A Flight-Representative Operational Cyber Test Environment

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ABSTRACT

An important aspect of modern cyber testing & evaluation is the immersion of the system under test (SUT) into an operationally relevant environment. This enables the SUT to be cyber-tested while performing a simulated mission at any time and place in the world, while sitting safely in a test facility. In addition to this being a more realistic test from the perspective that the SUT avionics are in operational states with operational dataflows, this type of testing also enables the tester to assess the mission impact of cyber threats. The U.S. Army Redstone Test Center (RTC) has developed a flight-representative environment to immerse Army systems into this type of operationally relevant cyber test environment. This environment is flight-representative in that it includes SUT stimulation with realistic Global Positioning System (GPS) signals, inertial sensor signals, physical air pressure to the SUT's pitot-static system, and other tactical data signals. This environment has been integrated with live inputs from simulation sources such as One Semi-Automated Forces (OneSAF), flight simulators, and other battlespace simulators and with pre-recorded flight data or flight simulation data. To date, these tools have successfully put several Army rotor wing aircraft into "simulated flight" for cyber testing. This paper describes several of the issues and challenges associated with developing this cyber test environment and how these challenges were overcome. Of particular interest are the challenges involved with integrating low-resolution data sources with GPS and inertial data simulators that require high-resolution data by using dynamic feedback-control theory and analysis methods. The chosen solution integrates both off-the-shelf and custom hardware and software to create high-fidelity SUT input signals from any data inputs agnostic of the input data quality or type.

ABOUT THE AUTHORS

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Steven Hildebrand is an engineer at Trideum Corporation and servers as a contractor at the U.S. Army Redstone Test Center. He received his Bachelor of Mechanical Engineering degree from Arizona State University in 2009 and Master of Science degree in Cybersecurity from University of Alabama in Huntsville in 2021. While working for the U.S. Army Test and Evaluation Command as both a contractor and a civilian, he has supported testing of a wide variety of ground and airborne military systems with a focus on instrumentation system design and integration.

Tara Clayton is a computer scientist at Trideum Corporation and serves as a contractor at the U.S. Army Redstone Test Center. She received her Bachelor of Computer Science degree from Auburn University in 2018. Her work at the Redstone Test Center has focused on instrumentation development and test support of multiple Army systems.

M. Andrew Smilie serves as an engineer for the U.S. Army Redstone Test Center (RTC) Modeling and Simulation Division located in Huntsville, AL. He has over 20 years of experience designing and executing electromagnetic environment effects (E3) tests on systems and subsystems. While still an RTC employee, he accepted a position at the Joint Pre-flight Integration of Munitions and Electronic Systems (J-PRIMES) located at Eglin AFB, FL in 2009. There, he learned installed systems test methodology and electronic warfare (EW) simulation techniques inside of an anechoic chamber while gaining valuable cross-service work experience. He also gained experience developing and maintaining software tools required to conduct 6DOF simulated flight on tactical aircraft using techniques and methods such as hardware-in-the-loop (HWIL) and modeling and simulation (M&S). In 2017 he returned to RTC Headquarters in Huntsville and has been working in the Modeling and Simulation Division developing similar test environments at RTC. He received an Electrical Engineering degree from Auburn University in 2002.

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INTRODUCTION

The U.S. Army Redstone Test Center (RTC) provides test and evaluation (T&E) support for Army aviation systems. As military systems become increasingly complex and connected, and adversarial cyber warfare capabilities advance, cyber testing becomes increasingly important to maintaining effective and resilient systems. The complexity of modern military systems combined with limited resources makes impractical any attempts to identify and remediate all possible cyber vulnerabilities. This inability to eliminate all cyber risks necessitates cyber testing methods that support risk management. To assist in cyber risk management, RTC has developed a capability to immerse the system under test (SUT) in an operationally relevant environment (O'Connor, M., LeSueur, K., Novak, J., & Blair, C., 2017). This wraparound environment provides the inputs to the SUT that it would receive while operating in the field and provides interfaces for the SUT to interact with other entities. These other entities can be live, virtual, or constructive simulations and communicate with the SUT in the simulated operational scenario.

When testing aviation platforms, a key component of creating this operationally realistic environment is stimulating the platform with the signals needed for the SUT to behave as though it were in flight. This flight-representative, or "virtual flight", capability is necessary for the system to respond during a cyber risk assessment as it would if it was exposed to the same threats in a fully operational state. A critical aspect of this SUT immersion is simulating high-fidelity Global Positioning System (GPS) signals, Inertial Navigation System (INS) signals, air data, tactical data links, IP data traffic, and data-bus traffic to the system under test.

The ability to integrate this capability into distributed Live, Virtual, and Constructive (LVC) test events where the simulation data source is not optimal for this type of high-fidelity signal generation has become a key area of concern for many recent test events. This challenge of producing highly realistic signals that can be driven by various data sources and the associated solution attempts and the final chosen solution used here provides useful insight for similar challenges encountered by the modeling and simulation (M&S) community.

MISSION-BASED CYBER TESTING

A mission-based cyber risk assessment enables the characterization of identified vulnerabilities based on mission impact, providing a logical reference for risk management. Performance of a mission-based risk assessment requires the system under test to be in a mission representative state. For aviation platforms, flight is an essential function of any mission. However, cyber testing of aviation platforms presents unique hazards which typically prevent flight due to unacceptable levels of risk. Cyber testing of aviation platforms in a mission representative state without the hazards and costs associated with flight can be achieved with operational wraparound and virtual flight capabilities.

Operational wraparound and virtual flight are achieved by the bridging of live, virtual, and constructive simulations with the SUT. This bridging is achieved through software and hardware that provides stimulation to the SUT through a variety of interfaces, most commonly RF, serial, ethernet, optical, and pneumatic.

Traditionally, cyber tests of aviation platforms have commonly been performed with the SUT in a maintenance state. Such an assessment is insufficient because it fails to include a significant amount of the threat surface and threat vectors. In particular, the following impacts cannot be identified or observed with a SUT in a maintenance state:

- Manipulation of Time Space-Position Information (TSPI) data
- Manipulation or denial of communications
- Manipulation or denial of flight instrument indications
- Exploit of the SUT that impacts the mission of remote systems
- Exploit of remote systems that impact the mission of the SUT

However, each of these impacts can be identified and observed with the SUT in a mission-representative state provided by a sufficient operational wraparound and virtual flight capabilities.

CAPABILITY ARCHITECTURE

The primary purpose of this flight-representative capability is to stimulate the system under test with signals to immerse the system in an operationally realistic environment. One challenge in developing this capability is determining a hardware/software architecture to allow for stimulation of various SUTs (many of which require different types of input signals) while using either live or pre-recorded simulation data from a variety of sources. While simulation can be described as a virtual representation of a real system or environment, stimulation involves providing a live system with signals to immerse it in the virtual environment. Stimulation often requires specialized hardware and software to generate high-fidelity, realistic signals to provide to the SUT.

The architecture of this capability is shown in Figure 1. This architecture allows for modularity in that the selection of stimulation signals into the SUT can be tailored to the needs of each individual test. As the figure shows, the simulation input data is captured by RTC's CMDR ("commander") software before being distributed to each of the stimulation hardware tools. This software performs data filtering and interpolation that is discussed in the next section, along with data translation to the formats required by each of the pieces of stimulation hardware. This software also allows for centralized configuration and control of each of the stimulation hardware tools.

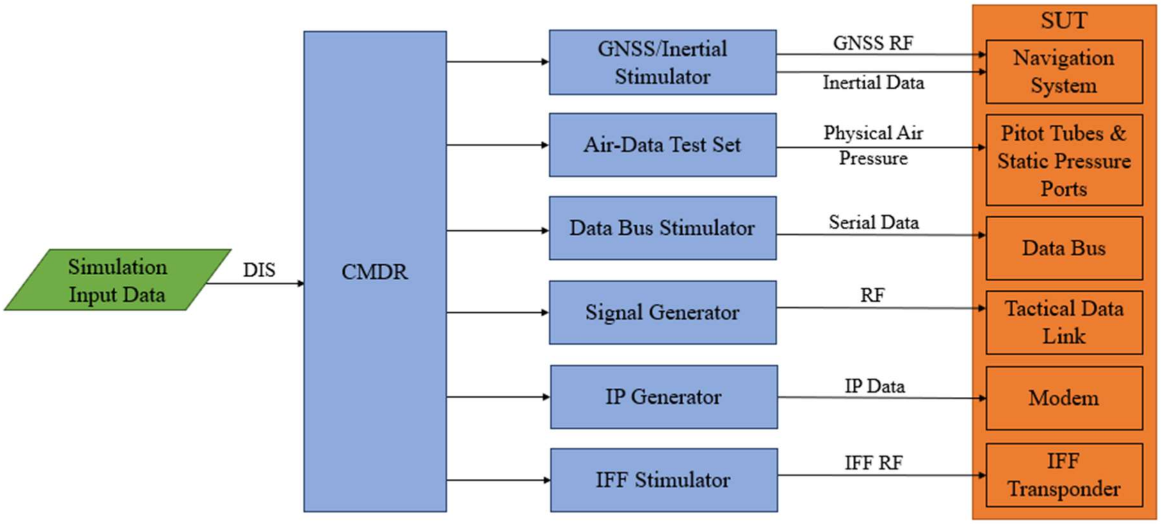

Figure 1. Flight-Representative Capability Architecture

The simulation data input into CMDR can be any type of live or pre-recorded motion profile data but is typically Distributed Interactive Simulation (DIS) data produced by a simulation environment such as OneSAF. After performing the necessary filtering operations, CMDR outputs this data to each of the stimulation hardware tools in the prescribed formats. Each of the stimulation tools then use this simulation data to produce a signal representative of what the SUT would "see" if it were in the simulated environment. These signals could be radio frequency (RF), pneumatic air pressures, serial data, or IP data and are fed into the SUT though standard antenna ports, standard pneumatic lines used for maintenance and calibration, or custom cabling to interface with different parts of the SUT.

GENERATING HIGH-FIDELITY SIGNALS WITH LOW-QUALITY INPUT DATA

The requirement to drive the stimulation hardware with potentially low-fidelity, low-resolution simulation TSPI data is an additional challenge. The stimulation hardware requires high-quality data to produce high-fidelity GPS, inertial, air-data, and other signals required by the SUT. High-quality data for this capability is considered to be high rate (ideally 1,000 samples/second for the chosen hardware), self-consistent in that integration of higher order terms yields correct values (i.e., integration of provided acceleration and velocity produces the provided position values), and smooth (i.e., there are no sudden "jumps" in the data that would create spurious dynamics for the SUT). While simply providing better data from the simulation source would be an easy solution to this problem, this is not possible in cases where this capability is leveraged as part of a broad distributed test where other, competing interests drive the selection of the simulation environment. In these cases, control of the simulation source data may lie with an outside party and RTC must use the data that is provided, regardless of whether it is sufficient by itself to drive stimulation hardware that requires high-quality data.

The DIS standard was created for and is widely used in distributed LVC test events (IEEE, 2012). It allows for simulations involving thousands of individual entities to be conducted in a distributed manner across numerous test sites while minimizing network congestion and latency. This minimization of network congestion does, however, impact the rate and quality of simulation data provided for each simulated entity. For example, in a simulation with 1,000 entities, if each entity provides its state at a constant 1,000 Hertz (Hz), with each Entity-State Protocol Data Unit (ESPDU) taking about 186 bytes to transmit, there will be approximately 1,500 Mbps of network traffic for the entity states alone. To account for low data rates, the DIS standard includes "dead reckoning" parameters and algorithms that allow the individual user of DIS data to propagate entities of interest's TSPI state forward in time even when that data is not directly provided from the simulation source. Using these dead reckoning parameters, data is provided at a much less frequent rate for each entity, and it is left to each individual simulation data user to propagate the states of their entity of interest forward as desired. The DIS standard provides several different dead reckoning algorithms with the most sophisticated algorithm providing entity position and attitude along with the dead reckoning parameters: linear velocity, linear acceleration, and angular velocity.

To address the low data-rate issue, using the built-in DIS dead reckoning algorithms was the initial approach. Using this technique, a dead reckoning model was run locally at a data-rate of 1,000 Hz for the vehicle of interest. This vehicle was initialized by the incoming DIS position and orientation data. After initialization, this model was dead reckoned using the parameters provided in the DIS ESPDU. Ideally, linear velocity, linear acceleration, and angular velocity are all provided in addition to the position and attitude states (DIS dead reckoning algorithms 4 and 8). In some cases, however, only linear velocity is provided with position and attitude. When this is the case, an issue arises when a new update is received after a period of dead reckoning; the vehicle position and orientation "snap" to the new truth position from the simulation. Figure 2 demonstrates this effect (Murray, 2022). Note that while the green, internal "truth" model may be of high-quality, it is not available to remote simulation data users. The remote user only receives periodic DIS ESPDU updates over the network.

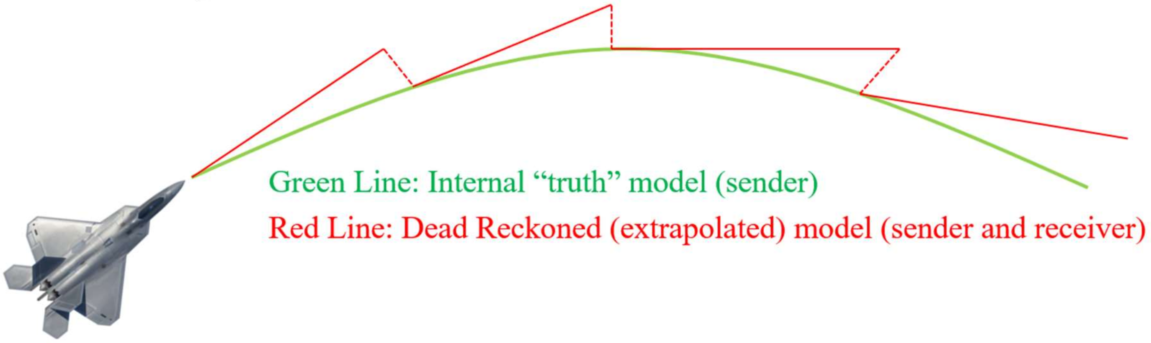

Figure 2. Dead Reckoning Model

This instantaneous jump produces extremely high inertial dynamics in the stimulation hardware and causes the GPS-INS (Inertial Navigation System) to lose an accurate position fix and quickly begin to drift from the simulated position. To account for this instantaneous jump when updated truth data is received, the DIS standard suggests the use of a data smoothing method. When using this smoothing method and new truth data is received, instead of instantly correcting the vehicle state, the vehicle state is more gradually corrected to the new dead reckoned position. This effect is shown in Figure 3 (Murray, 2022).

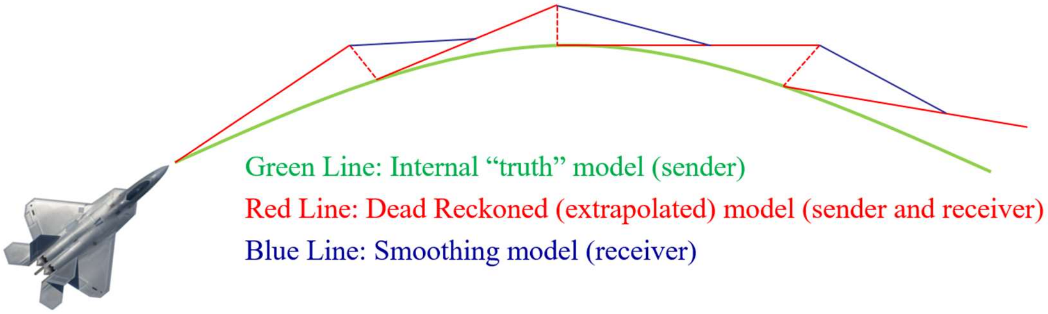

Figure 3. Dead Reckoning Smoothing Model

While this method eliminates instantaneous position jumps, it still includes instantaneous changes in linear and angular velocity. Because the vehicle inertial measurement unit (IMU) being emulated is directly measuring the vehicle's body-frame acceleration, this instantaneous change in velocity still results in extreme dynamics that cause the SUT GPS-INS to lose its ability to track the simulated GPS and inertial signals. Applying this same smoothing approach to the velocity states eliminates the instantaneous acceleration spike but results in the accumulation of error over time.

Filter Model Development

To both eliminate instantaneous changes in position, velocity, and orientation and eliminate the possibility of error accumulation over time, a dynamic approach was taken, based on feedback-control theory. A third order lowpass filter was defined for each of the three position states, as follows:

$$\dddot{x}_{k+1} = \left(a_{x\,input} - \ddot{x}_k\right) * k_1 + \left(v_{x\,input} - \dot{x}_k\right) * k_2 + \left(x_{input} - x_k\right) * k_3 \tag{1}$$

$$\ddot{x}_{k+1} = \ddot{x}_k + (\dddot{x}_{k+1} + \dddot{x}_k) * \frac{dt}{2} \tag{2}$$

$$\dot{x}_{k+1} = \dot{x}_k + (\ddot{x}_{k+1} + \ddot{x}_k) * \frac{dt}{2} \tag{3}$$

$$x_{k+1} = x_k + (\dot{x}_{k+1} + \dot{x}_k) * \frac{dt}{2} \tag{4}$$

Where $\dddot{x}$ is the rate of change of vehicle acceleration (in any of the three word-frame axes), $\ddot{x}$ is vehicle acceleration, $\dot{x}$ is vehicle velocity, x is vehicle position, the subscript k or $k+1$ represents the value at time k or $k+1$ respectively, dt represents the simulation time-step, $a_{x\,input}$ represents the acceleration data provided from the DIS ESPDU or other simulation input, $v_{x\,input}$ is the simulation input velocity data, and x_{input} is the position data from the simulation source. $k_1, k_2,$ and k_3 are filter gain coefficients.

Figure 4 gives a representative example of the desired response of this concept. Note that the filtered model eliminates any instantaneous changes in position or velocity while introducing a slight lag and overshoot that can be tuned to provide varied system responses by modifying the filter gain coefficients. Additionally, this method allows for dynamic limits to be set on the stimulation output data to protect the SUT from unexpected, inadvertent simulation inputs that can be caused by network outages or improper simulation source operation from a remote test site.

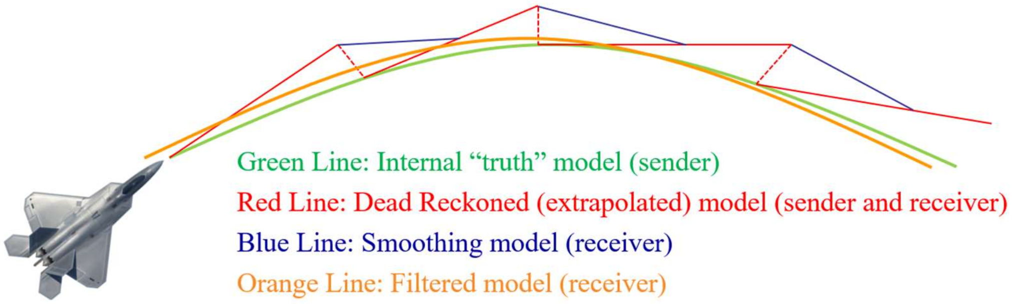

Figure 4. Filtered Model

A third order model was chosen to guarantee that the resulting position, velocity, and acceleration data profiles were all smooth and continuous with no discontinuities or jumps. While this model does produce instantaneous changes in the rate of change in acceleration, this parameter is unimportant because once integrated, it produces a continuous acceleration profile that is used by the GPS-INS. Further increasing the order of the lowpass filter here only serves to increase the natural instability of the filter and the higher order dynamic smoothing provided does not yield any improvement in the quality of the stimulation output signals. Reducing the order of the filter would result in instantaneous changes in acceleration which could potentially cause errors in the SUT GPS-INS solution. The gain coefficients k_1, k_2, and k_3 were calculated by defining the characteristic equation of the third order model above as:

$$s^3 + s^2 k_1 + s k_2 + k_3 = 0 \tag{5}$$

The desired polynomial roots are chosen based on the desired response of the filter. These roots are known as the eigenvalues or closed loop "poles" of the filter. While an in-depth discussion of the selection of these roots is out of the scope of this paper, in general, positive roots produce an unstable filter response, small negative roots produce a stable and slow response, and larger negative roots produce a more rapid, but less filtered response. The tuning of these parameters is done heuristically and is based on the desired response of the system under test. For more information on basic system dynamics, feedback controls, and the selection of filter eigenvalues, see Palm, 2013.

Filter Model Results

Figure 5 compares the raw input DIS velocity data to the resulting filtered velocity output from a flight path example scenario in the Earth-centered, Earth-fixed (ECEF) frame. As the figure shows, the quality of the input DIS velocity data is very poor. This data includes several near-instantaneous changes in velocity and sporadic velocity jumps throughout the flight path. While not obvious in the figure, this data comes in at an inconsistent sample rate, to eliminate the overloading of the network as discussed above. The filtered velocity output, on the other hand, is smooth and continuous at the desired stimulation hardware data-rate of 1,000 Hz.

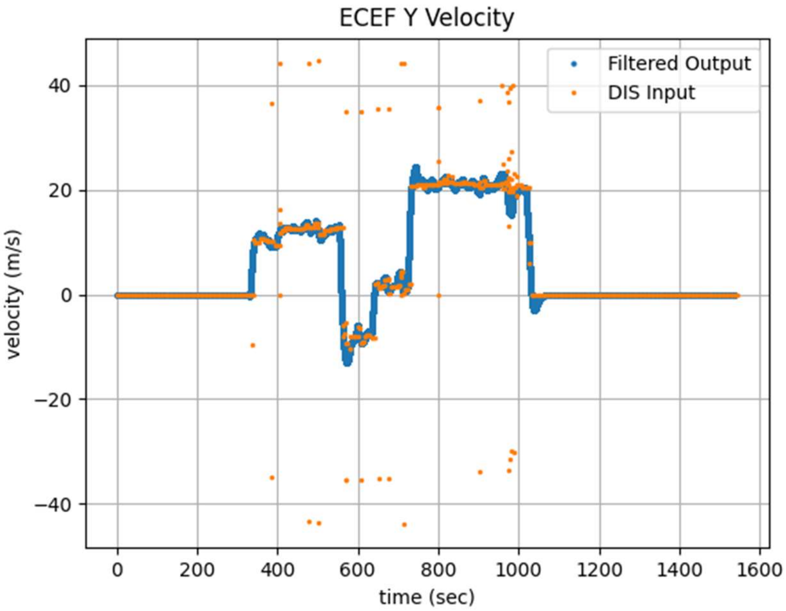

Figure 5. Filtered Velocity Data

In addition to the poor data quality, DIS dead reckoning algorithm 3 was used to produce this data. Therefore, acceleration data was not provided in the DIS ESPDU packet and must be calculated by the dynamic filter. Without running a dynamic filter, this acceleration data could also be calculated by numeric differentiation; however, this approach further amplifies noise in the data. The acceleration profiles for this flight path are shown in Figure 6 with a zoomed-in view of the same data in Figure 7. Note that the numerically differentiated DIS data is extremely noisy with large acceleration spikes, while the filtered data is smooth and continuous with no spikes. When provided to the simulator, the filtered data here produced an IMU data signal that adequately stimulated the SUT even though it was derived from poor quality input data. The raw incoming DIS data was unable to produce a sufficiently smooth inertial data profile to accurately stimulate the SUT.

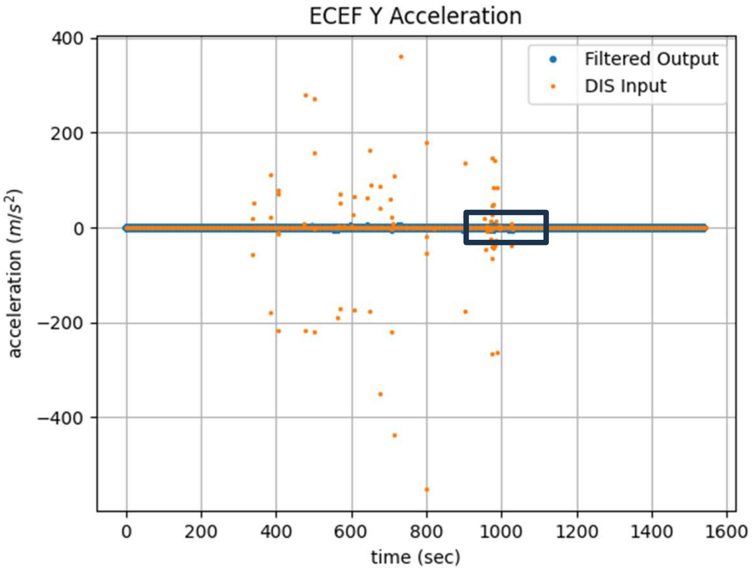

Figure 6. Filtered Acceleration Data

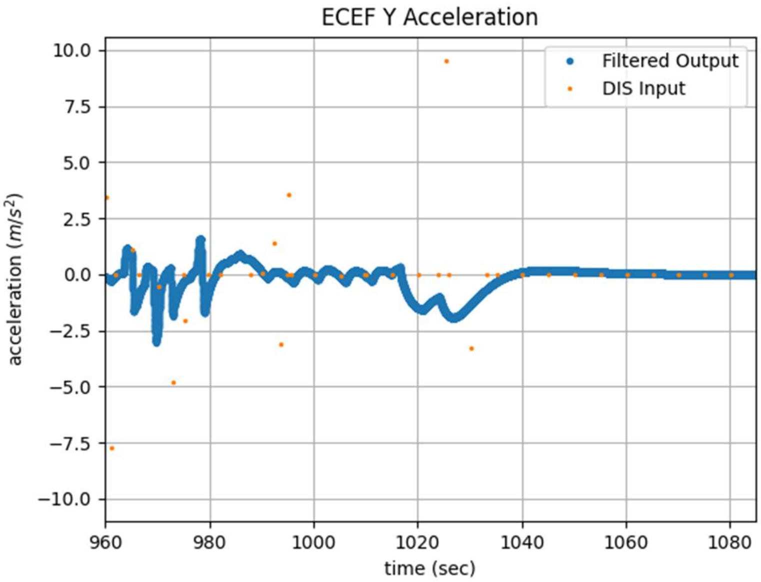

Figure 7. Filtered Acceleration Data, Zoomed-in

Figure 8 shows position data taken from the same flight path. Shortly after the 700 second mark, the DIS dead reckoned data has a significant deviation from the desired motion path before jumping back to the correct position on the next DIS ESPDU update. The filtered data was able to bridge this gap and continue to provide accurate position data. Whereas the dead reckoned data abruptly changes its direction of motion at the 740 second mark due to the poor underlying flight model, the filtered data overshoots this sudden change in direction before converging back to the inputted motion profile. This overshoot is more realistic to the desired vehicle motion than the raw input data provided by the poor flight model while also allowing the simulator to stimulate the SUT with smooth and continuous inertial, GPS, and air data signals. The amount of overshoot here is determined by the tuning parameters provided to the filter. This tuning is a trade-off between filter response quickness and the amount of smoothing desired. In practice, these parameters should be derived from the dynamic properties of the SUT.

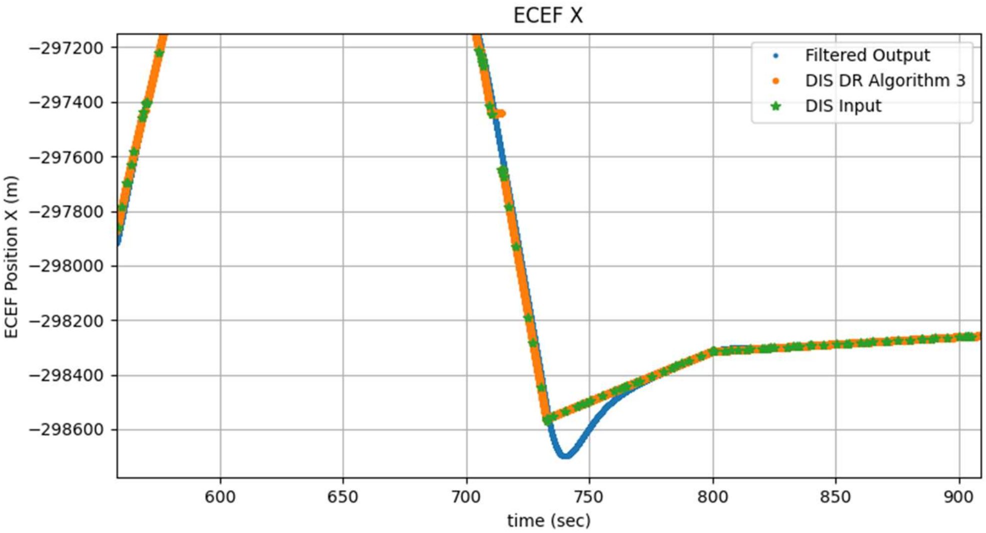

Figure 8. Filtered Position Data

The simulation source DIS data shown here was produced by a poor flight model with limited dead reckoning data. This type of data is typical for distributed test events where control of the simulation environment is in a remote location. In other cases, however, more realistic vehicle motion data is available along with more dead reckoning parameters. In these cases, filter performance is further improved by the additional dead reckoning data.

Attitude State Filtering

SUT attitude states are produced similarly, but with a second order lowpass filter. A second order filter is used for the orientation states instead of the third order filter because the stimulation hardware produces angular velocity, which is typically measured directly by the GPS-INS gyroscopes. Angular velocity is the first derivative of orientation, whereas acceleration (which is the parameter directly measured by the IMU accelerometer) is the second derivative of position. Where a third order filter was required to produce a smooth data profile for acceleration, velocity, and position, a second order filter is all that is required to produce smooth angular velocity and attitude data. The equations for the attitude filter are given here:

$$\ddot{\theta}_{k+1} = \left(\omega_{input} - \dot{\theta}_k\right) * k_1 + \left(\theta_{input} - \theta_k\right) * k_2 \tag{6}$$

$$\dot{\theta}_{k+1} = \dot{\theta}_k + \left(\ddot{\theta}_{k+1} + \ddot{\theta}_k\right) * \frac{dt}{2} \tag{7}$$

$$\theta_{k+1} = \theta_k + \left(\dot{\theta}_{k+1} + \dot{\theta}_k\right) * \frac{dt}{2} \tag{8}$$

Where $\ddot{\theta}$ is the rate of change of angular rate, $\dot{\theta}$ is the angular rate, and θ represents any one of the SUT Euler angles, ω_{input} is the angular velocity data from the DIS ESPDU, θ_{input} is the Euler angle provided in the DIS ESPDU, dt is the simulation time-step, the subscript k or $k + 1$ represents the value at time k or $k + 1$ respectively, and k_1 and k_2 are filter tuning coefficients. These parameters are calculated similarly to the gain parameters calculated above.

These equations provide sufficient smoothing to the incoming data when data is provided for each of the states directly in the DIS ESPDU. However, in some cases, a poor vehicle model is provided from the simulation source and several vehicle states are not directly provided (commonly pitch and roll). In this case, a vehicle model is required to fill in the unknown vehicle dynamics. Additionally, it sometimes may be desired to use an alternative vehicle model, even if all the states are given, to provide more realistic SUT vehicle dynamics. Using this filtering technique, those values can either be calculated directly and provided as inputs to the above lowpass filter or an alternative dynamic model could be used to provide vehicle dynamics that are specific to the SUT, instead of the third order filter previously discussed. This is an area of future work for this stimulation capability.

As stated above, the primary purpose of developing this filter model was to allow for the creation of smooth, continuous SUT stimulation signals, regardless of the quality of the simulation input data. To validate the effectiveness of the generated stimulation signals in various conditions, this capability was evaluated through a rigorous verification and validation (V&V) process.

VERIFICATION AND VALIDATION

Verification and validation are essential procedures needed when integrating a newly developed capability into an existing architecture. It is important to understand the definitions of these two terms before V&V activities can begin. The Project Management Body of Knowledge (PMBOK®) Guide defines the two terms as:

- "Verification. The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation."
- "Validation. The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. Contrast with verification."

Verification

Verification is a tool used when receiving or developing a product for the first time. The end user should make sure the received product meets all stated requirements. Specifications such as size, weight, current draw, and output voltage are all examples of parameters that can be verified. Before RTC received the GPS-INS stimulation hardware, RTC generated a Verification and Validation (V&V) test plan. Verification was conducted based on this V&V test plan.

The signal generator creates high-fidelity GPS and INS signals encountered by the SUT while wrapped in an operationally relevant environment. The signal generator drives the navigation system with the relevant operational scenario inputs, including realistic error modeling for atmospheric, timing, and dynamic effects, enabling the system to behave as if in an operational environment. The signal generator, software and inertial simulation capabilities were tested, making sure a simulated vehicle's receive antennas were receiving correct satellite signals for a given location and ephemeris. Additionally, verification was leveraged from work already conducted by the United States Space Force (USSF) Global Positioning Systems Directorate (GPSD) stating that the GPS signals generated by this system are a valid representation of the GPS constellation. The inertial drift model verification was limited to a generic error model.

Validation

Validation is used when determining how specific products, when used together, fulfill the capability gap the system is designed to accomplish for Army specific missions. In this application, the hardware delivered included a custom version of the GPS and INS simulator, and testing was designed and documented in a V&V test plan making sure it would meet the goal of aircraft flight simulation.

Several test events were conducted on Army platforms based on the V&V test plan's objectives. These test events were used when determining if the overall system could meet specific objectives the U.S. Army needs to conduct safe and successful missions. Due to the sensitive nature of data embedded within RTC's V&V report, the authors of this paper are unable to disclose many of the specific findings to the public. However, after thorough review, the assumptions, limitations, and constraints associated with this capability were deemed to have a low impact on the effectiveness of the stimulation environment. This V&V effort concluded that the outputted stimulation signals are sufficiently realistic to immerse a SUT in the desired operational environment (including GPS, inertial, air-data, IFF, tactical data link, serial data, and tactical IP data stimulation) even with low-quality simulation input data.

CONCLUSIONS

Using this flight-representative capability during a cyber assessment and immersing the system under test in an operationally realistic environment aids in identifying cyber risk when the hazards prevent testing in flight. Having the aviation platform in a mission-based operational wraparound increases the attack surface and aids in identifying mission critical vulnerabilities. This high-fidelity virtual flight simulation capability is necessary to prevent damage to the aviation platform and produce a high-quality flight model during test and evaluation.

This capability allows for the creation of output dynamics and signals that are independent but driven by the simulation input data. Therefore, the same high-quality output signals are produced regardless of the quality or type of the simulation input data. This method also allows for dynamic limits and other protections to be placed on the output signals to prevent the SUT from encountering unintended dynamics. Assuming that the SUT linear dynamics can be approximated by the third order dynamic filter and the SUT attitude dynamics can be approximated by the second-order dynamics described above, this solution provides smooth, continuous GPS, INS, air data, and other signals to the SUT. In some cases, this second and third order approximation may not provide sufficiently accurate vehicle dynamics for a given SUT. In this case, more specific vehicle dynamic models should be developed and used in place of the filters shown here for the system of interest. This is one avenue of future work.

This capability has undergone a rigorous V&V process to ensure the credibility of the simulated signals and has successfully been utilized to put several different systems into a simulated environment to add value to cyber tests. Future development is anticipated for this capability to interface with additional types of platforms with different stimulation input requirements along with interfacing with additional simulation input sources as needed.

REFERENCES

IEEE Standard for Distributed Interactive Simulation – Application Protocols, IEEE Std 1278.1-2012, New York, NY, 19 Dec 2012.

Murray, B. (2022). *IEEE 1278 Standard for Distributed Interactive Simulation (DIS): Concepts and Techniques.* I/ITSEC 2022, Orlando, Florida, United States.

O'Connor, M., & LeSueur, K. (2021). *Distributed LVC Based Testing Using a Hybrid Digital Twin.* I/ITSEC 2021, Orlando, Florida, United States.

O'Connor, M., LeSueur, K., Novak, J., & Blair, C. (2017). *LVC Environment to support System-of-System Cyber Testing*. I/ITSEC 2017, Orlando, Florida, United States.

Palm, W. (2013). *System Dynamics* (3rd ed.). McGraw-Hill Education.

Project Management Institute. (2008). *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)* (4th ed.).