Reference	CP63
Project Title	DARTER: Digital twins for Accessible Real Testing grounds for automotive Engineers and Researchers
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Project Duration	2022/12/01 - 2023/07/01

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Summary

Verification and validation (V&V) of Intelligent Transport Solutions and their components in real traffic is difficult (costs, passers-by, etc.) and running tests under all possible conditions (weather, traffic, etc.) is impossible. For these reasons, controlled proving grounds and simulations are being used to safely increase the coverage of V&V.

This project addresses two issues connected to these alternatives. On the one hand, the limited access to real proving grounds and their corresponding high-fidelity simulations of academic researchers, key in evaluating the benefits and social and environmental harms that technological advances can pose. On the other hand, the fidelity gap between the virtual and the real world, that prevents the usage of simulations at vehicle integration test level and needs to be understood and measured.

DARTER

1. Background

Academic researchers in the field of Autonomous Driving (AD) and Advanced Driver-Assistance Systems (ADAS) are key in evaluating the benefits and social and environmental harms that technological advances can pose. Nevertheless, compared to AD companies, **academic researchers have limited access to real-world testing platforms** to validate and experiment with their ideas.

Due to this, academic researchers typically turn to virtual environments or Digital Twins (DTs) as a replacement to climb up technology-readiness levels. DTs are dynamic virtual instances replicating physical systems' behaviour and characteristics. DTs can serve a wide range of purposes depending on their specific application, including simulating, analysing, and optimizing the performance of physical assets such as machinery, buildings, infrastructure, and virtual assets. Nevertheless, **there is still a gap between experimental evaluations in real proving grounds and simulations in *ad hoc* DTs**. For this reason, a more thorough and seamless integration between virtual assets and physical test sites is required to ensure the safety and reliability of AD systems in verification and validation (V&V) processes. Moreover, DTs complexity and resource-intensive nature highlights the need for more flexible, adaptable, and interoperable architectures for such V&V platforms.

In order to close this gap, we first need to understand the limitations of existing solutions, both commercial and open-source alternatives, and quantitatively and quantitatively evaluate them. Examples of these limitations include:

- Missing or too simple vehicle models.
- Simplified representations of the real proving grounds (2D, checkpoints).
- Errors in the 3D scans and difficulty to use them in simulation environments.
- Static environments, e.g., lighting, weather conditions, etc.
- Access to driving data is difficult and no unified formats are in use.
- Lack of realism in renderings due to computational resources.

These and more issues conform the "fidelity gap". However, given the complex nature of quantitatively and quantitatively evaluate the aforementioned gap, it was left out of the scope of the pre-study. Instead, understanding and measuring it is one of the goals of the "Enabling VIrtual valiDation and vErificatioN for ADAS and AD features (EVIDENT)" project. EVIDENT is therefore the natural continuation for the DARTER pre-study.

2. Project set up

2.1 Purpose

Academic researchers in the field of autonomous driving (AD) are key in evaluating the benefits and social and environmental harms that technological advances can pose. However, they typically have limited access to:

(i) physical testing resources (such as real proving grounds),
(ii) professional closed-source simulation software, and
(iii) the computational resources to run tests systematically.

Therefore, the purpose of the project was to explore alternative DT-based V&V strategies for ADAS and AD features in early stages of development that are cost effective, efficient, and accessible for all automotive engineers and researchers.

2.2 Objectives

The following table outlines the specific objectives as detailed in the application. These objectives have gone through changes as the project advanced. The reasons behind the modifications and clarifications the nature of these changes are also presented here.

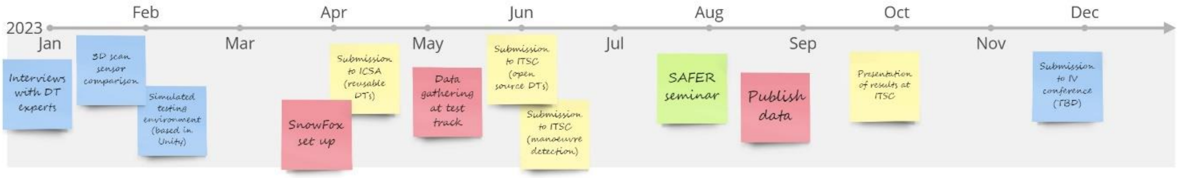
Objective (as described in the application)	**Methodology (DARTER pre-study results)**	**Lessons learnt and changes to objectives**
Create a comprehensive and seamless V&V strategy for early AD development	Interviews with DT experts on current V&V strategies in different domains	Not a unique strategy, architecture, or approach to implementing DTs
Close the gap between virtual environments and real testing sites	Literature review of technologies and tools, as well as their limitations	First: need to understand and measure the gap between virtual and real environments
Lay the foundation for a comprehensive, open, and reusable tool for academic researchers	Literature review of technologies, existing tools, methodologies, and potential partners	Many open-source options exist, yet it is difficult to access and integrate them
Integrate virtual assets from physical test sites within a simulation environment	-	Development of DT of physical site is the current focus of EVIDENT project
Integration of the dynamic model for SnowFox into a simulation environment	-	Improvements to the SnowFox dynamic model (including onboard sensors) might be part of the EVIDENT project

Objective (as described in the application)	Methodology (DARTER pre-study results)	Lessons learnt and changes to objectives
Creation of a demonstration of the suggested technologies	-	Demonstration is the shifted to EVIDENT project
Motivate a subsequent research project	Participation in meetings, interviews, and workshops	EVIDENT is the natural continuation for DARTER

2.3 Project period

The pre-study launched in December 2022, and thesis topics related to the pre-study where announced. As a result, a number of theses of students in the Software Engineering and Management bachelor's programme from the University of Gothenburg and the High-Performance Computer Systems and Software engineering and technology master's programmes at Chalmers were supervised in the first quarter of 2023. The conducted interviews, hands-on implementations, and comprehensive literature reviews conducted by the students have played a pivotal role in understanding the current academic discourse and existing commercial DT solutions.

A subset of these theses, listed in Section 6, has already been transformed into academic papers and submitted to relevant, competitive conferences. Several other theses, listed below, are expected to be submitted to the upcoming IEEE Intelligent Vehicles (IV) Symposium (call for papers submission page expected to open late 2023).



The second quarter of 2023 was devoted to setting up the resources needed to gather real data in AstaZero's real proving ground. On the one hand, in order to gather driving data (i.e., sensor readings) from the real proving ground, a preliminary series of tests on the vehicle was needed. On the other hand, securing a slot on the busy test areas at AstaZero, posed a logistical challenge. The available slots were limited and often booked well in advance. Moreover, two human roles were required for the tests (i.e., one person responsible for driving and the other for real-time recording and annotation), which added another layer of complexity to the coordination and scheduling process. Finally, data gathering took place in a sunny day in May 2023.

2.4 Partners

The pre-study involved three key partners: the University of Gothenburg, contributing with academic expertise; AstaZero, providing in-kind financing as one of the SAFER partners; and the Computer Vision Center, offering in-kind support from external funds.

Partners	SAFER partners (in-kind)	Financing from SAFER pre-study program (cash)	Financing from external funds / partners (in-kind)
University of Gothenburg		100 000 SEK	
AstaZero	50 000 SEK		
Computer Vision Center			50 000 SEK

The support from AstaZero has facilitated various operational aspects of the project, such as logistical arrangements and resource allocation, including access to the different areas of the test track. The contribution of the Computer Vision Center, actively participating in meetings and sharing its expertise, has been extremely valuable as well.

3. Method and activities

In order to address the goals of the DARTER pre-study, different activities have been conducted, namely: (i) supervision of bachelor's and master's thesis on topics related to DTs, their development, and usage, (ii) data gathering using ReVeRe's SnowFox car in different settings, including AstaZero's proving grounds, (iii) the presentation of partial results in the 2023 "International Conference on Intelligent Transportation Systems" taking place in Bilbo (Spain), and (iv) complimentary paper submissions later this year.

Different methods and research methodologies were used in these activities, including (i) a revision of the grey and white literature on DTs, (ii) a mapping study, (iii) an interview study with domain experts within industry and academia to gather rich, detailed data on the nuances and complexities of DTs, (iv) a second interview study consisting of open-ended questions about experts' vision for DTs and the role of Artificial Intelligence (AI) in their development, and (v) two hands-on experiments:

- An experiment using a virtual environment, created using Unity, and a VR interface to engage in a 3D scenario involving multiple autonomous vehicles.
- An experiment to compare three common interpolation methods to retrieve smooth 3D representations of real environments using depth sensors.

The results can be found in the final thesis reports listed in Section 6.

4. Results and Deliverables

The findings of the DARTER pre-study are reflected in the following deliverables:

Deliverable 1) Final reports for thesis found in the Gothenburg University Publications Electronic Archive and the Chalmers Open Digital Repository.
Deliverable 2) DARTER's final report (you are here) for SAFER pre-studies.
Deliverable 3) Accepted paper at the 26th IEEE International Conference on Intelligent Transportation Systems on how driving manoeuvres can be detected without relying on GDPR-sensitive data, such as GPS signals or video recordings.

Deliverable 4) Drafts for the planned paper submissions with partial results obtained in the scope of the DARTER pre-study (for internal revision).

Deliverable 5) Publicly accessible dataset with sensor readings and video recordings gathered with the ReVeRe's SnowFox car in AstaZero's testing grounds.

The gathered data (D5) is already being used in the scope of the EVIDENT project, as discussed below. Part of the gathered data is planned to be made publicly available shortly after the submission of the present report so that it is accessible to the academic community and SAFER partners. A second set of data, consisting of recordings of the driver, is meant to be internally used in the "Video-based Driver Condition Monitoring for Safe Driving (ViDCoM)" SAFER pre-study.

5. Conclusions, Lessons Learnt and Next Steps

Safety in human-AV interactions is the ultimate motivation of V&V of ADAS and AD features. In order to increase coverage during testing, many engineers and researchers rely on the digitalization of physical testing setups such as AstaZero's proving grounds. Take-aways from the studies conducted on the tools and approaches to achieve this are:

Take away 1) No unique, stable, or standard framework is in use for the development of DTs; instead, internal best practices and scattered standards that are used in other contexts are followed, which draws interoperability back.

Take away 2) Each tool used for V&V needs to undergo its own rigorous verification process to ensure its trustworthiness. This includes the synthetic data generation methods, the fidelity of the simulation environments, the reliability of the sensor models, the robustness of the decision-making algorithms, and the overall consistency of the results obtained through the DT.

Take away 3) It is logistic- and technically difficult to gather data using a real vehicle in a real proving ground. Moreover, the data needs to be downloaded, processed, anonymised, and shared. These tasks also demand significant resources that are often inaccessible for automotive researchers.

The conclusions of the DARTER pre-study therefore highlight the need to balance the testing coverage and the fidelity of the simulation environments, such as DTs, used during V&V. This balance, that needs to be understood in order to determine the appropriate abstraction level of DTs for diverse tests will be part of the research conducted in the scope of the EVIDENT project, the natural continuation of DARTER.

It is important to note that for these scenarios, it is important to both (i) integrate the data collected in the real world into the simulation environment and (ii) to replicate the trajectories defined in the use-cases in the test vehicle, which can be achieved thanks to AstaZero's ATOS system integration into the ReVeRe's SnowFox vehicle.

While the goals of the EVIDENT project contain certain aspects of DARTER's objectives, the discussion about academic researchers access to testing resources, open-source tools, and standard approaches to DT development to increase their interoperability and integration into existing V&V pipelines, deserves further attention.

These topics could potentially be addressed as part of multiple bachelor's or master's thesis in the 2023-2024 academic year.

6. Dissemination and Publications

The results will be spread in the SAFER seminar organised at the end of the pre-study, to which partnering companies and interested parties have been invited. Besides the DARTER final report, the research conducted in the scope of the DARTER pre-study has led to a number of works, including publications and thesis reports.

Peer reviewed publications:

- Berger, C., Cabrero-Daniel, B., Kaya, M. C., Esmaeili Darestani, M., & Shiels, H. (2023). Systematic Evaluation of Applying Space-Filling Curves to Automotive Maneuver Detection. In 26th IEEE International Conference on Intelligent Transportation Systems (ITSC).

Related bachelor and master thesis:

- Liteanu, G.-V., & Korkmaz, N. (2023). Human Performance and VR Interfaces: A Study of Digital Twin Monitoring in AI-Driven Fleets of Vehicles. Gothenburg University Publications Electronic Archive.
- Yasser, A., & Broberg, A. (2023). Digital Twins for Verification and Validation of CPS: Standardizing the Role of Requirements Engineering and AI with Digital twins. Gothenburg University Publications Electronic Archive.
- Wang, Z., & Chang, Q. (2023). A Solution for 3D Visualization on Soil Surface Using Stereo Camera. Chalmers Open Digital Repository.
- Ratushniak, O. (2023). Architecturally Significant Requirements and Design for Digital Twins of Semi-Autonomous Systems. Gothenburg University Publications Electronic Archive.
- Petrov, S. (2023). Digital Twins and Sustainability: A Comprehensive Review of Limitations and Opportunities. To be published in the Chalmers Open Digital Repository.

Related research articles under revision:

- A research article on Enhanced Reusability of Digital Twin modules, submitted to the 46th International Conference on Software Engineering.
- A research article on driver attention monitoring based on joint rotation estimation using a single RGB camera.
- A research article presenting a V&V pipeline for AD features integrating DTs and a mapping to existing open-source simulation software.
- A technical report describing the DARTER dataset and open challenges.
- A research article discussing the trade-off between fidelity (i.e., simulation "realism") and abstraction when using virtual environments for testing.

7. Acknowledgements

This work could not have been possible without AstaZero and the Computer Vision Center, who joined hands in this pre-study. The expertise of their engineers has added the real-world dimension to this project. We would like to take a moment to specially thank Professor Dr. Christian Berger, the team at the ReVeRe lab, and Adam Eriksson for their continuous support and for bearing with the driving tests and data gathering process.

Last, but not least, thanks to all intellectual sparring colleagues who shared their advice, insights, and motivation with us. Your perspectives, including those that are now the focus for the EVIDENT project, were key. Your interest has been a *driving* force.