Distributed LVC Based Testing Using a Hybrid Digital Twin

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ABSTRACT

The Test & Evaluation community has used Distributed Live Virtual Constructive (LVC) based environments for many years. Using LVC environments provides a cost-effective way to conduct repeatable testing, spans different environments and conditions, and allows tests to be performed that cannot be safely conducted live. When possible, the system under test is wrapped in an operationally realistic environment using modeling and simulation. When the live system is not available or practical for a given test, a digital twin may be a suitable solution. For aircraft, a digital twin may be selected if the test could impact the aircraft's flight worthiness. Redstone Test Center (RTC) is the US Army's organization tasked with testing aviation systems. Much of this testing is conducted by flying the aircraft. However, in some tests, it is advantageous to use LVC environments. One type of testing that requires LVC environments is Aircraft Survivability Equipment (ASE) testing. ASE is the set of sensors and countermeasures used to protect the aircraft from threat systems. RTC cannot conduct this testing using a full aircraft because of limited availability and the potential to affect the aircraft's airworthiness certification. RTC created a hybrid digital twin using a flight simulator, selected sensors, and aircraft processors to address this limitation. This hybrid digital twin includes two of the aircraft MIL-STD-1553B buses, sensors, and other hardware components. The hybrid digital twin allows the evaluation of human-in-the-loop and hardware-in-the-loop issues in the testing. This paper reviews the steps involved in creating this hybrid digital twin and the lessons learned from this process. The paper describes the distributed LVC environment developed to support this test.

ABOUT THE AUTHORS

Michael J. O'Connor is Chief Technologist at Trideum Corporation. Mr. O'Connor has more than 30 years' experience in Modeling and Simulation (M&S). He has been a key participant in the development of distributed modeling and simulation standards, including IEEE 1278 and IEEE 1516. He has held many community positions, including currently as the Chairman of the SISO Standards Activities Committee and previously as Chairman of the SISO Executive Committee. He has served as the chair of the I/ITSEC Simulation Subcommittee and the I/ITSEC Training Subcommittee and is currently a member of the I/ITSEC Tutorial Board. He has led the development of multiple simulations using DIS, HLA, and TENA. Mr. O'Connor has led the technical integration of several large multi-architecture distributed events. He holds a bachelor's degree in Computer Engineering from Auburn University and a Master of Science in Computer Science from the University of Alabama in Huntsville. Mr. O'Connor is a CMSP.

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INTRODUCTION

The US Army Redstone Test Center (RTC) is responsible for testing Army missiles, aviation, and sensors. In meeting the test needs related to Aircraft Survivability Equipment (ASE), RTC is leading an effort to develop joint test and evaluation (T&E) infrastructure, methodologies, processes, and procedures to enable Developmental & Operational T&E of Integrated ASE (IASE). This effort strives to establish formal T&E methods and procedures for conducting IASE test scenarios and environments that are representative of the complex, contested battlespaces in which current and future operations will be undertaken.

PROBLEM STATEMENT

The testing of traditional ASE is a complex challenge. The optimal test would require shooting real threats at piloted aircraft which is obviously not possible. The alternatives are all making use of live or virtual simulation of the threat and countermeasure kill chains as engaged by a suite of ASE detection systems and countermeasures. Currently, the most trusted techniques involve either flight testing and various ground-based threat stimulators typically on a system-by-system basis, or live-fire testing against the systems statically mounted in order to get a high-elevation, long range view at the incoming threat. Testing an IASE solution, meaning a system integrating a number of detection and countermeasure systems to improve threat detection, identification, and defeat is therefore much more complicated because so many systems, with many vendors, must be simulated or stimulated in concert with the pilot's responses in order to determine overall system performance and the relative improvement of the survivability by each iteration of improvement. Additionally, open-air live flight testing of IASE is greatly limited because of the cost, complexity, security, and safety concerns associated with operationally realistic test scenarios. Because of these limitations, it is necessary to utilize a Digital Twin for the majority of the IASE evaluations.

DIGITAL TWIN

Part of the effort to generate a Live, Virtual, Constructive (LVC) test environment is having a complete system, or system of systems operating as it would in the real world. It is often useful or required to have an all-digital or Hardware-In-the-Loop (HWIL) representation of the System Under Test (SUT) due to limited availability of the SUT, scale of the number of SUTs required, or safety limitations associated with the type of test to be performed. Models and simulation of this type have been used for these reasons in acquisition since the dawn of computers.

The term "Digital Twin" is relatively new to the modeling and simulation community and has added a new dimension to the age-old paradigm. According to Raghunathan (Raghunathan, 2019), "Simulations are typically used for design, and in certain cases, offline optimization. Digital twins, on the contrary, are used for the entire design-execute-change-decommission lifecycle in real-time". This new dimension is real-time in nature and exists as a representation or Twin of the SUT over the lifecycle of the program. The Defense Acquisition University (DAU, 2015) defines a digital twin as "An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin."

So, are we building a model, or a digital twin? Wright and Davidson (Wright, Davidson, 2020) state,

> "… a key strength of the digital twin approach is that it provides an accurate description of objects that change over time.

> "… a digital twin has to be associated with an object that actually exists: a digital twin without a physical twin is a model."
>
> "Digital twins are of most use when an object is changing over time, thus making the initial model of the object invalid, and when measurement data that can be correlated with this change can be captured."

Our paper presents a hybrid Digital Twin approach, where we have a model (digital and HWIL) associated with an actual system and the initial model will change over time but not in what we would term real-time. As algorithms, adversarial adaptations, and Techniques, Tactics, and Procedures (TTP) change over time the digital twin will be updated for use throughout the lifecycle of the program.

This approach has been labeled a hybrid Digital twin because combines the relatively new digital twin concept with the well-established HWIL approach. The solution proposed here is not a fully digital representation of the software and hardware in the system. The cost to fully replicate the required systems in a digital model was not justified. Many HWIL implementations are focused on a single component of a larger system. This solution required for this effort included multiple subcomponents of the ASE system as well as the flight dynamics of the aircraft. The requirement of the human interaction is also outside the constraints of most pure digital twin solutions. The term hybrid digital twin was coined to describe this combination of digital twin, HWIL, and human interface. The system described here does not implement the full system as would be done in a digital twin but does implement multiple components that would likely not be done for a HWIL implementation.

For reasons that were explained above, using a flight qualified aircraft for the testing is not feasible. Based on the primary purpose of the hybrid digital twin was testing ASE, a set of key systems to be included in the digital twin are identified. The key systems are flight control/dynamics, MIL-STD-1553 bus, a Decision Aid System (DAS), Ultraviolet Missile Warning System (UMWS), Radar Warning Receiver (RWR), and Laser Warning Receiver (LWR). Rotary wing aircraft (RWA) have many other systems, but detailed representations of them are not required to support the testing. Each key system could be represented in multiple ways. Five options were considered for the implementation of the hybrid digital twin in different combinations of the six key systems. Table 1 shows the selected configuration for each option of the key systems.

Table 1: Digital Twin Options

Option	Flight Control/Dynamics	1553 Bus	DAS	UMWS	RWR	LWR
1	RTC Simulator	None	SW running on laptop	Simulated Sensor over IP	Simulated Sensor over IP	Simulated Sensor over IP
2	RTC Simulator	Tabletop	Tactical DAS in a rack	Simulated Sensor over 1553	Simulated Sensor over 1553	Simulated Sensor over 1553
3	RTC Simulator	Tabletop	Tactical DAS in a rack	Live sensor with Scene Projection	Simulated Sensor over 1553	Simulated Sensor over 1553
4	RTC Simulator	Tabletop	Tactical DAS in a rack	Live sensor with Scene Projection	Live Sensor with Stimulation	Live Sensor with Stimulation
5	RTC Simulator	Aircraft Bus	DAS in Aircraft	Live sensor with Scene Projection	Live Sensor with Stimulation	Live Sensor with Stimulation

Option 3 was selected for the hybrid digital twin for several reasons. Option 5 was not selected because of concerns on the availability of an aircraft during the required time periods. Simulated Sensor based simulations were selected for the RWR and LWR because of the cost to develop new sensor stimulation systems that do not currently exist.

Scene projection of the UMWS was selected because a system that meets most of the requirements is available and offers the highest fidelity. Running the DAS on tactical hardware was selected because the associated algorithms are the focus of the test. Figure 1 shows the block diagram of the hybrid digital twin.

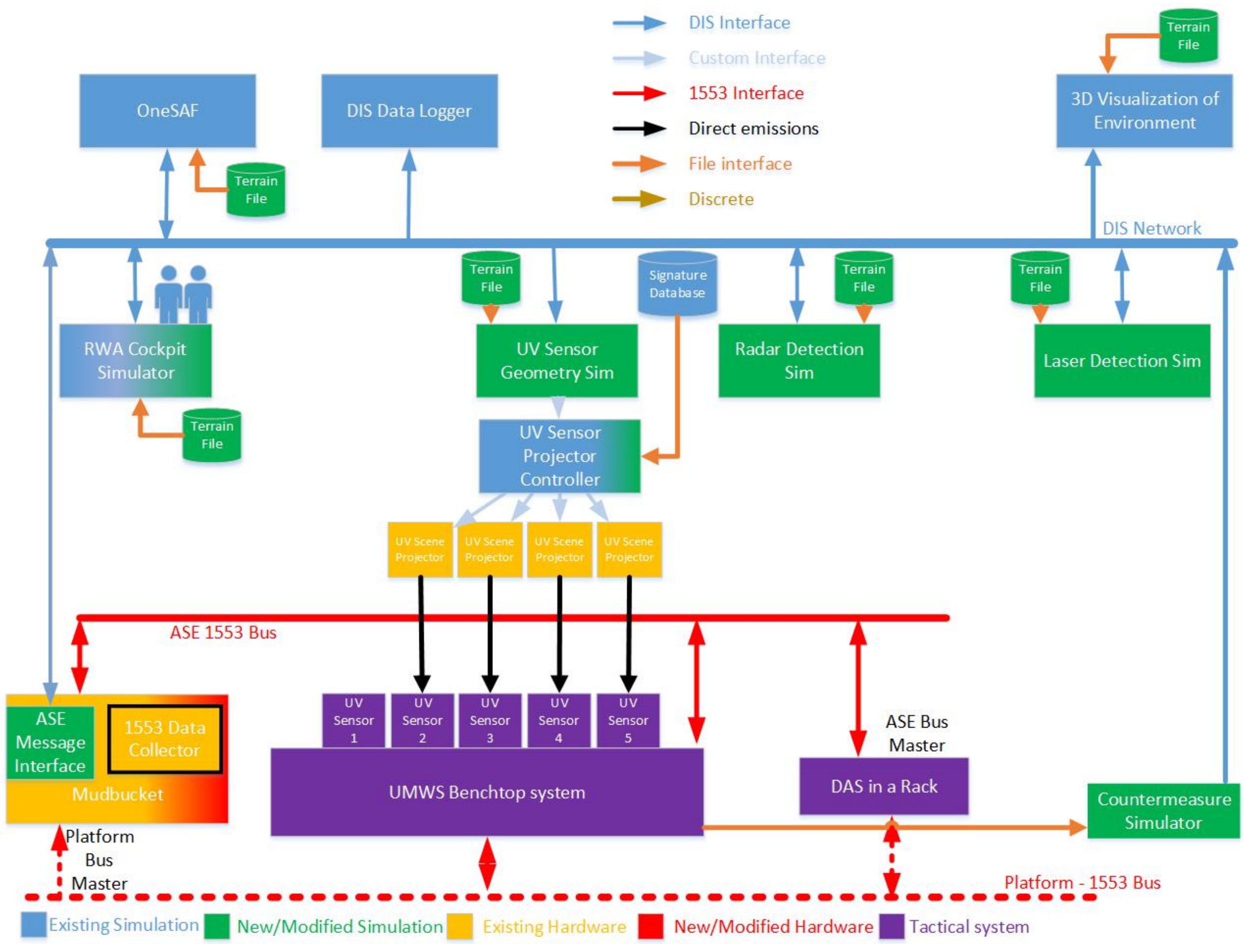

Figure 1. Hybrid Digital Twin

The following sections provide more detail on the possible representations for each key system and the rationale for selecting the representation in Option 3.

Aircraft Dynamics

RTC has tools that can inject data into an actual aircraft via ethernet, 1553 Bus, and direct energy (image projection), however a mechanism for using the actual flight controls of an aircraft does not exist. Any system that allowed this would be prohibitively expensive and potentially impact the flight worthiness of the aircraft. Even if a system that allowed use of the installed flight controls were built, a flight dynamics model would still be required. This left two options for the control of the aircraft, a constructive simulation or a manned flight simulator.

The primary requirement for aircraft flight in this digital twin is to follow a planned route. This behavior can be performed by constructive simulation. One Semi Automated Forces (OneSAF) is a simulation widely used by US Army organizations for constructive simulation and includes a model of several Rotary Wing Aircraft (RWA). There is also a requirement to provide human interaction with the ASE systems and react to warnings. OneSAF does allow limited control of the aircraft and displays could be created to present this information. However, the limited interactivity between the pilot and the constructive simulation did not meet the requirements of the digital twin. For this reason, the use of a constructive simulation for the aircraft dynamics was not selected.

The remaining option is the use of a virtual cockpit simulator. RTC has a RWA cockpit simulator developed by ZedaSoft to support tests requiring a manned simulator. The existing cockpit has touch screen multi-function displays (MDFs), loaded controls, a three screen out the window display, and a helmet mounted display. This simulator had previously been used to provide real-time location information to a real RWA under test. Figure 2 is a picture of the virtual RWA simulator used with the hybrid digital twin. While the simulator had many RWA control menu prompts (MFD pages), it did not include the ASE functions. It was determined that the ASE pages and audio warnings were required to meet the objectives of the test. RTC worked with ZedaSoft to add these pages to the simulator virtual MFDs. This included the threat display page and counter measure page. The simulator also required modifications to receive the data to populate the ASE pages and audio warnings. The options and decisions for implementing these messages are provided in the following sections.

Figure 2. Virtual Cockpit Simulator

Aircraft Bus

Most of the ASE related traffic in RWAs is sent over a MIL-STD-1553 bus. This is a serial data bus which is widely used in military aviation and other systems. RTC has extensive experience in the use of 1553 buses from testing US Army aviation systems. However, setting up and connecting to a 1553 bus can be expensive and time consuming. Three options were considered for the aircraft 1553 bus. The simplest option was to send the messages over ethernet. The second option was to setup a 1553 bus on a test bench. The final option was to use the 1553 bus in an actual aircraft.

Sending all of the ASE messages over ethernet would simplify the setup of the messaging network but would limit the options for the other components in the digital twin. This would particularly simplify the interface to the virtual cockpit simulator which did not directly support a 1553 interface. This option would prohibit the use any of actual hardware systems in the digital twin.

The required components of the 1553 bus could be assembled on a test bench and would allow the use of actual hardware devices in the digital twin increasing the fidelity and similarity to actual aircraft. There would be additional requirements for specialized power supplies and a bus controller, and this option would require adding a 1553 bus capability to the cockpit simulator.

The next option was the use of the 1553 bus in an actual aircraft. All of the hardware components are already installed with the correct controllers and power supplies. Using a live aircraft would limit the options for the ASE sensors to those that are actually integrated into the aircraft. There is a significant cost to operating a live aircraft for testing, even when it is just powered on in a hanger.

After considering the options, a hybrid approach was selected using both ethernet and a bench top 1553 bus. This option provided the most flexibility to select components for the digital twin. The components integrated in the digital twin could use ethernet or 1553. Figure 3 is a picture of the Mudbucket. RTC had previously purchased a Mudbucket which allows injection and extraction of data from a 1553 bus. The authors previously described the Mudbucket's use for testing Manned Unmanned Teaming (MUM-T) (O'Connor, LeSueur 2015). Mudbucket allows for the creation of a hybrid approach for the bus architecture by translating the messages between the 1553 bus to ethernet. Mudbucket provides the tools to intercept messages on multiple 1553 buses. Once the messages are intercepted, they can be translated and published on ethernet. The reverse process works as well taking messages from ethernet and translating them and inserting them onto the 1553 bus. RTC wrote the software that performed this translation.

There were several options on how to pass the messages over the ethernet. The messages passed over the 1553 bus are defined for the aircraft and cannot be modified. One option was to send the native 1553 messages over the ethernet. The 1553 messages are very packed and use bit level fields. These messages could have been sent to the components using ethernet. However, the ethernet based components do not natively process the format of the 1553 messages. The second option was to convert the messages from the 1553 format to something more easily processed by the non-1553 components of the digital twin. Because the non-1553 components included simulation interfaces using IEEE 1278 Distributed Interactive Simulation (DIS), it was decided to develop records for each 1553 message that could be sent using DIS Data Protocol Data Units (PDUs). This had the advantage of limiting the number of developers that had to process messages in the 1553 format and was the preferred method for adding the messages to the virtual cockpit.

Latency is always an issue with HWIL simulations. Using Mudbucket and the associated data translators does add some latency to the messages between the DAS and the sensors. This latency is the result of the Mudbucket processing the message, the translation to DIS PDUs, and sending over the ethernet. Mudbucket itself handles the tight acknowledgement and messaging timelines within the 1553 bus. The physical distance from the virtual cockpit simulator and the UMWS is approximately 3 miles. The total latency, speed of light coupled with the network latency, was measured below 1 millisecond between the facilities. This delay is well within the closed loop tolerance of the sensor systems to virtual cockpit communications. The speed of light latency will become a factor if the separation distance between the components is greater.

Figure 3. Mudbucket 1553 Interface

DAS selection

The Decision Aid System, or DAS, is the focal point of the testing for which the digital twin was being developed. There were initially three options for integrating the DAS into the digital twin. The first was to run the DAS software on commodity hardware. The second option was to run the DAS in a rack mounted setup. The final option was to use the DAS installed in an aircraft. Because using an actual aircraft as part of the digital twin was rejected, this left only the first two options for the DAS selection.

Running the DAS on commodity hardware would simplify the digital twin by not requiring the actual hardware components. This option would likely have been selected if the ethernet only bus option had been selected. Because the hybrid option of using both Ethernet and 1553 buses was selected, this made the actual hardware option for the DAS more attractive. Using the actual hardware allowed the DAS to directly connect to the two 1553 buses it natively uses. This also eliminated any issues associated with running the software on commodity hardware. This option did require additional infrastructure to support the tactical hardware.

UMWS Selection

One of the primary ASE sensors is the Ultraviolet Missile Warning System (UMWS). There were two primary options for integrating UMWS with the digital twin. The first was to create a sensor simulation that was coupled with the relative geometry of the missile and the aircraft and able to determine the azimuth and elevation of the threat as seen by the UMWS. This simulation could be connected to either the ethernet or 1553 bus. The second option was to use scene generators driven by the same relative geometry to drive UV scene projectors to stimulate the actual UMWS sensors. With the second option the UMWS would be connected directly to the 1553 bus. RTC has scene projectors to stimulate UMWS but could only play back prerecorded images and was not integrated with a real-time distributed threat simulation.

Because the exiting scene projector system did not support externally generated threats and a simulation did not exist, some level of development was required to meet the objectives. The need to process the incoming DIS Fire and Entity State PDUs would be required for either the scene projector option or simulation option. There is additional processing logic in the UMWS system that would have to be incorporated into the simulation. The existing scene projectors also required an upgrade to function in the environment.

Because of the large number of 1553 messages exchanged between the UMWS and DAS, using the real UMWS sensors with real-time scene projectors was selected for the digital twin implementation. This did require developing a front-in interface to DIS and upgrading the projectors. The upgraded projectors would support other test programs. Figure 4 shows the sensor benchtop system on the left and the scene projectors on the right.

Figure 4. Bench top UMWS and Projectors

Laser Warning Receiver

The aircraft ASE includes a Laser Warning Receiver (LWR). The LWR detects lasers aimed at the aircraft. There were three options for integrating this sensor into the digital twin. The first two options were creating a sensor simulation that used the relative geometry to determine if the simulated threats intersected with the aircraft. The only difference was how it was connected using ethernet or 1553. The third option was to directly stimulate bench top sensors. RTC has a “bell ringer” device for the LWR. This is a handheld device pointed at the sensors to trigger a response by the sensor. It does not represent any specific threat and is not tied to a distributed simulation threat. Selecting the third option would require significant development.

The simulation option connected via ethernet was selected for the digital twin. This option minimized development costs while meeting all of the requirements. The resulting simulation does not represent the performance of any actual

LWR, but does alert based on the externally generated threat. The LWR simulation listens for DIS Designator PDUs. The LWR simulation attaches virtual sensors to the RWA position and determines which sensors can detect the laser represented by the DIS Designator PDU. The LWR simulation determines detection and then sends the data to the DAS. DIS Data PDU records were defined to communicate with the DAS and Mudbucket was used to translate the data between the DIS PDUs, the simulations, and the DAS.

Radar Warning Receiver

The third aircraft ASE sensor is the Radar Warning Receiver (RWR). The RWR detects threat radars and can determine the operational modes of the threat radar. There were three options for integrating this sensor into the digital twin. The first two options were creating a sensor simulation coupled with the relative geometry to determine if the simulated threat radars intersected with the aircraft. The only difference was how it was connected, using Ethernet or 1553. The third option was to directly stimulate bench top sensors. RTC has “bell ringer” devices for the RWR. These are handheld devices pointed at the sensors to trigger a response by the sensor. They do not represent any specific threat and are not integrated with a distributed simulation threat. Selecting the third option would require significant software and hardware development.

The simulation option connected via ethernet was selected for the digital twin implementation. This option minimized development costs while meeting all of the requirements. The RWR simulation does not model a specific RWR. The simulation receives DIS Electromagnetic Emission (EE) PDUs to represent the beams of the threat. The EE PDU allows the generating system to indicate different radar modes including search, tracking, and targeting. A real RWR would determine these modes by the radar signal, however the data in the EE PDU would not be sufficient to determine that with the included mode fields. Determining the modes of the threat system radar are critical to the aircraft ASE system. The messages sent from the RWR to the DAS include information on the mode of the radar. DIS Data PDU records were defined to match the information the RWR communicates with the DAS. Mudbucket was used to translate the data between the DIS PDUs, the simulations, and the DAS.

RESULTS

The digital twin for ASE testing has been fully integrated and tested. This design has proved to be a preferred method to test ASE equipment, algorithms, and TTP, and is expected to enhance the joint T&E infrastructure in performing developmental and operational testing. The testing of IASE is a complex challenge but the hybrid digital twin approach has provided the community with a method to evaluate the performance in operationally realistic scenarios coupled with the response of the pilots. This approach provides the highest fidelity, cost permissive, repeatable technique within the safety and security constraints of these critical systems.

The approach used to create this hybrid digital twin is applicable to many virtual test environments. The hybrid digital twin is a mixture of aircraft hardware, a virtual cockpit simulator, sensor simulations, and bus simulations that will change over time, keeping pace with the ever-changing IASE real-world environment. While the hybrid digital twin does not represent all of the systems in the aircraft, it does represent the ones required for the test at the required fidelity. The design considerations made allow for seamless upgrades including more or different sensors, processors, and multi aircraft interactions. The number of threat actions and pilot/IASE reactions that can be tested is practically endless with the cost effectiveness and flexibility of the hybrid digital twin implementation.

The approach taken to develop this digital twin is applicable to other programs. The methodology for defining the options and the analysis to select the options will be useful to other programs.

FUTURE WORK

The most likely evolution to the digital twin is the one common to most LVC environments, moving from constructive to virtual to live increasing simulation fidelity along the way. The initial effort identifies the ability of current systems to better identify threats based on the identifications made by several warning systems and choose different countermeasures on that basis. One improvement would be to replace the constructive simulations for the LWR and RWR with the actual systems and leverage stimulators particular to those systems. This would also aid in acquiring improvements or replacements to those systems when the time comes as it would augment the usual test regimes with an integrated threat environment. Performing flight trials to verify and validate findings from the digital twin are also expected. Extending the integration across platforms is expected, as multiple aircraft could cooperatively detect and identify threats and deploy countermeasures in a fundamentally different manner than is possible currently, from multiple points in space. The digital twin should be expanded to represent multi-aircraft groups to explore the technology needed to enable this and the TTPs necessary for optimization.

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