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VERIFICATION, VALIDATION, AND ACCREDITATION (VV&A) OF MODELS AND SIMULATIONS THROUGH REDUCED ORDER METAMODELS

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ABSTRACT

This paper provides a new approach to support Verification, Validation, and Accreditation (VV&A) of models and simulations. The need for efficient and objective methods to verify, validate and accredit models and simulations is greater than ever. More and more decisions are based on computer generated data that are derived from models and simulations. The strength of these decisions is a direct function of the validity of this data. Based on the system identification of reduced order models, this new approach approximates a complex high-dimensional model or simulation by a relatively simple mathematical model valid over a specified domain and range of interest. Verification or validation is then accomplished by the straightforward comparison of the reduced order model structure and coefficients with the baseline data or system. Well-developed identification methods and a structured procedure make this process more efficient and objective than existing methods.

1 INTRODUCTION

Increasing computational capability combined with the rapid response and inherent flexibility has allowed M&S to replace some of the more conventional design and analysis methods. Also, our desire to more accurately represent detailed system behavior or to represent "systems of systems" has lead to highly complex models and simulations. These trends, combined with the increased use of M&S by decision makers and designers, demand that M&S results be correct. Yet, as our ability to model the real-world grows, our ability to verify or validate these models shrinks.

As the reliance on M&S continues to grow, the issue of Verification, Validation, and Accreditation (VV&A) takes on increasing importance. With respect to the overall issue of VV&A, there are two competing requirements. First, the decision makers need answers they can trust. This requirement lends itself to strict configuration control where a limited number of accredited models form the body of analytical tools. However, if we restrict our use of models and simulations to those that are accredited, how do we encourage innovation on the part of analysts, accommodate new questions, or respond to the ever-changing environment?

This leads to the second requirement. Decision makers must be able to answer specific questions about very complex environments and phenomenon. This requires a large body of techniques that can be appropriately applied to the specific situation. It also requires an innovative VV&A process that allows independent development while maintaining the validity of the results.

The capability that is lacking is the ability to clearly and efficiently compare a model or simulation with the phenomenon it is supposed to represent or to compare two different interpretations of the real-world. Reduced order metamodels provide this capability and a new approach to support VV&A of models and simulations. Although directed primarily at constructive (man-not-in-the-loop) models, the technique discussed here can also support the Distributed Interactive Simulation (DIS) environment.

The paper is organized as follows: Section 2 provides background on VV&A, definitions for common understanding, and introduces reduced order metamodeling; Section 3 demonstrates how to apply reduced order metamodeling to the VV&A process; Section 4 provides an example of the verification of two versions of the same simulation; and Section 5 summarizes the paper.

2 BACKGROUND

One of the major users of M&S has been the Department of Defense (DoD). DoD has long recognized the importance of M&S and with reduced budgets has become even more reliant on M&S. This increased reliance, and a concern for the proliferation of models and simulations, has led the Secretary of Defense to direct that each DoD Component shall establish VV&A policies and procedures for M&S applications managed by the DoD Component. Also, the "DoD M&S Executive Agent" shall establish VV&A procedures for their applications.

Current VV&A processes, however, are complex, time-consuming, expensive, and cannot handle the workload generated by the above directives. Consequently, there is insufficient time and money to accredit the models that deserve such status. Furthermore, the process can take so long that changes are often made to the model or simulation before the VV&A process is finished, again drawing the results into question.

The solution to this problem is a consistent, coordinated, requirements-based policy and the ability to efficiently analyze models and simulations. Both of these elements are required. Even with the best policy, it is not possible or desirable to "completely" accredit every model or simulation in existence. This is clearly a poor use of resources. Only models and simulations that need accreditation, for one purpose or another, need to go through this process. Given that we have such a policy, how does one go about the VV&A process so that by the time the simulation is accredited it is still relevant? This paper focuses on a technique to efficiently support verification and validation.

Standard VV&A techniques are not robust and still leave room for interpretation. They generally involve looking at the elements of the model or simulation, dissecting it, and coming to conclusions by analyzing these elements. If we cut a complex problem into smaller more manageable pieces while maintaining the overall complexity, we really do not reduce the overall complexity of the problem that were are trying to solve. We just make it tractable. If we have a complex model, analyzing each and every piece does not make the overall analysis less complex.

This paper provides an alternative solution to this paradigm that will allow the VV&A process to meet the competing requirements and workload demands. This technique is cost effective, timely, and objective. Rather than look at the parts of the model and attempt to integrate the results, we look at the whole model or simulation and identify its ability to represent the behavior of the phenomenon we are interested in.

We do not maintain the overall complexity of the model or simulation. We propose that the analysis of the model or simulation be accomplished via aggregation of the model details into a more manageable piece that has a reduced order (more abstract) representation. This is accomplished by increasing the level of abstraction (reducing the order) of the model or simulation until it is consistent with data used to define the model or simulation. This reduction provides the ability to clearly and efficiently compare a model with the phenomenon it is supposed to represent or to compare two different interpretations of the real-world.

Since reduced order metamodels provide this aggregation and abstraction, we provide a possible solution to the VV&A dilemma. Our technique provides the opportunity to verify or validate a model in a very short period of time, with few resources, and with objective results. With this capability, it is also possible to verify and/or validate (without going through a formal validation process) models or simulations developed to adapt existing models and simulations to new circumstances.

2.1 Definitions

We begin with some definitions to clarify our views on the relationships between models and simulations, verification, validation, and accreditation.

2.1.1 Models and Simulations

A simulation can be defined an instantiation or realization of a model. In this case, the simulation is different from the model. We will use a more abstract definition.

To begin with, a model is a method of expressing a theory. The expression of the model – its representation – distinguishes classes of models. A model can be physical, such as a wind tunnel model of an aircraft. It can be conceptual, like the construct of the Bore atom. Also, the model could be a mathematical relationship or a method (algorithm) of expressing that relationship – a simulation. Therefore, we consider a simulation to be a particular representation of a model and will not distinguish between them.

2.1.2 Verification

Verification is the process of determining that a model implementation accurately represents the developer's conceptual description and specifications.

The verification process confirms that the model functions as it was originally conceived, specified, and designed. Here we compare the output of the model to the conceptual description, specifications, or definitions that were used in its development.

There are two elements to verification. If the model is an original development, it must be verified against its design specifications. If the model is a revision, update, or modification of an existing (verified) model, the performance of the model (and its differences) can be verified with respect to the original specifications or to the original model.

2.1.3 Validation

Validation is the process of determining the degree to which a model is an accurate representation of the real-world from the perspective of the intended uses of the model.

Validation addresses the credibility of the model in its depiction of the modeled world. In this case, the model is not compared to the structure from which it is developed, but to the behavior that it is supposed to represent. An important issue in the validation of a model is its level of fidelity. Our understanding of the phenomenon that the model is supposed to represent must be at the same level of fidelity as the model.

2.1.4 Accreditation

Accreditation is the official certification that a model or simulation is acceptable for a specific purpose.

The accreditation process is the procedure followed by the application sponsor that culminates in the determination that the model is suitable and acceptable for its intended application.

We do not specifically address accreditation, only a method to support accreditation through verification and validation.

2.2 VV&A Methods

While the growing need is real, procedures for VV&A have not kept pace. Current VV&A processes generally involve looking at the elements of the model or simulation via a functional decomposition, and coming to conclusions by analyzing these elements or by a direct comparison with other models. This process is complex, time-consuming, expensive, and still subject to interpretation. General methods of VV&A include:

1. Algorithm checks
2. Peer or independent review
3. Computer aided software engineering tools

Verification is usually accomplished by either logical or code verification methods. Validation can be accomplished either by internal measures (structure of the model) or a comparison of the output of the simulation with other (external) data. We discuss each separately.

2.2.1 Logical Verification Methods

Logical verification requires the identification of a set of assumptions and interactions for which the M&S correctly produces intended results. It determines the appropriateness of the M&S for a particular application and ensures that all assumptions and algorithms are consistent with the conceptual M&S. Methods to accomplish this determination are:

1. Documentation review
2. Design walk-through
3. Comparison of specifications to requirements
4. Comparison of design to specifications

2.2.2 Code Verification Methods

Code verification methods require a rigorous audit of all compilable code to ensure that the representations of verified logic have been properly implemented in the computer code. This audit is usually accomplished by one of the following techniques:

1. Sensitivity analyses and stress tests
2. Code walk-through
3. Algorithm checks
4. Automated test tools
5. Mathematical stability across platforms
6. Units check
7. Statistical test design for stochastic M&S
8. Rule-based systems tools

2.2.3 Validation of the Structure

Validation of the structure analyzes the sensitivity of the output to the input data. It attempts to determine how accurately the model represents the real-world. It ensures that the representation(s) is (are) balanced and consistent.

2.2.4 Output Validation

Validation of the output begins with the feasibility of the results. Are they reasonable relative to the inputs? If the outputs are reasonable, they are compared with historical, test, or laboratory data.

2.3 Metamodels

From the above discussion we see that there is no unifying approach to VV&A. The VV&A process uses essentially the same methods that would be appropriate for design of the model. Without a truly independent and unified approach, VV&A has become manpower intensive and is often subject to interpretation. The reliance on subject matter experts makes the results of the VV&A a direct relation to the capability of the expert, their familiarity with the specific behavior and representation, and the amount of time that they have to complete the process. In addition, VV&A for DIS requires a separate class of experts in that environment (Lewis 1994).

The problem with VV&A stems from the fact that the underlying phenomenon is high dimensional and complex; representation of these systems is difficult. This is why simulation models are often used. The modeler takes the part of the phenomenon of interest that he understands, and develops an algorithm to represent that part of the behavior. Comparison of this part of the phenomenon to the actual occurrence is not always possible.

This is why we propose that part of the VV&A process consists of an aggregate analysis of the model or simulation using a reduced order (more abstract) representation. Metamodeling has the ability to facilitate this type of abstraction (Zeimer, et al. 1993).

2.3.1 Higher levels of Abstraction – Reduced Order Metamodels

A model is a method of expressing a theory and the expression of the model is its representation. Assume that the representation of a particular model is a simulation. As such, the representation is an algorithm that does not have a closed form representation.

The VV&A methods we discussed above are examples of direct verification or validation of this representation. Another approach to verification or validation of this representation is through a more abstract "black-box" approximation of the causal time dependent behavior represented by this simulation – a metamodel.

Metamodels can be used for hierarchical simulation or for analysis. Used to support hierarchical simulation and model reuse, the metamodel is used in conjunction with (coupled to) other simulations or simulation elements. Analytical metamodels are an independent structure that is used to understand and extract information from the model. This analysis can be focused on the VV&A task.

Sometimes metamodeling is confused with sensitivity analysis. Sensitivity analysis is an analysis of the data given the model. It can be used to reduce the order of the model by considering the sensitivity of the output to certain variables. Our approach is similar but different. In our procedure, we are considering the sensitivity of the model given the data, behavior, or the phenomenon we are trying to model.

2.3.2 General Framework

As an abstraction, a metamodel is a projection of the model onto a subspace defined by new constraints or regions of interest. It is a projection of the behavior from a higher order to a lower order subspace – a reduced order model. One of the most important aspects of this projection is the definition of the basis of that subspace; i.e., the definition of the variables that are to be considered.

There are three ways to define these variables. If we are working with an element of a simulation or if we are comparing a simulation to an exercise or some other real-world data, the variables are defined by the data set. If we are comparing the behavior to the concept used to develop the model, that concept defines the variables. If we are going to compare two versions of the same model, we must first determine the important variables by an analysis of the simulation under consideration.

The construction of a reduced order metamodel (selection of the parameters used for the projection) involves: *a priori* knowledge; the data; a set of metamodel structures; and rules to determine the best model to realize the data. There are two basic techniques available for reduced order modeling: direct and inverse modeling.

2.3.3 Direct Methods

First, a reduced order model could be developed by applying basic principles to generate a more abstract (approximate) version of the original model. This would be an example of direct modeling. Direct modeling is characterized by a specification of the elements of the model. Complicated systems are modeled by "tearing" a system into its components, modeling these components in a process called "zooming," and then interconnecting these components to construct a "physical" realization of the system (Sisti 1992, Willems 1991, Sisti 1989). The level of abstraction is controlled by the detail of the specification. The model reveals the structure of the theory and allows the prediction of the response to exogenous inputs as a function of the state of the system. The solution of this modeling problem requires an understanding of the process being modeled and methods to express this understanding **at the desired level of fidelity**.

Reduced order models developed using this technique have been proposed in the VV&A literature (Phase 3 – Concept Validation in Lewis (1994)). They are "standalone" versions – completely new models. The relationship between the real system, the original model, and reduced order model is contained in the two mappings from the underlying system to each of the models. Figure 1 depicts this correspondence.

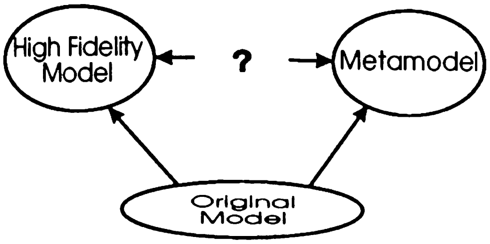

Figure 1: Direct Model Correspondence

As seen from the figure, there is no guarantee that a usable correspondence will exist between the reduced order model and the high fidelity model (Naylor and Sell 1982, Royden 1988). Traceability from the high-fidelity model to the more abstract, lower fidelity, reduced order model becomes a significant issue. Also, this technique still requires an *a priori* understanding of the structure of the elements and the interconnections between these elements at the specific level of fidelity selected. This could be a difficult and risky task and lack of this knowledge is often the reason that a high fidelity simulation was used in the first place.

Since traceability is not guaranteed, this technique does not provide any efficiencies beyond standard VV&A procedures.

2.3.4 Inverse Methods

The second technique develops the reduced order model from the input-output data generated by the original model or simulation. This technique is an example of the "inverse problem," and is represented by Figure 2. From the figure, we see that the correspondence between the original model and the reduced order model is direct. The issues now are the level of fidelity, range of applicability, and accuracy of the response. These are a function of the reduced order modeling technique and data.

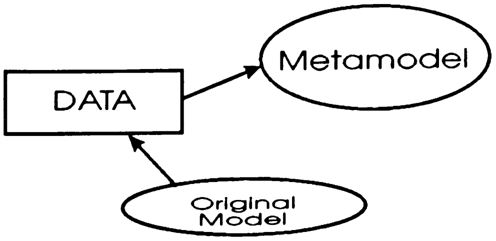

Figure 2: Inverse Model Correspondence

Properly developed, a reduced order model derived from inverse modeling is clearly a mathematical approximation between a set of input factors and responses generated by the high fidelity model. Traceability to the high fidelity model is immediate. As such, it allows the assessment of individual factors on the performance of the model and can be used to study system behavior, verify responses with specifications, or validate the model with respect to real-world data.

3 REDUCED ORDER METAMODELS FOR VV&A

VV&A has many dimensions. Although the procedure is the same, we consider each case separately to facilitate understanding. Assume that we have a reduced order model of an existing simulation and that we also have a similar description of the real-world data that can be used for comparison.

3.1 Verification of an Original Model

In our first case, we have a model that was developed from a specification or conceptual design. Verification is straightforward. We directly compare the reduced order metamodel structure and coefficients to "expected values" inherent in the design specification that came from the real-world experiments, exercises, or test data used to develop the specification.

3.2 Verification of a Modified Simulation

Here we have an existing accredited simulation that has been modified for some purpose (improved execution speed, hosted on a new platform, new capability, etc.). As stated above, we can verify the model with respect to the specifications or, for the portions of the modified simulation that do not add capability, to the existing (unmodified) simulation. If we use the original specification as the baseline, we proceed as above. If we use the existing simulation as the baseline, verification consists of developing a reduced order model of the original and modified simulations using the same model structure. Now, since the structure of each reduced order model is identical, we simply compare the reduced order metamodel coefficients.

3.3 Validation

This is the most complex use of reduced order metamodeling. In order to use reduced order metamodeling to validate a model, we must compare the reduced order model to real-world data. This requires that we have a record of the phenomenon that we have modeled. Also, this record must contain all of the behavioral characteristics that have been incorporated into the model. Given this record, we develop a reduced order model of both the real-world event and the model we are going to validate. Once we have these reduced models, we simply compare the reduced order model coefficients.

If additional information was included in the model that was based on subject matter expertise or analogy and not available in the real-world data, this additional data must be also added to the real-world data to make the comparison possible.

4 RESULTS AND DISCUSSION

The theory supporting reduced order metamodels has been developed and successful applications have been demonstrated. Zeimer, Tew, Sargent, and Sisti (1993) developed a static least squares metamodel of the Tactical Electronic Reconnaissance Simulation Model (TERSM) that approximated the number of emitters reported with a CEP of 5 nm or less. Caughlin (1994a) outlined a general framework for approaching the reduced order metamodeling problem that would support dynamical system models and presented an output-error dynamical metamodel of TERSM. In Caughlin (1994b) we expanded the dynamics to include Ito stochastic systems and applied an optimization technique (Adaptive Simulated Annealing) to generate a TERSM metamodel that accommodated the stochastic nature of the simulation.

All of the above were examples of analytical metamodels (although the last two could be used as simulation metamodels). The first metamodel addressed the final results of the simulation (in terms of modeled system accuracy). The output-error metamodel approximated the system behavior as represented by the simulation. The third metamodel represented the performance of the system in locating a single emitter and approximated the accuracy of the location estimate as the number of measurements increased.

We now provide a simple example of reduced order metamodeling for verification of a modified simulation (the situation described in Section 3.2 above).

The static least squares TERSM metamodel generated by Zeimer, Tew, Sargent, and Sisti related aircraft altitude, aircraft velocity, sensor azimuth coverage, and sensor channel capacity to the number of emitters located within a 5 nautical mile circular error probable (CEP). This model is shown below:

$$\begin{aligned}\sqrt{y} \;=\; & 23.567 - 0.669x_1 - 2.842x_2 + 1.298x_3 + \\ & 3.344x_4 - 0.491x_1x_3 + 0.963x_1x_4 + \\ & 0.414x_2x_3 + 1.155x_2x_4 + 0.231x_3x_4 + \\ & 0.404x_1x_2x_3 + 0.198x_1x_2x_4 - \qquad (1) \\ & 0.285x_2x_3x_4 + 2.037x_1^2 - 0.788x_3^2 + \\ & 0.201x_1x_3x_4 - 2.743x_4^2 + 0.714x_1^3 + \\ & 5.836x_2^3 + 0.744x_3^3 - 2.947x_1^4 - 5.823x_2^4\end{aligned}$$

This model was developed from the Version 1 data (shown in Table 1) that came from simulation runs on a Sun workstation. This simulation was optimized for this workstation and included code to support a RAMTEK display of the emitter field and results.

Another version of the code (Version 2) was recovered from the archive and hosted on a 100 MHz i486 PC using Lahey Fortran 77L EM/32. Answers provided by this version of the simulation were similar but not the same as the results from the experiment run on the Unix workstation. If the original simulation was accredited, could this second representation also be considered a "verified" representation of the tactical electronic reconnaissance system?

Standard VV&A procedures could have been used to answer this question. This would require an extensive analysis of the code, the different compilers, and the effects of the numerical accuracy. Instead, we used reduced order metamodeling. The same conditions that were run on the workstation were duplicated on the PC. The least squares metamodel (using the same model structure) generated from this data is:

$$\begin{aligned}\sqrt{y} \;=\; & 22.4331 - 0.0148x_1 - 2.7822x_2 + 0.1432x_3 + \\ & 3.1432x_4 + 0.3653x_1x_3 + 1.2439x_1x_4 + \\ & 0.1483x_2x_3 + 0.4430x_2x_4 + 0.2698x_3x_4 + \\ & 0.4369x_1x_2x_3 + 0.3286x_1x_2x_4 + \qquad (2) \\ & 0.0960x_2x_3x_4 - 0.2791x_1^2 - 0.8326x_3^2 - \\ & 0.7642x_1x_3x_4 - 1.8413x_4^2 + 0.7577x_1^3 + \\ & 4.9038x_2^3 + 1.0924x_3^3 - 1.1907x_1^4 - 4.8443x_2^4\end{aligned}$$

The angular difference between the subspaces defined by the vectors of coefficients is .15 radians indicating that, while similar, the two metamodels contain different information. With the standard assumptions on the data, the probability of error in accepting the hypothesis that both of these models represent the same simulation is approximately 70%. Clearly, the two versions of the simulation do not represent the same behavior.

There are two potential reasons for the differences between the output of the two versions of the "same" simulation. First, it is possible that the experimental procedures were different. Since all of the data sets for the original experiment were not available, one or more of the 53 other parameters used in TERSM to

Table 1: Input-Output Data for Metamodel Construction

ALTITUDE	VELOCITY	AZIMUTH COVERAGE	CHANNEL CAPACITY	EMITTERS VERSION 1	EMITTERS VERSION 2
40000	1150	150	30	615	514
40000	1150	150	4	193	158
40000	1150	60	30	327	329
40000	1150	60	4	53	69
40000	186	150	30	247	278
40000	186	150	4	73	73
40000	186	60	30	111	174
40000	186	60	4	47	61
5000	1150	150	30	436	284
5000	1150	150	4	226	183
5000	1150	60	30	322	250
5000	1150	60	4	138	149
5000	186	150	30	180	180
5000	186	150	4	116	94
5000	186	60	30	98	105
5000	186	60	4	66	66
22500	668	105	17	62	519
5000	668	105	17	439	307
40000	668	105	17	570	523
22500	186	105	17	181	210
22500	1150	105	17	464	412
22500	668	60	17	419	414
22500	668	150	17	607	505
22500	668	105	4	240	252
22500	668	105	30	658	617
31250	909	128	24	621	521
31250	909	128	10	424	361
31250	909	82	24	512	489
31250	909	82	10	347	322
31250	427	128	24	634	579
31250	427	128	10	489	399
31250	427	82	24	570	556
31250	427	82	0	434	396
13750	909	128	24	602	486
13750	909	128	10	441	346
13750	909	82	24	560	469
13750	909	82	10	373	339
13750	427	128	24	651	567
13750	427	128	10	526	404
13750	427	82	24	605	535
13750	427	82	10	471	411
13750	668	105	17	580	495
31250	668	105	17	584	504
22500	427	105	17	575	524
22500	909	105	17	529	446
22500	668	82	17	512	499
22500	668	128	17	597	523
22500	668	105	10	441	406
22500	668	105	24	640	585

define the aircraft and sensor performance may have been set in such a manner that the simulated systems were not the same. Correcting the differences in the parameters may result in the same behavior.

If different experimental procedures are ruled out, the simulated systems should be identical. In this case, we conclude that the two simulations are not representations of the same high fidelity model. Version 2 should not be considered a "verified" representation of the Tactical Electronic Reconnaissance Simulation Model.

5 CONCLUSION

In this paper we have presented an alternative approach that will allow the VV&A process to meet the competing requirements and workload demands. This approach does not maintain the overall complexity of the model or simulation, but verifies or validates a simulation through analysis of a reduced order (more abstract) representation of the simulation. By increasing the level of abstraction (reducing the order) of the model or simulation, we aggregate the model details into a more manageable form.

Reduced order metamodeling was then used to examine two versions of the same simulation. The procedure clearly demonstrated the probability of error in accepting the second version of the "same" simulation as representative of the first.

This technique is cost effective, timely, and objective. Increasing the level of abstraction provides the ability to clearly and efficiently compare a model with the phenomenon it represents or to compare two different interpretations of the same behavior.

A reduced order metamodel is a projection onto a lower order subspace. The parameters that define this projection are well defined for simulation and analytical metamodels. Since reduced order metamodeling for VV&A is a new application of this method, further research is required to define the best approach to define the projection parameters.

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