SENSITIVITY ANALYSIS OF HARDWARE-IN-THE-LOOP (HWIL) SIMULATION SYSTEMS

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Abstract*:* The verification and validation (V&V) of models and simulations (M&S), and their components, is essential to ensuring timely accreditation decisions by Department of Defense (DoD) and Service Accreditation Authorities. However, in specifying acceptability criteria for accreditation decisions and obtaining broad community consensus on when "good enough" is good enough is problematic. This is especially true for system software and hardware-in-the-loop simulations used in test and evaluation (T&E) applications that need to be accredited to satisfy the requirements of Title 10, United States Code (USC).

Our thesis is that sensitivity analysis can contribute to building confidence in a model or simulation by studying the uncertainties that are often associated with parameters in the model. Many parameters in system dynamics models represent quantities that are very difficult, or even impossible to measure to a great deal of accuracy in the real world. Also, some parameter values change in the real world. Therefore, when building a dynamic simulation, the accreditation agent is usually at least somewhat uncertain about the parameter values and associated acceptability criteria to choose a priori for the accreditation decision.

Sensitivity analysis can assist in determining the sensitivity of the outcomes of an alternative to changes in its parameters. If a small change in a parameter results in relatively large changes in the outcomes, the outcomes are said to be sensitive to that parameter. This may mean that the parameter has to be determined very accurately or that the alternative has to be redesigned for low sensitivity. Consequently, sensitivity analyses can assist the simulation user (accreditation authority) to understand the dynamics of the system being modeled. Sensitivity analysis can enable accreditation agents to determine what level of accuracy (or error) in a parameter is necessary for it to make the model sufficiently useful and valid (or invalid). If the simulation behaves as expected from real world observations, it gives some indication that the parameter values reflect, at least in part, the "real world." Sensitivity tests can assist the accreditation authority to understand the dynamics of the system being modeled. If the sensitivity analyses reveal that the modeled behavior is relatively insensitive, then it may be possible to consider the parameter impertinent to the accreditation decision for the simulation application.

This paper will examine how simulation resources being developed for the United States ballistic missile defense program can meet this challenge through sensitivity studies. We will demonstrate how sensitivity analysis can be used to determine how sensitive a model is to changes in the value of the input parameters of the model, and to changes in the structure of the model. In this paper, we will focus our sensitivity analysis for key parameter variables in the missile defense kill chain.

We will demonstrate how parameter sensitivity analysis can be performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the model. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. We will also illustrate how sensitivity analysis can also indicate which acceptability values are reasonable to use in the accreditation of the simulation. Experimenting with a wide range of values also offers insights into behavior of the simulation in extreme situations. Discovering that the simulation behavior greatly changes for a change in a parameter value can identify a threshold value for establishing the acceptability criteria – what is "good enough" in the model—a parameter whose value significantly influences the behavior mode of the simulation.

1. INTRODUCTION

1.1 Purpose

In this paper we will illustrate how sensitivity analysis can indicate which acceptability values are reasonable to use in the accreditation of complex, software and hardware-in-the-loop simulations. We will focus on parameter sensitivity analysis for key variables in the missile defense kill chain, using the US ballistic missile defense program as an instance.

1.2 Thesis

Sesitivity analysis assists in determining the sensitivity of the outcomes of an alternative to changes in its parameters. If a small change in a parameter results in relatively large changes in the outcomes, the outcomes are said to be sensitive to that parameter. This may mean that the parameter has to be determined very accurately or that the alternative has to be redesigned for low sensitivity.

Consequently, sensitivity analyses can assist the simulation user (accreditation authority) to understand the dynamics of the system being modeled. If the simulation behaves as expected from real world observations, it gives some indication that the parameter values reflect, at least in part, the "real world." As a result, sensitivity analysis allows the accreditation agent (and user) to determine what level of accuracy (or error) in a parameter is necessary for it to make the model sufficiently useful and valid (or invalid) for their specific question. If the sensitivity analyses reveal that the modeled system is relatively insensitive, then it may be possible to consider the parameter impertinent to the accreditation decisions for a simulation application.

2. HWIL SIMULATION CONTEXT

In view of the diversity of ballistic missile threats, environments and conditions under which a ballistic missile defense system (BMDS) must operate, there is no practical, cost-effective method to assess system capabilities through physical (open air) testing alone. Consequently, the BMDS program requires a modeling and simulation infrastructure be in-place that can support and gage progress and assist in establishing the actual and projected capabilities of the BMD elements and system currently under development.

The Groundbased Midcourse Defense Joint Program Office approach to capabilities assessment, therefore, is to integrate models and simulations (M&S) into its ground and flight test program. These M&S are the lynch pin to an effective test framework that can be used at many different levels and venues. These M&S range from the lowest fidelity to highest fidelity, from lowest level (component) to highest-level (integrated system) using different simulation/stimulation drivers, tools, hardware and software models, emulations, and simulations that are embedded into the system.

These complex software and hardware-in-the-loop simulations serve a key role in the assessment of BMDS capabilities against scenarios and threats that cannot be tested due to physical testing (range, safety and environmental) limitations and cost constraints.

2.1 System Test Lab (STL)

The GMD System Test Laboratories (STL) serves as a forcing function to maintain a "unique" test tool/driver to support "all" test venues from component, to element, to system. This test capability is invaluable to assessments of GMD system capabilities against scenarios and threats that cannot be tested due to physical testing constraints.

The STL provides a common framework intended to provide test execution control, sensor element stimuli, and analysis capabilities supporting integration, check out, and performance analysis of the GMD system at a number of venues.

The STL provides in a controlled environment the following functionality:

- Test execution and control.
- GMD Element stimulus and emulation.
- Analysis capabilities for integration testing.
- System checkout of the GMD System.
- Performance analysis of the GMD System.

The STL hosts a computer-based apparatus to integrate GMD elements into a system configuration and drive elements of that system with realistic data and scenarios called Embedded Test (ET). The ET supports both software-in-the-loop (SWIL) and hardware-in-the-loop (HWIL) integration and testing in the STL. Use of this standard simulation architecture to drive SWIL and HWIL reduces development risks by demonstrating early prototype capabilities. The design of the ET software enables testing of elements co-located at the STL venues, and at remote sites. Its distributed nature will allow for scalability in performance as Element capabilities and the nature of threats evolve.

The ET supports system verification through ground testing in the STL and also supports monitoring of live fire and non-live fire flight tests at the Reagan Test Site (RTS). The ET consists of two major components, the Test Execution controller (TEC) and the Test Framework Unit (TFU). Each of these components is briefly discussed in the sections below.

2.1.1 Test Execution Controller

The TEC provides the ET with a centralized command and control capability for all test activities. It exchanges messages with the controlling Battle Management Command and Control (BMC2) node to prepare for, execute, and terminate tests. It controls the execution of the test via the ET TFUs. The TEC provides the human interface to the ET, pre-test preparation and test setup, post-test data collection, data storage, and the security to prevent unauthorized use of the ET. The TEC provides the tools needed for post-test data analysis. The TEC will contain element representations for all of the elements/Test Bed components except for the BMC2. (The BMC2 must be present for the operation of the Test Bed and the ET.) Element representations will be used to represent any component that is not available.

2.1.2 Test Framework Units

The TFUs provide the ET with Element and site specific interefaces. The TFUs issue commands to the elements in response to TEC direction, inject scenario data to appropriate elements to stimulate the system engagement operations, receive and pass element health monitoring information to the TEC, and pass recorded data to the TEC for post-test analysis.

As test and control requests are sent to each element, an element-specific TFU will receive those messages, reformat the messages to element specific structures, and send the reformatted messages to the element. The TFU will receive element responses including health and status (H&S) messages and reformat them to TEC specific formats, before sending the reformatted messages to TEC. The sensor element TFUs, in addition to test and control, will reformat MSG threat and environment information into an element specific data stream and inject this data into the element. It is here that "Truth" data is provided to the element. Local environmental conditions that may degrade sensor sensitivity, such as rain attenuation, are modeled in the sensor TFUs.

3. ANALYSIS SCOPE

During an Initial Defensive Operation (IDO) M&S Stakeholders Meeting in February 2004 an action item was established to evaluate the specified accreditation criteria for key parameters used in the second Integrated Ground Test (IGT-2) executed in the System Test Laboratory (STL).

Previously, each criterion for an IGT accreditation decision was based on an allowable tolerance for a specific parameter and the tolerance was based on the judgment and opinion of subject matter expects (SMEs) for the respective phenomenology. To augment these subjective judments, a quantitative analysis effort was proposed at the M&S Stakeholders Meeting to actually measure and extablish a standard for these aceeptability criteria. This quantitative analysis would then augment and support the definition of these acceptability thresholds, many of which were subjective in nature.

This proposed effort became known as "Sensitivity Analysis". The resultant analysis briefing was included in the classified portion of the GIGT-2 Accreditation Documentation Archive.

This paper will summarize this sensitivity analysis process, the attendant issues, and principal lessons learned from executing this activity while avoiding a discussion of the specific threshold values established.

3.1 Analysis Goals

Results from this sensitivity analysis were intended to augment the acceptability criteria for the GMD element components that formed the GIGT-2 system configuration.

The purpose of these analyses was to assist the GMD program to determine whether the magnitude of differences measured between the simulation and test data would affect the ability of the STL configuration to predict GMD and BMD performance.

The sensitivity analyses also were to provide a means to determine confidence -- at the data level -- in the ability of the STL to characterize BMD functionality / performance.

A key objective of this sensitivity analysis was to aid the accreditation agent in the design and application of quantitative criteria to assess "When a Difference Really Makes a Difference."

3.2 Analysis Approach

In a perfect world, the sensitivity analysis would have been executed within the STL, using a stochastic set of input data to evaluate the resultant system behaviors and their impact on the resultant GMD BMD functionality / performance.

However, due to resource and time constraints, the analysis instead was executed using an all-digital simulation of the GMD system called LIDS. The overall analysis methodology is graphically illustrated in Figure 3.2-1, below.

Several LIDS output parameters with a linkage to corresponding STL variables were assessed. Using LIDS, a Monte Carlo series of simulation trials were executed with a focus on the behaviors of the Cobra Dane (CD) sensor and the Exoatmospheric Kill Vehicle (EKV) using fifty early shots (enagegements) and fifty

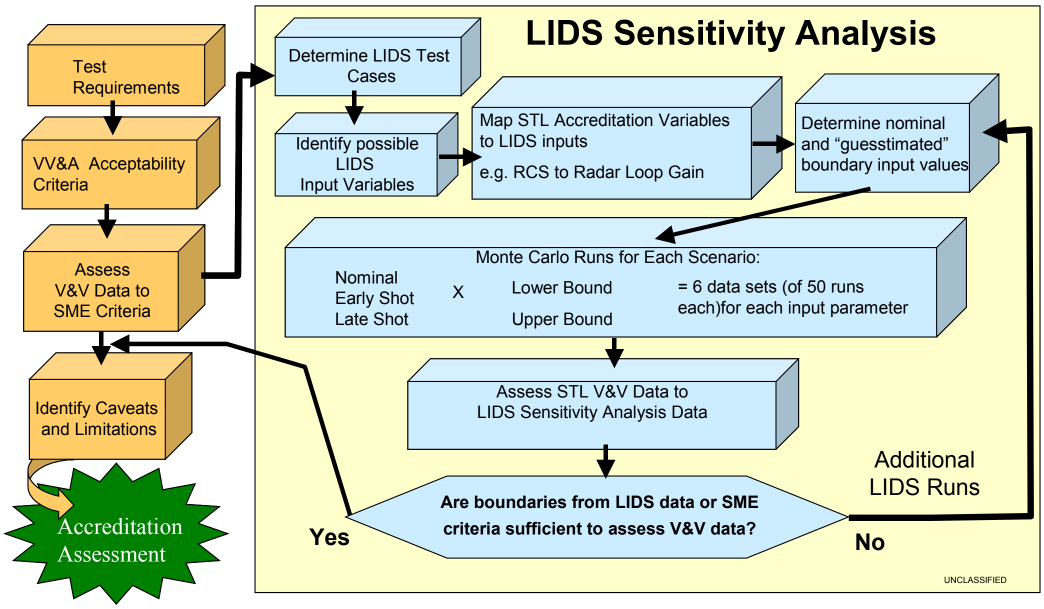

Figure 3.2-1. Overall Approach for Execution of the GMD M&S Sensitivity Analysis.

late shots (engagements). Key parameters examined in these trials included the:

- Cobra Dane (CD) radar loop gain, which modifies power and thus acquisition range, along with detection threshold values.
- Minimum elevation angle for CD.
- CD Signal to Noise Ratio (SNR).
- CD Track Accuracy Multiplier.
- Exoatmospheric Kill Vehicle's Maximum Fuel Available.
- EKV Divert Gas Rate.

Booster performance in LIDS was modeled by an end-of-boost covariance. SBIRS was modeled by a covariance related to the number of satellites and the line-of-sight of each satellite. The plume radiant intensity was not modeled in LIDS. However, LIDS did model and vary cloud cover, thus having an impact on target acquisition and the time and accuracy of the booster burnout state vector provided by the Space Based Infrared System (SBIRS) model. The booster and SBIRS covariance, along with cloud cover height, was randomly varied throughout this assessment.

To determine the effect of azimuth and elevation errors, LIDS perturbed the track accuracy multiplier used in the simulation trials. This multiplier modified the slope of the sensor's track accuracy versus time-in-track curve provided by the Sensor Simulation Test Bed (SSTB). Sensitivity to EKV fuel load and flow rate was also conducted.

Analysis of UEWR acceptability parameters was postponed until LIDS has the capability to model the launch of interceptors from Vandenburg Air Force Base.

The Accreditation Agent met with staff from the GMD JPO's Systems Engineering Division and Joint National Integration Center (JNIC) to discuss the inputs and outputs of the LIDS simulation and finalize the sensitivity analysis. The JNIC personnel in Colorado Springs executed the simulation runs required for the sensitivity analysis and provided the results to GMT for assessment. The sensitivity analysis included conducting a complete Monte Carlo analysis to establish the LIDS / GMD baseline performance for three missile types and three aim points, based on the GIGT-2 test cases.

3.3 Analysis Challenges

There were several challenges that reduced the scope of the sensitivity analysis, and impacted the overall effectiveness of the study. Theses difficulties included the following:

- In all cases, a correlation had to be established between STL criteria (e.g. CD RCS) and LIDS input variables (e.g. CD Loop Gain).

- All of the IGT-2 STL accreditation variables could not be directly mapped to LIDS input variables.

- Key LIDS input variables differed in dimension and value from the equivalent variables used for the STL accreditation decision. Specifically, the:
    - LIDS Radar Loop Gain (dB) was not equivalent to the STL Range Accuracy (km).
    - The LIDS Radar Loop Gain Perturbation (± 20 dB) was not equivalent to the STL RCS Accuracy (± 5dB).

3.3 Limitations and Constraints

The sensitivity analysis was further constrained in a number of ways, including:

- The modeling of the EKV booster using an end-of-boost covariance, which was applied in each test case, inherently limited the examination of the selected EKV performance parameters.

- The SBIRS was modeled by a covariance related to the number of satellites and the line-of-sight of each satellite.

- Sensitivity of the Upgraded Early Warning Radar (UEWR) was not assessed because the version of LIDS used in the analysis did not have interceptors at Vandenburg Air Force Base. Consequently, analysis parameters associated with the UEWR were deferred.

- Embedded Test / Threat sensitivity required the execution of additional simulations trials using the SSTB and LISIM to generate new performance look-up tables. Consequently, element discrimination sensitivity was very difficult to assess.

- The LIDS GMD Fire Control (GFC) Model was not based on the most current GFC software.

4. FINDINGS

Results from this sensitivity analysis were useful in augmenting the government's subjective acceptability criteria for the components that comprised the GIGT-2 configuration. The sensitivity analysis allowed the GMD JPO to determine whether the magnitude of the differences measured between the simulation and test data for the selected parameters affected the ability of the STL configuration to predict system performance.

The sensitivity analysis provided a means to determine confidence, at the data level, in the ability of the STL to characterize BMDS functionality and performance. The sensitivity analysis aided the GIGT accreditation agent in application of quantitative criteria to assess: "when a difference really makes a difference."

Sensitivity to changes in RCS and IR signature for discrimination purposes were not easily evaluated in LIDS because it computes the RCS and IR signatures in real-time based on the relative range and aspect angle between the target and the sensor. These computed values are then used to determine when acquisition occurs. Once the threat has been acquired, the sensor tracking and discrimination performance is based on lookup tables in LIDS.

The target's reentry vehicle (RV) dynamics and signature principally affect sensor discrimination performance. Although threat RV spin rate, coning angle, precession rate, and tank-RV separation velocity can be varied within LIDS, the effects of these conditions cannot be observed since LIDS utilizes SSTB look-uptables for sensor track accuracy and classification based on time-in-track.

Similarly, the EKV discrimination effectiveness is provided to LIDS from the Raytheon EKV simulation (LISIM). Therefore, to evaluate the sensitivity to these parameters would require the execution of both LISIM and SSTB to provide new tables for LIDS for each value to be evaluated.

Significantly, the GIGT-2 STL accreditation variables could not be directly mapped to LIDS input variables. In all cases, correlation had to be established between STL criteria and LIDS input variables. But, the LIDS input variables differ in both dimension and value from the equivalent STL validation variables, introducing additional difficulty in executing and completing the analysis.

To accomplish the sensitivity analysis, each Cobra Dane and EKV parameter tolerance had to be converted to a value that could be associated with the LIDS input variables. Then, each LIDS variable had to be isolated and its impact on engagement success assessed. If the LIDS input variable showed minimal impact on engagement success, then the tolerance value on the equivalent STL GIGT-2 parameter was deemed sufficient.

The bottom line assessment findings established that:

- Changes in the Cobra Dane's Elevation Angle and Radar Loop Gain showed significant impact on engagement events.

- Changes in the other LIDS input variables showed minimal effect on engagement events.

In summary, this sensitivity analysis enhanced the understanding of the accreditation criteria used for IGTs and added analytical rigor to the SME criteria and design requirements previously used for accreditation.

Future GMD accreditation efforts should continue to incorporate sensitivity analyses indicating the confidence limits of output data. This can be done efficiently by using up-to-date statistical techniques as it is done in others fields.

Findings from these future sensitivity analyses should be considered when developing models and simulations and accrediting them for use

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