

Component, Context, and Manufacturing Model Library 1 (C2M2L-1) – Technical Area 2

Final Report

28 February 2013

Reporting Period: 11/1/2011 – 5/1/2013

Contract Number: D12PC00241

Prepared For:

Defense Advanced Research Projects Agency
3701 North Fairfax Drive
Arlington, VA 22203-1714

Prepared by:

BAE Systems Land & Armaments L.P.
4800 East River Road
Minneapolis, MN 55421-1498

Distribution Statement C: Distribution Authorized to U.S Government Agencies and their contractors. Other requests for this document shall be referred to the DARPA Technical Information Office

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>						
1. REPORT DATE (DD-MM-YYYY) 28-02-2013		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) November 2011 - February 2013		
4. TITLE AND SUBTITLE Component, Context, and Manufacturing model Library 1 (C2M2L-1), Technical Area 2 Final Report				5a. CONTRACT NUMBER D12PC00241		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Challou, Daniel; Pukite, Paul; St. Louis; Polston, Roger; Ames, Jeremy; Wentland, Christopher				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) BAE Systems, Land & Armaments 4800 East River Road Minneapolis, MN 55421-1498					8. PERFORMING ORGANIZATION REPORT NUMBER 0001002059	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Advanced Research Project Agency 3701 North Fairfax Drive Arlington, VA 22203-1714					10. SPONSOR/MONITOR'S ACRONYM(S) DARPA	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Statement C: Distribution Authorized to U.S Government Agencies and their contractors. Other requests for this document shall be referred to the DARPA Technical Information Office						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The role of environmental context models in the Adaptive Vehicle Make program is to help verify that the design solution (i.e., model of an amphibious infantry fighting vehicle) produced by design teams participating in the FANG challenges is capable of meeting or exceeding the mobility and drivetrain related requirements as specified by DARPA's AVM program management team. The BAE System's team employed an iterative, requirements-driven approach to develop the environmental context models, examples of their use, and web-based repository. Our extensive knowledge in the area of military ground vehicle development and testing and the unclassified documentation describing the standard tests and procedures used by the United States Army Test and Evaluation Command (ATEC) were the foundation for capturing a cohesive collection of context models and examples.						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF: a. REPORT b. ABSTRACT c. THIS PAGE U U U			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Stephen F. Panciocco 19b. TELEPHONE NUMBER (Include area code) 763-572-6124	

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

Table of Contents

1.	Introduction and Overview.....	1
2.	Creating and Using Context Models	2
2.1	Role of Context Models in AVM.....	3
2.2	Deriving the Requirements for Context Models	5
2.2.1	Bottom-up derivation of Requirements for Environmental Context Models.....	5
2.2.2	Top-Down Derivation of Requirements for Environmental Context Models.....	9
2.3	Creating Context Models	9
2.3.1	Discussion	10
2.3.2	Technical Challenges	11
2.3.3	Technical Results	11
2.3.4	Findings and Conclusions	12
2.3.5	Implications for Further Research.....	12
2.4	Applying (Representing/Storing and Using) Context Models.....	13
2.4.1	Technical Challenges	13
2.4.2	Context Model Scope and Representations	13
2.4.3	Technical Results	14
2.4.4	Findings and Conclusions	17
2.4.5	Implications for Further Research.....	17
2.5	Examples of Context Model Use in Design Verification.....	17
2.6	Storing and Accessing Context Models and Examples.....	19
2.6.1	Technical Challenges	20
2.6.2	Overview of Development Methodology	20
2.6.3	Technical Results	22
2.6.4	Findings and Conclusions	22
2.6.5	Implications for Further Research.....	23
3.	Results	23
3.1	Technical Challenges.....	23
3.2	Discussion	24
3.3	Technical Results	24
4.	Conclusion	27
4.1	Avenues for Further Research.....	28
5.	References	29

List of Figures

Figure 1: Overview of the Scope of our Effort for Environmental Context Modeling	1
Figure 2: Context Models Support the META Verification Process. Interactions illustrate the use of the context model library and environmental context models in the verification process.	3
Figure 3: Description of a simulation for computing 6-watt power for a model of a road wheel of an Amphibious Infantry Fighting Vehicle (e.g., a Quarter-Car), and the interaction between the model of the design solution (the road wheel) and the environment (terrain derived from a stochastic representation).	4
Figure 4: Land Use-Cases mapped to required contexts	7
Figure 5: Aquatic Use-Cases mapped to required contexts	7
Figure 6: Atmospheric Environmental Context Models required to carry out mobility testing on an IFV.	8
Figure 7: Land Environmental Context Models required to carry out mobility testing on an IFV.....	8
Figure 8: Aquatic Environmental Context Models required to carry out mobility testing on an IFV.....	9
Figure 9: Outline of Process for Creating Models	10
Figure 10: Integration of stochastic modeling with the semantic web	12
Figure 11: State-space for model-based verification	13
Figure 12: Ontological organization of Context Models.....	14
Figure 13: Terrain representation at a gross topographic resolution, suitable for long range analysis, and a fine resolution suitable for vehicle suspension analysis.....	16
Figure 14: Usage of context model in a vehicle model checker	17
Figure 15: Track Builder: A Unity-based Application for Validating Context and Vehicle Concept Models Performance in Various Land and Sea Contexts. More detail on the application and example can be found in Appendix L.....	18
Figure 16: Extension to Track Builder for Validating Vehicle Concept Performance in Surf Zones. More detail on the application and example can be found in Appendix L	19
Figure 17: Filter Example to Demonstrate interaction between Atmospheric Contexts and Vehicle Subsystems. More details on the example can be found in Appendix O	19
Figure 18: Ontological System for Context Artifacts and Resources (OSCAR) Architectural Overview. OSCAR is described in Detail in Appendix E	20
Figure 19: Dynamic Context Server Home Page. The Dynamic Context Server is described in detail in Appendix D.....	21
Figure 20: Overview of the Context Modeling Effort in relation to the Appendices	27

List of Tables

Table 1: Brief Description of each of the steps in our Environmental Context Modeling Effort depicted in Figure 1	2
Table 2: Data Sources used to extrapolate requirements for Vehicle Test Cases (i.e., “Use Cases”), and environmental context models	5

List of Symbols, Abbreviations, and Acronyms

Symbol, Abbreviation, Acronym	Definition
AVM	Adaptive Vehicle Make
C2M2L	Component, Context, and Manufacturing Model Library
CAD	Computer-Aided Design
CML	Component Model Library
CSIR	Council for Scientific and Industrial Research
DARPA	Defense Advanced Research Project Agency
DCS	Dynamic Context Server
FANG	Fast, Adaptive, Next-Generation
FMI / FMU	Functional Mockup Interface / Functional Mockup Unit
IFV	Infantry Fighting Vehicle
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory
MBE	Model Based Engineering
NRMM	NATO Reference Mobility Model
OSCAR	Ontological System for Context Artifacts and Resources
PCC	Probabilistic Certificate of Correctness
PDF	Probability Density Function
PoC	Probability of Correctness
PSD	Power Spectral Density
SWEET	Semantic Web for Earth and Environmental terminology
TA	Technical Area
TOPS	Test Operating Procedures

1. Introduction and Overview

The goal of the Defense Advanced Research Project Agency's (DARPA) Adaptive Vehicle Make (AVM) program is to develop a radically innovative approach to the development of military vehicles, resulting in significant reductions in the cost and schedule required to develop such vehicles. To achieve that goal, a novel approach to the model-based verification of vehicles is required. Thus, in response to DARPA's call to construct a Component, Context, and Manufacturing Model Library (C2M2L) to help achieve their goal, we developed a comprehensive suite of environmental context models necessary to verify the model-based mobility and drivetrain systems of a land-based or an amphibious Infantry Fighting Vehicle (IFV).

More specifically, the objectives of our efforts for the Component, Context, and Manufacturing Model Library (C2M2L-1) were as follows:

1. To develop a comprehensive suite of environmental context models that can be utilized to thoroughly evaluate model-based representations of the mobility and drivetrain systems of land-based or amphibious Infantry Fighting Vehicles for their ability to meet or exceed their performance requirements.
2. To ensure that the models we developed would be correctly and effectively used for their analysis tasks, we created examples of how to use them for requirements verification, and made the models, examples of their use, and information about the models accessible (searchable and retrievable) via a web-based Ontological System for Context Artifacts and Resources (OSCAR). We also formulated and delivered a spreadsheet detailing model and example locations in a Subversion repository as an alternate means of locating and utilizing many of the models and examples.

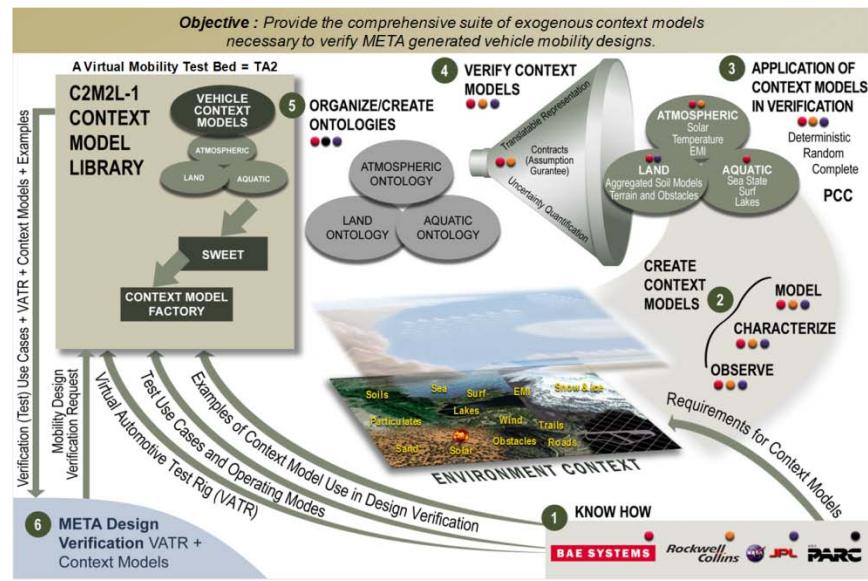


Figure 1: Overview of the Scope of our Effort for Environmental Context Modeling

Figure 1 outlines the steps we followed in order to meet our objectives. **Table 1** presents a brief overview of each of the six steps outlined in **Figure 1**.

Table 1: Brief description of each step in our Environmental Context Modeling flow depicted in **Figure 1**

1.	Derived the set of use cases/mobility verification requirements for testing land-based and amphibious mobility systems and drivetrains. Derived the requirements for environmental context models from the use-cases / mobility verification requirements.
2.	Created the set of environmental context models necessary to thoroughly test the mobility and drivetrain system and subsystem designs constructed by META toolset from their requirements using novel and adaptable algorithms and methods
3.	Synthesized novel (stochastic) and other representations to facilitate the application of Context Models for different classes of verification.
4.	Created executable examples to verify the context models and to illustrate the use of each of the context models in design verification scenarios.
5.	Created a semantic web-based executable architecture based on the Semantic Web Earth and Environmental (SWEET) ontology populated with translatable representations of the context models, information used to construct the models, examples of model use, and methods for translating the models
6.	Created a template of a surrogate mobility and drivetrain system (A Virtual Automotive Test Rig (VATR)) for use with context models and utilized it, along with the context models, in the executable examples we formulated.

Table 1 briefly describes each of the steps we carried out over the course of our context modeling effort. The following sections describe our approach/methodology, challenges, results, and findings as applicable to each of the steps in the table.

Section 2 provides a more detailed discussion on creating and using context models (Steps 1-6 illustrated in **Figure 1** and described in **Table 1**);

Section 3 discusses the technical challenges of the overall modeling effort and provides an overview and pointer to the detailed results documented in the appendices.

Section 4, reviews our notable developments over the course of this project in the areas of model development, examples of context model use, and ontologically-based web services.

Finally, accompanying this report is a series of appendices that provide greater technical detail on the results of our efforts. The appendices are listed and summarized in Section 3.3, Technical Results, on page 24.

2. Creating and Using Context Models

We employed an iterative, requirements-driven approach to develop the environmental context models, examples of their use, and web-based repository. We determined what environmental models would be required for evaluating mobility and drivetrain designs by drawing on BAE's extensive knowledge in the area of military ground vehicle development and testing; by reviewing unclassified documentation describing the standard tests and procedures used by the United States Army Test and Evaluation Command (ATEC) to evaluate the ability of military vehicles to meet their performance requirements, and by reviewing the requirements for the Fast, Adaptive, Next-Generation (FANG) infantry fighting vehicle (IFV) supplied by DARPA's Adaptive Vehicle Make (AVM) program leadership. Once we had the requirements, our task was fairly straightforward. Collectively, the requirements directly or indirectly

specify what environments vehicles will be evaluated in, and they also specify the use-cases for constructing the examples of vehicle use. Thus, we proceeded as follows.

First, we synthesized environmental models from relevant data sources and put them into representations that were most suitable for storing and utilizing the data. In cases where data describing the environment was already available, test course data documented in publications such as ATEC's Test Operations Procedures (TOPs), we obtained (i.e., scanned) the data from the documentation and put it into representations that best facilitated its use.

As the models of the environment became available, we began to synthesize examples illustrating the use of the environmental models in requirements verification scenarios.

As the models and examples were completed, we stored them in a Subversion Repository. Once the Ontological System for Context Artifacts and the Dynamic Context Server became operational, we made the models, examples, and information on the models available through these mechanisms.

In the remainder of this section, we address the following

- Role of Context Models in AVM (Section 2.1, Page 3)
- Deriving the requirements for Context Models (Section 2.2, Page 5)
- Creating Context Models (Section 2.3, Page 9)
- Application of Context Models (Section 2.4, Page 13)
- Examples of Context Model Use in Design Verification (Section 2.5, Page 17)
- Storing and Accessing the Context Models and Examples (Section 2.6, Page 19)

2.1 Role of Context Models in AVM

The role of environmental context models in the Adaptive Vehicle Make program is to help verify that the design solution (i.e., model of an amphibious infantry fighting vehicle) produced by design teams participating in the FANG challenges is capable of meeting or exceeding the mobility and drivetrain related requirements as specified by DARPA's AVM program management team. **Figure 2** below depicts a high level view of the role of environmental models in AVM and design solution development.

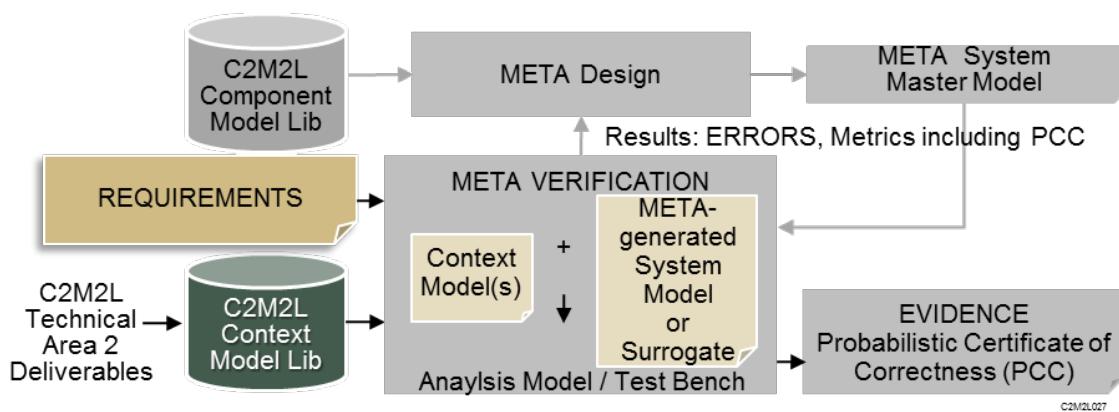


Figure 2: Context Models Support the META Verification Process. Interactions illustrate the use of the context model library and environmental context models in the verification process.

Currently, as implied by **Figure 2**, META verification processes being developed by the META performers use the environmental context models to place a “load” on the design solutions formulated by

their tools. They are accomplishing this by creating simulations which couple the model of the design solution formulated by their toolset to the context model data that will interact with the design solution during the execution of a use case.

For example, one typical military ground vehicle requirement, and one of the FANG IFV mobility requirements, is to determine if the load on the driver's seat will exceed six watts of power as the vehicle is being driven across a test course¹. **Figure 3** outlines how this would be modeled and simulated to compute an estimate of the input to the six watt power calculation for a single vehicle road wheel. Once this is done for a single road wheel, it is relatively straightforward to accomplish for n road wheels. The environmental input is depicted as a green section of terrain depicted in the lower right side of **Figure 3**; the actual input is an X, Z profile of a course that the quarter car is driving over.

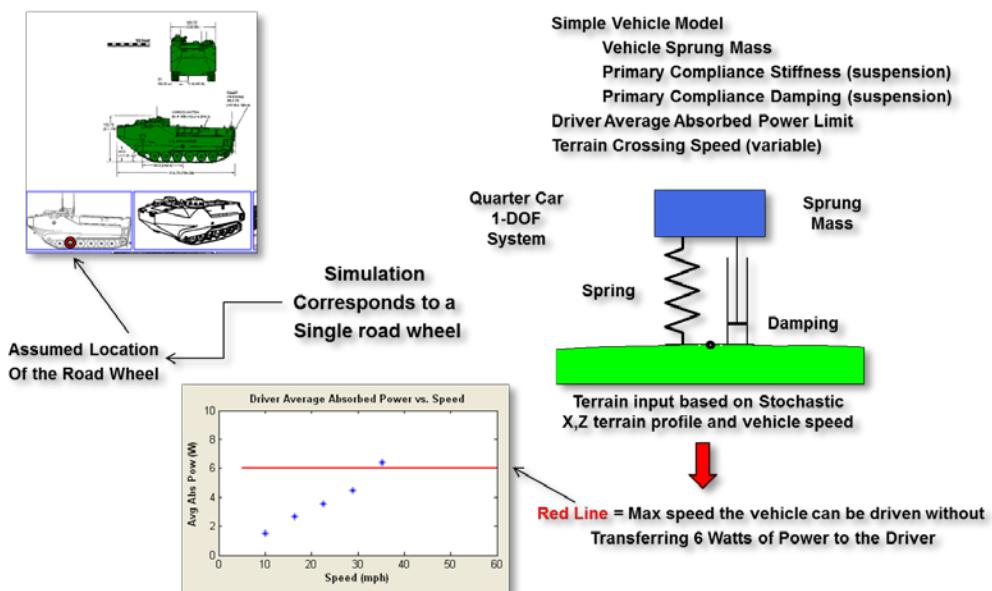


Figure 3: Description of a simulation for computing 6-watt power for a model of a road wheel of an Amphibious Infantry Fighting Vehicle (e.g., a Quarter-Car), and the interaction between the model of the design solution (the road wheel) and the environment (terrain derived from a stochastic representation).

To facilitate the synthesis of the simulations to verify design performance, which are referred to as “test benches” by AVM performers, we created over 20 executable examples that incorporate each of the context models we synthesized or obtained. The examples illustrate how to construct simulations of the interactions between the each of the context models and a surrogate design solution. The executable examples illustrating the use of context models are discussed in more detail in Section 2.5. In the next section we discuss how we identified the context models that were required for evaluating IFV mobility and drivetrain designs.

¹ “... the tolerance limit for representative young American males is approximately 6 watts of continuously absorbed power, ...” NATO Reference Mobility Model, Edition I, User’s Guide Oct 1979 (Referencing: Pradko, F., Lee, R. A., and Kaluza, V., “Theory of Human Vibration Response”, Paper 66-WA-BHF-15, presented at ASME Meeting, Nov 1966)

2.2 Deriving the Requirements for Context Models

We pursued two avenues for identifying the set of context models required to test mobility and drivetrain designs. Since the requirements for the FANG vehicle were not available at the beginning of our effort, we generated the candidate use-cases for a typical vehicle in a bottom up fashion. Specifically, we used BAE's in-house experience in the development of military ground vehicles and descriptions of tests and the environmental contexts in which they are carried out – which are effectively the use-cases for the vehicle. Once the use cases were documented, it was straightforward to derive the context models required to carry them out. This is discussed in more detail in section 2.2.1.

DARPA Program Management made the draft set of FANG requirements available in the July timeframe. The FANG requirements essentially specify the use-cases for the vehicle, and we worked with personnel from Ricardo and Vanderbilt to specify what contexts would be required to test the requirements for the first FANG Challenge. This is discussed in more detail in section 2.2.2.

2.2.1 Bottom-up derivation of Requirements for Environmental Context Models

While the tests that the ATEC community uses vary, the scope of the potential tests, i.e., the vehicle use cases, and the environments in which use cases occur, are relatively invariant. Moreover, the tests and detailed descriptions of the environments in which they are carried out are well-documented. Thus, the requirements for context models can be derived in “bottom up” fashion as follows. By using BAE’s long time expertise in the design, evaluation, delivery and support of amphibious and land-based IFV’s, and reviewing the information on tests and environments contained in the sources that are enumerated in **Table 2**, we were able derive the mobility centric use-cases for an IFV. The mobility centric use cases for land and aquatic mobility testing we derived are listed in the left-hand column in **Figure 4** and **Figure 5**. The columns on the right side of the **Figure 4** and **Figure 5** indicate the general properties of the environment required to carry out each test / use case. The columns on the top right hand side of the figures list the characteristics of the environment necessary to execute each use case.

Table 2: Data Sources used to extrapolate requirements for Vehicle Test Cases (i.e., “Use Cases”), and environmental context models

Description of Data	Reference
Military specifications, regulations, and test operating procedures	<ul style="list-style-type: none"> ■ Mil-Std-810G ■ AR-70-38, Research, Development, Test and Evaluation of Materiel for Extreme Climactic Conditions ■ TOP-1-1-010, U.S. Army Test and Evaluation Command Test Operations Procedure “Vehicle Test Course Severity (Surface Roughness)” ■ TOP-1-1-011, U.S. Army Test and Evaluation Command Test Operations Procedure “Vehicle Test Facilities at Aberdeen Test Center and Yuma Test Center” ■ TARADCOM Signal Analysis Program ■ TOP-1-1-014 Ride Dynamics ■ APG Report No. APG-MT-3635, Special Study of Technique and Study of Automotive Test Course Index, Phase I and II, TECOM Project No. 9-CO-011-000-019, P. Paules and S. Harley, August 1970. ■ APG Report No. APG-MT-4105, Special Study of Establishment of Quality Control Charts for Test Course Inspection Roughness, TECOM Project No. 9-CO-011-000-055, John P. Sobczyk, July 1972. ■ APG Report No. APG-MT-4533, Special Study of Technique and Study of Automotive Test Course Index, Phase III, TECOM Project No. 9-CO-081-000-007, W. Scott Walton, October 1974.

Description of Data	Reference
	<ul style="list-style-type: none"> ■ APG Report No. APG-MT-5882, Final Report on Profiling the Yuma Proving Ground Mid-East Desert Analog Test Course, TECOM Project No. 7-CO-RD3-AP1-012, T. Shrader and W. Connon III, Sept. 1983.
US National Weather Service (NWS) data	www.weather.gov
American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) handbook data	2009 ASHRAE Handbook – Fundamentals
National Solar Radiation Data Base (NSRDB)	http://www.nrel.gov/rredc/solar_data.html http://rredc.nrel.gov/solar/old_data/nsrdb/
Digital Elevation Model (DEM)	http://ned.usgs.gov/

Land Operating Mode and Use Cases		Vehicle Type Applicability	Required Contexts					
			Air Properties	Features	Contaminants	Surface Character	Discrete Obstacles	Terrains
		Atmosphere	Land	Key:				
Unpowered Performance (Ground Clearance, Wheel Loads)		All	I I I	R N R	R	R	R	R
Level Ground Static		All	I I I	R N R	R	R	R	R
Longitudinal Slope		All	I I I	R N R	R	R	R	R
Side-to-Side Slope		All	I I I	R N R	R	R	R	R
Lifting Load (Cranes, Winches, Booms)		All	I I I	R N R	R	R	R	R
Transitioning (Unpowered to Powered)								
Engine Start		All	R I R	I N R				
Engine Idle		All	R I I	I N R				
Engine Tactical Idle		All	R I I	I N R				
Engine Quiet Watch		All	R R I	I N R				
Powered Performance								
Ride Quality								
6-Watt Absorbed Power Curves		All	I I I	R N R				
Average Absorbed Power at Average Speed at $\leq 2.5g$		All	R I I	R N R				
Average Speed at $\leq 2.5g$		All	R I I	R R R				
Cross Country Course at Speed		All	R I R	R N R				
Turning and Steering (Left and Right)								
Straight Ahead		All	I I I	R R R				
Pivot (Retard inside track, power outside track)		Skid Steer	I I I	R N R				
Neutral Axis (Power inside & outside track in opposite direction)		Skid Steer	I I I	R N R				
Moderate Turns		All	I I I	R R R				
High-g Turns		All	I I I	R N R				
Slalom Course		All	I I I	R N R				
Lane Change		All	I I I	R N R				
Turning Performance								
Curb-to-Curb		All	N N N	R N R				
Wall-to-Wall		All	N N N	R N R				
Minimum Inside Wheel Turn Radius		All	N N N	R N R				
Automotive Performance								
Level Ground Constant Speed		All	R R R	R N R				
Acceleration		All	R R R	R N R				
Braking		All	R R R	R R R				
Panic Stop		All	R R R	R R R				
Top Speed		All	R R R	R N R				
Creeping Speed		All	R I R	R N R				
Tractive Effort (TE)								
Max TE Both Sides		Skid Steer	R N R	R N R				
Max TE Per Side		Skid Steer	R N R	R N R				
Continuous TE		All	R N R	R N R				
Differential TE		Skid Steer	R N R	R N R				
Fuel Economy		All	R R R	R N R				
Towing (TE, Braking, Clearances)		All	R I R	R R R				
Towed (TE, Braking, Clearances)		All	R I R	R R R				

Figure 4: Land Use-Cases mapped to required contexts

Aquatic Operating Mode and Use Cases		Vehicle Type Applicability	Required Contexts					
			Air Properties	Features	Contaminants	Surface Character	Discrete Obstacles	Water Properties
		Atmosphere	Land	Aquatic	Key:			
Unpowered Performance								
Static Buoyancy Reserve (Hydrostatics)	Amphibious	I I I	N N N	R R R	R R R	R R R		
Self-righting Buoyancy	Amphibious	I I I	N N N	R R R	R R R	R R R		
Powered Performance (Drag and Hydrodynamics)								
Forward (Transition, Fording, Swim)	All	R R R	R N R	R R R	R R R	R R R		
Reverse	All	R R R	N N N	R R R	R R R	R R R		
Turning and Steering (Left and Right)	All	R R R	N N N	R R R	R R R	R R R		
Towing	Amphibious	R R R	N N N	R R R	R R R	R R R		
Towed	Amphibious	R R I	N N N	R R R	R R R	R R R		

Figure 5: Aquatic Use-Cases mapped to required contexts

After we identified the set of tests necessary to verify the performance of an IFV, we revisited the documents in **Table 2** to determine the contexts required to carry out each use case, and then enumerated them. **Figure 6**, **Figure 7**, and **Figure 8** list the environmental context models required to carry out the mobility centric use cases. With these requirements in hand, we began synthesizing the context models required to thoroughly analyze the mobility performance of an IFV design upon inception of our C2M2L-1 TA2 contract.

Descriptions of Atmospheric Contexts Delivered	
Atmospheric Environment	
Air Properties	
Pressure	
Density	
Moisture	
Temperature (Arctic, Cold, Normal, Hot)	
Temperature (Locally Induced)	
Atmospheric Features	
Wind	
Solar Radiation	
Contaminants	
Corrosive Components (Salt spray, SO ₂ , NO _x)	
Particulates (Dust, Sand, Volcanic Ash, Rain, Snow, Ice Crystals)	
Electro Magnetic Interference (EMI)/ <i>Electro Magnetic Pulse (EMP)</i>	

Figure 6: Atmospheric Environmental Context Models required for mobility testing on an IFV.

Descriptions of Land Contexts Delivered	
Land Environment	
Surface Characteristics (for Depth of Interest)	
Concrete	
Paved	
Dirt	
Sand	
Wet	
Mud	
Snow	
Ice	
Discrete Obstacles (Forward and Reverse, and at Angles)	
Step Climb	
Step Descend	
Gap Crossing	
V-Ditch	
Half-Round	
Curb	
Features found in MOUT (Military Operations in Urban Terrain)	
Jersey Barrier (Highway Divider)	
Improvised Obstacles (e.g., passenger cars)	
Terrains	
Terrains of varying roughness (Flat to 5" in rms)	
Longitudinal Grades (Forward and Reverse)	
Side-to-Side Slopes (Either side up-hill)	
Combined Grade and Slope (Fore-Aft and Side-to-Side)	
Curvature (Turns, Crown, Trough)	

Figure 7: Land Environmental Context Models required for mobility testing on an IFV.

Descriptions of Aquatic Contexts Delivered	
Aquatic Environment	
Water Properties	
Density	
Temperature	
Viscosity	
Thermal Conductivity	
Specific Heat	
Water Body Features	
Depth	
Calm	
Surf	
Currents	
Sea-State	
Contaminants	
Salt	
Particulates (Sand, Volcanic Ash)	
Debris (Vegetation, Spills)	

Figure 8: Aquatic Environmental Context Models required for mobility testing on an IFV.

2.2.2 Top-Down Derivation of Requirements for Environmental Context Models

Once the performance requirements for the mobility and drivetrain system to be constructed for the FANG-1 challenge became available (in the July 2012 timeframe), we worked directly with the authors of the requirements to derive the environmental context models required to test the requirements in top-down fashion. This was accomplished via a series of weekly meetings with system engineering representatives from Ricardo, the authors of performance requirements for the FANG-1 challenge, and META tool chain implementers from Vanderbilt (CyPhy) and CyDesign. For the most part, the team met on a weekly basis from the end of July 2012 through December 2012.

By the time the FANG performance requirements were made available, our C2M2L-1 TA2 efforts were well underway as our participation in the program began in the March 2012 timeframe. Fortunately, the requirements that we derived in bottom-up fashion listed in **Figure 6**, **Figure 7**, and **Figure 8**, which we used to guide efforts to synthesize context models and examples, yielded a set of context models compatible with the requirements that we derived in top-down fashion from the FANG performance requirements. As of this writing, a subset of the models we produced is being utilized by the CyPhy and CyDesign toolset implementers to perform verification in the toolsets being utilized for the FANG-1 challenge.

In the next section, we discuss the methods we employed for synthesizing environmental context models based upon the requirements we derived, our results, and our findings and conclusions.

2.3 Creating Context Models

As a general approach to creating models, we use the process shown in **Figure 9** below. The process entails observation, characterization and modeling.

In **Figure 9**, the *observations* essentially supply the set of data that we use to formulate a model. The *information* step is a process of characterizing the data to determine whether it could be used in deterministic “go/no go” test settings (such as an obstacle profile), or whether it is a stochastic variate that requires a full probability measure of its state space (such as significant wave height prediction for sea-state modeling).

The last *knowledge* capture step uses the results of characterization to create the necessary numerical model for the environmental context being tested against. For high-fidelity models, this is often the most unwieldy step, as it may require multi-disciplinary physics to adequately represent. On the other hand,

the consideration of statistical physics or thermodynamic laws may allow the model a concise mathematical representation which agrees with the empirical data.

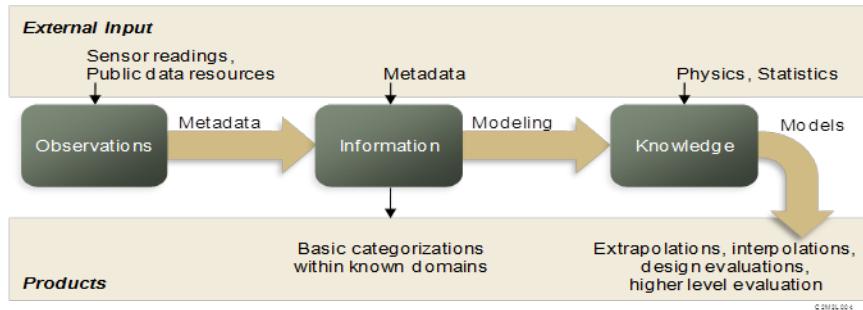


Figure 9: Outline of Process for Creating Models

The observations were typically taken from previously collected and published data, while the characterization step was used to determine whether we could apply any patterns of use from other modeling domains.

The pattern that we often employed leveraged the maximum entropy (MaxEnt) principle [1] to fit empirical distributions based on a key set of characterized statistical moments. For example, we could often fit empirical distributions based only on the characterized statistical mean or mode of an observed variate (this worked well for wind, rain, particle sizes, among other domains).

2.3.1 Discussion

Several of the modeling domains that were required for environmental contexts were either lacking in characterization detail or pedigree, or had limitations placed on their use (e.g. proprietary IP, classified-use, etc.). Based on the extensive collection of environmental modeling domains that a vehicle context typically involves, we had to apply several shortcut heuristics and basic algorithms to ensure we had enough fidelity to cover all the cases. A goal of modeling is also to reduce the complexity and magnitude found in raw data, and we have high-resolution evidence (courtesy of data collected by our C2M2L colleagues at CSIR [2]) as to where this information reduction is applicable.



An effective strategy we used was to develop models that were founded on essential stochastic patterns observed in nature [3]. From this foundation, a general pattern that we relied on involved creating probability density functions (PDF) based on applying the maximum entropy principle to the observed

data. This was an approach predicated on limited information or knowledge that leveraged Jayne’s information theory concepts [1].

Another strategy was based on applying heuristics to restricted-access (ITAR) information. For vehicle dynamics context models, we were restricted to indirectly using power spectral density (PSD) plots of terrains which could then generate an equivalent real-space terrain profile.

2.3.2 Technical Challenges

The paths of developing context content involved (1) creating models from scratch, (2) extending models from public data sources, or (3) applying heuristics on related data that would retain a substantial portion of the information content.

In some cases, we had to process significant amounts of data from available environmental repositories; this was necessary to generate adequate statistical precision for the low-probability cases that we were interested in (e.g., gathering significant wave height statistics for severe sea-state classifications).

In one class of cases, we needed to apply screen-scraping to extract the non-classified parts of critical test data, and then apply a key heuristic to produce tolerable fidelity that would be suitable for focused crowd-sourced² contextual use.

The ongoing challenge is to produce environmental models for the state-space that a vehicle interacts with. The issue with detailed proprietary physics models is that they are often considered valuable intellectual property (IP) and so to simplify even some of these models in a fashion suitable for open development has enormous benefits.

2.3.3 Technical Results

For the domain of terrain profiling we evaluated a number of approaches. A heuristic model based on PSD data sets produced adequate results for nondescript/random terrain. A semi-Markov approach that we developed during the course of this project worked very well to model recent high-resolution data produced by CSIR [2]. These terrains included semi-periodic structures such as Belgian block cobblestone and potholes. Another promising approach developed during this project uses a kernel transform that is an outgrowth of shock and vibration modeling [4].

The set of results is more completely covered in the following appendices: Appendix A covers the stochastic modeling approach and the results from applying MaxEnt to a number of environmental domains [5]. Appendix B covers fine terrain and gross terrain (topography) and evaluates the effectiveness of heuristics[6]. Appendix C covers stochastic growth models that find application to thermal and corrosion modeling [7]. Appendix H covers the kernel approach to terrain profiling [4].

For compliant modeling, Appendix I describes a library containing nominal climate conditions and a thermal design example, and Appendix J and Appendix K describe approaches for granular and soft soil terrain.

² This is not crowd-sourcing in the current use of the term, but focused on technically proficient engineers who often can offer non-traditional design experience.

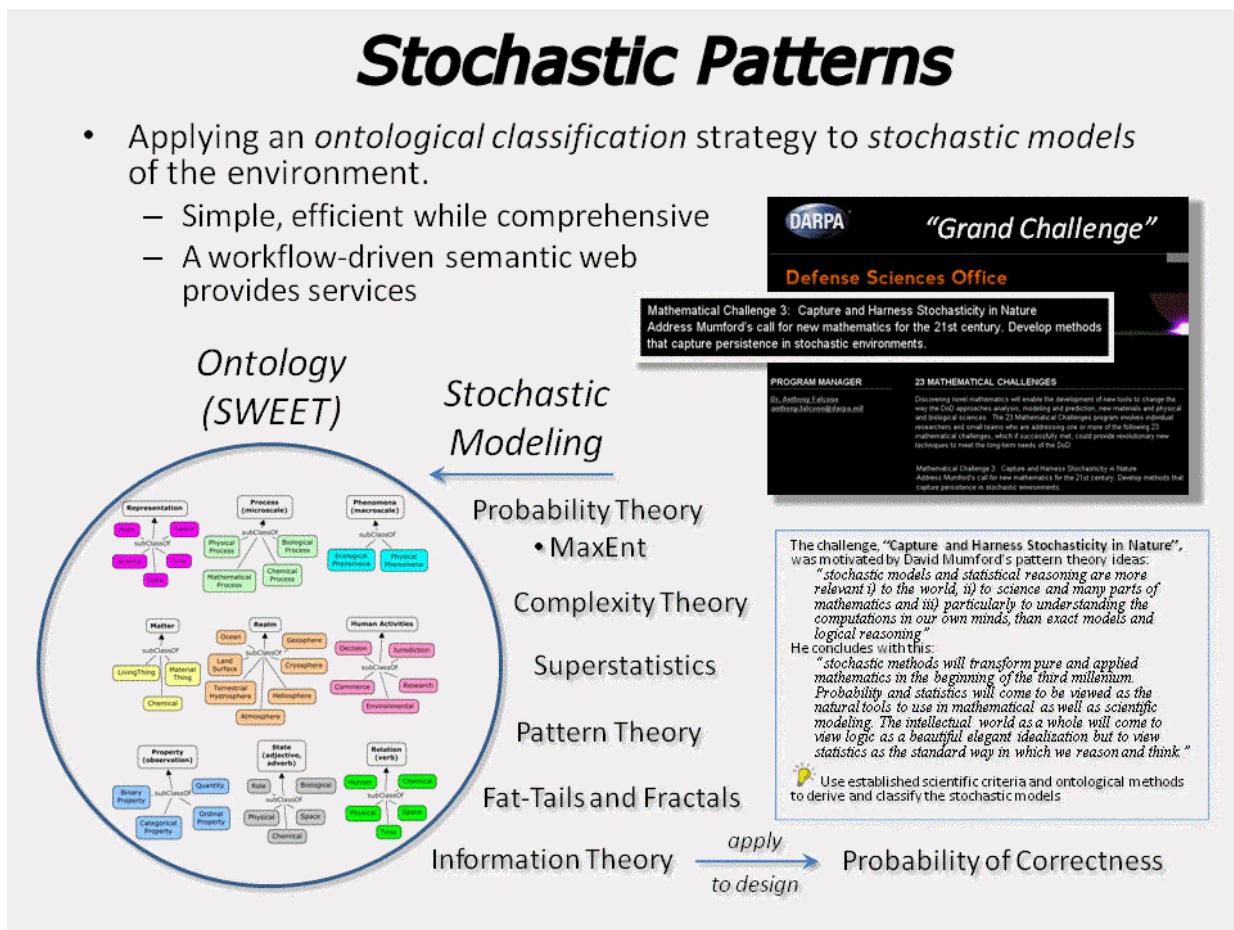


Figure 10: Integration of stochastic modeling with the semantic web

2.3.4 Findings and Conclusions

The most frequent result we came across when characterizing and modeling domains was how often we could apply previously observed patterns, and especially those derived from MaxEnt principles.

The combination of stochastic patterns mapped onto ontology allowed us to classify the patterns as well as the environmental domains (see Appendix D).

Within the domain of terrain modeling, data from state-of-the-art terrain profiling data collected by CSIR benefited from the models we are currently developing. The spatial resolution was high enough that the stochastic and periodic features of the track features could be clearly delineated and reduced to compact parametric models. By doing this we can reduce data that could occupy potentially gigabytes of storage into a representation of a few parameters.

These findings resulted in several research papers that we either have submitted, or are submitting, for peer-reviewed publication.

2.3.5 Implications for Further Research

The approach we took was partly inspired by a DARPA mathematical grand challenge, "Capture and Harness Stochasticity in Nature", which seeks to address "Mumford's call for new mathematics for the

21st century, methods that capture persistence in stochastic environments” [8]. As **Figure 10** shows, we embraced and utilized Mumford’s ideas, and believe that this strategy holds great promise for future modeling work.

2.4 Applying (Representing/Storing and Using) Context Models

Context models can fill the role of verification for a vehicle design and for evaluation of fitness-of-use within a specific operating environment. This has the potential to be an unbounded exercise — as the possible environmental conditions are combinatorially unlimited — yet we can address the problem with alternative strategies. The alternate approaches can involve estimating probability densities for model outputs and/or generating Monte Carlo simulations based on modeling observed stochastic behaviors. These become suitable for evaluating correctness (i.e. PCC) of vehicle designs when used in an environmental context. This section describes the classes of context models available to implement for use in a model library.

2.4.1 Technical Challenges

The challenge of verification remains one of essentially proving that a given vehicle design will meet its requirements over all the environmental and climatic states it may be subjected to. The options for this class of state-space evaluation are shown in **Figure 11** below. The simplest case is to consider *deterministic* paths through the state-space. This is typically taken as a path through a specific test-track[9] or the operation under a nominal set of climatic conditions[10].

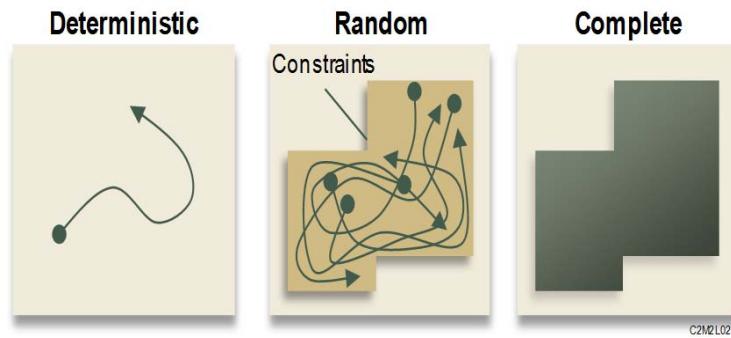


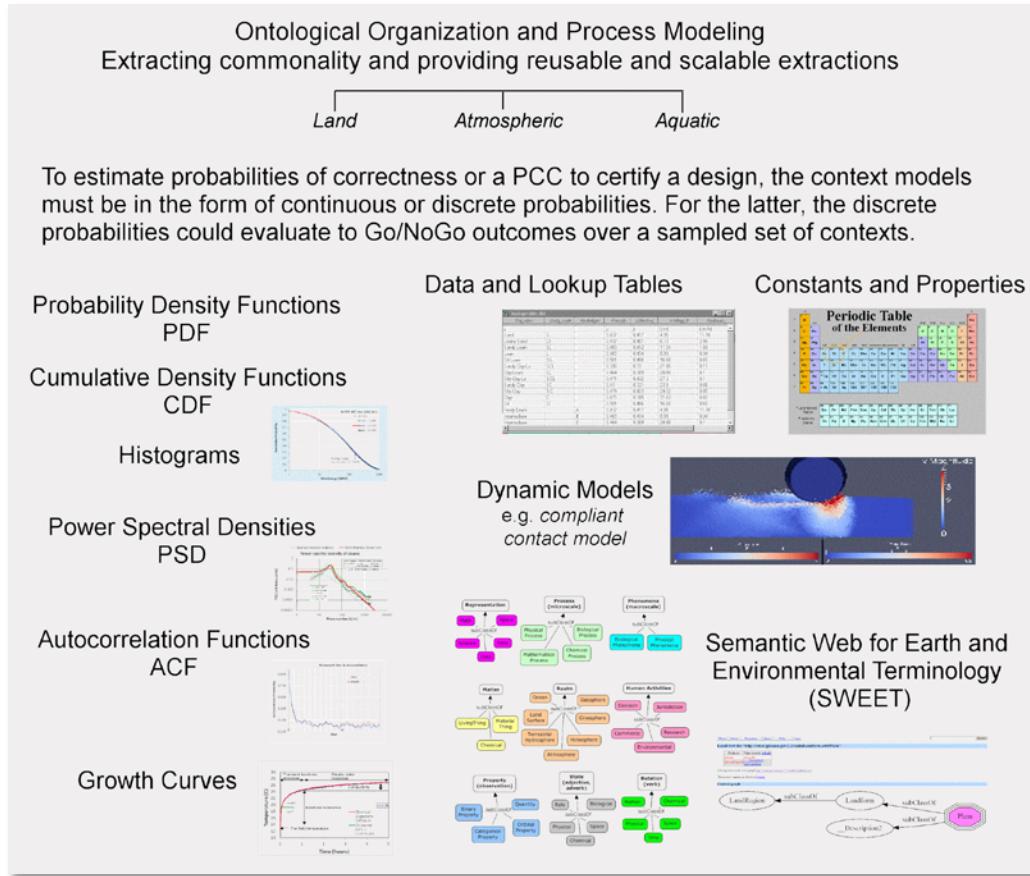
Figure 11: State-space for model-based verification

On the other side of the spectrum, it becomes almost intractably complex to assume that all possible states of the environmental context can be covered. This is considered the *complete* situation, yet this approach is often the only option if one needs to prove some conjecture in formal terms.

In between the range of complexity from deterministic to complete is the *random* or stochastic space of probabilistically-based states; with the outcomes also specified as probabilities. The challenge is to create models of sufficient fidelity so as to represent the environment context adequately. In this case, the most critical states are the ones that occur rarely or are considered extreme values. Since these occur on the tail of the probability curve (i.e., they occur with low probability), they are more difficult to estimate.

2.4.2 Context Model Scope and Representations

The hierarchy of **Figure 12** describes the range of models that we utilized to represent and store environmental context models. Models cast as PDFs or CDFs (and even raw histograms) can be used to generate Monte Carlo samples for use in simulations, once they are inverted.

**Figure 12:** Ontological organization of Context Models

2.4.3 Technical Results

The list below is a sampling of results on the set of terrain models we have either evaluated or formulated as part of this effort. This set reveals the various levels of abstraction that a modeler can apply to terrains:

- Heuristics:** Terrain profiles can be recovered from a PSD through the Fourier series superposition of sine waves method. Although not necessarily precise due to loss of information [11], these are adequate to express the root-mean-square (RMS) of the course profile, which is vital for vehicle suspension and ride comfort modeling. This was implemented as a functional mockup unit (FMU) to interface to clients of the terrain model integrated within a vehicle test-bench via the Functional Mockup Interface (FMI), and it was also used to interface to a 3D rendering package.
- Improved Heuristics:** To improve on the Fourier transform heuristic, a kernel-based spectral decomposition approach was formulated during this project. The algorithm derived from a shock-and-vibration analysis application which was then applied to modeling fine-grain terrain profiles[4] (see Appendix E).
- Stochastic PDF:** Given enough data, such as is available with large topographic data sets, we can extract probability density over many orders of magnitude. In the case of characterizing terrain slopes, we modeled the PDF with a single mean value and specific profile shape over the USA lower 48 states (see Appendix B).

4. **Markov model:** Where we have good data on topography, and can perform pair-correlation on variants such as terrain elevation, we can provide models based on Markov step transitions. Covered fully in Appendix B, we were able to automatically assess and parameterize a marginal probability model for a given region. The simulated terrain relief could be recovered by applying a random walk algorithm to the Markov model parameters.
5. **Semi-Markov model:** Where we have very precise data on fine terrain relief and which may also include specific features, we can apply a semi-Markov model that was developed during the course of this project. This stochastic approach is able to parameterize partially-ordered or quasi-periodic phenomenon such as cobblestones, pot-holes, and wash-boarding features on track profiles. We can recover the realistic detail by taking the parameters of the semi-Markov model and then feeding those into a variation of a random walk simulator (see Appendix B).
6. **Compliant Physics-based models:** We have two detailed reports, on the modeling of compliant environments - “Massively Parallel Discrete Element Modeling of Wheeled Mobility” on Granular terrain in Appendix J, and “Simulation of tracked wheels on soft soil substrates” in Appendix K. Compliant environments are models of the environment (e.g., sandy soil) that change during the course of simulated vehicle interaction, while non-compliant environments are not affected by their interaction with the vehicle during the course of simulation. As appendices J and K indicate, the complexity of a simulation increases significantly when compliant terrains are used in simulation, but they produce more accurate results than simulations that utilize non-compliant environments.
7. **Formally Complete:** The Markov model of topographic elevation changes described in (4) was applied to a formal tool called Prism. A state-machine vehicle description was integrated with a Markov chain representation to prove correctness over a range of possible slopes and elevation changes (see Appendix F).
8. **Deterministic:** Obstacle profiles were provided for specific test courses, including cross-tie, side-slope, staircase, etc.

Depending on the application and the resolution required, we can choose the appropriate terrain model. For example, **Figure 13** below illustrates the need for a resolution at two levels, a fine detail to represent roughness (as a spectral model) and a gross detail to represent elevation changes.

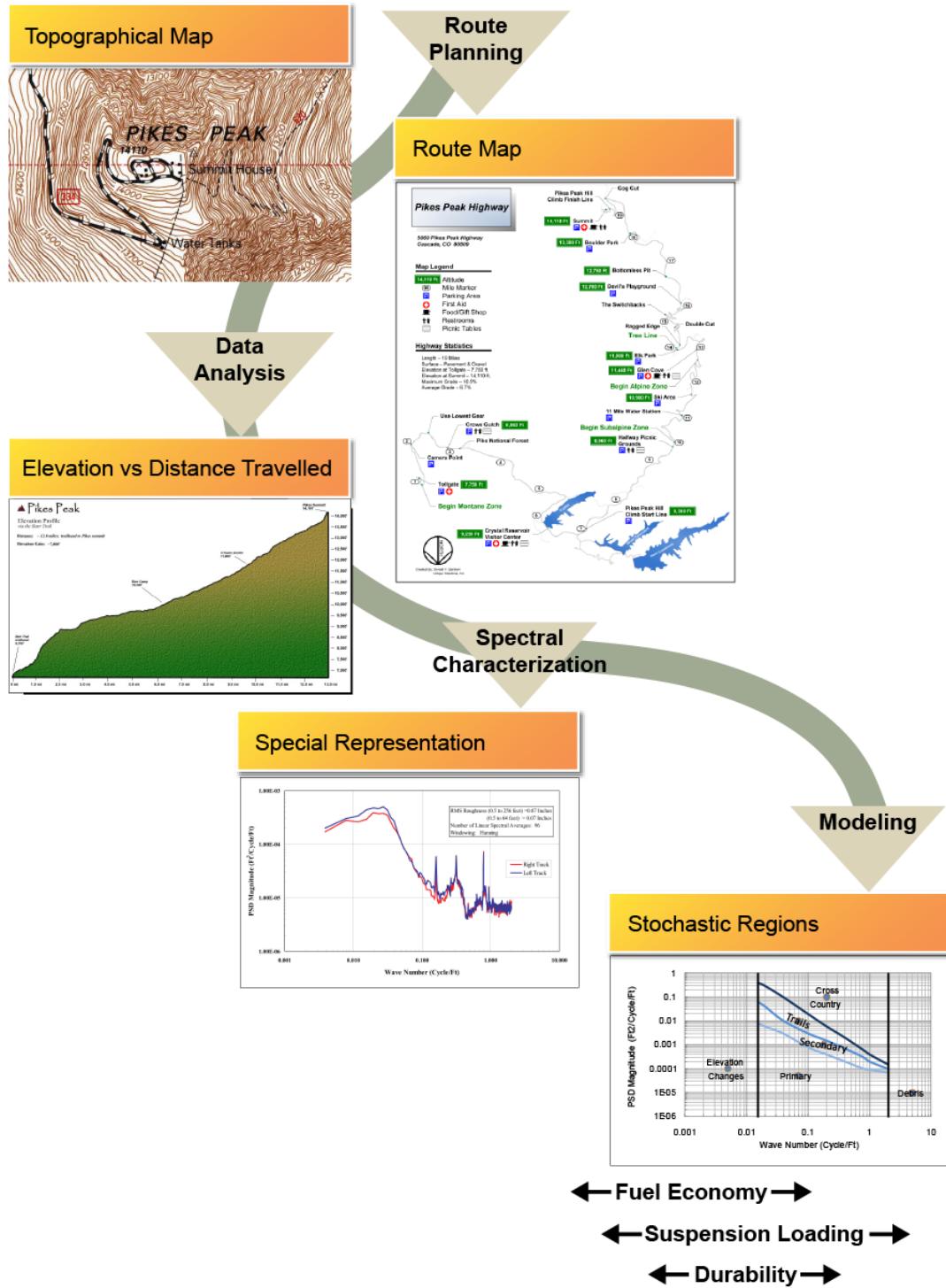


Figure 13: Terrain representation at a gross topographic resolution, suitable for long range analysis, and a fine resolution suitable for vehicle suspension analysis.

A similar classification of models was done for models in the aquatic and atmospheric realms.

2.4.4 Findings and Conclusions

The potential for the generation of unlimited simulation outcomes from a stochastic model allows a systematic coverage of the environmental state-space to be performed. As the set of outcomes remains probabilistic, it is not yet considered complete, but is nevertheless useful for evaluation of a PCC and other measures of correctness.

In Appendix F, we demonstrate how a Markov terrain elevation model is used to provide constraints on a vehicle model. This is essentially an example of integration with formal verification tools. This approach is illustrated in **Figure 14**.

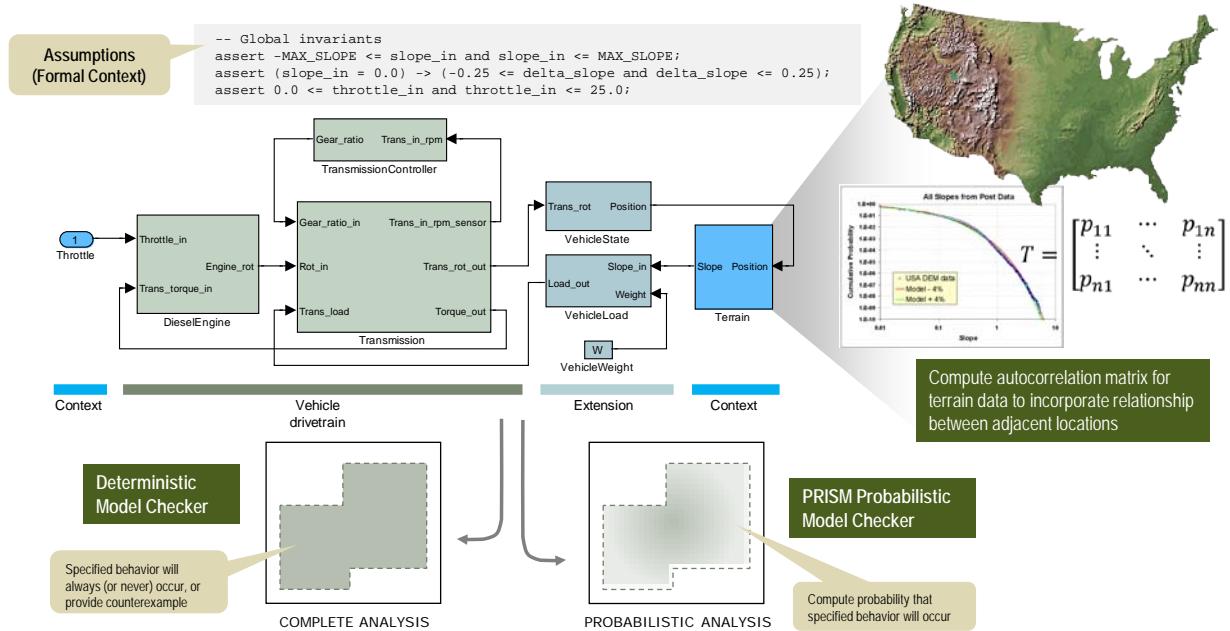


Figure 14: Usage of context model in a vehicle model checker

Considering the span of models we have investigated, which can range from the application of heuristic approaches, to more formal Markov and semi-Markov models, and then to detailed physics models, we have made in-roads toward formulating a comprehensive set of usage patterns.

2.4.5 Implications for Further Research

In terms of design problems that require a probabilistic certificate of correctness, the probabilistic and complete approaches discussed above are of vital importance.

2.5 Examples of Context Model Use in Design Verification

We created over 20 examples to verify the context models and to provide illustrations of how to use each instance of a model in a simulation to validate a typical IFV performance requirement. Appendices G, K, L, M, O, and P provide more detail on each of the examples using non-compliant environments (i.e., environments that do not change during interaction with the vehicle). Appendices J and K provide details on examples that have contexts which are compliant (i.e., environments that do change during interaction with the vehicle). Finally, Appendix Q discusses the examples we formulated and delivered illustrating

how to interface our context models to designs simulated in Open Modelica via the Functional Mockup Interface.

We created executable examples illustrating the use of each context model in each of the 45 classes of environmental context models listed in **Figure 6** (10 Classes of Atmospheric Context Models), **Figure 7** (25 Classes of Land Context Models), and **Figure 8** (13 Classes of Aquatic Context Models) in requirements verification scenarios. Appendix Z, the Context Model Map, contains a mapping of the 45 classes of context models to each instance of a context model in a class, and examples of their use in verification scenarios.

Figure 15, **Figure 16**, and **Figure 17** provide a sampling of the how environmental contexts in the Land, Aquatic, and Atmospheric realms are coupled with designs to validate a design's ability to meet its performance requirements. **Figure 15** depicts a view of the Unity-Based simulation we formulated to facilitate the visualization of terrains generated from Spectral representations of the Army test courses we obtained, and the effect of those courses (i.e., terrains) upon a conceptual design when the design interacts with the terrain as it is driven across that terrain. In this case, the context models we synthesized provide insight into how the design will perform against its requirements to traverse terrains of varying roughness and frictional coefficients.

Figure 16 depicts a view from that same Unity Based engine simulating the interaction between a Conceptual Vehicle design and water, as well as a surf zone. In this case, the context models provide insight as how the design will perform against its requirements to navigate through various sea-states and when traversing surf zones. Note, the vehicle design model pictured in **Figure 16** is the surrogate design that we use in the majority of our examples, which we refer to as a Virtual Automated Test Rig (VATR). It is based on an actual amphibious vehicle available from Hydratek (www.hydratek.com). A detailed description of the model, including a computer aided design rendering in the tool Pro-Engineer can be found in Appendix O under the discussion labeled Amphibious Context Model.

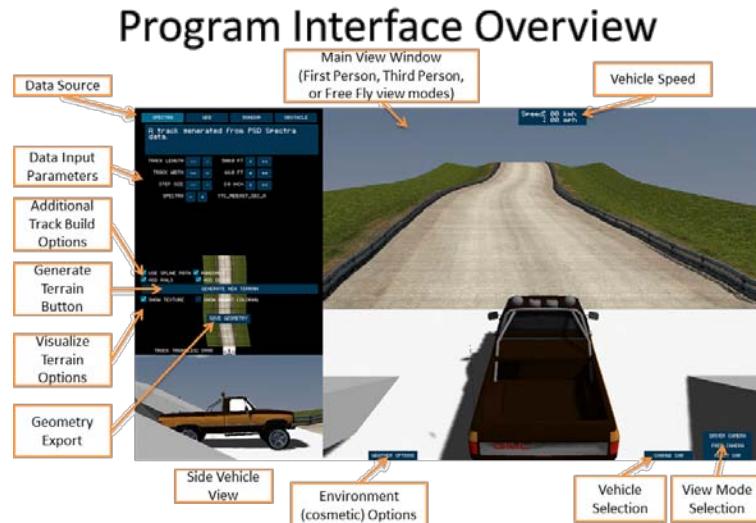


Figure 15: Track Builder: A Unity-based Application for Validating Context and Vehicle Concept Models Performance in Various Land and Sea Contexts. More detail on the application and example can be found in Appendix L

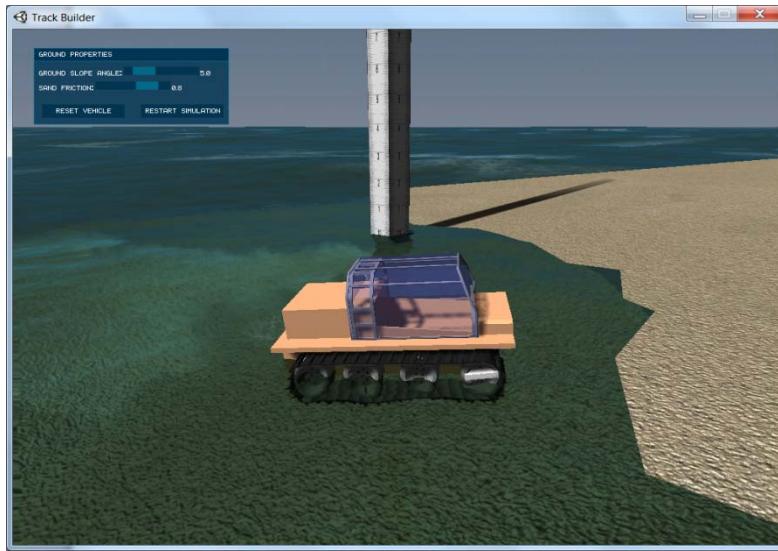


Figure 16: Extension to Track Builder for Validating Vehicle Concept Performance in Surf Zones. More detail on the application and example can be found in Appendix L

Figure 17 illustrates interaction between that atmosphere and a portion of a vehicle design, an air filter on an intake blower to a vehicle's engine. In this case, the simulation is used to determine the effect on vehicle performance when the intake flow decreases due to the build-up of particles on the air filter. Specifically, the simulation can be used to determine how long it will take the vehicle flow rate to drop below the required performance when filtering particles of various sizes.

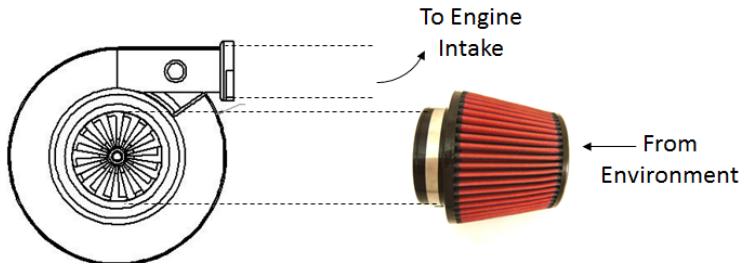


Figure 17: Filter Example to Demonstrate interaction between Atmospheric Contexts and Vehicle Subsystems. More details on the example can be found in Appendix O

2.6 Storing and Accessing Context Models and Examples

As with any library, a Context Model Library requires a certain level of organization and categorization to make it usable and to keep it maintainable. It must also provide a reliable means of delivering models and related artifacts, as well as providing documentation where needed. The executable context models and their documentation, as well as the context models associated with the examples are available via the Subversion system that we used for revision control as we developed the context models and examples of their use. Appendix Z, lists the location of the context models and their examples of use within the SVN (SubVersion Network) repository.

We then engineered and delivered a library delivery system based on a semantic web organization[12] and classified according the Semantic Web for Earth and Environmental Terminology (SWEET) ontology. The system was built as an interactive web server that consisted of two major parts, a model

delivery service called Ontological System for Context Artifacts and Resources (OSCAR) and a flexible interactive knowledgebase called Dynamic Context Server (DCS). As architected, OSCAR and DCS perform as portals for serving context models and knowledge which can meet the needs of vehicle design and test. In addition to the SVN locations of the Context Models and Examples, Appendix Z also lists the means for locating and accessing context models and examples of their use using OSCAR and DCS.

2.6.1 Technical Challenges

The challenges in creating a semantic web server for C2M2L related mainly to the breadth of coverage required in managing models that crossed the land, aquatic, and atmospheric environmental realms. The scope of effort was large enough that the library required various means of searching and selecting models. Part of the challenge was to make it automated so that the user could provide project requirements and the built-in library reasoner could find and present choices of models that the user could select and that would meet the need of an environmental context requirement.

2.6.2 Overview of Development Methodology

The approach taken was to apply state-of-the-art semantic web development processes to build OSCAR and the DCS. For OSCAR, we used a Java-based production model, while for DCS we employed a first-order logic language (Prolog) that was cleanly coupled to a triple-store knowledgebase. The mix of an established architecture (OSCAR) with a next-generation declarative knowledge-based approach (DCS) allowed us to experiment and prototype a wide range of service mechanisms. We applied patterns and archetypes to optimize the amount of reuse in both context models (which often had similarities across physical domains) and in the semantic web building blocks.

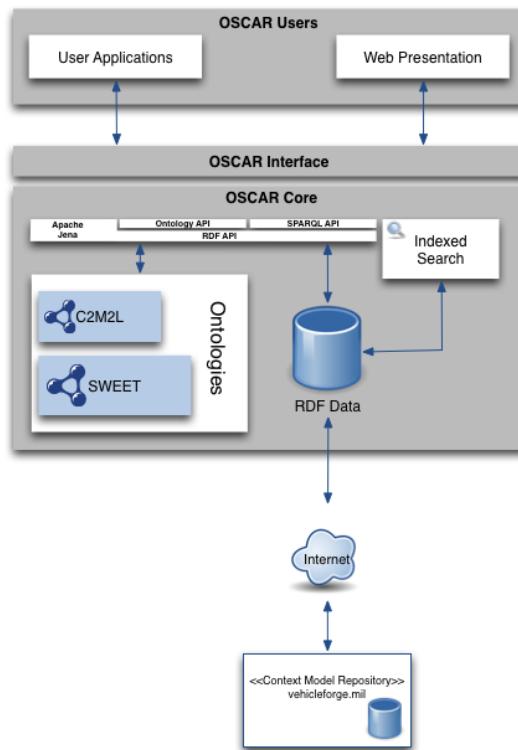


Figure 18: Ontological System for Context Artifacts and Resources (OSCAR) Architectural Overview.
OSCAR is described in Detail in Appendix E

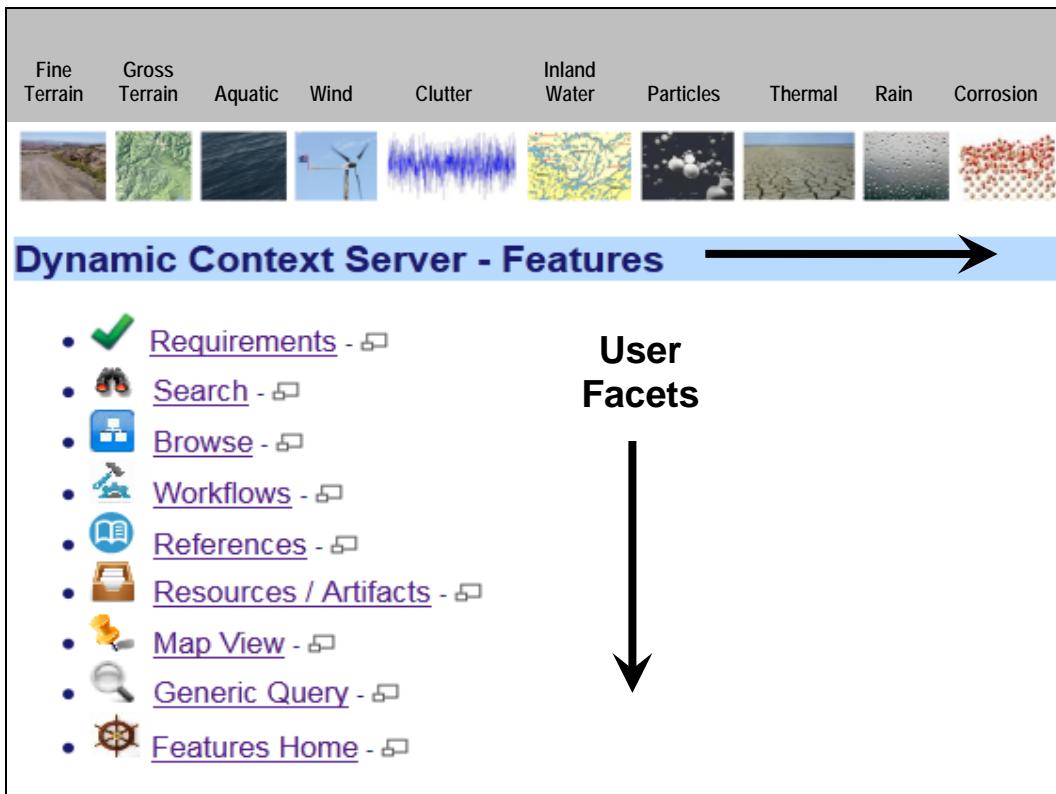


Figure 19: Dynamic Context Server Home Page. The Dynamic Context Server is described in detail in Appendix D

For serving models and artifacts, we organized services into several categories discussed in the following sections.

2.6.2.1 Standalone or embedded models

The model is delivered as executable code that is linked to a vehicle simulation test-bench. After C2M2L-1 TA2 program inception, in the July timeframe, AVM program management selected the Functional Mockup Interface[13] as the preferred interface mechanism, although other approaches include S-functions in Matlab, general compiled C-code, or interpreted embedded Python.

The standalone/embedded models can be potentially generated from a reasoner which uses information on algorithms and data to construct the necessary code. We used OSCAR as a vehicle for this.

2.6.2.2 Served models

The model resides on a web server hosted on a cloud computing environment. Information is served for Monte Carlo simulations run by clients that can interface through a web service. Organization is provided by the DCS semantic web back-end which keeps track of the models available.

Most of the environmental context models have similar patterns, in that they possess salient characteristics that follow standard representations such as probability density functions (PDF), power spectral densities (PSD), and amplitude profiles. Since these are standard formulations, they can be aggregated and distilled through a common pattern and reuse framework.

2.6.2.3 Data file models

Data files are either delivered through a web service or file server, with the semantic web service again providing organization above that a file server will provide. Both DCS and OSCAR supply data files.

2.6.2.4 Model artifacts (graphs, visuals, etc.)

Artifacts for models can include interactive PSD and PDF charts, and generated Monte Carlo profiles. These are useful for the user to understand the ranges, extreme values, and severity of the various models. More elaborate are context model visualizations which can include 3D rendering of terrains and aquatic surfaces. Both DCS and OSCAR supplied artifacts.

2.6.2.5 Model metrics

Similar to artifacts, metrics contain auxiliary meta-information on models such as maturity and potentially complexity, which will be useful for model curation activities.

2.6.3 Technical Results

The context server covered approximately 10 physical domains spread across the land, aquatic, and atmospheric realms. The main feature classifications included fine terrain (for vehicle suspension contexts), gross terrain (for vehicle range), corrosion, thermal, precipitation, aquatic wave, inland water, particulate, EMI, and wind models.

The main usability aspects related to providing search, browsing, requirements, technical resource access (such as standards tables and a comprehensive reference and citation database), and workflow interfaces to the featured domains, with context-sensitive help guiding the process. Most of these usability features took advantage of semantic features such as terminology look-ahead and sophisticated pattern-matching based on similar modeling archetypes.

Examples across the domains were provided for how to use models of sea-state, rough track profiles, obstacle courses, temperature and thermal diffusion, topography, fording, EMI clutter, corrosion, buoyancy, droplet size, and atmospheric properties. The examples included generation of artifacts such as probability density functions (PDFs) and power spectral density (PSD) plots, and use cases where constraints or environmental extremes played a role.

2.6.4 Findings and Conclusions

The delivery of models based on requirements worked well and we were able to create rules that would be robust against churn in how requirements were specified.

The dynamic context server was deployed on an evaluation computing cloud and found to work well, with plans to include it on a Vehicle Forge site for test development.

Appendix D titled “Knowledge-Based Environmental Context Modeling” goes more deeply into architectural decisions made and utility of the overall approach.

Appendix E titled “Ontological System for Context Artifacts and Resources” provides a supplemental view for user manipulation of models (registering, modifying, and downloading).

2.6.5 Implications for Further Research

The performance and scalability afforded by state-of-the-art semantic web development architectures indicates that the OSCAR and DSC servers can evolve -- simply by the addition of knowledge to the triple-store. By adding a more comprehensive set of geospatial location-specific models and models outside the domains evaluated for this project, we can extend the functionality, while the pattern-matching and reasoning afforded by a knowledgebase-aware server does the rest of the heavy lifting.

As with many semantically-based systems, as long as users and curators maintain ties to an ontology, the approach can continue to grow and expand into any realm. For example, by tying in a component ontology (which we prototyped with the XSB component ontology), we can associate available component materials[14] with environmental models of corrosion and thus better integrate the design and verification space.

3. Results

The primary objective of this project was to provide environmental context models for use in vehicle design efforts.

3.1 Technical Challenges

The objective presented dual challenges in delivering context models for practical use, as we needed to (1) provide comprehensive coverage across the land, aquatic, and atmospheric realms within scope for this effort and (2) maintain sufficient accuracy and fidelity such that they are both usable and adequate for vehicle simulation needs.

Concerning accuracy, any empirical, analytical, or computational data that comprises the foundation of a context model will necessarily have some uncertainty associated with it³. This can be either aleatory uncertainty, which exists as part of natural variation, or epistemic uncertainty, associated with our inability to quantify the data precisely. To certify the correctness (to a given confidence level) of a system design within the constraints of the environment requires uncertainty quantification of the context models.

Concerning fidelity, the objective should be to trade-off the level of accuracy in the environmental characterization and its resultant context model, with extra flexibility necessary to adjust the models in light of changing or emerging accuracy requirements. As this extra flexibility leads to more choices, the challenge is to provide automated ways to search, manipulate, and translate context models to aid in the use and maintenance of the model library. Any documentation and pedigree data needs to go with each context model.

As is the case with component models, the context models need to be supplied in a suitable domain-specific or multi-domain modeling language with well-defined, formal semantics and interface specifications. The choice of language needs constructs and operations that are grounded in mathematical terms. This enables us to more easily prove or verify that a modeling behavior holds true, while also making it easier to interface with clients of the models. The ultimate challenge is to prove that model constraints and conditions are met and that intended states are reachable and undesirable states avoidable,

³ unless we deal with the most simple of contexts and phenomena, such as the practical measure of gravitational force, which can be made accurate for terrestrial use

which is a necessary ingredient to formulating criteria with regard to the correctness and completeness of a vehicle design.

3.2 Discussion

The models we developed were based on the initial aim of the project, which was to evaluate an amphibious vehicle’s drive-train and mobility subsystems with respect to their ability to meet specified performance requirements. In addition to a nominal list of domains that were pre-selected based on past needs, specific environmental features were modeled based on vehicle requirements developed during the course of the project. This included discussions with the test-bench teams that were responsible for evaluating vehicle designs.

An ontology-based semantic web-server was selected to provide organization of models at various levels of fidelity.

3.3 Technical Results

The classes of context models we synthesized and delivered are listed in **Figure 6**, **Figure 7**, and **Figure 8**. Details of the technical results are provided in several appendices, which are described as follows:

Appendix	Description
A Stochastic Modeling	Fundamental principles of thermodynamics and statistical physics can be used to create compact parameterized models capable of statistically capturing the patterns exhibited in wide range of environmental contexts. Such models allow more efficient and systematic assessment of the strengths and weaknesses of candidate designs than is possible using benchmark datasets or test tracks, and this can play an important role in utilizing computer simulation to produce better designs of complex cyber-physical systems more quickly, affordably, and reliably.
B Terrain Spectroscopy	For terrains the underlying behavior is rarely controlled by a completely ordered process, and any model characteristics will carry along with it a level of aleatory uncertainty governed by the natural disorder. This appendix applies novel uncertainty characterization approaches to classes of topographic models to demonstrate how to quantify the natural order and distinguish from artificial (man-made) order.
C Uncertainty Quantification in Growth Models	Environmental models by their nature contain a great deal of uncertainty. Since the underlying behavior of the model is rarely controlled by an ordered process, all model characteristics will carry along with it a level of aleatory uncertainty governed by the natural disorder. This appendix applies novel uncertainty quantification approaches to classes of diffusion problems such as corrosion which illustrate the benefit of assuming natural variability.
D Dynamic Context Server	This appendix describes a semantic web architecture based on patterns and logical archetypal building-blocks well suited for comprehensive environmental modeling framework. The patterns span a range of features that cover specific land, atmospheric and aquatic domains intended for amphibious vehicles. The modeling engine contained within the server relied on knowledge-based inferencing capable of supporting formal terminology (through the SWEET ontology and a domain specific

		language) and levels of abstraction via integrated reasoning modules.
E	OSCAR	OSCAR (Ontological System for Context Artifacts and Resources) is a knowledgebase library system for context models. We implemented an archival system that is driven by the backend ontology designed for environmental context along with concepts for common archival transactions.
F	Formal Methods and Model Checking	Describes work on probabilistic context models and associated probabilistic analysis methods. This covers (1) developing a probabilistic ground vehicle drive train model to interact with terrain context models, (2) creation of probabilistic terrain context models suitable for model verification, (3) developing analysis tools for assume/guarantee-style contracts in probabilistic models.
G	EMI Modeling	This appendix presents a set of modeling methods and general context models for predicting susceptibility of electronic equipment to MIL-STD-461F environments with respect to reception of interference via the cable/connector assemblies. This covers three areas – system electromagnetic environment flow-down to equipment and cable/connector assemblies, modeling method for cable/connector assemblies, and a detailed example.
H	Novel Synthesis of Shock & Vibration Profiles with Potential for Terrain Profiling	An approach is presented to synthesize a base shock-and-vibration acceleration time-history that is compatible with a prescribed power spectral density (PSD). The synthesized acceleration is developed using the summation of sinusoids with frequencies that cover the frequency range of the PSD. The peak amplitude of the envelope is sized to match the total power of the prescribed PSD to that of the PSD that results from the synthesized base acceleration. Examples are presented to illustrate the process for shock-and-vibration data and extended for potential use in terrain roughness analysis.
I	C++ Library	A C++ class library of nominal and extreme climate-based environmental models drawn from the AR 70-38 and ASHRAE specifications.
J	Compliant Modeling	Quantitative understanding of wheeled mobility on granular terrain such as sand or gravel is critical for design and effective operations of ground vehicles. This presents findings of massively parallel discrete element modeling of wheeled mobility on granular media such as sand, resulting from parametric studies with varying levels of both wheel penetration and mobility conditions. The important details of the problem are retained by simulating granules of the size encountered in real terrain to overcome the fidelity limited issues of other comparable methods that use much larger granules.
K	Tracked Wheels on Soft Soil Simulation	Multiple analysis strategies were applied to the problem of simulating a tracked wheel on soft soils, with the ultimate goal of generating results that could be compiled into a context model. The strategies included Finite Element Analysis, FEA using eroding solid elements, SPH (Smoothed Particle Hydrodynamics) technology, and SPH technology utilizing adaptive solid elements.
L	Surf to Shore	The mixed surf and shore environment, due to its chaotic nature, is perhaps the most difficult context to model. The vehicle is simulated using

	physics provided by the Unity 3D visualization rendering engine. Physical properties are assigned to the geometry in the scene. Properties include static and dynamic frictions. Forces and torques are applied to a rigid body, which cause the vehicle to move. Buoyancy forces act while the body of the vehicle is in water. Friction properties react between the wheels and linkages making the track, as well as the track with the ground when it is in contact.
M Test Case Amphibious Vehicle Model	A vehicle model to serve as a platform for evaluating terrain models was provided.
N Ecto-VATR	The Early Concepting Tool – Virtual Automated Test Rig (ECTO-VATR) is a system design tool that enables editing of a model of vehicle design primarily through the hierarchical assembly and manipulation of components from the Component Model Library (CML). It is focused on empowering a designer operating in an early design phase to be able to incorporate and manipulate major design drivers and rapidly assess the quality of system concepts. Resultant concepts can be used as the basis for more detailed design. It illustrates a working concept and our vision of how context models should be integrated into the design verification process in system development.
O Examples of Context Model use with Vehicles	This section describes context models used with stand-alone executable vehicle simulations. The simulations were developed in Matlab or C++, either directly linked to context models, or run-time linked via FMU interfaces.
P Amphibious buoyancy, range, and stability	Several different attributes make up the amphibious context model but the main results are reserve buoyancy, range and stability. An excel spreadsheet was put together to contain all of these results based on inputs of a vehicle's basic dimensions and weight information. An example vehicle was chosen in order to prove out the calculations; this example was created using Pro/engineer and basic information from a public domain website, Hydratrek (www.hydratrek.com).
Q FMU usage	Examples of context models within Functional Mockup Units

In summary, appendices A, B, C, H, I, J, K describe the novel approaches that we have devised to create and verify models (steps **2****3****4** in **Figure 20** below). Appendices D and E describe the approach to organizing and maintaining models using an ontology (step **5**). Appendices F, G, L, M, N, O, P, and Q describe the application of the models to META design challenges (step **6**). The entire process is initiated in step **1** as requirements knowledge from the customer and design community flows into a completed project.

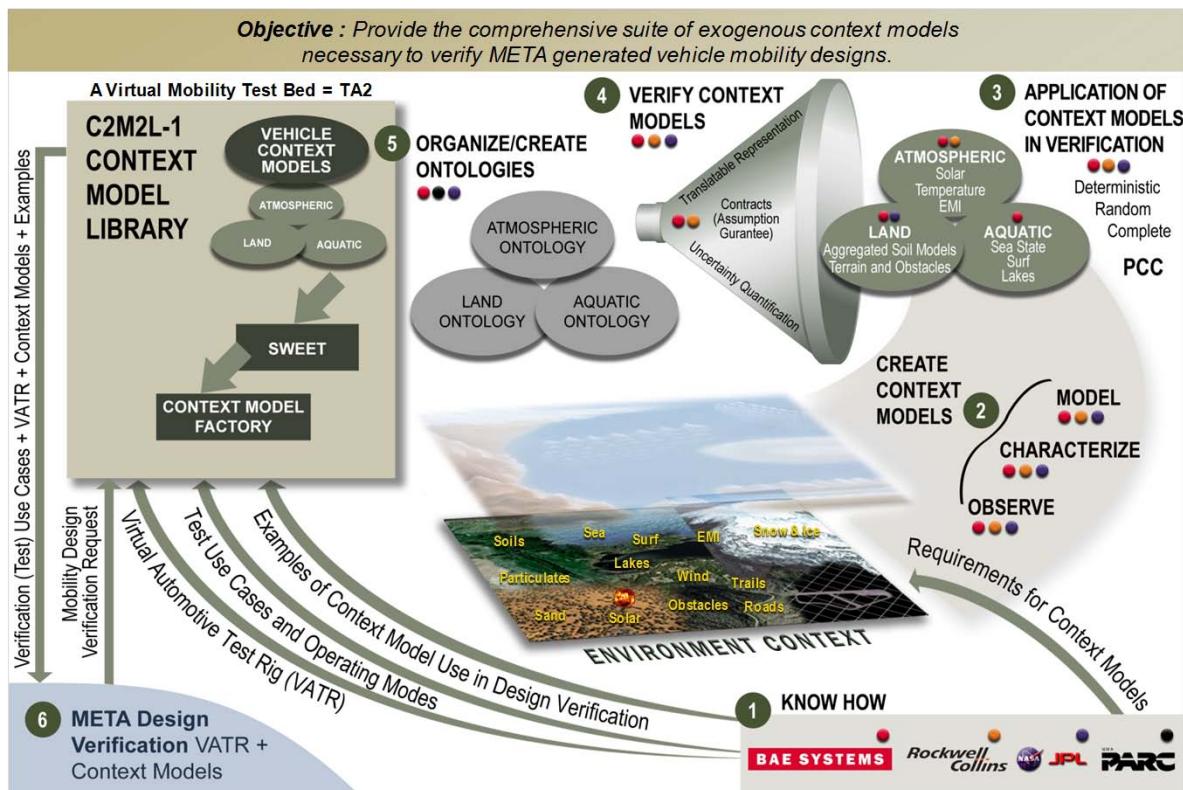


Figure 20: Overview of the Context Modeling Effort in relation to the Appendices

The delivery of models was organized along two paths. The Ontology path consisted of all semantic elements used to deliver the dynamic context server and OSCAR. The Model path consisted of all stand-alone or library elements used in traditional simulation integration. An adjunct to the latter was a demonstration of a simulated vehicle test-bed developed to show the suitability of the context models.

4. Conclusion

Our notable developments over the course of this project were in the areas of model development, developing the examples of context model use, and developing the ontologically-based web services to facilitate access to the context models and examples of their use.

Our important developments in the area of model development include:

1. Devising a spectral decomposition algorithm to model semi-Markov terrain features
2. Devising a terrain elevation correlation approach and applying it to the modeling of geospatial regions
3. Devising a pattern-based stochastic approach to model sample spaces
4. Using the principle of Maximum Entropy to synthesize model distributions with very concise formulations. These concise formulations can be easily inverted to provide sampling for Monte-Carlo simulations
5. Applying a depth-corrected wave height model to synthesize models of various bodies of water
6. Devising and diffusion model of oxidation and corrosion applying uncertainty quantification
7. Devising a novel heuristic method for Synthesis of a PSD Compatible Acceleration Time-History.

Our important developments in the area of formulating examples of context model use in design verification include:

1. Synthesis of over 20 examples, which demonstrate the use of each context model in vehicle simulations for the purposes of both verifying model correctness and for illustrating how the models can be used to verify the ability of a vehicle design to meet its performance requirements. Thus, each of the context models belonging to each of the 45 classes of context models listed in **Figure 6**, **Figure 7**, and **Figure 8** has been used in an example.
2. Formulation of standard approaches to interfacing context model units with external simulations via a number of development and interface platforms (The Functional Mockup Interface, MATLAB, C/C++, XML, and Java)
3. The synthesis of the Ecto-VATR, a concept synthesis tool that utilizes test benches that incorporate a subset of the context models we developed. The Ecto-VATR is a prototype of our vision for integrating context models into model-based development and verification processes.
4. Reuse of the context models on DOD development and research projects. In particular, we used context models obtained from the TOPS to perform ride quality and gun stabilization analysis for the U.S Army's Ground Combat Vehicle Program; We used the thermal network solver we devised as an example for the U.S Navy's Long Range Land Attack Projectile (LRLAP) Pallet analysis of the 40 degree functional test and slow cook off, and the prototype compositional verification tools developed by Rockwell Collins are the basis for Rockwell Collin's work on the DARPA's High-Assurance Cyber Military Systems program.

Our important developments in our efforts developing the ontologically-based web services to facilitate access to the context models and examples of their use include:

1. Organizing the models semantically using the SWEET ontology
2. Design and implementation of a semantic web server to facilitate model search and interaction
3. Design and implementation of a logic-based domain specific language for formal specification and model generation.
4. Design and implementation of a scheme for Phrase-based matching of requirements to context models

Finally, we completed and documented a thorough study to aid in Predicting Susceptibility via Cable/Connector Assemblies in a MIL-STD-461F Environment

4.1 Avenues for Further Research

The semantic organization will scale for other contexts. Among the missing contexts which were deemed out of scope for this effort include that of the human context and reliability contexts. For the human context, such factors as response times and unpredictable behaviors have a significant effect on vehicle design and performance objects. Although we only scratched the surface with models of corrosion, the impacts of demanding environments would fit in well as models of reliability, maintainability, and availability.

5. References

- [1] E. T. Jaynes and G. L. Bretthorst, *Probability theory: the logic of science*. Cambridge Univ Pr, 2003.
- [2] C. Becker and P. S. Els, “GEROTEK data from CSIR for C2M2L program.” .
- [3] D. Mumford and A. Desolneux, *Pattern Theory: The Stochastic Analysis Of Real-World Signals*. A K Peters, Ltd., 2010.
- [4] J. E. Alexander, “Synthesis of a PSD Compatible Acceleration Time-History,” *Submitted to Shock & Vibration Symposium (November 5-9, 2012)*.
- [5] P. R. Pukite, S. Bankes, and D. Challou, “stochastic_analysis.docx.”
- [6] P. R. Pukite, S. Bankes, and D. Challou, “terrain_characterization.docx.”
- [7] P. R. Pukite, S. Bankes, and D. Challou, “diffusive_growth.docx.”
- [8] D. Mumford, “The dawning of the age of stochasticity,” *Mathematics: Frontiers and Perspectives*, pp. 197–218, 2000.
- [9] Automotive Directorate, “Test Operations Procedure (TOP) 1-1-010 Vehicle Test Course Severity (Surface Roughness),” ATEC, Aberdeen Proving Ground, MD, Final TOP 1-1-010, 2006.
- [10] Army, “Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions,” APD, Headquarters, Dept of the Army, Army Regulation 70-38, Sep. 1979.
- [11] A. Steinwoff and W. H. Connon III, “Limitations of the Fourier transform for describing test course profiles,” *Sound and Vibration*, vol. 39, no. 2, pp. 12–17, 2005.
- [12] S. Bankes, D. Challou, T. Haynes, H. Holloway, P. Pukite, J. Tierno, and C. Wentland, “META Adaptive, Reflective, Robust Workflow (ARRoW),” BAE Systems, Final Report TR-2742, 2011.
- [13] Wikipedia, “Functional Mock-up Interface - Wikipedia, the free encyclopedia.” [Online]. Available: http://en.wikipedia.org/wiki/Functional_Mock-up_Interface. [Accessed: 11-Feb-2013].
- [14] D. S. Warren, T. L. Swift, T. Vidrevich, I. Ramakrishnan, L. R. Pokorny, A. Beggs, C. Rued, M. Epstein, H. Singh, and H. Davulcu, “Methods for determining the similarity of content and structuring unstructured content from heterogeneous sources.” Google Patents, 02-Jun-2009.