**Web Simulator Interface for Autonomous Vehicle Software Stack.**

**This thesis is confidential.**

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# Table of Abbreviations Style Template: Überschrift 1 / Headline 1 (delete the number)

Convention: Mark the letters that make up the abbreviations by making them bold

|  |  |
| --- | --- |
| ASCII  ROS  AV  VTD | **A**merican **S**tandard **C**ode for **I**nformation **I**nterchange  **R**obot **O**perating **S**ystem  **A**utonomous **V**ehicle  **V**irtual **T**est **D**rive |

# Glossary Style Template: Überschrift 1 / Headline 1 (delete the number)

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|  |  |
| --- | --- |
| **Actuator** | Component for the conversion of an information carrying, low-energy control signal to a high energy signal capable of process intervention |

# Abstract

**Key Words:**

# Introduction

Autonomous systems in general are widely used in today’s world. Autonomous driving has been the latest trend in the market with rapid advancement in the AI, sensor, and the software technology. Major players in the automotive market are conducting research in autonomous driving and shifting towards increased levels of autonomy. A completely autonomous car with level 5 autonomy is expected to drive without any human intervention and handle any situation safely. This means that the vehicle should be intelligent enough to be able to take decisions in worst of the situations that are on par with the human decisions [1]. For this, the autonomous vehicle should be tested thoroughly under various scenarios such that they are safe enough to operate on roads. That brings us to the most important and wide research topic in autonomous driving – Validation of Autonomous Driving.

Before an autonomous vehicle is made available in the market, it must be validated and deemed fit enough to operate safely on the roads under any circumstances. The public trust in autonomous vehicles can only be achieved by continuous validation of the autonomous vehicle software [1]. One way of performing the validation is to directly test the vehicle on road. This technique, though possible to use is not convenient in terms of the number of miles that need to be driven to certify safety of autonomous vehicle and poses threats to the human life and property. To demonstrate that the failure rate of autonomous vehicles is statistically significantly lower than the human driver failure rate they need to be driven an approximately 5 billion miles [2]. This is highly inconvenient validation activity and it would take years to cover all weather conditions, road and traffic conditions in different parts of the world.

The other way of validation is to perform the simulation of the scenarios and test the performance of the autonomous vehicle software. A scenario consists of different weather, road, light and traffic conditions in different parts of the world, on different terrains and with contrasting driving conventions. For the autonomous vehicle software to be deemed safe, it must perform optimally under various scenarios as mentioned. The autonomous vehicle under test in the simulation is controlled by the autonomous vehicle software depending on the inputs received from the simulation environment. In this master thesis the validation of autonomous driving system using the simulation technique is considered.

## What is Autonomous Driving Software?

Autonomous driving software is the main component or the control unit of the autonomous vehicle. It basically receives the environment data from various sensors embedded in the vehicle, processes and makes decisions on the received data and sends the control commands back to the autonomous vehicle. The control commands include the throttle, gear, brake and acceleration values that determine the next position and the action of the autonomous vehicle. Any autonomous vehicle software stack consists of Localization, Perception, Prediction, Planning and Control as its core components.

The ‘Localization’ module is responsible for single digit centimeter level accuracy localization of the vehicle in the environment. Generally, the data from GPS, IMU (Inertial Measurement Unit) and LiDAR sensors is input to this component. ‘Perception’ module takes in the data from LiDAR, RADAR, Camera sensors and performs tasks such as classification, detection, segmentation and learning convolutional neural networks to perceive the surroundings of the vehicle. ‘Prediction’ module predicts the movement of other traffic elements like cars and pedestrians with respect to the autonomous vehicle. This information is consumed by the ‘Planning’ module to generate the right trajectory for the vehicle. Finally, the ‘Control’ component ensures that steering, throttles and brake commands are issued to the vehicle to execute the planned trajectory [3].

## Current Setup

The Robo-Test demonstrator has the LGSVL simulator connected to the Apollo autonomous vehicle software stack, a proprietary simulator VTD (Virtual Test Drive) and a web interface designed to create the test scenarios for the LGSVL as well as the VTD simulators. The web application was designed in MT-3136 [4] and VTD was introduced and integrated at a basic level in the web application in MT-3183 [5].

MT-3192 [6] has established an interface between the VTD simulator and the Apollo autonomous software stack using ROS [6]. The interface doesn’t support all the sensor data exchange between VTD and Apollo, also it introduces a few problems that are analyzed further in this thesis.

## Scope of the Thesis

This master thesis explores the possibility of creating a flexible interface between the LGSVL, VTD simulators and the Apollo software stack using ROS or ROS2. A feasibility check regarding a ROS based interface is performed before taking the decision. Depending on the outcome of the feasibility check, the existing Robo-Test web application interface is enhanced with new features and the details are discussed in the sections to follow.

Furthermore, in this thesis a detailed literature survey regarding the traceability techniques between the requirements and the test results is performed and a concept has been worked out for the current setup of the Robo-Test system. The concept tries to link the requirements engine to the test execution and test results. A detailed literature review regarding the techniques for automatic generation of test cases from requirements is also presented.

The rest of the report is structured as follows. Chapter 2 discusses the analysis of the current system and the fundamental design decisions. In the Chapter 3, we discuss the software architecture and corresponding system model. The implementation details are discussed in the Chapter 4, followed by the results in Chapter 5. Chapter 6 presents the concept for traceability for our system along with a literature review of the automated test case generation techniques. User manual is provided in the Chapter 7, followed by the conclusion.

# Analysis and Design of AV Software stack

For the selection and connection of an autonomous vehicle software stack with LGSVL and VTD simulators using a flexible software interface, the analysis of the current system architecture must be performed and the interface options must be explored. In the following sections, we will analyze these aspects and arrive to a decision with the help of certain criteria.

## Existing Interface Architecture

Let’s understand the existing interface architecture for our simulator and autonomous software stack system.

Robo-Test Web Application

VTD Connector

LGSVL Connector

VTD Simulator

LGSVL Simulator

ROS Interface

Apollo Cyber RT

Apollo 5.0

Apollo 6.0

Figure 2.1: Architecture of Simulators and Apollo AV software stack.

The architecture shown above consist of the VTD and LGSVL simulators connected to the Robo-Test web application using the individual connector components. The web application is a tool developed to generate test scenarios easily, without knowing the process to create scenarios on different simulators. The process and scenario creation details for the LGSVL simulator using the web application can be found in MT-3136 [4], whereas the details for VTD are in MT-3183 [5].

Both the simulators are connected to different versions of Apollo software stack using different interfaces. The LGSVL connects to Apollo 5.0 using the Cyber-RT based interface and the VTD connection is using ROS interface to Cyber-RT developed in MT-3192 [6]. The Cyber-RT layer is a common layer that connects both the simulators to Apollo. To better understand this, let’s look at these concepts in more details.

### Apollo AV software stack

Apollo is an open-source, high performance, flexible software architecture developed by Baidu for development, testing and deployment of autonomous vehicles [7]. It provides all the AV software stack components like localization, perception, prediction, planning, control and its own HD map format specifications. The Apollo versions upto 3.0 support the ROS interface to connect any external component. Since Apollo 3.5, Baidu has developed a robust Cyber-RT layer that takes care of Apollo’s interactions with the external components. So, the versions starting from 3.5 don’t support a ROS interface with Apollo directly as there is a Cyber-RT layer in the middle.

### Apollo Cyber-RT

The Apollo Cyber-RT is a robust framework and offers developers with a high-performance computing to support complex tasks of autonomous driving [8]. It enables a high concurrency of execution, low latency and high throughput [8]. The newer versions of Apollo have improved since the introduction of Cyber-RT making it one of the most robust open-source AV software stacks available. Integration of external software components with Cyber-RT framework is easy due to its plug-and-play architecture.

## Interface options between Simulators and Apollo

As per the current architecture of our system, we have Apollo versions 5.0 and 6.0 which come with a Cyber-RT layer on top of it. Thus, any interface for our simulators with Apollo must interact with Cyber-RT layer to establish communication with Apollo. The analysis of different possibilities of interface with Apollo is discussed in this section.

### Cyber RT Interface

One way of connecting both the simulators to Apollo AV software stack is to interface them directly with Apollo’s Cyber-RT layer. The LGSVL simulator offers this functionality and offers support for a connection with Cyber-RT. In the architecture that we showed, the LGSVL is interfaced to Apollo using Cyber-RT without any additional middleware component. The LGSVL simulator offers four types of bridges where each bridge has its own message format – ROS, ROS Apollo, ROS2 and Cyber-RT [9]. Using the Cyber-RT message format, it is convenient to exchange data between both the components. Let us look at a couple of important factors that must be considered for the interface between the simulators and the AV software stack with respect to our system.

#### Addition of a new Simulator

What if a new simulator must be integrated into our system? A standardized middleware interface layer will ensure the flexibility to accommodate a new simulator. The table below shows a few simulators and the interface support that they provide.

Table 2.1: Simulators and Interface Support.

|  |  |  |
| --- | --- | --- |
| Simulator | Type | Interface Support |
| LGSVL | Open Source | ROS, ROS2, ROS Apollo and Cyber-RT. |
| VTD | Proprietary | ROS and ROS2. |
| Carla | Open Source | ROS and ROS2. |

Table 2.1 indicates that the VTD simulator does not explicitly offer any support for Cyber-RT interface data communication. Being a proprietary simulator, there are quite a few limitations on the exchange of data into and out of VTD. Since there is no Cyber-RT message format supported in VTD, there is a need of an additional layer to convert the messages into Cyber format and vice versa. Also, most simulators provide a ROS/ROS2 based interface support for further data exchange.

#### Migration to a new AV software stack

How about the software interface if a migration to a new AV software stack is desired? The following table contains different AV software stacks and the interface support they provide to communicate with the external components.

Table 2.2: AV stacks and Interface Support.

|  |  |  |
| --- | --- | --- |
| AV Stack | Type | Interface Support |
| Baidu Apollo | Open source | Apollo Cyber-RT |
| Autoware | Open source | ROS migrating to ROS2 |
| Nvidia Drive | Proprietary | NVIDIA Driveworks SDK |

In case of our system, the possibility of migration to Autoware AV stack is high as it is an open-source AV stack and supports open-source ROS based interface for data exchange. Based on the inputs from the above tables, a ROS/ROS2 based interface looks a better option. Thus, the idea of having a single Cyber-RT interface that handles data exchange for both the simulators is not possible due to the factors analyzed above. Moreover, the VTD doesn’t support a Cyber-RT type message exchange, so designing a full Cyber-RT interface is not an option.

### ROS or ROS2 Interface

The analysis so far suggests that it is better to design a ROS/ROS2 based software interface to connect the LGSVL and the VTD simulators to Apollo. There already exists a ROS interface between the VTD and the Apollo but the system is not fully functional with this interface. Also, the LGSVL is connected to Apollo using its Cyber-RT message support. Thus, we explore the possibility of a ROS2 interface between both the simulators and the Apollo AV software stack by migrating and enhancing the existing ROS interface. A comparison between ROS and ROS2 is presented based on certain features.

Table 2.3: Comparison between ROS and ROS2 [10].

|  |  |  |
| --- | --- | --- |
| Feature | ROS | ROS2 |
| Multi-machine application | Set one machine as ‘master’. | No ‘master’ required. Independent working. |
| ROS Master | Required. | No more necessary. |
| Parameter Server | Global parameter server. | Local parameters to nodes. |
| Underlying Middleware | Central discovery mechanism. | Based on DDS standard. |
| Nodes in a process | One node per process. | Multiple nodes per process. |
| Roslaunch | XML | Python (Complex logics) |
| Language Support | C++ 03 and Python 2. | C++ 11,14 and Python 3.5 or greater. |

Table 2.3 compares ROS and ROS2 on a few features and ROS2 prevails better due to its distributed mechanism, support for modern C++ and Python for application development, multi-master capabilities, multiple node support in a process and good support for a next few years depending on the version.

## Problems with VTD connection to Apollo

As discussed above, there is a ROS interface between the VTD and Apollo software stack which was developed in MT-3192 [6]. The work puts forth a few problems that were encountered during the design and development of this ROS interface to connect the VTD and Apollo. This analysis is very important for our decision regarding the software interface between simulators available in our setup and the Apollo stack. The issues that occurred are discussed below in details.

### Camera Video Data Stream

The camera sensor data includes the camerainfo, image or compressed image provided by VTD. Since, sending the video image data over the TCP/UDP network may cause overload issues, the VTD does not support to take image data as a sensor plugin. Only the information regarding the image is available at the port 48196 using the TCP communication. A VTD API allows to save the image of every frame in a video to a local memory and it can be then published to the ROS topic. So basically, this approach introduces a delay in the camera sensor video data exchange with the ROS server [6].

Analysis of possible options to address this issue was done by contacting the VTD support team. We proposed the use of an API that streams the data without saving each frame to the local memory and sought feedback from the VTD support. The VTD support team confirmed that the use of streaming API would result in a poor quality of the camera sensor video data. No other API is available in VTD to address the video data issue in a different way. The approach to save every image frame by frame and publish it to ROS would cause performance issues in the system and is thus discarded.

### VTD LiDAR Sensor Point Cloud

The LiDAR sensor point cloud data collection from the VTD causes troubles in the current ROS interface system. The simulation hangs in between if the LiDAR sensor plug-in is enabled in the Module Manager configuration file. Disabling the LiDAR sensor plug-in makes the system function properly [6].

Disabling the LiDAR sensor data is not a solution as point cloud data from the LiDAR sensor is an important input to Apollo’s localization and perception modules. Incorrect or loss of data as inputs to these modules would lead to an incorrect control of the autonomous vehicle by the Apollo AV software stack.

### HD Map conversion

HD maps are being used as a fast-track solution to boost the self-driving ability of the autonomous vehicles. The self-driving vehicle understands the world with the help of a HD map. HD map basically filters out the 3D graphics and simplifies the road layout, traffic lights and other objects in it [6].

VTD uses the standard OpenDrive format for the road layout and OpenSceneGraph for the 3D graphics. Apollo on the other hand uses its own modified version of OpenDrive format. Since VTD does not have any communication interface with Apollo, there is no implicit map conversion from VTD’s format to Apollo’s format. One way is to convert standard HD map to Apollo HD map using Apollo’s OpenDrive specifications. But Apollo has stopped sharing its OpenDrive specifications to the outside world. The other way is to use some software like Roadrunner and Unity LGSVL Map Annotation to convert standard maps into HD maps. The problem with Unity LGSVL tool is that it supports OpenDrive version 1.4 whereas the VTD maps are in version 1.5. Also, the HD map is generated without road boundary and junctions. In the Roadrunner tool provided by MathWorks, only simple maps are converted correctly. Complex maps generally end up getting converted with loss of features or sometimes the conversion crashes. Moreover, the location of the Ego vehicle is also incorrect on the new generated HD map [6].

The HD map conversion to Apollo’s format is an important step as Apollo’s modules will work based on the vehicle’s location in its HD map. For the simulator and Apollo to function as expected an accurate conversion of HD map is required, which unfortunately lacks at the moment.

## Decision on flexible Software Interface

The above sections present a detailed analysis from the perspectives of the LGSVL and VTD simulators as well as the Apollo AV stack. Analysis of the existing ROS interface between the VTD and Apollo is also presented. Also, possible interface options that suit both the simulators are discussed keeping in mind the possibility of integrating a new simulator or migration to a different AV software stack in the future. A discussion of the important factors that affect the design of the flexible interface is summarized below.

1. The analysis suggests that a ROS based interface is better than the Cyber-RT interface given the current status quo of our system.
2. An interface developed using ROS2 would benefit given that ROS2 is more advanced than ROS and benefits from a better community support.
3. The analysis of existing ROS interface between VTD and Apollo highlights a few problems from the VTD end discussed in section 2.3. The issues discussed are important from the system performance and functionality perspective. Migration of this interface into a new ROS2 interface would add no value to the system unless the VTD can provide API’s that solve these data exchange issues in a better way.
4. From the LGSVL perspective, it is connected to Apollo using the Cyber-RT bridge. A new ROS2 interface in between could mean an additional layer that is not necessary for LGSVL to function. Though a standard interface in between simulators and Cyber-RT + Apollo would benefit the system from a flexibility perspective as discussed earlier, the problems from the VTD end have ensured that a new interface would add a little value and further complicate our existing system.

Considering all the factors discussed, a new interface between both the simulators and the Apollo AV software stack is not a value adding option. Therefore, this idea is not taken into consideration further.

## Which AV stack with VTD?

The decision of not having an interface in between the simulators and Apollo has brought up a question – Which AV stack to use with VTD simulator? Since, the LGSVL is connected to Apollo using a Cyber-RT bridge there is no need to contemplate a new AV stack for LGSVL.

Rather than exchange of VTD data with an external component such as any AV software stack, utilization of VTD’s internal AV software stack could be a better solution. Our system will benefit from this as there is no need of any interface to exchange the data in and out of VTD. In the below sub-section, we will discuss the usage of VTD’s AV stack with our system.

### VTD Internal AV stack

Vehicle dynamics and Driver are two important components inside VTD that are responsible for the control of the Ego and other traffic elements in VTD. They can be internal components from the VTD or external user defined components like Apollo AV software stack to control the vehicles [11]. The functions of these two components are as described.

1. **Driver**: It sends the control commands like steering, speed, brake and acceleration to the traffic elements. Driver belongs to VTD’s task control module whose output is available at port 48190. Either an internal or external VTD driver can be selected at one time, else there is a conflict [11].
2. **Vehicle Dynamics**: Vehicle dynamics utilize the driver control commands and different vehicle parameters to calculate the updated position of the vehicle. VTD offers a configurable simple and a complex vehicle dynamic [11]. In this thesis, a simple vehicle dynamic has been utilized.

A quite sophisticated model for driver is available in VTD’s internal implementation. It is referred as ‘ghostdriver’ or VIRES driver. This driver model is responsible for the control of all traffic elements in the VTD [12]. In this thesis, the internal VTD driver has been utilized as an AV software stack with the VTD simulator.

### Using VTD Internal AV stack

The VTD’s internal AV stack can be used and tested with more complex scenarios where the tester has a choice to apply certain actions to the scenarios and configures different driver types for different scenarios. This allows to test the behavior of internal AV stack under different scenarios. The Player Action Control Concept in VTD is discussed below to understand this better.

#### Action Control Concept

In VTD, a deterministic behavior of a player is achieved by assigning it with some specific actions. By default, the traffic module controls the vehicles autonomously and ensure that they follow the road, keep distance between each other and obey the recommended speed. The action control concept allows the tester to test the Ego vehicle with some action like Lane change, Speed change or Autonomous control. Player actions are linked with trigger points which ensure certain conditions are fulfilled before an action set by the tester becomes active. In general, the actions can be added for any player in the simulation, but this master thesis focuses on the actions for Ego vehicle [13].

Let’s discuss about the types of triggers that could be created to associate an action with the Ego vehicle.

1. **Absolute Trigger:** This trigger is in absolute (inertial) co-ordinates and the actions associated with it would get activated inside a circular range around the Ego vehicle called activation radius [13].
2. **Relative Trigger:** This trigger is activated when the distance between the selected player i.e., the Ego vehicle and the pivot player is less than the activation radius. A pivot player can be the Ego vehicle, or any other vehicle present in the simulation scenario. But for relative trigger it is necessary that the pivot is anything other than the Ego vehicle [13].

For the players in VTD, three actions are available which could be active concurrently. We will discuss all with respect to the Ego vehicle as the focus is the same.

1. **Action Autonomous:** This action controls the Ego vehicle autonomously using the VTD simulators internal AV software stack. If the force option is enabled, this action interrupts other running actions if any [13].
2. **Action Lane Change:** If this action is enabled, the Ego vehicle will change the lane. The direction of lane change could be left or right and is selected using the Directions field in the test scenario editor. The duration of the lane change is set using the fields Type and Time [13].
3. **Action Speed Change:** In this action, the Ego vehicle will change its speed from the current speed to the target speed that is set, with the rate of speed change set by the tester [13].

There are a few attributes that are common to all the actions that we just discussed.

1. **Delay Time:** It specifies the time in seconds by which the activation of given action is delayed after the trigger condition is met [13].
2. **Activation Event:** It specifies whether the action is active on enter (when the conditions are met) or on exit (when the conditions are false again) [13].
3. **Number of Executions:** It specifies the number of times an action is executed in one run of the simulation. It could be any positive number, infinite or never [13].

In our system, a web application Robo-Test allows the tester to create different scenarios and run the simulation using LGSVL and the VTD simulators. In this thesis, the VTD scenario creation using the web application is enhanced with the action control concept discussed above to utilize and test the VTD AV software stack under different driver types and the scenarios. Furthermore, the test results of the simulation are also captured and displayed on the web application.

# System Model

In this chapter, let us discuss the model for our system. We will look at the use-case diagram for our system and discuss the important use-cases. The existing use cases of the Robo-Test web application for the LGSVL simulator remain the same whereas for VTD two new use cases are added. The use case ‘Manual Test Editor’ is modified and improved to include a new use case – ‘Select Driver’ which further extends the ‘Add Player Actions’ use case. The database use case stays the same, but the functionality is enriched to accommodate the data generated from the new use case.

## Use Case Diagram

Diagram

Description automatically generated

Figure 3.1: Use case diagram

## Use Case Description

Table 3.1: Use case ‘Select Driver Type’ description.

Table 3.2: Use case ‘Add Player Actions’ description.

|  |  |  |
| --- | --- | --- |
| **USE CASE** | *Add Player Actions* | |
| **Objective** | To allow the tester to set various actions on EGO vehicle and enable autonomous control. | |
| **Category** | Optional | |
| **External Actors** | Tester | |
| **Preconditions** | Tester is successfully logged into the application and is creating a test scenario. | |
| **Success End Condition** | Player Actions are added and saved to the database. | |
| **Failed End Condition** | Tester is not able to create player actions and data is not saved to the database successfully. | |
| **Trigger** | Tester starts creating a test scenario. | |
| **DESCRIPTION** | **Step** | **Action** |
|  | *1* | The application renders the page with Player Action options when requested by the tester. |
|  | *2* | Entered values by the player are stored in the respective database. |
|  | *3* | Further actions are handled by the use case ‘Database’. |
| **EXTENSIONS** | **Step** | **Branching Action** |
|  | *1a* | None. |
| **SUB-VARIATIONS** |  | **Branching Action** |
|  | *1a* | None. |

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