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SCALED TESTBEDS FOR AUTOMATED ROBOTIC SYSTEMS

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ABSTRACT

The automotive and defense industries are going through a period of disruption with the advent of Connected and Automated Vehicles (CAV) driven primarily by innovations in affordable sensor technologies, drive-by-wire systems, and Artificial Intelligence-based decision support systems. One of the primary tools in the testing and validation of these systems is a comparison between virtual and physical-based simulations, which provides a low-cost, systems-approach testing of frequently occurring driving scenarios such as vehicle platooning and edge cases and sensor-spoofing in congested areas. Consequently, the project team developed a robotic vehicle platform—Scaled Testbed for Automated and Robotic Systems (STARS)—to be used for accelerated testing elements of Automated Driving Systems (ADS) including data acquisition through sensor-fusion practices typically observed in the field of robotics. This paper will highlight the implementation of STARS as a scaled testbed for rapid prototyping, accelerated testing and verification and validation (V&V), and its applicability as a simulation tool for additional CAV concepts, such as modeling edge cases like swarm behaviors for route delivery and vehicle cyber security testing on sensors.

INTRODUCTION

In this paper, we consider the validity of using a scalable vehicle platform for conducting hardware-in-the-loop (HIL) experimentation with respect to a virtual transportation model. The Scalable Testbed for Automated Robotic Systems (STARS) platform is designed to be a cost-effective modeling and simulation tool combining physical and virtual testing to drive conclusions about Connected and Automated Vehicles' (CAV) functionality. The STARS system consists of five physically identical remote-controlled cars, modified with commercial off-the-shelf (COTS) electronics, and an external ground control station (GCS) for developing path planning modules.

Initially, STARS was designed to test cybersecurity mitigation strategies of vehicle swarming patterns and tracking functions, but since it uses modular components, it was adapted to match distinct use cases for connected vehicle technology (e.g., platooning, lane changing, and lane keeping assistance). The advantage of this system lies in the modularity and scalability of vehicle data being collected: The experiment discussed in this paper highlights a small-scaled test orchestrated to observe and record CAV behaviors to understand real-world challenges in full-sized vehicles. This combined small-scale physical and virtual platform allows the project team to perform cost-effective rapid verification and validation (V&V) of CAV functionalities and vehicle design features.

The platform leverages prototype and simulation-based testing to generate analysis of frequent driving scenarios and edge cases not typically replicated in the real world. The objective of this research is to provide insight to manufacturers and certifiers on how they can use small-scaled test beds like STARS to validate CAV behaviors and consider edge cases like swarm behaviors and vehicle cyber-security mitigation techniques—concepts that are becoming prominent to both the automotive and defense industry.

BACKGROUND

The focus of this paper is the experimentation and analysis of field testing a platooning scenario of an “automated convoy,” an application in which a group of automated vehicles follows a manually driven vehicle throughout a path, maintaining consistent speed and spacing.

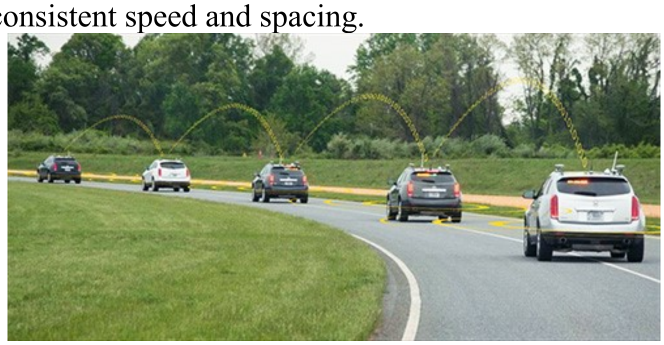

Figure 1: Automated Vehicles Demonstrating a Platooning Proof of Concept at Aberdeen Proving Ground in 2017 [1]

The project team conducted a series of field tests in an isolated, controlled environment in which test vehicles demonstrated a platooning simulation built out in a transportation modeling tool for validation. By comparing simulated data with empirical field data, the project team analyzed performance metrics of both platooning scenarios to conclude V&V for small-scale testing. Principles of modern control theory were used for developing simple control algorithms to compare the virtual and real-world model.

As part of developing a methodology for STARS, the project team explored the use of HIL for scaled vehicle testing and V&V through a state-of-the-art assessment of facilities and techniques used in the industry. Findings from this research of relevant HIL literature determined the following:

- HIL is already widely utilized in the automotive industry.
- HIL models consider many external factors to make each simulated model more accurate including gravity, resistance, and friction [2].
- A very low construction cost and short development cycle allow for testing variable conditions including road surface material, road geometry and slope, and static or dynamic obstacles [3].
- Embedding physical vehicle parts into a platform requires specialized space.
- The HIL method is highly reproducible and allows for flexibility in simulating real-world traffic operations.

Small-scale testing and HIL have been used by the automotive and defense industries, and both have been successfully implemented for V&V in the past. For example, the National Highway Traffic Safety Agency (NHTSA) Vehicle Research Test Center (VRTC) has conducted HIL simulation for validating braking components for heavy trucks [4]. It is evident that the application of HIL in STARS will allow the project team to remain agile and innovative as it addresses the Federal Government’s evolving needs for CAV regulation.

METHODOLOGY

The validation of the STARS platform is conducted by comparing the scaled physical vehicle's path trajectory with simulated trajectories from VISSIM, an industry-standard transportation simulation tool. The following diagram presents the steps in validation.

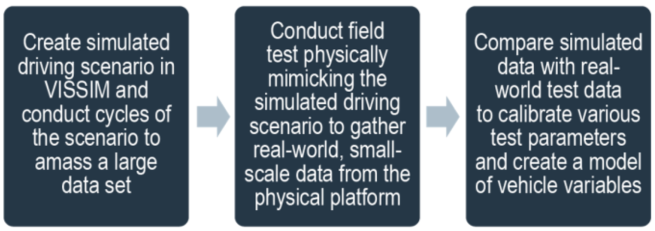

Figure 2: Validation Process of STARS Project

The experiment begins with user-defined parameters: two vehicles (leader/follower) traveling in a straight path where the vehicle parameters are set to a default mid-sized vehicle, measuring 4.92 feet wide by 15.62 feet long. Within the VISSIM simulation, an extended intelligent driver model (eIDM) was used to create an ideal scenario of cooperative-adaptive cruise control (CACC), which is a fundamental concept behind vehicle platooning used in commercial vehicles. A CACC illustration can be seen in Figure 3, where the follower vehicles' speeds and distance can be observed.

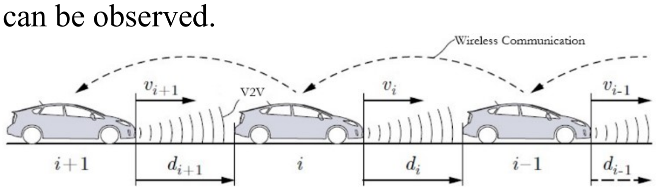

Figure 3: Diagram of a Simple CACC Model

The eIDM reflects an ideal scenario used in CACC modeled in VISSIM. The generalized equations can be seen here:

$$a_{IDM}(s, v, \Delta v) = \frac{dv}{dt} = a[1 - \left(\frac{v}{v_o}\right)^{\delta} - \left(\frac{s^*(v,\Delta v)}{s}\right)^2] \quad (1)$$

.

$$s^*(v, \Delta v) = s_o + vT + \frac{\mathrm{v}\Delta\mathrm{v}}{2\sqrt{ab}} \quad (2)$$

$$\mathrm{u}(t) = K_p e(t) + K_i \ {}_0\!\int^t e(t')dt' + K_d \frac{de(t)}{dt} \quad (3)$$

$$\mathrm{u}(t) = K_p e(t) + K_i \ {}_0\!\int^t e(t')dt' \quad (4)$$

Equation (1) defines the acceleration for an eIDM, where the ideal vehicle acceleration can be seen as a continuous function. This takes into account the velocity difference (Δv) and effective minimum gap between the vehicles. The free acceleration is characterized by desired speed v_o, the maximum acceleration a, and the exponent δ characterizing how the acceleration decreases with velocity (sigma = 1 denotes constant decrease while sigma = infinity denotes constant acceleration).
Equation (2) defines the effective minimum gap, (S*) composed of minimum distance (s_o), the velocity dependent distance (vT) which corresponds to the "follower" vehicle pursuing the "leader" vehicle with a constant desired time gap T [5]. It can be assumed that Δv ≠ 0 in which the "intelligent" driving behavior in normal situations limits braking. The eIDM model generalized in equations (1) and (2) was used for developing a platooning scenario through our transportation modeling tool, VISSIM.

The primary method for developing a control algorithm can be mathematically expressed in Equation (3) Where K_p, K_i, and K_d denote the coefficients for the proportional, integral, and derivative terms—commonly referred to as PIDs in the field of mechatronics.

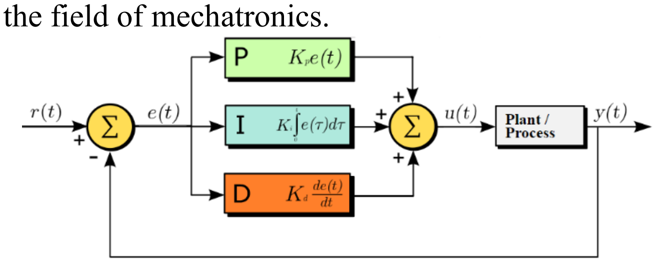

Figure 4: A Generalized Flowchart Diagram of a PID Control Loop

For a simplified control algorithm, both the VISSIM model and field experiment were observed to have a Proportional-Integral (PI) control loop. Equation (4) summarizes a PI control loop. The PI controls inputs through a pair of proportional and integral ratios. It is a special case of the PID controller in which the derivative (D) of the error is not used (assume $K_d = 0$). By removing the derivative action, the HIL control system can focus on generalized inputs from a use case such as a platooning scenario. These generalizations allow the PI to scale a vehicle's outputs: As the PI is tuned, the control system is less responsive to noise, allowing for the state of the controlled experiment to provide proportional outputs.

The platform's execution of vehicle platooning conforms to the real-world concept: Multiple vehicles travel together on a road, with the follower vehicles maintaining the same distance from each other and same speed as the lead vehicle. Current experiments involving the platooning of actual vehicles are based on this model, with a CAV following a human-driven lead vehicle.

Transportation Simulation

The research team developed and deployed a vehicle platooning model in VISSIM Microscopic Simulator. The control algorithm is the enhanced Intelligent Driving Model (e-IDM), which aims at using automated longitudinal control of the follower vehicle to maintain the effective minimum gap (S*) while following a known lead vehicle trajectory. The model helps the follower vehicle gather lead-vehicle speeds, acceleration, and position. CACC, the CAV application, is calibrated and validated using real-world vehicular data as demonstrated in a literature assessment [2], [5], [6], [7], and [8]. The research team used VISSIM's *DriverBehaviorModel.dll* API interface to code-in the eIDM vehicle platooning model. The following diagram shows the simulation architecture of CACC.

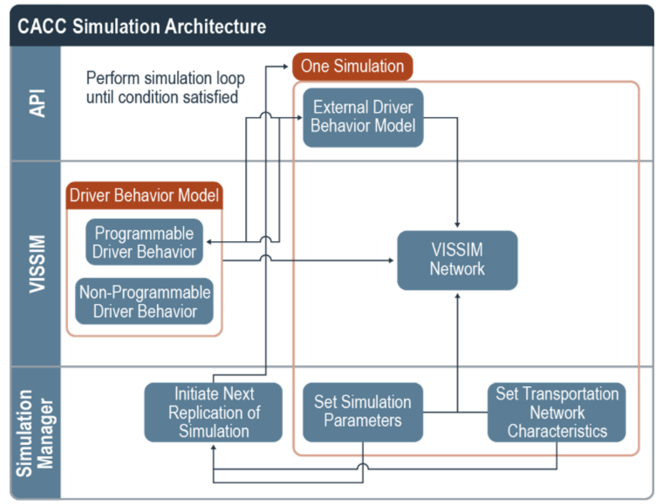

Figure 5: Driver Behavior Model for Platooning Scenario

Using similar concepts from the eIDM, the research team developed control algorithms to simulate CACC behaviors for vehicle platooning in physical experiments conducted in the field.

Hardware in the Loop (HIL)

The HIL simulation piece for this paper starts with illustrating the platform itself. Each STARS vehicle has an identical sensor suite comprising COTS components:

- GPS/Magnetometer Unit
- USB Camera
- Wi-Fi Antenna
- Autopilot Flight Controller
- Onboard Computer
- Telemetry Radio
- Vehicle Chassis

An assembly of the components can be illustrated in Figures 6-8:


Figure 6: Two Stationary STARS Platforms

The system can be segmented into two subsystems: the STARS vehicle and the Ground Control Station (GCS) as illustrated here.

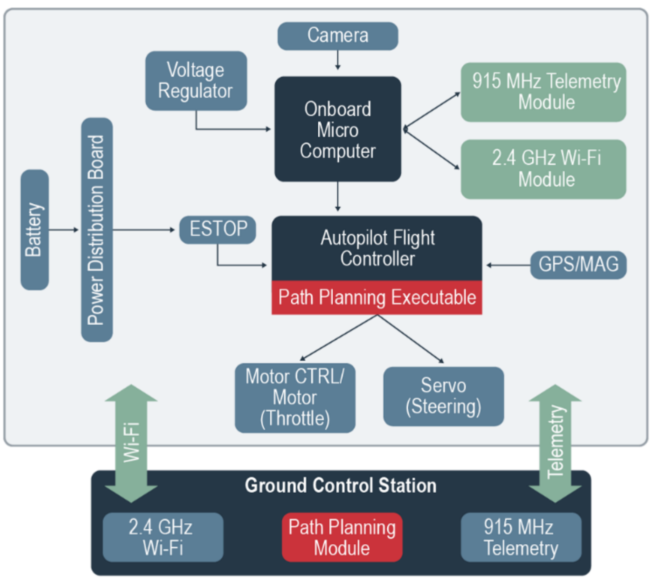

Figure 7: STARS System Diagram

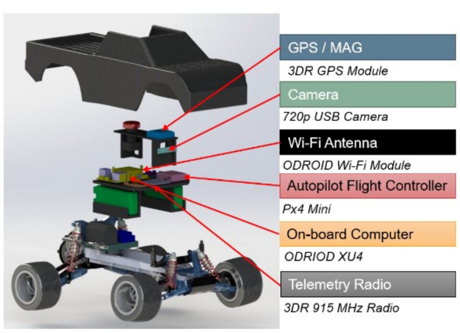

Figure 8: CAD Render of a STARS Vehicle with Labeled Sensors

The STARS architecture diagram is shown in Figure 9. It can be compared to the VISSIM driver behavior model architecture diagram described earlier in this paper, where the subject vehicle shows simulated feedback from CACC behaviors.

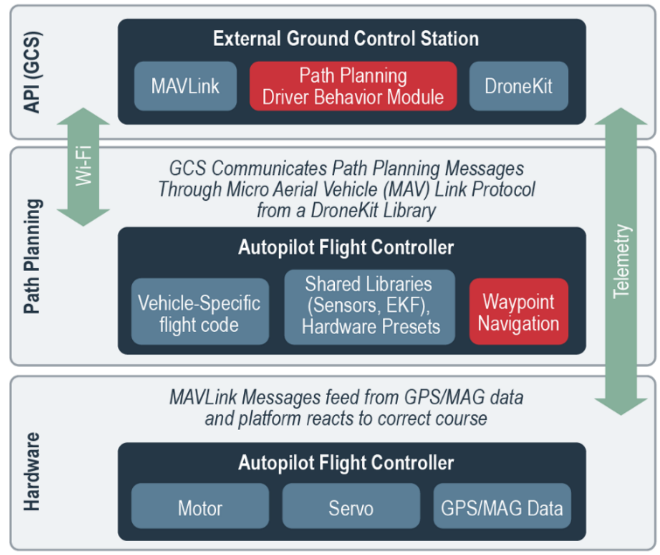

Figure 9: STARS Architecture Diagram

The vehicles were tested in a quiet park to practice safe operations away from pedestrians and automotive traffic. The course is shown in Figure 10.

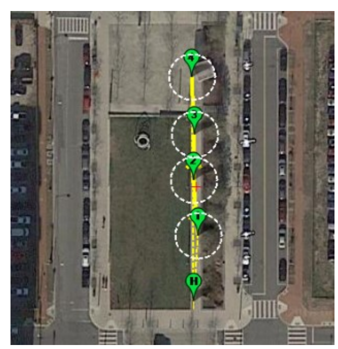
Figure 10: STARS Outdoor Test Site with Route Overlayed

This physical outdoor track is 190 feet long and 10 feet wide. By scaling the dimensions of our test course, we can measure scalable outputs from the vehicles operating in it. Wireless communication is acquired by using Wi-Fi through a 2.4 GHz receiver for telemetry and data logging. The research team conducted three separate trials, where the leader vehicle began a course and the follower vehicle tracked the leader's last known location via Micro Aerial Vehicle link (MAVlink) protocols from Global Positioning System (GPS) navigational waypoints. These MAVlink protocols enable the follower to track the leader's waypoint coordinates with a high frequency, allowing for consistent and fast following speeds.

The primary method of control for this unit is the GCS. For this project, the team used Mission Planner, a popular open-source GCS tool used by hobbyists and industry leaders alike, which provided real-time software-in-the-loop (SITL) features, and PID algorithmic control for the vehicle's flight controller.

Figure 11: User Interface of Mission Planner GCS

Mission Planner's intuitive interface allows the user to provide real-time diagnostics and interfaces during operations. For the scale of this project, the primary sensors used were GPS and flight controller (built-in Inertial Measurement Unit [IMU] and Compass). Due to the scope of this project, traditional sensors seen in CAVs such as ultrasonic sensors, cameras, or Light Imaging, Detection, and Ranging (LiDAR) units were not tested. Limitations in staffing availability, project budget, and time requirements reflect the limited scope of research. Future work on this platform will be considered to reflect multiple elements of HIL testing.

Scaling Parameters

Developing an accurate small-scale testing platform that yields valuable results requires the correct scaling parameters [9]. Since this is a simplified experiment with limited sensors and data sets, the scaling factor for vehicle comparison is linear.

First, the VISSIM model reflected a generic mid-sized car: 16 feet by 4 feet traveling in a straight path for a set speed of 60 mph. The STARS platforms are 19 inches by 9 inches and were traveling at an average speed of 3.4 meters per second (m/s). Since the experiment was directed for a straight course, handling characteristics such as lateral steering were not addressed. The primary scalable sensor is an onboard GPS which, when coupled with readings from the flight controller unit, provides a basic test parameter for comparing the platform's relative speed and size. The primary sensors being measured are the GPS and flight controller which would match the vehicle's speed and relative displacement. A unit conversion of imperial to metric shows the vehicle's scaled size and speed to match the parameters of the VISSIM model.

ANALYSIS AND RESULTS

Once data from all three trials were obtained, the data sets were overlaid to the baseline model to show the results.

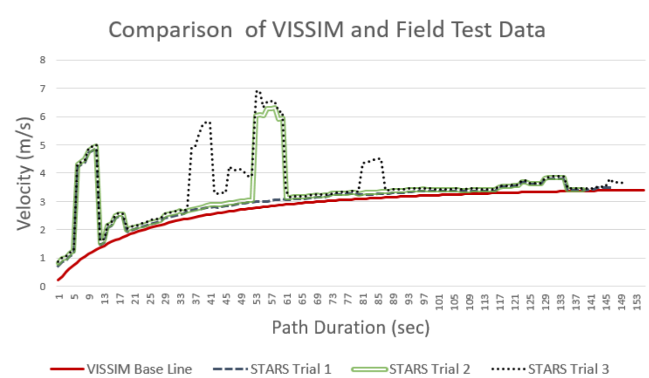

Figure 12: Comparison of VISSIM and Field Test Data

The VISSIM baseline model, shown as a solid red line, served as the basis for comparison in the field experiments. The baseline model captured the follower vehicle pursuing the leader vehicle at a consistent speed of 3 m/s. Each STARS trial logged the events of a follower vehicle pursing the leader vehicle's last known location through GPS coordinates. As the graph indicates, the baseline model and the three field trials show the follower vehicles traveling to the set of desired points, but not maintaining a consistent speed. Since the STARS follower vehicles are set to track the leader's last known position, the follower vehicle accelerated to the last known waypoint, halted, and continued to speed to the course.

The variance in the platforms was anticipated, but possible discrepancies in what is shown can be traced to the gains set in the control algorithms of the STARS platform. The VISSIM baseline shows typical results for an idealistic model: vehicles traveling in a straight path uninterrupted, whereas the real-world model reveals spikes where the vehicle accelerated to reach a last known position and stopped to wait for queued commands.

The outcomes of this experiment provided the research team with valuable insight on HIL simulation testing. The research team experienced utilizing HIL for experimental testing and members gained a better understanding of how HIL can expand/limit project scope. Overall, STARS can provide a low-cost, highly flexible learning environment for Booz Allen to build subject matter expertise in the CAV market if the experiment is maintained within the limitations of the system. Ultimately, STARS could benefit from the addition of particular sensors such as a low-cost radar or ultrasonic sensor for responsive feedback. Furthermore, the platforms' USB cameras should be leveraged for better perception and for lane-keeping assistance.

The STARS concept has a high applicability for manufacturers and certifiers in both the defense and commercial transportation domains in the CAV industry. The platform was designed to allow for this type of extensibility where it could be used to investigate particular cyber security applications (such as noise injection of sensors, like GPS spoofing) and resulting behaviors on sensors' performance or the behavior of swarms.

The field testing site used for physical testing for STARS presents a potential for different sources of noise in experimentation. This includes the GPS noise from surrounding buildings and the vibration caused by uneven surfaces to the physical platforms' 3D-printed mounts.

The physical platform could benefit from better protection for sensors and components to address potential sources of noise during the experiment. The 3D-printed mounts, adhesives, and wiring on each platform could be made more secure for use on uneven testing surfaces.

Currently, STARS is built using a limited number of sensors where only GPS and autopilot data can be gathered and analyzed. With the introduction of additional sensors including a camera, LiDAR, and radar, STARS could perform additional V&V and introduce more scenarios such as a lateral motion seen in obstacle avoidance or lane changing. This would increase the platform's value from only confirming a simple proof-of-concept to using it for increasingly complex models that better emulate an actual vehicle and use case.

Furthermore, the project team could create additional parameters and better-defined use cases to raise the applicability of STARS to the real world.

Ultimately, the scope of research was limited by the architectural design of the sensor suite. Although the experiment allowed researchers to conduct sample experiments at a relatively low cost on a modular platform, the experiment cannot *fully* replicate the self-learning and complexity of a CAV. It can, however, serve as a foundational vessel that can support more COTS components for CAV testing.

Analysis of the STARS process and its resulting data set indicates the need for more accurate, higher-level sensors for rigorous testing and data that more closely resembles actual vehicle tests. In addition, relying on a GCS designed for aerial systems and retrofitting it for a CAV was not optimal for the functionality required. Nonetheless, this experiment served as a proof of concept for using COTS equipment to conduct small-scaled simulations for the V&V HIL testing.

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