# Challenges in Digital and Hardware in the Loop Simulation Integration

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## ABSTRACT

MDA relies heavily on simulation to assess the functionality and capabilities of the ballistic missile defense system. In particular, hardware-in-the-loop (HWIL), or equivalently processor in the loop (PIL) simulation is often employed to ensure high confidence in simulation outcomes through the use of the highest possible fidelity models. The cost and complexity of HWIL simulation, however, naturally limits the scope of exercises that can be conducted, necessitating the use of constructive simulation surrogates to augment the test event.

Such a mix of HWIL and digital constructive simulation poses challenges for the simulation architecture and the achievement of the necessary interoperability. This paper addresses the techniques in use today and under development by MDA to improve the integration of HWIL and digital simulation to satisfy the growing requirements for test support. Specific topics addressed include: integrating discrete-event and frame-based time-stepped models, priority processing, and algorithms for graceful degradation in short-term overload situations.

## ABOUT THE AUTHORS

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## MDA SIMULATION USE CASES

The Missile Defense Agency (MDA) is organized to develop and deploy a capable Ballistic Missile Defense System (BMDS) assembled from sensors, weapons, and communication systems that are produced by various *elements*. Each element provides a number of *components* to the BMDS. For example, the sensor (SN) element provides numerous radars, while the Aegis element provides both sensor (Long Range Search and Track) and weapon (SM-3) components.

Both organizationally and technically, integrating the BMDS is a complex problem and requires sophisticated simulation to ensure that the system will operate as intended. To better organize the development of the simulations of the BMDS, the problem is defined in terms of a number of use cases, each with a specific content, audience, and execution requirements.

### System Level Use Cases

The MDA Modeling and Simulation (M&S) Needs Statement defines a number of system-level modeling and simulation use cases that are required by the agency to support the development and fielding of the BMDS. These use cases include Performance Assessment, Ground Test, Flight Test Support, Wargames, Exercises, Training, Concept Development, Scenario Certification, Element Integration, and Planning. In addition to the formal use cases, a number of important intended uses have arisen in recent years including Concurrent Test, Training, and Operations and System Characterization. Use cases such as Wargaming and Training require real-time execution, and models that provide human-in-the-loop interfaces. The Performance Assessment use case requires highly detailed models with rich representations of the underlying physics. The other use cases similarly have varying key characteristics.

As can be seen from the wide scope of intended uses, the challenge for system-level modeling is daunting. The cost of the high-quality, detailed engineering and physics modeling essential to representing BMDS functions is such that attacking individual use cases in an uncoordinated fashion is unaffordable. Instead, the approach taken by MDA's simulation architects is to identify groupings of use cases that share a high degree of commonality and thereby provide an opportunity for a single set of models to cover multiple use cases efficiently.

### Use Case Clusters

The approach is to define a set of use case clusters that allow a single collection of model representations operating on a common simulation framework to cover multiple use cases with little or no additional effort. The clustering recommended by the simulation architecture team is based on the traditional DoD taxonomy of Live, Virtual and Constructive simulation applied to the MDA problem space. In our case, the Constructive uses divide into two major categories, characterized by their level of detail and execution time. Highly-detailed models executing much slower than real time are used to support detailed analysis, while more abstract, rapidly-executing models are used to support planning and concept development.

More detail on these clusters is available in the Digital Simulation Architecture Description Document. For the purposes of this paper we will focus on two use cases: Performance Assessment in the Analysis cluster, and Ground Test in the Live cluster. These two use cases drive the fundamental requirements for Digital-HWIL interoperability.

## EXISTING SIMULATION ARCHITECTURES

The Ground Test and Performance Assessment use cases developed independently in MDA and were satisfied by two different product lines. Ground Test is largely supported by a global distributed infrastructure and sophisticated HWIL laboratories that stimulate fielded command and control and sensor systems. Performance Assessment has been supported by detailed all-digital simulations initially federated in an ad-hoc manner, but now operating on a common simulation architecture. These two very different architectural approaches must be reconciled to address the complete suite of MDA system level simulation use cases.

### Digital Simulation Architecture (DSA)

The DSA is being developed as the result of a fundamental disagreement on the correct approach for system level simulation: the use of pure discrete-event models, or the use of traditional time-stepped or frame-based models. This disagreement led to the establishment of a Digital Simulation Infrastructure study that produced the recommendation for the DSA and an associated model development approach.

The DSA is a compromise framework that allows pure discrete-event representations to operate in a mixed modeling environment along with time-stepped models. This approach allows the legacy element models that emulate or employ tactical code to operate in conjunction with high-performance discrete-event models developed prior to the adoption of the DSA. The framework uses a simulation engine built on the JSPEEDES (JNIC Synchronous Parallel Environment for Emulation and Discrete-Event Simulation) optimistic parallel discrete event product along with standardized gateways that permit optimistic time-managed models to interoperate with clock-constrained real time models.

### Single Stimulation Framework (SSF)

The SSF is being developed out of a need to produce a single source of threat and environmental truth for stimulation of the HWIL laboratories, rather than using an ad-hoc collection of element-provided stimulators. It is a real time simulation framework designed to efficiently distribute complex content to remote locations to permit the BMDS hardware and software to be executed in the absence of real-world events or relatively expensive and infrequent flight tests.

The SSF draws on a legacy system known a the Missile Defense System Exerciser (MDSE) that began as a Distributed Interactive Simulation (DIS)-based engine and has since evolved to a CORBA-based infrastructure for more efficient higher-rate state updates using binary messaging.



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## CRITICAL DIGITAL-HWIL USES

There are two use cases that drive the need for interoperability between the DSA and SSF simulation infrastructures. The first arises out of the cost and availability of the HWIL laboratories. There are too few HWIL labs to represent all the components in the global BMDS for a ground test event, requiring some components to be represented digitally. The second case arises out of the need to have the most realistic possible representations of the BMDS for performance assessments. This argues for the use of HWIL representations where possible in the annual performance modeling of the deployed BMDS.

### Augmentation Using Digital Surrogates

Because there are insufficient numbers of HWIL labs, and because they are used for element-level simulation as well as system-level simulation, it is not generally possible to represent all the components of the BMDS using the high-fidelity HWIL environment. As the system grows more complex, the need to test all the components simultaneously in ground test grows, imposing demands for some representation of the "missing" components in digital form. Digital surrogate models are therefore required to augment the HWIL environment.

It is freely acknowledged that digital surrogate models are not able to replicate the function of the HWIL labs in detail at the same level of fidelity (if it were possible, we would use the digital models instead). This implies that the augmented digital-HWIL combination will have some limitations and caveats that must be addressed in the final integration approach.

### HWIL Models in Performance Assessment

Performance assessment is a use case motivated by the need to provide regular reports to the Congress on the capabilities of the fielded BMDS for a given year. This requirement drives a desire for the highest quality models, soundly anchored to flight and ground test results, and producing undisputable results with the highest possible confidence. The difficulty in producing such high confidence digital models argues for the use of HWIL representation when they are available and to the extent that it is feasible to do so.

It is important to consider that this use case drives a need either for a non-real time capability in the HWIL architecture, or for performance assessment simulation ensembles that are able to execute in real time and provide the HWIL environments with the necessary stimulation. These considerations have an impact on both the underlying framework and on the models that utilize them.

## INTEROPERABILITY APPROACH

Digital and HWIL models operate very differently, usually in a complementary fashion. What is easy for one class of models is often a limiting factor for the other and vice versa. It is not surprising, then, that making an interoperable architecture that effectively hosts both kinds of models requires compromises and demands a realistic view of what can be accomplished.

In our case, the interoperability of the DSA and SSF frameworks is being focused on three key areas: the mechanics of data interoperability, the approach to time management, and the mechanisms that allow simulation traffic of sufficient quality to flow across the global networks used for distributed ground test events.

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## Digital Components Attached to the SSF

Element-provided HWIL representations usually attach to the SSF using *element drivers*: specialty simulation components that bridge the gap between the published interface for the SSF and the internal interfaces used by the hardware emulations. These element drivers are often complex and do more than just translate between data fields—they can also condition the data based on the simulated environment or on events and object states that affect the HWIL inputs.

A promising approach for building digital surrogate models is to develop them as extended element drivers. Rather than conditioning the battlespace for an HWIL lab, the surrogates act on the SSF interface content and derive all the simulation state and results, providing the framework with the outcome of the equivalent hardware process. In doing this, the surrogates must often use modeling representations that are less detailed than the hardware and that take advantage of various techniques to ensure real time execution. This implies that the models are appropriate for the Live use case cluster rather than the Analysis cluster, and are almost certainly distinct from the models used in the pure digital performance assessment events.

Because the content of these models is not of the quality of those used for performance assessment, and because they are often derived from a different pedigree, the caveats and limitations on a digitally augmented ground test event can be substantial. This is especially true when ground test events are later used to anchor other digital simulations! The analyst and assessor must take care to understand the specific configuration of the ground test and must know the compromises made to produce real time digital surrogate models as a means of “filling in” the simulated world.

## Time Management

For HWIL labs that use time-aware tactical code or deployed hardware and software, the only choice for execution rate is necessarily real time. When digital surrogates are employed in this environment, they must ensure that they execute quickly enough to produce the data required on the frame boundary, and they should be robust enough to degrade gracefully if they are unable to complete all the calculation required within the frame time. This is discussed further below. The key framework requirement that emerges is that real time execution must be considered a *constraint* if the configuration includes such time-sensitive component representations.

On the other hand, there are tactical emulations that are able to execute at other than real time rates if given sufficient power and a virtual clock that provides the necessary synchronization information. This is an important capability to support the use of HWIL components in a performance assessment use case where the high-resolution digital representations are unable to execute in real time. In this case, the ability of the SSF to operate in *scaled real time* becomes essential. Scaled real time execution differs from nonlinear, event-based execution in that a unit of real time maps to a fixed unit of simulation time, but the ratio can vary dynamically over the course of execution. There are some practical limits to the frequency of changes in the scale factor, motivated both by the distributed nature of the infrastructure and the limitations of the HWIL components. Still, this feature allows the simulation as a whole to “throttle” through high-density portions of the event and still take advantage of the power of the hardware representations to support a performance assessment.

### Data Distribution Management

The limitations of the highly distributed ground test network led to the implementation of the SSF with highly optimized bandwidth requirements. Most of the simulation content is pre-computed and regenerated locally at the site of the element HWIL lab or deployed component. While this minimizes the required network traffic, it does present issues that complicate the modeling of dynamic events or the operation of digital models that do not have a predictable course of execution that can be pre-computed.

One of the challenges of the increased complexity of the simulation content that is coupled to the digital-HWIL intended uses is that the distributed network can more easily be overwhelmed by dynamic traffic. A "broadcast" approach as originally used by MDSE is not efficient, especially when a pre-computed state may still be appropriate for some models. This implies that greater attention must be paid to development of a formal data distribution management scheme that can ensure the appropriate data gets to the simulation consumers. The SSF uses multicast groups as a means of controlling the distribution of dynamic content and so requires a multicast-aware network to take advantage of this feature.

It should be noted that the real value of this scheme depends on analysis of the expected simulation content and careful construction of the multicast groups in advance of the exercise. General purpose multicast approaches usually fail due to the need for large numbers of groups often not supported by the networking hardware on readily available computing platforms.

## FRAMEWORK CONSIDERATIONS

In late 2007, the MDA began an effort to produce an interoperable framework that would support combined digital and HWIL events using models designed for each environment separately. This effort involves the system level modeling and simulation architecture team (office symbol DESA) and the developers of the hardware in the loop simulation infrastructure (office symbol DESH). The task resulted in the development of a multi-year plan to produce prototype framework content, select design alternatives, develop and test a combined architecture, and produce standards governing the inclusion of models onto this architecture.

In early technical interchange meetings, it became clear to the technical team that several key aspects of the combined digital and HWIL frameworks would dominate the engineering solution. These aspects came under the general categories of real time execution, architectural flexibility, and real world considerations. Without knowing anything about the models that would use the framework, it became clear that the features associated with these key aspects would form the driving requirements.

### Maintaining Real Time Processing

The importance of having mechanisms for robust timing and graceful degradation can easily be derived from the cost of a ground test campaign. These events involve the use of multi-hundred million-dollar facilities, global networks, and hundreds of support personnel. Real time execution limits the total number of scenario executions to the minimum number consistent with the event objectives. Down time is extremely costly and can easily interfere with the successful completion of the event. It is extremely risky to produce a framework in this environment that is


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intolerant of computing errors or that is brittle under high loads.

In our case, we are working to develop approaches to allow the framework to be more cognizant of the degree of "headroom" available to the digital surrogate models so that changes in execution rate, processing power available, or even model resolution changes can be invoked to ensure that the simulation as a whole can execute in real time through congested networks, high loading periods, or processor failures. These techniques are complex and require careful testing of the framework code to ensure that they are reliable and robust in the ground test environment.

### Execution Flexibility

It goes without saying that the system level simulation use cases faced by MDA are comprehensive in scope and the problem space is large. This means that the combined architecture must be able to accommodate the use of digital surrogate modes and HWIL components in unanticipated ways and in uses that fall outside today's boundaries. Because the cost of transitioning completed models to a new framework is very high, it is important to build the most flexible solution we are able to anticipate today, thereby ensuring that the framework remains viable as far as possible into the future.

Practically, this means that the interfaces should be built to accommodate a flexible conceptual model of the mission space, the framework should be designed to allow technology growth, and standards used to enforce compliance must be minimally invasive and constructed using a collaborative environment that accommodates change.

Finally, the desire to arbitrarily mix and match models drives the requirement to execute both in constrained real time and non-real time, depending on the particular configuration. Similarly, the event may call for the use of distributed networks, or may seek the highest possible performance out of a local cluster of computers. The framework should be able to accommodate all of these configuration-dependent requirements without impacting the interfaces, execution engine, or model validity.

### Safety Concerns

For large-scale distributed ground tests, the execution environment usually contains real world command and control components and sometimes even real world sensors. The simulation framework must not be allowed to trigger real world responses or produce adverse consequences such as the launch of an interceptor. This requires careful attention to embedding safety considerations into the framework from the outset. As is the case for security, it is much more effective to design in the safety at the outset than to attach it as an appliqué after the fact.

Fortunately the developers of the SSF have included safety considerations as an important part of their work almost since inception, and controls have been built into the framework to accommodate these concerns. Additional challenges have been brought to the forefront since the advent of concurrent test, training and operations, since deployed assets form the backbone of this use case.

## MODEL REQUIREMENTS

A well-designed framework is critical to the success of the goal of interoperability between digital and HWIL models, but the models themselves also have to be designed to operate in this environment. In the context of MDA system simulation, element providers develop models to represent their own components.

These models are supposed to provide the most faithful representation of their components appropriate to each of the system level use cases. The system level simulation architecture and modeling team imposes constraints on these representations using modeling and simulation standards. The standards contain objective criteria that the models must conform to. These criteria impose essential requirements necessary for interoperability and performance, but leave the maximum possible latitude to the developer to implement within those bounds. In this way, developers can take advantage of their expertise and legacy capability in the most effective way while still considering the needs of the system simulation as a whole.

**Loading and Timing**

Digital models suffer from the problem of slowing down relative to real time as the complexity of simulation content goes up. This produces a problem for execution constrained to real time, as it can be difficult to guarantee that a digital model will never encounter a simulation presentation that cannot be accommodated. Of course, if any digital model falls behind real time, the whole distributed simulation will also fall behind, with potentially catastrophic consequences for the HWIL components relying on data at each frame boundary.

The need to stay within real time regardless of the simulation content leads to the desire for models that are able to throttle their execution and remain on a “frame budget” under a huge range of entity, interaction, and update loads. Ideally, this means the models are able to assess their execution rates, project the future rate based on simulation conditions, and perform adjustments accordingly. A variety of techniques exist to support this kind of processing, including executing with reduced frame rates (gaining processing efficiency by sacrificing integration accuracy), shedding tasking based on a priority scheme, reducing the complexity of the representations being employed, or shifting computing resources from underutilized threads to heavily loaded ones.

While the ultimate responsibility lies with the model to ensure that overloading doesn’t produce adverse consequences, some of the techniques listed above are dependent on the framework to provide services for load shedding, health and status alerting, or frame rate modification. The framework architecture and model development must be coordinated to ensure that the resulting system will function in accordance with the demanding requirements of the HWIL environment.

**Use Case Coverage**

We have focused on only two critical use cases that drive the digital and HWIL interoperability needs: augmented ground test with digital surrogates and performance assessment using HWIL components. But the digital models being used in these venues are not unique to these two use cases; we cannot afford to develop such a multiplicity of diverse models in support of MDA system level M&S.

The models produced by the elements, therefore, must be built to satisfy multiple use cases across an entire use case cluster, and that cluster will sometimes include a combination of digital and HWIL representations. The additional cost of building digital models that take into account safety and load balancing should be significantly lower than the cost of producing specialty representations for these use cases.


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### Verification and Validation

Both of the driving use cases referred to previously have costly consequences for erroneous models. In the case of augmented ground test, the behavior of the real system may be adversely impacted by the outputs from a model that is improperly coded. Similarly, the goal of performance assessment is to determine whether the BMDS will function as required in the event that it must be used in a real world situation. Poorly coded or misrepresentative models can produce outcomes that are either too favorable or too pessimistic, in either case producing an inappropriate view of the behavior of the system.

It is crucial, therefore, that the models used in the combined digital HWIL environment be properly verified and validated, using a process that involves both element-level V&V and system-level V&V of the overall ensemble. Such a process has been in effect for the performance assessment use case since early 2008 and is now being applied to the development of HWIL models that are intended for use in these assessments. As new digital surrogate models are produced for the combined framework, they will be assessed in the same way. The full gamut of V&V techniques must be employed to ensure that the models are of the highest quality and that the conclusions drawn from their execution can be trusted within the error bounds they produce.

## SUMMARY AND CONCLUSIONS

The construction of high resolution, detailed digital models and a simulation environment for authentic hardware-in-the-loop models is radically different, due in large part to the fundamentally different constraints in each venue. The challenge posed to the simulation architecture team at MDA was to find a way to produce a framework that permits these very different model types to interoperate and to usefully enhance the quality of ground tests and performance assessments alike.

An activity was begun in late 2007 to address this request and it has produced a set of key constraints for the combined digital and HWIL framework as well as for the models that must be developed to attach to this framework. The constraints draw on experience in high fidelity simulation, real time virtual environments, prior work in performance assessment and ground test venues, and the latest developments in modeling and simulation technology.

Though challenging, we believe that the resulting simulation environment is technically feasible, appropriate for the two critical use cases mentioned, and achievable within the constraints of resources available to model developers, thanks to the organization of use case clusters which efficiently group related models.

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