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A MODULAR OPEN SYSTEM APPROACH TO A DIGITAL AUTONOMY TESTBED

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ABSTRACT

With the arrival of robotic autonomy in future Army ground combat vehicles there is an intrinsic need for modeling and simulation infrastructure for autonomy. Taking a Modular Open System Approach to designing modeling and simulation architecture facilitates creating a flexible, scalable, and adaptable infrastructure that can be applied to a wide range of scenarios to assist Army programs of record and accelerate technology maturation while providing a low-cost, efficient way to reduce program risk and ensure next-generation robotic ground vehicles provide greater value to the soldier.

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1. INTRODUCTION

The arrival of robotic autonomy in future Army ground combat vehicles such as the Robotic Combat Vehicle (RCV) signals the need for a versatile digital testbed capability that can support Army Program of Record (POR) decisions surrounding the complex and diverse design and implementation of such vehicles. These needs include digital representations of the vehicles and the ability to quantify vehicle performance in a multitude of operational scenarios and threats in realistic and representative environments. Operational scenarios are equally complex and include varying mission objectives, vehicle formations, and coordination, multi-echelon integration, vehicle tele-operation, and semi-autonomous modes, varied mission packages, and more. Traditional methods of developing, testing, and evaluating ground vehicle systems must evolve to keep up with the fast pace of innovation in autonomous robotics and Artificial Intelligence (AI) and to position the Army at the forefront of modernization.

The Army's Modular Open System Approach (MOSA) is a strategic framework that aims to enhance the development and modernization of defense systems. [1] Torch believes incorporating MOSA as the backbone of the Army's Modeling & Simulation (M&S) autonomy testbed will provide the tools and framework necessary to answer questions related to vehicle performance; autonomy behavior; logistics; vehicle buses; power utilization; survivability and protection; cyber and electromagnetic (CEMA) posture; crew safety, fatigue, and efficiency; external communications; GPS denied operations; lethality; and much more. In this paper Torch has identified key attributes of a MOSA testbed based on research and implementation and will explore how their inclusion can improve fact-based decision making, accelerate technology maturity evaluations and trade studies, and provide early soldier feedback resulting in improved answers for next-generation combat vehicle programs, ultimately providing schedule reduction, program risk reduction, cost savings, reduced integration risk, and improved warfighter acceptance.

2. TORCH AUTONOMY TESTBED

In response to emerging robotic autonomy needs, Torch developed the Autonomy Testbed (ATB) under an Independent Research and Development (IRAD) effort to identify best practices for enterprise M&S of robotic and autonomy systems, and to create a prototype testbed for evaluation and demonstration, leading to sharing and technology transfer to Army Combat Capability Development Command (CCDC) Ground Vehicle System Center (GVSC) and ground vehicle programs to augment their existing capabilities. The relevant ATB use-case is a crew station (CS) concept simulator for RCV manned-unmanned teaming (MUM-T) operations, with requirements derived from Torch's experience and interactions with GVSC and the GV community. A primary goal for the ATB was to identify key attributes required for a MOSA implementation in the digital autonomy testbed that accounted for all elements shown in ***Figure 1***, including simulation development, physics-based modeling, CS simulation, virtual terrain and model asset development, and simulation interoperability.

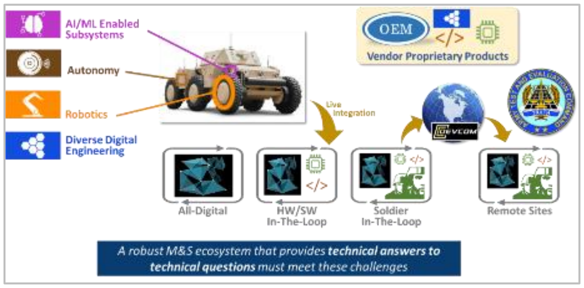


Figure 1: Torch ATB IRAD

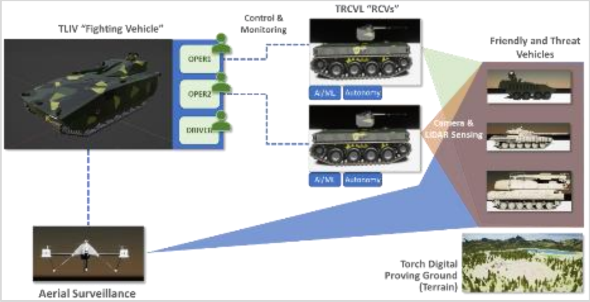


Figure 2: Autonomy CS Scenario

The prototype scenario is depicted in ***Figure 2***. The goal of this multi-crew CS use-case was to allow multiple operators to manage MUM-T in an immersive simulation environment with the goal of developing MUM-T Concepts of Operation (CONOPS), Techniques, Tactics and Procedures (TTPs), and to create and refine program requirements. Two operators can work within the vehicle together, one operating using a Virtual Reality (VR) CS and the other operating using a desktop user interface virtual CS. This approach of having multiple technologies for user interfaces working together demonstrates interoperability for multi-user support and allows digital modeling and assessment of soldier interoperability with Aided Target Detection and Recognition (AiTDR) and autonomy algorithms. Physics-based models were created for a concept Torch Light Infantry Vehicle (TLIV) and a concept Torch Robotic Combat Vehicle Light (TRCVL) with vehicle kinematics and dynamics, sensors (e.g., lidar, camera, IMU), and communications channels. Additionally, the Torch Digital Proving Ground virtual terrain, vehicle interiors and exteriors, and human 3D model assets were created. The physics and 3D models were combined into an interoperating distributed simulation environment that included digital twin simulations for each vehicle, a simulation of the CS, and the open-source Gazebo autonomy simulation. [2]

3. MOSA DISTRIBUTED AND SCALABLE DESIGN

As in any system of systems, modularity is important for evolving technology and program sustainability. Modularity isolates integrated components for independent testing, provides interchangeability for evolving mission environments and emerging technology integration, and helps promote competitive innovation. An advantage identified during implementation of the ATB is that using MOSA for a digital testbed reduces the scope of testbed software development and shifts most of the focus to the performance and function of the interoperating ecosystem that enables hardware and simulated component integration into the testbed.

The widely adopted open-source ROS owes much of its popularity to a modular node-based design. [3] A MOSA digital autonomy testbed that adopts a similar node-based design can incorporate any mixture of preexisting or new software that is adapted to match a defined MOSA node protocol. A concept of this design is shown in ***Figure 3*** where a central base testbed has autonomy software and simulation packages attached as nodes.

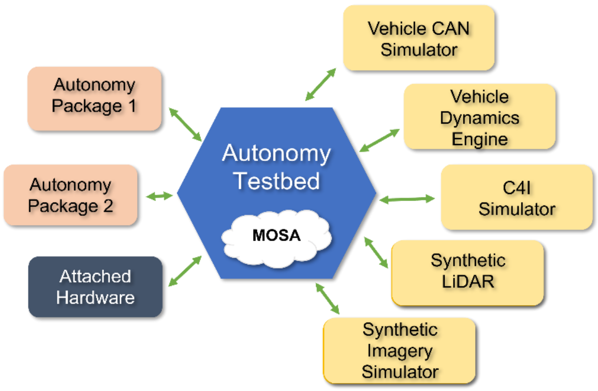


Figure 3: Expandable node-based digital testbed architecture.

A robust and universal protocol for component-to-component data transportation is also required in the testbed architecture to support the node-based design. A MOSA defined standard for communication between nodes support interoperability within and between unmanned systems and control stations while keeping each component independent from the technology employed by the others, resulting in a plug-and-play approach to integration of components into the testbed environment.

The Torch ATB defines a node as a single physical computational endpoint in the system. This could be a computer, or vehicle hardware, and each node can contain one or more components which provide specific information or services to the system like sensor data or navigational motor control signals. Each node and component of the system strictly followed our defined MOSA protocol when communicating with other components. This approach aided rapid reconfiguring of components and inter-mixing of physical and all-digital components, and achieved the goal for interchangeability which is also scalable.

Using nodes and components as building blocks for MOSA M&S, a scalable, distributed system can be built and re-built to suit the demands of different applications and scenarios of interest. Vehicles or components being exercised do not need to be entirely digitized, nor must they all interface directly with or reside on the same high-end, expensive computer as simulation or rendering software. Instead, as shown in ***Figure 4*** below, the testbed components can be distributed amongst several, cost-effective computers. Additional nodes and components can be added or removed to scale the testbed to the needs of the system under test (SUT).

With this approach a developer designing a test scenario has greater flexibility when choosing what is incorporated, and the resulting testbed bed can be integrated and executed more rapidly and with lower cost than other architectures that do not adopt a MOSA strategy.

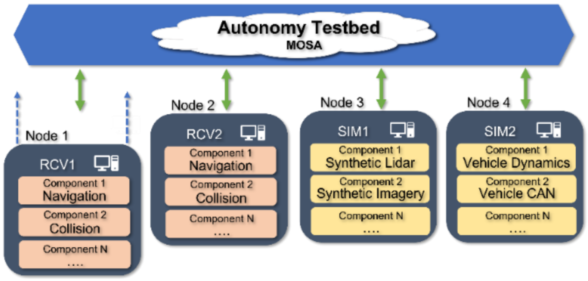


Figure 4: Scalable distributed testbed infrastructure.

3.1. Torch Autonomy Testbed Example

The Torch ATB demonstrated this concept of plug-and-play modularity in support of developing AiTDR algorithms. During early concept development, Gazebo was used to generate synthetic imagery data for the AiTDR synthetic environment. However, as development progressed and AiTDR algorithms required more realistic scenes, the concept vehicle's AiTDR sensor component, originally developed to sense in the Gazebo environment, was replaced with a new component sensor that provided higher-fidelity synthetic scene data from an independent but connected Unreal Engine [4] (UE) node. Our MOSA to ATB facilitated seamless interchange between these different component representations of the scene for AiTDR algorithms as needed with minimal-to-no impact on the rest of the testbed configuration.

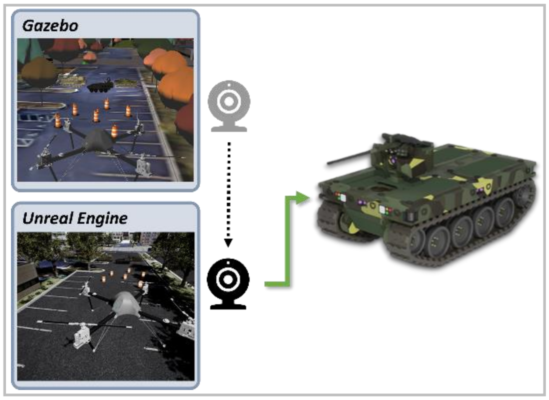


Figure 5: MOSA enables rapid swapping of digital components in testbeds, such as synthetic scene sensors.

3.2. Torch Autonomy Testbed Objective

The Torch ATB has an objective for 2024 year to demonstrate that MOSA is easily scalable and interoperable between autonomy of vastly different types, mission objects, and operating software. Torch plans to introduce a digital twin of an autonomous unmanned aerial system (UAS) into the multi-vehicle, multi-user, MUM-T scenario.

The two TRCVL vehicles already implemented into the ATB scenario use ROS-2 based operating software and navigation algorithms. However, to integrate them into the MOSA testbed, and communicate with other vehicles and CS they use a plugin to translate specific ROS messages to the define universal MOSA messages. These messages include teleoperation commands, autonomous waypoint commands from the CS, camera image feed, and positional data. This plugin, once created, can be used for any ROS enabled system.

The UAS targeted for integration operates using the opensource autopilot software ArduPilot [5] which uses the MAVLink [6] protocol for inter and intra process communication. Running software in the loop mode, the UAS will use tools like JSBSim [7] or Gazebo for flight physics and synthetic sensors in the shared virtual terrain.

Following the guidelines laid out above, a MAVLink to MOSA protocol translator plugin will be created. Allowing the UAS to function seamlessly with all existing nodes and components including the CS's waypoint and teleoperation commands. This plugin, after creation, can serve as a migratable software package that will work with all systems using the MAVLink protocol. Truly creating a scalable, distributed, and interoperating M&S ecosystem that could benefit any new or existing Army program.

4. MOSA HARDWARE IN THE LOOP

An important capability for modern and future PORs is to integrate prototype or tactical hardware and software into a common digital environment, using hardware-in-the-loop (HWIL) and software-in-the-loop (SWIL) simulation techniques to integrate, test, and evaluate system components earlier, resulting in decreased technical risk for POR lifecycle activities. POR digital testbeds for robotic autonomy that are built with MOSA are key components of this capability. Although it is highly beneficial to have a complete digital twin of the SUT, it is not always possible or cost-effective. Hardware components can provide highly credible representations in digital assessments and conversely, digital twins that are representative of component hardware can support evaluation and assessment in scenarios where hardware is unavailable or physical evaluation is difficult or cost prohibitive. Likewise, there are key advantages to integrating tactical software into a M&S configuration to support software development, integration, and simulated operational testing. Testbed environments can utilize MOSA to support interoperation with digital twins, real hardware, and tactical software – a crucial capability for evaluating system integration.

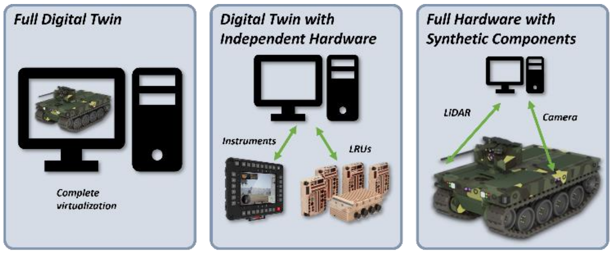


Figure 6: MOSA testbeds can support interoperation of digital and physical system components.

Figure 6 illustrates three levels of hardware in the loop simulation. First is a completely digitized twin of the SUT. Every component required has a digital counterpart modeling its function. Second is a digital twin with independently attached hardware components such as instrument panels or line replacement units (LRUs). Third is the complete system hardware connected with minimal synthetic data generation.

A MOSA digital testbed is able support all three levels of HWIL interoperation. A universal component-to-component transport protocol is again part of the solution. For components that are not natively written with the defined MOSA data transportation protocol, plugins can be written to adapt them. Plugins are small, lightweight, non-intrusive translators that transform the native technology protocol into the testbed's standard, making it compatible with every component in the simulated system. ***Figure 7*** illustrates the concept of plugins to integrate hardware into the digital testbed. In the scenario shown, a vehicle is connected to the simulation via a plugin where its LiDAR and camera are synthetically simulated. New LRU hardware under consideration for integration is being evaluated *"in the loop"*

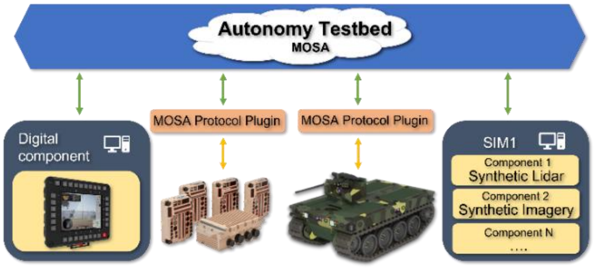


Figure 7: Combination of synthetic and plugin enabled hardware

with the plugin connecting the native technology. Finally, traditionally hard-to-acquire instrumentation for the vehicle control station is digitally simulated as a separate node of the simulation.

Using plugin translation layers in the testbed, hardware, software, and other commercial simulation tools can be swapped in or out or be replaced by other components entirely without affecting the simulation because they are connected to the modular digital environment in a uniform fashion. In addition to providing new opportunities for engineering development, assessment, and integration earlier in a program's lifecycle, this approach affords a built-in ability to verify and validate digital component performance against real-world hardware and tactical software, increasing the credibility and confidence of results derived from the digital testbed.

4.1. Torch Autonomy Testbed Example

The Torch ATB demonstrated all three levels of autonomy HWIL simulation using the prototype MOSA testbed. There are two TRCVL units operating in the CS scenario. The first TRCVL ROS2-based autonomy algorithms were completely encapsulated in software as a digital twin, while the autonomy for the second TRCVL operated on an Nvidia Jetson Orin compute module, ***Figure 8***.

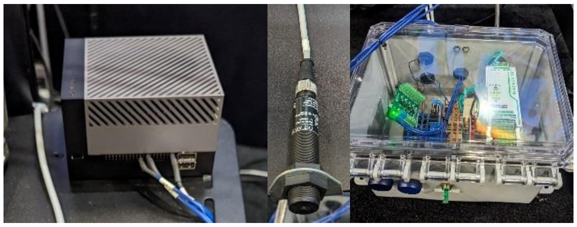


Figure 8: HWIL components interfaced with the ATB.

The Orin represented a real vehicle autonomy module, and because it was following the defined MOSA data interchange protocol, it could be connected into the MOSA simulation seamlessly, where it preformed navigation and obstacle avoidance algorithms from the synthetic sensor data sent over the interface from the UE scene. The ATB also connected a hardware LRU proximity sensor component to the simulation though a MOSA protocol plugin. The first TRCVL digital twin in the simulated scenario received the hardware proximity sensor data though the MOSA data transport and reacted just as it would out on a real test range by adding the sensed data point to the navigational cost map.

4.2. Torch Autonomy Testbed Objective

The Torch ATB has an objective for 2024 to integrate a realistic hardware LRU into its MOSA architecture in a HWIL configuration. Torch is experimenting with creating a small UAS protective deployment box for the MAVLink UAS mentioned in an above section and it will communicate with the SUT via CAN protocol. This integration will not only receive output from the simulation in the form of deployment hatch open and close commands but also return input into the simulation by sending the angle of the hatch and only enabling the UAS to launch or land when the hatch is fully open. Demonstrating that a MOSA M&S infrastructure can integrate multiple communication protocols and realistically provide I/O that blends software digital twins and hardware LRUs in a seamless manner as if they were connected to the real vehicle.

M&S simulation with this capability would aid the Army in technology integration testing and selection.

5. MOSA NETWORK SIMULATION

Army systems, future combat vehicles, and autonomy, depend heavily on networks for intra-vehicular, vehicle to vehicle (V2V), and vehicle to infrastructure (V2I) communication. Effective communication and networking are essential for autonomy data processing and responsive action, along with coordinating actions for human machine integration and formations (HMI-F) across multidomain operations. Understanding if a network has the capacity and is correctly implemented before fielding is essential for operation effectiveness and lethality. Unexpected latency, bandwidth limitations, and corrupt packets can lead to delayed real time response, compromised situational awareness, and endanger lives. A MOSA modeling and simulation infrastructure can be the solution for early understanding of networks within unexpected environments that can help guild decisions and requirements that reduce this risk.

A MOSA autonomy M&S infrastructure should be designed to allow for communication characterization built into the universal messaging protocol. Digital twins interfacing with the simulation architecture should be able to have its network characterizations defined though variables including maximum bandwidth, data rate, latency, corruption level, and others depending on the type of network. Furthermore, each of these variables must be dynamic and capable of changing per iteration or during the scenario to realistically reflect changing environment conditions or battle damage. Lastly, each connection to the simulation infrastructure should be able to define these characteristics per connection. For example, if one autonomous vehicle is sending telemetry data to another vehicle close by via a line-of-sight link, that characterization would be different from the telemetry data sent to a distant command station using a long-range radio link. This same concept can extend to other simulated vehicle electronic and bus types like CAN, serial, and even hardware digital signals.

Figure 9 shows a visual concept of digital twins in a MOSA simulation environment using the described network characterization as a software plugin to the simulation to communicate with themselves and other systems in the scenario.

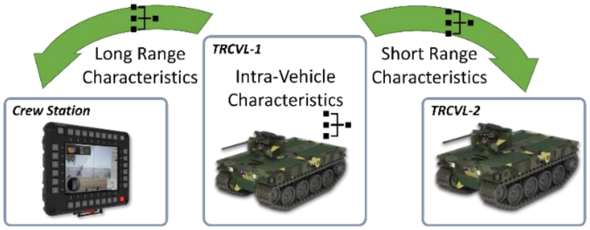
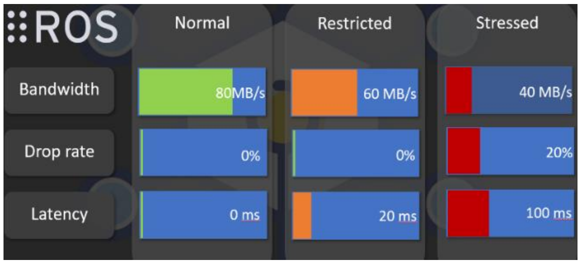


Figure 9: Network characterization profiles defining different communication methods.

There are challenges to implementing this programmatically, but to accurately create a digital twin, accurate network characterization should be included. If these networking characterization tools are created and available in the MOSA infrastructure directly as a universal software plugin, then the powerful networking capabilities and program benefits would be available to all integrations.

5.1. Torch Autonomy Testbed Example

Torch views network characterization as critical for modeling and simulation of autonomous and future combat vehicles and is executing a phased development approach. At the 2024 MDEX conference, Torch successfully implemented and demonstrated an intra-vehicular network characterization of the ROS2 enabled TRCVL digital twin executing in the autonomy testbed. ***Figure 10*** below shows a chart of three profiles we defined for the vehicle.



ROS	Normal	Restricted	Stressed
Bandwidth	80MB/s	60 MB/s	40 MB/s
Drop rate	0%	0%	20%
Latency	0 ms	20 ms	100 ms

Figure 10: ATB network characterization profiles.

The first is a normal network where there is a high ceiling for bandwidth with no latency and no packet drops. The second represents a restricted network where there could be a lower end network controller integrated into the SUT, or an additional load on the network limiting the available bandwidth for ROS2 messages. The Stressed profile severely limits the system network bandwidth, increases the latency, and causes many packets to be lost in transmission. This is intended to represent a worst-case scenario for the vehicle network which could be caused by battle damage, electromagnetic interference, or cyber-attack.

5.2. Torch Autonomy Testbed Objective

Torch maintains the goal of extending the network characterization of the MOSA autonomy testbed to include realistic real time over the air V2V and V2I network characterization in the future with realistic radio communication modeling. Torch has identified some open-source tools like ITU-Rpy [8] which is a python implementation of the international technical standard developed by the Radiocommunication Sector of the International Telecommunication Union (ITU) [9].

ITU-Rpy allows for fast computation of strength and intensity of electromagnetic signals as they travel though earth’s atmosphere. These algorithms account for location, elevation, rain, dust, and more of which can be used in the simulation to accurately impact the real time characteristics of the SUT’s radio communication in the simulated terrain.

Torch continues to research how the ITU-R resources and other tools can be utilized to accurately simulate networks in its ATB.

6. MOSA ENABLED TOUCHPOINTS

Live operation of MOSA is accomplished using touchpoints which are representative Human Machine Interface (HMI) components for operating part of the system. Touchpoints are critical to next-generation combat system development because they provide a mechanism to formulate feedback on, and a enable operators to test the system using their field experience. Immersive touchpoints go a step further enabling increased accuracy for the response from the operator because immersion provides an environment where the operator can believe they are in control of the complete physical system and will exert that control according to that belief. Touchpoints provide value in several other ways as well including potential for training of the system operation, interaction with HMI-F/MUM-T and requirement design and validation. MOSA enabled Touchpoints can be created and operated early in the system development process because they do not require a complete system to physically exist. In a MOSA architecture, touchpoints following the node-based design can be represented as a hardware component in the loop as described above or can be a virtual touchpoint which is a software digital twin of the physical system component. Touchpoints can be as trivial as a single touch display unit, handheld controller, or as complex as a full-sized command station. Touchpoints should function the same as it would in the field when adhering to the MOSA transport protocol to communicate with other nodes and components to send and receive the data.

Virtual touchpoints enable soldiers to be directly involved with influencing the system development outcome. For example, a soldier could be driving a leader vehicle of an autonomous platoon and designating targets and identify that harm might have been inflicted to the operator in a safe environment which poses no physical danger.

Virtual touchpoints can be used by developers, testers, and program managers to gain an understanding of the system and how it performs by viewing the scenario from a third person perspective in VR just as they would in the field. Where now an operator can experience each scenario as many times as desired and from any position or angle.

6.1. Torch Autonomy Testbed Example

The Torch ATB IRAD demonstrated the concept of solider in the loop immersive virtual touchpoints using the MOSA testbed. A VR Head Mounted Display (HMD) is used to present the operator with a virtual model of the cockpit with the controls necessary for its operation. The scenario demonstrates how soldiers can use an immersive virtual touchpoint to operate and command a mixed human and machine formations the same as in the field.

In this demonstration, one or two users are positioned in the digital twin cockpit with CSs for a notional command vehicle, shown in ***Figure 11***, where they can control the vehicles movement through the terrain. Additionally, either of the operators can command either of the two TRCVL digital twins in the scenario though autonomous waypoint commands or teleoperation. Situational awareness is provided through the UAS and TRCVL sensors on the virtual displays.

Figure 11: Operator, and command vehicle touchpoint.

The virtual CS is modeled based on future combat vehicle concepts and included a steering yolk, and three display monitors. The CS component is connected through the MOSA testbed which enables each of the three monitors to be able to receive remote sensor information in real time. The CS setup can be seen in ***Figure 12***. The central monitor received camera information from a tethered UAS above the command vehicle while the left monitor is toggled by the operator between the camera, LiDAR, and AiTDR feeds for either of the two TRCVLs. The right monitor displayed a map of the operation area with real time position updates from both TRCBLs and other simulated vehicles.

Figure 12 : MOSA VR vehicle CS.

This capability is reusable for any scenario or vehicle requiring this type of touchpoint because the software was developed following the MOSA architectures.

7. MOSA SUPPORT FOR NON-REAL-TIME DIGITAL EXECUTION

For a digital testbed to be suitable a wider range of applications, it must be able to adjust its digital clock to run both faster than real time, and slower than real time. A test scenario may require a simulation testbed to run slower than real time because a simulated component requests extra time to synthesize data for certain high-fidelity sensor and thus the simulation must halt all other process for it to catch up. On the other hand, it is common for computers running simulated nodes to have sufficient computational power to process all necessary data faster than real time. This is a substantial benefit to automated testing because it enables more tests with more iterations to be evaluated in a shorter amount of time. Special consideration must be taken for HWIL digital environments, as it is not always possible for physical hardware to execute at the simulated timescales used in non-real-time digital environments. Despite these considerations, non-real-time execution in a digital testbed affords unique opportunities to provide technical answers that can be difficult to provide in other environments. For these reasons, a future MOSA digital testbed should support non-real-time scenarios uniformly on all connected nodes, components, and hardware.

To accomplish this, a time synchronization component is needed in the MOSA data transport protocol and possibly additional software logic to handle processing data in segments. Although this has not been demonstrated yet in the Torch ATB IRAD, ***Figure 13*** below shows an abstract discrete-time execution prototype where each component in a node processes a definable length of time in the digital environment, then waits for all other components to reach the same timestamp before simultaneously continuing to the next.

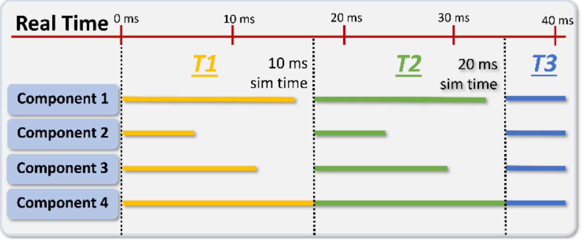


Figure 13: Concept – component time synchronization.

A non-real time MOSA capable digital autonomy testbed can exercise rapid Monte Carlo style iterative tests with immense numbers of iterations at large scales. [10] Additionally all-digital simulations and digital twins can be exercises in tests via cloud environments, enabled by the scalability afforded in the MOSA architecture. More tests can be completed with more permutations in each scenario or system than could ever be tested on a real test range, which can assist in bringing a program to maturity faster.

8. MOSA M&S ENABLED ANALYSIS

Future compact and autonomous vehicles can no longer be called simply standalone platforms. They are increasingly more and more complex systems made up of many smaller but equally important subsystems such as vehicle protection, drive by wire, soldier interfaces, autonomy, formations, networks, and much more. All of which contribute to the complexity of a program in all phases and especially young program in the early phases of exploration and development. Systems are becoming too expensive and complicated to adequately test in a cost-effective manner that grants complete understanding of the system. For example, it is difficult to test how an RCV performs in a nighttime sandstorm without having to fly large amount of people to the desert and wait for the perfect conditions. Furthermore, autonomy and AI are inherently non-deterministic and do not always act the same given similar conditions. Performing enough real-world test to fully touch all scenarios a SUT might experience would cost too much money and time. This can be even increasing difficult when the system is still a concept and is not yet built. Not understanding technology and failing to provide adequate system requirements leads to program failure and cancelation. However, M&S based analysis can help bridge the knowledge gap by providing cost-effective and quick scenario specific testing over more iterations than could ever be done with physical testing.

Simulation based analysis does not replace real field testing but is supplementary and can help better prepare a system for successful field testing. For instance, digital trade studies and digital system technology integration, using digital twins of new modules, packages, and sensors following the MOSA messaging protocol can integrate into existing program M&S ecosystems seamlessly and be evaluated before acquisition. Collecting data and evaluating the performance first without having to modify existing equipment can save cost and reduce risk while providing valuable data for informed choices.

The software used to generate the data, and the tools for analyzing it should be built into the MOSA architecture to ensue that the program benefits from incremental changes throughout its lifespan. A program that adopts a MOSA M&S architecture early can improve the process of integration by providing original equipment manufacturers (OEM) with copies of the M&S architecture for testing their proposed technologies. This gives the Army a single source of truth when it comes to evaluation of potential integrations. Due to the MOSA design, OEMs can confidently integrate their hardware or software equipment for fair evaluation and the Army can compare the same test criteria for each of the offered solutions which builds confidence in the system.

The below sections cover a few more M&S enabled analysis topics and tools Torch developed in the ATB IRAD.

8.1. Autonomy and Navigation Analysis

The Torch ATB demonstrated the effectiveness of M&S analysis at the 2024 MDEX conference by performing what we called a digital rodeo for autonomy and navigation. In this case, a digital rodeo is taking a digital twin and making small incremental adjustments to it and recording the system performance. In this digital rodeo, one TRCVL attempted to safely navigate an unknown environment and detect a target at the end using and AiTDR algorithm.

Optional parameters on the RCV under test included a choice between two different path planning navigation algorithms, two route obstacle detection algorithms, three realistically modeled commercial off the shelf LiDAR, five AiTDR camera positions, and four different intra-vehicle network profiles. Additionally, target type, terrain location, time of day, and level of fog in the environment could be adjusted.

The goal of the digital rodeo was to fully evaluate the systems performance given variations with the vehicle and environment. This small data set of options made up of over 9,000 unique test scenarios. This many scenarios would be impossible to test in the real-world cost effectively. However, leveraging Monte Carlo style automatic processes, the ATB preformed over 200 iterations automatically overnight and saved all the metrics for analysis.

Figure 14 shows a capture of the ATB analysis tool developed for evaluating the SUT's autonomy during the digital rodeo. Each path the robot took to reach its goal (the green marker) is drawn on the map. Blue lines indicate a successful detection of the target at the end, and white indicates the

Navigation	Detection	Lidar Type	AITDR	VEA	Target	Map	Fog	Day/Night
Pure Pursuit	Voxel	Velodyne_Puck-Lite	Position 5	TRCVL - None	SAM	Bridge	No Fog	Night

Figure 14: Digital rodeo autonomy analysis.

identification failed. Any of these lines could be selected and the configurations chosen for the selected iteration would be displayed above the map in yellow lettering.

This type of tool would be valuable to Army autonomy programs because it can help identify outliers in the robotic behavior. For example, over the 200 iterations, nearly all routes followed a distinctive path, however, there were a few that strayed in different direction and one that chose to go north around an obstacle where all other iterations went south. With this data provided by this analysis tool, a test engineer could view exactly the parameters used for that run and identify what was different, what potentially caused it, and what would need to change to eliminate unwanted behavior. It is very unlikely this behavior would have been captured on a real test range and the unwanted behavior could have been deployed to the field where it could pose a significant risk to soldier safety. If changes were made to the digital twin, the scenario with the same initial parameters could be loading again and testing over and over to ensure desired behavior.

This M&S based analysis would be significantly less cost than real field testing, and programs could have higher confidence in the system before production and fielding. Ultimately contributing to a safer more effective warfighter.

8.2. Vehicle Network Characterization Analysis

Vehicle internal networks are difficult to capture and are mostly invisible. However, as discussed before, networks are critical to system lethality and having the tools to view and analyze them in an M&S infrastructure is crucial. Torch demonstrated such a tool developed for ATB at MDEX 2024. This tool is used to analyze the vehicle network performance and characteristics for each message communicated in a ROS2 intra-vehicle network.

During execution of all the 200+ iteration mentioned in the previous section all ROS traffic traveling within the TRCVL was captured for post analysis. For each individual iteration, the network analyzer tool can determine some key captured characteristics such as total topics, average message size, total megabytes, and more. It can also breakdown each topic and display the rate and bandwidth of messages transmitted on that topic. ***Figure 15*** shows a portion of the analysis tool. This chart shows the aggregate bandwidth for every topic over the complete iteration stacked together. Interestingly, in the SUT, map updates consume the most bandwidth in the system while lidar points clouds do not take up nearly as much of the network capacity.

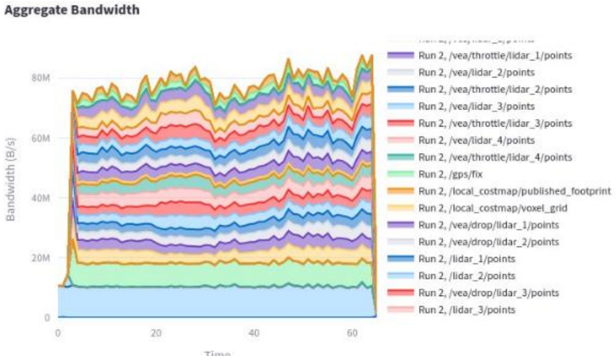


Figure 15: Vehicle network characterization analysis.

This type of tool can give valuable insight into what is causing throughput blockage, and what is required for each topic to maintain mission effectiveness.

Troch plans to adapt this analysis tool to be used with the objective of modeling and capturing over the air communication characteristics, as well as non-ethernet communication methods.

9. VALUE OF A MOSA DIGITAL AUTONOMY TESTBED

Digital twins and vehicle hardware, integrated in a digital testbed framework, allow for concepts to be evaluated across a wide and diverse array of potential scenarios, contexts, and use cases. By leveraging MOSA, these testbeds promise long-term digital engineering advantages by blending the traditionally separate domains of digital simulation and hardware testing. Digital autonomy testbeds provide a low-cost, effective engineering environment that persists throughout program lifecycles, helping early concepts mature into fully realized solutions that can be integrated and evaluated with ground vehicles and weapon systems. For early concepts, digital twins support autonomy development with training pipelines, tools for synthetic data generation, and early evaluation of digitally integrated vehicle concepts. Digital testbeds allow all-digital, all-hardware, and mixed HWIL configurations to be exercised in realistic synthetic environments to provide significant information for data-driven decisions while reducing risk and time associated with physical prototyping and testing. MOSA digital testbeds allow integration and evaluation activities to commence prior to and between availability of prototype hardware or production samples. In addition, these testbeds can support rapid and early soldier touchpoints, development of decision aids, and assessment of HMI through virtual experimentation and training environments. Digital testbeds can mature as programs mature, enabling software- and hardware-in-the-loop solutions that reduce programs test and evaluation costs and schedules. These same virtual products can be applied to diverse areas of a program’s lifecycle, adding value by providing savings for activities such as integration with complex vehicle platforms and systems-of-systems for MDO, new requirements closure, hardware obsolescence, open-architecture support, and identifying solutions to urgent operational needs.

10. CONCLUSION

A Modular and Open System Approach is necessary for the growing systems-of-systems that are inherent in modern ground vehicles. The nature of autonomy is complex, and quickly evolving and thus it is important to define a modular system that is flexible and can adapt at the same speed as innovation and of new threats. The proposed aspects of a MOSA autonomy testbed are distributed which allows it easily to grow both horizontally as each simulation scenario grows with more moving parts and nodes, and in-depth due to the ease of interoperability. A MOSA enabled digital autonomy testbed will provide confident, fact-based results empowering good decisions which in turn positively impact the next-generation warfighter.

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