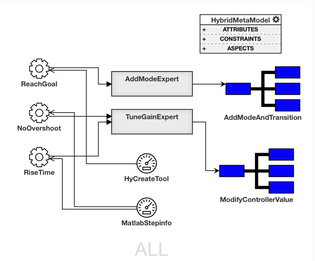
Dynamic Constraint Feedback



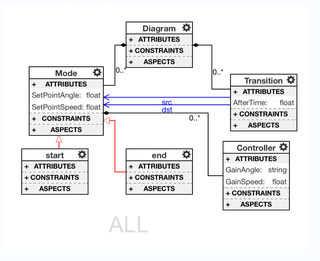
The approach performs transformations when the analysis of the source models does not satisfy dynamic constraints.

Example: Hybrid Controller Language

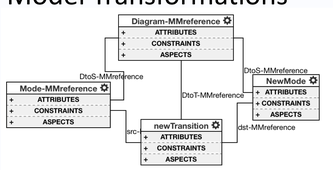
DCF Metamodel



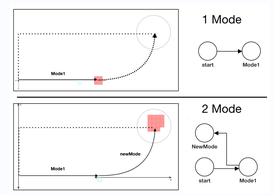
Language Metamodel



Model Transformations



Result: Hybrid Language With DCF



Application Domain: Autonomous Ground Vehicles

Outreach and Broad Impact

- Personnel participated as mentors in the CATVehicle NSF REU Site at the University of Arizona (2013-2019)
- CATVehicle Challenge with CPS-VO online verification and undergaduate student build models.
- Significant media coverage of the project kickoff, and various public talks have taken place (or are scheduled).
- Elementary school student autonomous vehicle programming using reachability verification feedback.

More Reading

1. Bunting, Matt, and Jonathan Sprinkle. "A meta-metamodel for dynamic constraint feedback in modeling languages." Proceedings of the 17th ACM SIGPLAN International Workshop on Domain-Specific Modeling. ACM, 2019.
2. Bhadani, Rahul, Jonathan Sprinkle, and Matthew Bunting. "The CAT Vehicle Testbed: A Simulator with Hardware in the Loop for Autonomous Vehicle Applications." arXiv preprint arXiv:1804.04347 (2018).
3. M. Bunting, Zeleke, Y., McKeever, K., and Sprinkle, J., "A Safe Autonomous Vehicle Trajectory Domain Specific Modeling Language For Non-Expert Development", in Proceedings of the International Workshop on Domain-Specific Modeling (DSM 2016), Amsterdam, Netherlands, 2016, p. 42--48
4. S. Whitsitt, "Automatic Verification of Dynamic Constraints in LTI Control Systems Through Model Transformations", *NSF Young Professionals Workshop on Exploring New Frontiers in Cyber-Physical Systems*. Washington, DC, 2014.
5. Sean Whitsitt. "A Methodology for Mending Dynamic Constraint Violations In Cyber Physical Systems By Generating Model Transformations." PhD Dissertation. Dec. 2014.
6. Kun Zhang and J. Sprinkle, "A Closed-loop Model-based Design Approach Based On Automatic Verification and Transformation", *The 14th Workshop on Domain-Specific Modeling*. pp. 1-6, 2014.

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