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THE USE AND BENEFITS OF MODELING AND SIMULATION WITH AUTONOMOUS VEHICLES

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ABSTRACT

Traditional live testing of autonomous ground vehicles can be augmented through use of digital twins of the test environment, the vehicle mobility models, and the vehicle sensors. These digital twins combined with the autonomous software under test allow testers to inject faults, weather, obstacles, find edge case scenarios, and collect information to understand the decision making of the autonomous software under test. With this new capability, autonomous ground vehicles can now be tested in four stages. The first stage is testing the autonomous software using digital twins. In this stage with the help of a High-Performance Computer thousands of scenarios can be run. Once issues are communicated and addressed, stage two, hardware in the loop testing can begin. Hardware in the loop uses simulators that already exist to test systems such as autonomous convoys with a virtual leader and a live follower. Stage three employs a live virtual constructive approach by using one vehicle to test a convoy on the live track. Stage four allows traditional live testing to occur but with the help of a hardware and software applique kit to prevent the autonomous software from doing anything unsafe on the test track.

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1. INTRODUCTION

After several instances of receiving autonomous ground vehicle only weeks before they were required to support Soldier demonstrations, the U.S. Army Aberdeen Test Center (ATC) identified a need to virtually test autonomous ground vehicles. The U.S. Army Aberdeen Test Center (ATC) is a subordinate of the U.S. Army Test and Evaluation Command (ATEC), who is ultimately responsible for writing safety confirmations that support Soldier demonstrations and fielding. The short timeframe and limited funding upon a vehicle's arrival weeks before the demonstrations, was inadequate for ATC to fully assess and vet the systems. This resulted in a cautionary safety release. In May of 2020, ATC began development of the Autonomous Systems Test Capability (ASTC) to provide necessary tools for virtual testing. It is approximately a $16 million project funded by the Test Resource Management Center as part of their Central Test and Evaluation Investment Project Portfolio. The project completed development in June 2023.

2. PURPOSE

The purpose and intent of this paper is to educate readers on a current software development project that will bridge the gap and make virtual testing of autonomous ground vehicles possible. This paper will also educate readers on a methodology that will be employed by ATEC to test future autonomous systems and ensure they are ready for live testing. Readers will also learn about validation and verification processes underway to ensure virtual environments match actual environments from a visual and sensor perspective.

3. SCOPE

The scope of the paper covers autonomous ground vehicles as well as autonomous convoys. Weaponized unmanned ground vehicles and unmanned aerial vehicles will not be addressed. It will specifically address the use of digital engineering tools to test autonomous systems not the development phase although that is an additional benefit.

4. METHODOLOGY

ASTC will produce two distinct products. The first is a virtual environment that allows ATEC to test the decision making of the autonomous software on autonomous systems in a virtual environment. This utilizes six distinct methodologies to maximize what can be tested in a virtual world. The first is using digital engineering tools to create a digital twin of the terrain, a mobility model of the vehicle, a sensor model of the sensors being used, and integrating the autonomous software under test. ATC used a physics-based simulation named UNREAL to integrate all of the components. Figure I shows a Palletized Load System (PLS) operating on a digital twin of the Aberdeen Test Center's high speed test track.

Figure 1: PLS Driving on a Digital Twin of ATC's High Speed Test Track

The second methodology involved adding a Hardware in the Loop (HITL) capability that allows one to test an autonomous convoy in which virtual vehicles are interacting with live vehicles on a simulator or on a test track. The third methodology involves connecting the virtual simulations to a High-Performance Computer (HPC) to run thousands of scenarios with incrementally varying conditions. The scenarios aren't run faster than real time but with the help of a HPC ATC can run multiple scenarios simultaneously. With the help of the HPC we can also automate the modification of scenarios and judge them against specific criteria.This shows how many of the test scenarios passed against the criteria, how many failed against the criteria, and how many were on the cusp of passing or failing. These latter scenarios allow testers to head to the test track with this information to consolidate their live testing.

The fourth methodology involves instrumentation and collecting information. Using a data logger, we can collect information such as what obstacles were in the scene, where they were at in the scene, as well as the messages getting sent back and forth between the autonomous ground vehicles. ATC used a government developed and owned Advanced Distributed Modular Acquisition System (ADMAS) data logger. This data logger was integrated into the virtual environment. Figure II below is an example of one of the forms of the data logger.

Figure 2: ADMAS Data Logger

The fifth methodology is the capability to cause things to go wrong on purpose using fault injection. Examples of this are: Global Positioning System (GPS) loss, GPS degradation, Light Detection and Ranging (LiDAR) degradation, LiDAR loss, communications degradation, or communications loss. Other examples of fault injection are to generate false system health messages from the mechanical components of the vehicle to the autonomous software. Examples of this include sending messages that tell the autonomous software the engine overheated, the emergency stop is on, the tire pressure is low, or the brakes are not functioning correctly. By using the virtual world, it reveals the decision-making process the software undergoes when parts of the vehicle or system are not functioning correctly. The last methodology involves injecting weather and obstacles into the virtual scene but not limited to a visual perspective. To do this successfully, the autonomous kit must be stimulated from a sensor perspective. Below are some visual pictures of objects that have been created as well as what the objects look like from a LiDAR perspective.

Figure 3: Digital Twin of a PLS in a Snowy Environment

Figure 4: Digital Twin of a PLS in a Thunderstorm

Figure 5: Digital Twin of a PLS in Moonlight

Figure 6: Deer Injected into the Scene

Why is employing these six methodologies together important? Six methodologies drastically change how the Army approaches the testing of autonomous systems and allows for more robust and repeatable testing. By using the six methodologies listed earlier, the Army can now employ a new four stage approach to testing autonomous ground vehicles. Stage one allows the Army to test the autonomous software without a physical prototype being developed. This means that the testing community can get involved months if not years earlier in the process. The software can be tested in this virtual environment allowing testers to evaluate and characterize the decision making of the software much earlier than the current acquisition cycle employs. Thousands of scenarios can be run solely on the software and feedback can be provided to vendors and Army program managers much earlier than what is currently capable. After stage one is satisfied, autonomous software enters stage two.

Stage two employs the use of HITL and taking advantage of simulators that already exist. ATC has a roadway simulator that is a treadmill for military vehicles. The belts and wheels on the simulator move but the vehicle remains stationary. It can also simulate the vehicle conducting turning maneuvers as well as straight-line movement. With the help of simulators like this, autonomous convoys can be tested with just one live vehicle. A virtual leader on a digital twin can be used to interact with a live follower and potentially other virtual followers. The live follower performs as if it's following the lead vehicle on a road, but in reality, it is on a simulator. Figures VII, VIII, IX demonstrate this capability where a person drove the virtual leader on a digital twin of the Perryman 3-mile test track at ATC while sending location breadcrumbs to the live follower on the roadway simulator in December of 2021. Figure IX also illustrates the injection of a deer into the digital twin and the live follower responding appropriately by stopping. This was able to be accomplished by turning off the sensors on the live follower and instead feeding it sensor stimulation feeds direct from the virtual scenario.

Figure 7: Virtual Leader Commanding a Live Follower on the Roadway Simulator

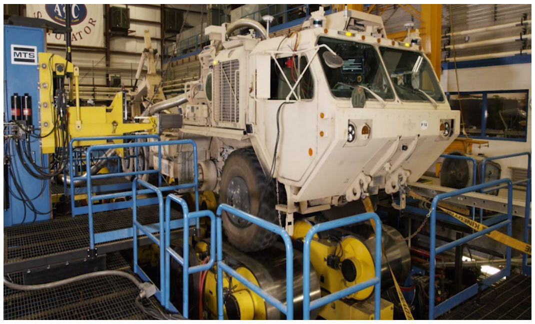

Figure 8: PLS on the Roadway Simulator

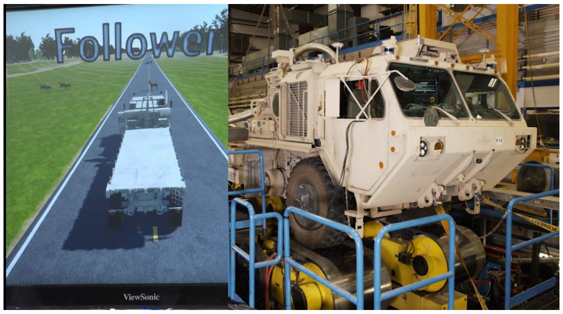

Figure 9: Live Follower Stopping After Interacting With A Virtual Deer

Stage three allows for the ability to move from a HITL perspective to a live virtual constructive standpoint. Using the concept mentioned earlier, the vehicle is taken off the roadway simulator and put it on a live track. After things have been verified on the simulator, one can now perform very similar operations with the vehicle on a track. The benefit at this stage is that we can virtually stimulate the vehicle with various parameters that may be unavailable for reasons such as geographical and safety limitations while assessing the performance of live vehicles in a convoy. Figure X below shows the demonstration of this concept that took place in February of 2022.

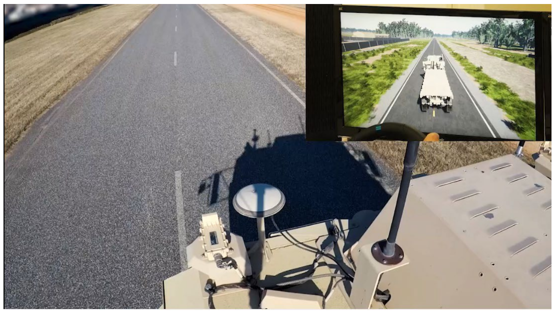

Figure 10: Virtual Leader Interacting with a Live Follower on a Digital Twin of ATC's High Speed Test Track

After functionality have been tested and verified, the autonomous vehicles are now ready for live, traditional testing at stage four. Now, a full convoy of live vehicles can be tested with a much higher confidence and reduction of issues found in previous tests. However, as vehicles gradually remove manual steering wheels, brake or accelerator pedals, a new method must be identified to take control of these systems during testing should they not function correctly. The traditional method has been to use safety drivers. However, with newer vehicle modifications that eliminate seats and other controls, using a safety driver is not feasible.. Stage four employs the use of a hardware and software applique kit that acts as a parent to the autonomous software under test. In essence, if the software attempts unsafe movement, the applique kit recognizes that and takes over. It is being developed with independent sensors that will give test operators the ability to stop the autonomous system under test if it gets too close to an object; stop the system if a data channel like engine temperature exceeds or drops below a predetermined limit; stop the system if it drives out of predetermined boundaries and stop the system if the emergency stop built into the system stops working. Figure XI documents the four-stage process to test autonomous ground vehicles.

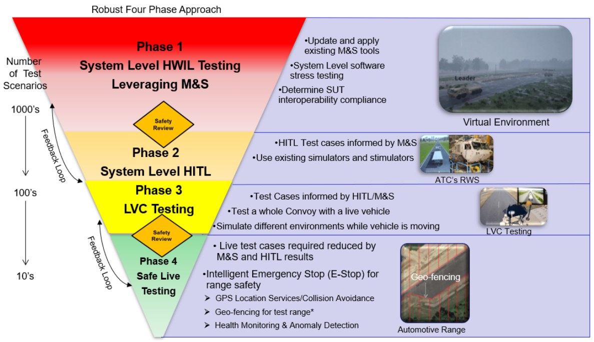

Figure 11: Four Stage Process to Test Autonomous Ground Vehicles

The ultimate goal described above and in Figure XI is not to replace live testing but to augment live testing and act as a gate to live testing. By conducting many tests earlier in the system lifecycle, this process ensures the autonomous software and system are ready for live testing.

The next question is how does one know what is happening in the live environment matches the virtual environment using digital twins? The key to this is the data logger mentioned previously. This data logger also collects information from live vehicles on the test track. With this data logger, the tester can compare previous live data collected to current simulated data. ATC has access to over five years of data collected on the PLS with the Expedient Leader Follower program. The comparison of this data to the simulated data allows a proper validation and verification to be done on the tool. ATC is not just looking at the tool by itself, but we are also diving into validating and verifying specific aspects of the tool. For example, the sensor stimulation is feeding what rain and snow look like from a LiDAR perspective. This simulated LiDAR information has been compared against LiDAR information that has been collected during actual rain and snow events.

5. RESULTS

The modeling and simulation capabilities employing these methodologies were implemented in June 2023. The software hardware emergency stop mentioned in the methodology section is under development and will be implemented starting in the 2nd Qtr. of Fiscal Year 2025. Initial analysis was performed to determine how many scenarios could be run at the same time compared to live scenarios. A specific scenario of making one lap around ATC's high speed test track determined that an autonomous ground vehicle would take fifteen minutes to traverse the terrain in a live format. Based on that scenario and the use of the HPC, we determined that 100 scenarios could be run virtually in fifteen minutes compared to one live scenario. To determine any cost or time savings, the team looked at the Expedient Leader Follower program which conducted testing at ATC in 2020 and 2021. According to the test program lead, it took approximately eight to ten weeks to conduct testing on a new release. Using that time frame, we determined that stage one in Figure XI alone could have run those scenarios in 2.5 hours. This would not be done to replace live testing but to focus what scenarios are done on the live track. For instance, by doing the scenarios mentioned above in stage 1 first, they could have been performed at 1/50th of the cost, reducing the carbon footprint by 3,200 gallons fuel while collecting 192 gigabytes of data. This combined with the edge case scenario method mentioned earlier would have guided the live testing phase.

6. CONCLUSIONS

The concept of a four-stage approach while combining six methodologies into one tool has the potential ability to drastically change how Army autonomous systems are tested and fielded. This approach will lead to autonomous ground vehicles when they physically arrive for live testing being more ready to test.. Also, the results from the modeling and simulation phases will instill more confidence and help shape additional test procedures. This is important because more data will be available to the test community to allow them to accurately quantify the risk of specific testing scenarios that previously would not have been tried live.

7. IMPACT

As the Army continues to transform and places priority on these efforts, this digital engineering tool will play major roles in the development and testing of programs like Autonomous Transport Vehicle and Robotic Combat Vehicle. ATC's ASTC can also be used and modified to support the testing of systems with Artificial Intelligence, where safety and performance become even more paramount without a human in the loop. ATC’s ASTC will help to ensure the safety and performance of these systems.

8. REFERENCES

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Appendix A

List Of Acronyms

ADMAS – Advanced Distributed Modular Acquisition System

ASTC – Autonomous Systems Test Capability

ATC – Aberdeen Test Center

ATEC – Army Test and Evaluation Command

GPS – Global Positioning System

HITL- Hardware in the Loop

HPC – High Performance Computer

LiDAR – Light Detection and Ranging

PLS – Palletized Load System