04S-SIW-070

Semantic Descriptors of Models and Simulations

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Keywords:
Semantics, Composable Simulations, Interoperability, Abstraction, Validation, Requirements Definition

ABSTRACT*: Accurately describing simulation characteristics is essential for their interoperability and composability. The internal processes and results produced must be rigorously characterized and valid in the context of their application. Only if this is possible in an effective and economic manner can simulations be extensively reused, through either composability or tailoring. To describe simulations accurately and with confidence, and to ensure that the simulation is valid in the context of the application, an understanding of the model semantics and semantic interdependencies is required. This paper describes an initial effort to develop a set of systematic descriptors that capture the characteristics and interdependencies of a simulation. We describe a framework for the identification and organization of semantic descriptors and provide some examples. We discuss a process for identifying associated metrics and present an experimental design for developing their scales. The paper concludes by presenting some experimental results and by discussing directions for continuing and building upon this work.*

1. Introduction

Description of models and simulations exist at two basic levels; functional and syntactic. The functional description provides a general understanding of the purpose of the model such as radar performance or entity level battlespace representation. The syntactic description provides an understanding of the inputs and outputs of the model or simulation. It is the syntactic level that is currently most often used to address issues of interoperability. If the two models can exchange data in a prescribed format, they are considered interoperable.

These simulation descriptions are, however, insufficient in some very key areas. They offer little or no insight into the constraints and assumptions implicit in the models. It is therefore difficult, if not impossible to determine if the results from a model would be valid in a specific context. It is also difficult to determine if simulations that are federated will produce coherent or consistent results. Lack of such semantic interoperability can lead to outcomes that are invalid or inaccurate, perhaps in subtle ways that are not immediately obvious.

The establishment of well structured semantic descriptors, therefore, could play a significant role in several areas of the design and use of simulations. The information they provide would be essential to the realization of composable simulations. This information could also be used to assess the validity of a simulation federation and define the context under which that validity would hold. That is, they could help define the limits of the utility of a federation.

The association of semantic descriptors with context validity also suggests a role for them in requirements definition. A framework for the organization of descriptors that address the capabilities of models could also provide an efficient means to identify and organize simulation requirements statements. If the same language was used for both simulation requirements and a description of model capability, the groundwork would be in place for development of automated user-defined composable simulations.

2. Goal and objectives

The goal of this research is to provide a foundation for developing semantic descriptions of models and simulations. To provide this foundation, this research has the following specific objectives:

1. Recommend an infrastructure for the organization and definition of semantic descriptors,
2. Develop an initial set of semantic descriptors for models and simulations,
3. Propose an approach for the assignment of metrics to be associated with each semantic descriptor,
4. Identify procedures for evaluating the validity and applicability of candidate descriptors.

3. Semantic descriptor definition and framework

3.1 Working definition

As a starting point, a working definition of a semantic descriptor is needed. In this definition, it is important that both the functionality and limitations of semantic descriptors are articulated. That is, a definition of what a semantic descriptor is and is not needed to be developed. Fundamentally, the semantic descriptors should capture the assumptions and abstractions relevant to the model. They ought to convey a sense of quality and associated operational range. Some descriptors will reflect the direction, dependency, and dimension of information flow. These will likely explicitly address inputs, outputs, and connectivity. As a result, some semantic descriptors will need to incorporate syntactic data. For example, if a descriptor addresses accuracy, it will need to include units, such as ±0.1 dB re μPa.

In the context of model interoperability and composable simulations, an analogy to the direction, dependency, and dimension of information flow is represented by the semantic descriptors aids in visualization. Consider “Lego-type” blocks in which the pegs and holes are neither of uniform size nor in uniform locations. The pegs and holes are analogous to the direction, dependency, and dimension of information flow between models. If the size and location of the pegs on one block match the size and location of the holes of another block, the blocks can be joined. There are also conditions under which a precise match of peg and hole size and location are not necessary for the blocks to be joined. Blocks may be flush if the peg is smaller than the hole, or no peg is present. This results in the blocks not being held together as tightly as when holes and pegs precisely match, but this may be good enough for the structure being built. This analogous to two models not being a perfect fit for each other, but their interoperability is sufficient for the specific purpose at hand.

Misalignment of pegs and holes is analogous to a mismatch of syntax between the models. One model requires one an input of X, but the other model has an output of Y. There can be cases where the syntax agrees, however, and yet the models do not interoperate properly. This would be represented in the Lego analogy as the peg being too big for the hole. Figure 1 represents the when models can work together or not work together using this Lego analogy.

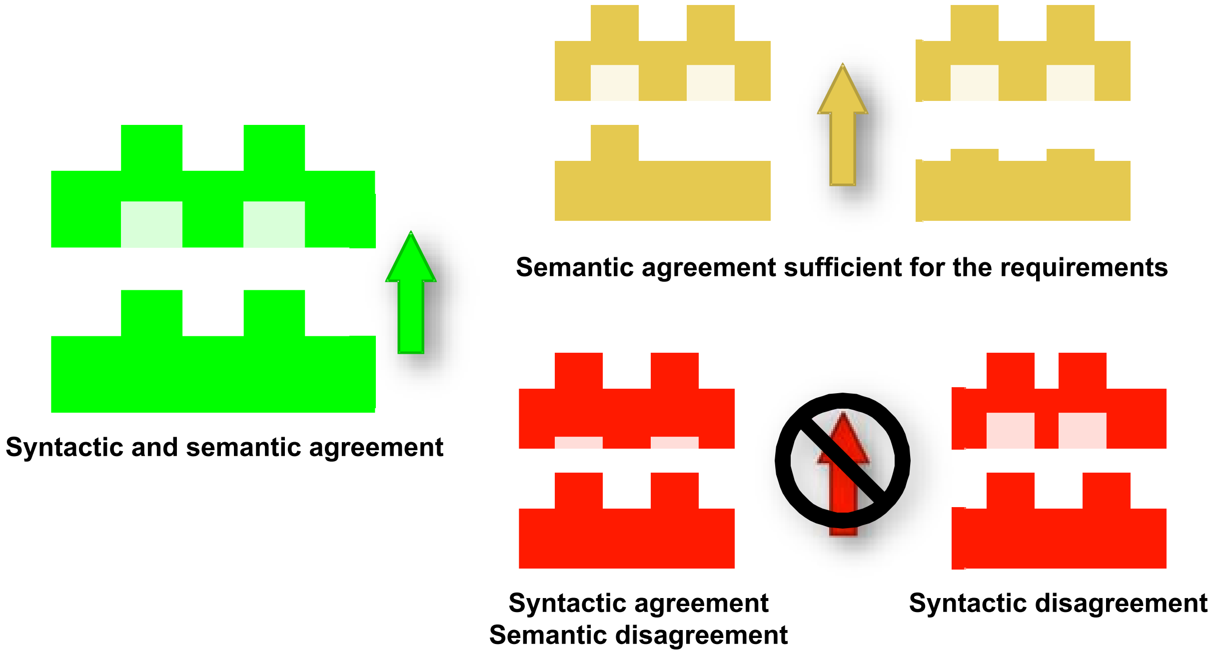

Figure 1. Lego representation of descriptors

The concept that models may not be semantically equal, but sufficiently close to jointly satisfy some specific application again highlights the tie between the semantic descriptors and requirements. A semantic descriptor will have a specific metric value of a for a specific model implementation. Simulation requirements can then be stated in terms of the metric values needed to provide types and level of results required. Requirements statements such as "I need a simulation with a minimum value of X for descriptor A and Y for descriptor B" can be formed to assist in the automated composition of simulations to meet the current need.

Semantic descriptors are not completely descriptive of simulations, however. Some information critical to determining model interoperability is not currently included as part of a semantic descriptor. Examples of such information would be a model's security classification and its execution speed relative to wall clock time. Such aspects do not generally address the assumptions and abstractions made in model development but rather deal with implementation decisions. As the definition of semantic descriptors matures, it may be expanded to include such additional factors.

3.2 Organizational framework

To avoid being based on any specific instantiation, semantic descriptors should be based on conceptual models. There are many options as to the type of conceptual models to be used as the basis for the semantic descriptors. One is to use entity types as a basis. Another is to use a model of functionality.

Basing semantic descriptors on entities has some drawbacks. This results in conceptual models that are not based on interactions and often have more of a database appearance. The need for many conceptual models is highly probable. Exacerbating this is the need for many redundant descriptors across the collection of conceptual models since many entities can have the same or similar functional roles and behaviors.

A logical next step is then to investigate a framework for semantic descriptors that is based on functional areas. The premise is that relatively few general functions can be used to completely describe any simulation scenario. This allows for the use of a small number of types of conceptual models and eases the configuration management of the semantic descriptor system. Additionally, basic functions apply to all levels of resolution that may be modeled so different domains are not required to address components of objects, objects, and collections of objects.

Drawing on some of the principles of the Object Management Group's Model Driven Architecture approach to software design, these functional areas should be highly cohesive and loosely coupled. By highly coherent is meant that all functions within a domain are closely and naturally related. Such relationships could be, for example, different instantiations of the same function or actions that combine in a sequential or cyclic manner to result in a given function. The cohesion within a domain lends itself to easy analysis by a subject matter expert. It also allows the domains to be defined tightly enough so that there is little doubt as to what functions belong in each domain. By loosely coupled is meant that the interdependencies between domains should be minimal and the interfaces can be well defined in precise contracts.

Based on this, the requirements for the functional areas can be established. The functional areas need to encompass the fundamental actions that comprise the (military) operations to be simulated. Each functional area needs to be broad enough to accommodate many forms of the generic actions. This is desired so the number of functional areas can be kept manageably small. At the same time, a functional area must be specific enough to be clearly distinguished from other functional areas.

This still leaves the tasks of identifying the functional areas to be used as a basis for semantic descriptors. To those familiar with military operations, a breakdown of functionality that may at first seem natural to modeling military operations is that of warfare areas. Upon closer examination, however, it is soon discovered that this choice, like that of entity-based conceptual models above, would result in the need for excessively redundant descriptors throughout the functional areas. That is, the functions within a specific warfare area are composed of functions that are not unique to that warfare area. Because of this, a more fundamental list of functional areas upon which to base the framework for semantic descriptors is proposed. This initial set of functional areas is comprised of move, sense, engage, navigate, command and control (C2), communicate, exist, and environment.

Since models address the world at various levels of abstraction, the framework for semantic descriptors must also address these levels. This suggests a hierarchical structure to the functional area based framework. A notional three level hierarchy for each functional domain is also proposed. The functions at each level are identified as components of conceptual models of the appropriate resolution. The three proposed levels of the hierarchy within each domain are the aggregate, platform, and component levels. These three levels have been extensively used within the simulation community for a number of years. They are often called, for example, theater, entity, and engineering. This current research effort does not attempt to propose a formal definition of these levels but instead will rely on the reader's intuition as to what these levels mean and offer only these casual observations.

- Typically, discussions of aggregate level simulations involve theater or strategic operations.
- The term platform level is applied to simulations that represent individual combat entities such as aircraft and armored vehicles, but can be large and complex as an aircraft carrier or a small as an individual combatant.
- Component level simulations typically represent individual combat systems or mechanisms of combat systems or entities.

These hierarchical levels are used here in much the same way as the simulation community has for years, but with one critical difference. Instead of using them for the classification of simulations, they are used to stratify functional domains.

Within these functional areas, there is a natural flow down from one level of the hierarchy to the next. There is also, in general, a natural expansion to the number of functions as resolution increases. This arises for two reasons. The first is the natural consequence of additional detail. The second is that there may be multiple different breakdowns of detail needed to account for the ways different objects perform the same function. Consider, as an example, the entity level function of "move (at a given velocity)." If the platform is a submarine, the functional decomposition could include functions such as generate steam and rotate shaft, while for an aircraft they could include ignite jet fuel and rotate turbine. In general, the functional decompositions should be kept as generic and widely applicable as possible. Therefore, it could be argued that a preferable decomposition to "move" might be something like convert energy form and generate thrust. Still, it is probable that at some level the fundamental differences between the functions of an aircraft and its parts and a submarine and its parts must be represented.

The definition of the domains and example functions at each level of resolution are provided in Table 1. It is recognized that additional functional areas will likely be required such as political or socio-economic environment. This preliminary set is sufficient, however, for the initial presentation and discussion of the semantic descriptor framework needed for community vetting. Within the hierarchical based framework, the semantic descriptors associated with any given functional domain provide an understanding of the level of resolution at which the model operates.

Domain	***Definition***	***Aggregate***	***Platform***	***Component***
Move	Relocation of objects through the battlespace	Battle force center of mass	Entity velocity and acceleration vectors Fuel state Rate of turn	Lubricate Combust Rotate Jet engines Ship engineering plant configuration
Sense	Passive and active means of detection, localization, tracking, and identifying other objects in the virtual battlespace	Receive and interpret intelligence reports Coverage of organic sensors	Performance of organic sensors Sensor beam patterns	Pulse repetition rate Transmit power Element level signal Detailed signal-to-noise ratio
Engage	Any active or passive means of interaction with other objects	Force on force	Detect, generate fire control solution, fire weapon; Range gate pull-off; Missile vs. aircraft; Tank round vs. BRDM	Seeker head movement; location of expanding rod fragments vs. aircraft component location
Navigate	The means of identifying location in the battlespace and determining the movement required to carry out the assigned mission	Respond to commands to move or deploy	Determine position GPS posit Come to course and speed	Left 10 degrees rudder; thrust vs. airspeed
C2	Behaviors and logic for determining and directing courses of action	OPORDER	Attack by fire; assume plane guard station	Servo motor commands
Communicate	Passing data, information, or perception	Shared COP	OTH Gold	Data bits Link-16
Exist	Aspects of physical objects that arise because of physical existence and not contained in other functional areas	The center of mass of a battle group	Mass Volume Composition	Coefficient of friction, tensile strength
Environment	Representations of the natural environment	Air mass Ocean areas	SVP by region	Complex fluid flow on molecular level

Table 1. Proposed functional domains and hierarchy for semantic descriptors

For any scheme used as the foundation of describing qualities of models, there will be areas of uncertainty in its implementation, and the above scheme of functional domains is no exception. While one of the major objectives in the development of the above scheme was to ensure non-ambiguous assignment of functions to domains, there are still implementation decisions to be made. The following discussion provides examples of two such cases.

Consider the issue of energy signatures. Such signatures arise from activities such as the radiation of a radar to sense, the noise of a torpedo launch, or the thermal trail left by the engines moving a jet aircraft. The signature is an unavoidable consequence of the functions and so descriptions of the models of signatures could logically be placed in the respective functional areas. It could also be argued, however, that signatures are a consequence of an objects existence in a certain state (the state of radiating a radar or flying through the air, for example), and therefore all signature representations ought to be contained under the “exist” function. This would have the potential advantage of placing all semantic descriptors associated with signatures or operational state in one functional domain. A potential disadvantage is that this may force tight coupling between semantic descriptors in different functional domains. For example, the semantic descriptor associated with the resolution of a radar’s radiation pattern (and thus detection performance) would be closely related to the semantic descriptor of its signature description. It is currently unclear if either option provides a clear operational benefit.

As another implementation issue, consider the logic associated with many functions. As a minimum, functions in the domains of sense, engage, navigate, command and control, and communicate require logic to determine such things as target classification, when to engage, course and speed required to reach a specific point at a specific time, when to send a message, and what information the message should contain. Analogous to the above discussion, such logic could be embedded in the appropriate functional domain, or could all reside in a single domain; command and control in this instance. The argument for putting all the logic in one domain is that such logic falls under the actions of command and control and, therefore, should be concentrated in that domain. The benefit of this is the avoidance of some redundant or nearly redundant descriptor constructs in multiple domains. The disadvantage is again forcing a tight coupling between domains that might otherwise not be necessary. Further study is required to determine if one implementation has benefits over the other.

4. Metrics

Semantic descriptors must not only convey what attributes a model has, but must also provide a sense as to the degree to which it possesses each of those attributes. This highlights the need for measurement or metric associated with each semantic descriptor. Like the descriptors themselves, the scale for the metrics needs to be model and implementation independent.

In the formulation of metrics, all relevant scales and value types are being considered. This includes nominal, ordinal, interval, and ratio. Each of these types is appropriate for different semantic descriptors and for some descriptors, multiple types might be appropriate. When multiple types are applicable, they can be assigned in an hierarchical manner. The presence of the representation of an attribute (nominal) could be checked first. If the attribute is represented, its quality on an ordinal scale and interval scale could be checked for suitability for the intended application.

As an example of a multi-metric semantic descriptor, consider a descriptor that addresses the number of organizational levels represented in command and control (C2) simulations. This descriptor is to be evaluated relative to two simulation; one that addresses the interactions between an Air Intercept Controller (AIC) and an aircraft, and another that considers the interactions between the Battle Group, the carrier's air boss, the AIC, the aircraft, and the Radar Intercept Officer (RIO). For both simulations, the initial nominal evaluation of the descriptor would be "yes." That is, each simulation addresses multiple organizational levels. Evaluation of the ordinal value would then be required. For the first simulation, this might have a value set like (max 2, min 1). For the second, it might be (max 4, min 1), representing the maximum and minimum number of levels represented. Continuing with the assignment of metrics, the assignment of interval metric data might yield values like 2/1 & 1, and 4/1 & 3 respectively for these simulations, representing the ratio of the maximum to the minimum values and the value most often found. For a simulation which for which the nominal value was "no," no assessment of ordinal or interval data types would be required or appropriate.

Many aspects of a model's representation are naturally ratio data. Physical attributes are the most obvious example of this. Representation of weight to within 0.001% accuracy, or bearing resolution to within 0.1 degrees would be examples of this.

An open question being addressed through experimentation is if appropriate parametric ranges can be associated with such scales. Such a notional relationship is shown in Figure 2. The questions to be addressed are not only what the boundaries of the ranges are, but what is the significance or applicability of the ranges. It could be, for example, the models that both fall within the same range could be expected to provide satisfactory interoperability for specified applications, but models in different ranges should not be expected to provide suitable interoperability for those applications.

Bearing Resolution	***Parametric Range***
360 ↓ 90	0
↓ 15 ↓	1
5 ↓	2
0.1	3

Figure 2. Notional parametric ranges

Like the association of two different scale types to represent one semantic descriptor, there will be cases where there will be relationships between different semantic descriptors. In these cases it will be necessary to account for interdependence, correlation, or even dominance amongst or between descriptors. Such relationships foreshadow the utility of multi-variant semantic descriptor values. Although it is beyond this initial effort to characterize and quantify these values, the structure being developed allows for their addition.

5. Experiments

5.1 Purpose and design of the experiments

A key component of this research is experimentation. The data from the experiments will support two critical analyses relative to the semantic descriptors. First, the experiments will be used to test the relevance of candidate descriptors. Secondly, the experiments will provide data to support the determination of the applicability and validity of metrics associated with each descriptor. Part of this second analysis will be, as discussed above, investigation into the feasibility of assigning parametric ranges to interval or ratio valued descriptors.

To support this initial experimentation on semantic descriptors, we constructed two simple model sets. The use of new models provided two distinct advantages over the use of existing models. First, the new models were constructed to allow for the easy and highly controllable modification of most of their aspects. This control is much more than simply controlling input parameters associated with a model. These models were constructed such that aspects of fidelity and accuracy were easily controllable. The second advantage of using new models is that we had total insight into their construction and associated assumptions. When an aspect of the model associated with a semantic descriptor was modified, this insight provided an understanding of exactly what was changing about the model and provided confidence that unknown secondary effects were not affecting the experiment.

Testing the relevance of candidate descriptors is essentially a sensitivity analysis. The model aspect associated with a candidate descriptor is varied. The results of repeated experiments are then analyzed to see if that variation affected the interoperability of that model with the other models in the set. As an example of how this might be done, consider a descriptor associated with accuracy of a propagation-loss calculation. The model could be constructed to add a known amount of white noise. In this manner, its accuracy and the value of the associated semantic descriptor could be altered in the controllable manner needed for repeatable experimentation. An aspect of the model associated with one candidate semantic descriptor is varied at a time. If varying the model aspect, and thus the value of the model's candidate descriptor, affect the model's interoperability with other models, the candidate descriptor is a relevant one.

Assessment of applicability and validity of the metrics associated with a descriptor requires the careful association of values with representation types and levels. Once a representation structure is developed, investigation into assignment of values or parametric ranges of interval or ratio data is done empirically. The aspect of interest is systematically varied. Break points in the degree or manner of interoperability with the other models of the set are then sought. The boundaries between ranges occur at these break points.

Two different model sets were developed to support the testing of semantic descriptors. One set addresses physics-based models and the other addresses command, control, and communications (C3) models. The physics-based models are for an anti-submarine warfare (ASW) scenario. It employs two submarines (red and blue) that attempt to detect and engage each other. One submarine is executing a search pattern while the other is executing a transit through the area. The basic approach to testing interoperability is to assess deviation from an established baseline. A number of runs are made with all aspects of both submarine models identical with the exception of tasking as patrolling or transiting. This establishes the definition of "a level playing field" for the scenario. Aspects of the models on the blue side of the encounter are then systematically varied and the effect on the level playing field recorded. The modification process is repeated with the models of the blue submarine held constant and the models of the red submarine varied to test the reciprocity of the effects.

Initial implementation of the ASW models was completed in the Sensible Agent Testbed [1][2]. The Sensible Agent Testbed offers a highly composable, distributable simulation environment. Modeling functionality is encapsulated in components called Effects Modelers that interact through a message broker. Four different Effects Modelers were used to model the ASW domain: (1) a model of acoustic signal propagation from acoustic emitters to acoustic sensors, (2) a kinematic model of submarines and torpedoes, and (3&4) models of the commanders of both submarines. All of the Effects Modelers are highly configurable, enabling a wide range of experiments. The Sensible Agent Testbed also employs a simple yet powerful mechanism for specifying which data to collect during an experiment using topical tags and/or component names.

The scenario of the C3 model set emphasizes features differently than the physics-based ASW scenario and thus provides a degree of robustness to the testing of the semantic descriptors. The emphasis of the C3 scenario is on decision making, the relevant results, and communications. The scenario contains the fundamental features of any C3 simulation. It consists of a fighter aircraft, in contact with a ground controller, which is vectored toward a tanker. The aircraft obtains the tanker, control is passed from the ground controller to the tanker, and the final approach is executed. This scenario provides a second means of testing the relevance of semantic descriptors. Instead of measuring the effect on a level playing field in force on force encounters, for this scenario a baseline is defined and statistical parameters collected. The representation of the pilot and controller are at comparable levels for this baseline. Excursions are then conducted to examine the impact of implemented changes.

5.2 Limitations on initial experiments

Both of the experimentation scenarios have stochastic elements to them. Therefore, to establish the baseline for the C3 scenario and the definition of a level playing field for the ASW scenario requires a statistically significant number of simulation runs. Similarly, each instance of a variation will require an equal number of runs. For the ASW scenario, seven aspects of the models have been identified for change for the submarines. Most of these could also be applicable to the torpedoes. For the C3 scenario, five aspects have been identified. These aspects are listed in Table 2 along with a nominal minimum number of variations for each aspect.

	Model aspect	*Nominal minimum variations*
ASW Scenario		
	Update rate	5
	Bounded volume resolution	3
	Damage assessment detail	3
	Radiated noise resolution	5
	Movement dynamics	3
	Navigation	3
	Array gain resolution	5
C3 Scenario		
	Degrees of freedom	3
	Decision representation	3
	Elapse time	3
	Organizational stratification	2
	Systems impacted	2

Table 2. Model aspects associated with candidate descriptors for experimental scenarios

For exhaustive testing of all possible combinations or variations, the total number of simulation runs grows geometrically with the number of aspects to be changed. Even for the small model sets in these experiments, the total number of trials required quickly becomes prohibitive. In theory, exhaustive testing would only be required if there were no independence between any of the aspects. For aspects that are independent of all the others, their variations could be rune while holding all other aspects to their values of the base case. No additional information about the semantic descriptor or metrics associated with that aspects would be gained from additional runs made with varying the values of the other aspects. If all the aspects for a given model set were independent from each other, the total number of required simulation runs rises arithmetically rather than geometrically. The total number of simulation runs required to characterize all the semantic descriptors and associated metrics will typically lie between the arithmetic and geometric limits.

It was beyond the scope of the current effort to identify and characterize the dependence of pairs or groups of semantic descriptors. An example of a likely dependent pair from the ASW scenario is array gain resolution and radiated noise resolution. One could ask at what level of resolution of array gain is no significant difference in detection rate noticed for a source that is modeled as omni-directional.

In the experimental designs for this effort, the assumption was made that all the aspects investigated are independent of each other. This assumption was made for two reasons; to keep the total number of required simulation runs manageable, and because the question of semantic descriptor interdependence was beyond the scope of this investigation. Because of this assumption, the results of the experimentation must be considered as preliminary. They are sufficient, however, to provide a first order assessment of the semantic descriptors and associated metrics.

5.3 Results

At of the time of this paper, only the first few runs of the ASW scenario needed to define the level playing field have been completed. The most current results on the validity and applicability the candidate descriptors for this scenario will be presented at the Workshop.

6. Conclusions and future direction

This research into semantic descriptors has so far resulted in a working definition of semantic descriptors for models and simulations. It has also provided a recommended infrastructure for the organization and definition of these descriptors. It has also provided an approach for the assignment of metrics to be associated with each semantic descriptor. It has also provided an initial prototype set of semantic descriptors. It has also provided prototype experimental techniques for evaluating the validity and applicability of candidate descriptors.

While this research effort has made significant accomplishments, there is still much to be done. A few specific follow-on efforts are recommended.

- This effort has proposed eight different functional domains for the organization of semantic descriptors. This is not a complete set. One follow-on effort would, therefore, be to develop a necessary and complete set of functional domains and test the completeness of this set.

- The test scenarios used in this deal with descriptors at the mid (or platform) level of the hierarchical domains. A logical extension would be to develop prototype descriptors and their associated metrics that address models at the other levels of abstraction.

- The current effort developed a set of semantic descriptors that are good in the context of the test scenarios. A logical next step would be to test the utility of these descriptors in the context of multiple scenarios. How well, for example, can the descriptors developed in the context of the C3 scenario address C3 requirements added to the ASW scenario. This would essentially test the descriptors in a proof of principle demonstration of composability by constructing simulations to meet different requirements sets from a collection of described models

7. Acknowledgements

VisiTech gratefully acknowledges sponsorship of the Defense Modeling and Simulation Office and all the guidance, direction, and feedback they have provided during the course of this research.

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