Assuring Fully Autonomous Vehicles Safety by Design

The Autonomous Vehicle Control (AVC) Module Strategy

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***Abstract*—Massive investment in 'intelligent' vehicle technologies is going to turn autonomous vehicles into reality in a few years. The insertion of this intelligence at the road vehicles is expected to cause a reduction in traffic accidents due to the mitigation of human drivers errors and imperfections by computerized autopilots. However, autonomous vehicles shall mitigate the existing hazards at the roadway transportation systems while not creating new hazards. Thus, some critical aspects need to be better considered, such as how to ensure safety in this new vehicle paradigm. There is no specific method to analyze and assure the safety levels of the autonomous vehicle system. Despite the ISO 26262 – a new safety standard that specifies requirements and activities throughout the road vehicles development lifecycle – it cannot be applied to the autonomous road vehicles scope. This paper proposes a design strategy that may be used at the architecture design level of autonomous vehicles that may facilitate the development, analysis and, consequently, safety level assuring. The main idea is to implement an independent module – the Autonomous Vehicle Control (AVC) – that is going to both interact with the vehicle's systems and create a protection layer that is independent of the way the vehicle's system was developed. So, the AVC could be used with any autonomous vehicle system and could be tested individually. This strategy is based on both recommended practices published by Society of Automotive Engineers (SAE) and on approaches used on other transportation system domains. Another important point is that the proposed module will be intended, in principle, for fully autonomous cars (high levels of driving automation). So, it is expected that, in the future, the proposed module can be used to develop a safety software standard or to suit the existing ones to the needs of autonomous road vehicles.**

Keywords—autonomous vehicle control; autonomous vehicles; design strategy; safety

I. Introduction

About 1.25 million people die each year as a result of road traffic crashes according to World Health Organization (WHO) [1]. The development and advances in Intelligent Transportation Systems (ITS), more specifically in intelligent vehicle technologies, tend to influence this scenario in a positive manner, making it safer. Autonomous vehicles are included in this context, which originated from the advances in the areas of robotics, sensing, embedded systems, machine perception, navigation, and others [2]. As a result, high-tech sensors, cameras, and radar have been developed and are being applied to monitor the vehicle and the environment around it, as well as requesting the vehicle or the driver to take actions depending on the situation (in some cases, hazardous situations). Technologies like park assistance and longitudinal control/guidance are part of the necessary technology to support the autonomous vehicle operation. Thus, these vehicles are gradually becoming capable to perform the same actions that human drivers have always executed. In other words, autonomous vehicles systems are capable of not only properly guiding the vehicle (for example, defining routes, acceleration, braking points, and even the acceleration for overtaking), but also controlling possible problems related to the vehicle stability (for example, vehicle maneuver).

There is much speculation concerning autonomous vehicle impacts over the currently roadway transportation system dynamics. It is believed that self-driving vehicles can extend the mobility-on-demand systems, enabling themselves to travel automatically between locations of high demand, which would help address issues such as congestion, space use, pollution, and even energy use [3]. Due to the substantial benefits that autonomous vehicles should provide, their development has been attracting the interest of many stakeholders, mainly the automotive industry. According to [4], the automotive industry is racing to build self-driving cars in the next 5 years. Therefore, it is expected that between 2020 and 2025 the autonomous vehicles will be running in the current Roadway Transportation System (RTS). There is already concern about how to ensure safety in those systems - for example, if safety aspects are overlooked in vehicles that are manufactured too fast.

Safety is an important property in any system, particularly in transportation systems like the RTS, in which there is interaction among vehicles, drivers, roadway, and environment (surroundings like obstacles and pedestrians). When inserting autonomous vehicles into the RTS, at least the same safety levels that are achieved when human drivers control the vehicle must be guaranteed. As a result, safety-critical tasks have already been raised mainly regarding the planning of motions that basically interfere with autonomous vehicle control. Regarding those tasks, some studies have proposed planning

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and control algorithms that could assure safety[1] [6]. Besides, other studies related to design technologies (longitudinal and lateral warning systems) can be useful to avoid collision [7], which has a relation with the planning and control tasks also.

Although the ideas proposed in such research intend to make the autonomous vehicle system safer, none of these studies address how these proposals, systematically and at the system level, contribute to improving the safety levels of the autonomous vehicles.

There is already an international standard ISO 26262 for Automotive Electric/Electronic Systems that defines functional safety features for automotive equipment applicable throughout the lifecycle of all automotive electronic and electrical safety-related systems [8]. However, autonomous vehicles are not within its scope.

So, this paper proposes a design strategy to be considered during the system design level phase of the autonomous vehicles. The main element of this design strategy is the Autonomous Vehicle Control (AVC) module, which is responsible for adequately controlling the autonomous vehicle. This correct control is possible due to the AVC sub-modules that properly separate the vehicle control functionalities, thus allowing greater control over the vehicle operation mission.

The development of the AVC module considers high levels of driving automation for on-road vehicle, as defined by Society of Automotive Engineers (SAE) [9], as well as also approaches used at the rail transportation field, notably standard [10].

Even considering all the embedded automation, autonomous vehicles are still vehicles. Thus, preexistent rules for manufacturing and operating the vehicle itself – that are defined by regulatory agencies and are different depending on the country – shall also be followed [11]. Therefore, it would be interesting to have a control module, which, in addition to having the driver's functionality, would also provide a protection layer. In this way, the relationship among vehicle, road, environment and driver would be maintained, and the safety analysis could be performed considering the protection layer present in the AVC module.

This paper is structured in three sections. Section I refers to the introduction, which covers the problem that is being addressed and a succinct explanation of the proposed AVC module. Section II presents a detailed explanation of the proposed AVC module, covering its state-of-the-art overview in light of its current development through a postgraduate work. Lastly, section III presents how the AVC could be connected with a fully autonomous vehicle system.

II. AVC Module Proposal

One of the critical points when talking about autonomous vehicles is how they will behave when facing dangerous situations. Thus, autonomous vehicles must be prepared to identify the state of the elements belonging to the most critical situations so that, when they are in such situations, they are capable of reaching the safe failure state. In other words, autonomous vehicles must be prepared for unexpected, abnormal situations. These situations could be reached by failures in the autonomous vehicle systems that cause a malfunction in it and by the RTS behaviors that are not predicted by the autonomous vehicle system.

Considering non-autonomous vehicles, but those with some level of automation, when a dangerous and unpredicted situation happens, the human driver must assume the vehicle's control and solve the safety issue. In some cases, the human driver is responsible for monitoring and detecting safety issues (or abnormal operation) in both the vehicle and the surrounding environment. In a fully autonomous vehicle, we understand that the driver element – who monitors the vehicle and the environment and has the mission of controlling the vehicle – continues to exist. Consequently, its relationship with the vehicle and the environment (as illustrated in Fig. 1) is maintained. But, in this case, this driver element will be a machine.

Given that the relationship among RTS elements could be maintained regardless of the vehicle automation level, and the elements main missions/functionalities remain the same, we propose to create a system element – the Autonomous Vehicle Control (AVC) module – that will execute the driver functionalities in a fully autonomous vehicle. The AVC module is composed by a two-layer hierarchical architecture, with the lowest layer being responsible for protecting the vehicle movement and controlling it in critical situations. The AVC module is analogous to the Automatic Train Control (ATC) concept, applied in railway systems. Thus, before detailing the AVC module proposition, we first present the main concepts related to the ATC.

A. ATC Overview

In order to propose the AVC module, other transportation domain were observed, specifically railway transportation. In the railway domain, there is a concept called Automatic Train Control (ATC), which is a system that automatically controls train movement, both enforcing train safety and managing train movement. By standard [10], the ATC system includes a subsystem called Automatic Train Protection (ATP), which is responsible for maintaining the fail-safe protection against collision, excessive speed, and other hazardous conditions. Besides, the ATC system may also include the Automatic Train Operation (ATO) and/or the Automatic Train Supervision (ATS). The former is responsible for performing any or all of the functions of speed regulation, programmed stopping and other functions otherwise assigned to the (human) train operator. The latter monitors trains, adjusts the performance of individual trains to maintain schedules, and provides data to adjust service to minimize inconveniences otherwise caused by irregularities.

It should be noted that these systems do not interfere in the development of the vehicle 'train' (named Rolling Stock, composed by trucks, propulsion and brake systems, HMI, doors management system, etc.). In this way, the ATC system is adapted to control the train safely, considering the various

[1] According to [5], safety is defined as *"absence of catastrophic consequences on the user(s) and environment"*.

aspects (protection, operation and supervision) presented before.

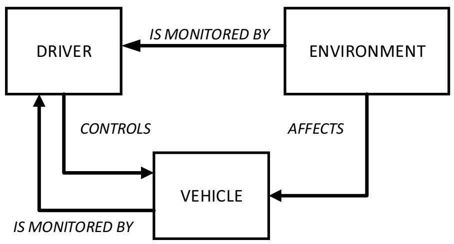

Fig. 1**.** Relationship among roadway transportation system's elements

B. Autonomous Vehicle Control (AVC) Proposal

Based on the ATC system applied to the railway transportation systems, we consider that the same approach could be applied to autonomous vehicles, i.e. an autonomous vehicle could be formed by the vehicle (equipped with sensors, and/or radars, and/or LIDAR) and a module (in this case, the AVC) that would represent the driver element. Thus, the AVC system would have to be able to perform all the driver's activities (route planning, vehicular control and vehicle system monitoring) in an autonomous vehicle, without relying on human interventions to accomplish its mission. Thus, although this type of system is able to receive instructions from a possible driver, it is considered that the AVC should have the ability to make safe driving decisions by itself.

The AVC module, which would have the mission of controlling the vehicle in a safe way, was formulated in this context. The AVC module could be used no matter how the vehicle system is implemented, because the AVC module only requires specific data sets to control the vehicle. The AVC module separates the operational layer from protection layer – the Autonomous Vehicle Operation (AVO) and the Autonomous Vehicle Protection (AVP), respectively. Unlike ATC, the AVC module will not have a layer corresponding to the ATS. Thus, the functionalities will be distributed into the two sub-modules (AVO and AVP) in order to make the autonomous vehicle behave properly.

The AVO sub-module is responsible for the navigation of the vehicle, setting the direction and the correct speed. The AVP sub-module, in turn, monitors the system variables (e.g., vehicle speed) and, if they exceed their respective safety limits (e.g. maximum speed of the road), it takes the vehicle to a safe state (e.g. the AVP reduces the vehicle speed). AVP also monitors the 'health' of the system, taking it to a safe state whenever it detects an abnormal/fault situation. Thus, AVP is also always monitoring the roadway elements in order to detect problems that may arise during the vehicle movement, and, when a safety issue is detected, AVP must enforce a safe state to the vehicle. Therefore, the sub-modules AVO and AVP are both important parts of the AVC because they are the ones that are responsible for adequate operation (AVO) and safe control (AVP) of the autonomous vehicle.

Most autonomous vehicles decompose their architectures into four basic subsystems: sensing, perception, planning and control. The sensing subsystem is responsible for taking raw data measurements in order to both orient the vehicle and perceive the static and dynamic urban environment. The perception subsystem is the one that creates usable information about the vehicle and its surroundings. The planning subsystem includes path planners, map planners, and behavioral planners. Lastly, the control subsystem includes the actual actuators and commands to drive the car [3]. Thus, these subsystems functionalities should be considered when developing the AVC module (AVP' and AVO sub-modules).

As mentioned before, the AVO and AVP sub-modules form the AVC module. Thus, their functionalities in an autonomous vehicle were allocated as follows:

- AVO is the sub-module who interprets the data coming from the sensing subsystem that is embedded in the vehicle (perception subsystem functionality), makes the route plans and maneuvers the vehicle from the processed data (planning subsystem functionality), and, finally, issue commands to the vehicle (control subsystem functionality). These commands can be related to: new values of acceleration, braking or steering angle (when a maneuver is required).
- The AVP sub-module monitors the environment through its own equipment (AVP sensing subsystem), which is independent of the vehicle's (sensing) subsystem. The sensing subsystem gives the necessary data that enables the AVP to observe elements that can take the vehicle from its safe state, such as the weather conditions, the road surface, and all the traffic conditions, as well as to enforce restrictive actions to vehicle movement whenever a safety issue is detected. Besides, AVP can also send the command messages to the vehicle.

AVO and AVP are independent sub-modules from which commands are issued to control the vehicle. However, since AVP is the protection layer, its commands take precedence over the commands issued by AVO. It is important to mention that the AVP does not constantly send commands to the vehicle; instead, it will send such commands while monitoring the elements, whenever it detects that they are behaving in a way that can lead the vehicle, and/or the passengers, and/or the environment to an unsafe situation. We believe that not only the vehicle and its passengers should be safe, but also the vehicle cannot generate situations that negatively affect the environment around it. Inappropriate behavior (for example, a vehicle that is moving in the wrong direction) of the elements that are monitored by the AVP sub-module depends on the hazardous situation that the vehicle may encounter. This detail will be part of the results obtained from AVC module tests, which are not within the scope of this paper.

Several algorithms have already been developed and are suitable to be used in the operational (AVO) layer, and many of them that already consider safety. Thus, the software that will be used in the AVO sub-module does not have to be homogenized, that is, each developer can choose what one deems to be the best choice, as long as they perform the necessary functions of the operational layer with an acceptable safety level. This is due to the fact that AVP protects the vehicle constantly, so if there is an operational layer error that results in an undue command, AVP is also able to detect that an error has occurred and act in a safe way. For example, considering the accident that occurred with the automated vehicle of the Tesla [12], our proposal of AVO/AVP sub-modules could have the potential to detect that an error occurred in the AVO, since AVP would identify the truck, and it could send a command to the vehicle to reduce its speed.

In this context, the AVP is an important sub-module in the AVC module. The AVP must be safe and reliable. Thus, when comparing the AVP sub-module with other subsystems present in the autonomous vehicle, the data acquisition at the AVP sub-module, in addition to being independent from other systems that perform the same function, shall have more reliable equipment, and may even have redundancy. Although it seems that the total cost will increase, the AVP sub-module enables other equipment to be used in the other autonomous vehicle systems. Therefore, the development process of AVP sub-module should achieve higher levels of safety. A high level structure of the AVC module is presented in Fig. 2.

Another aspect presented at Fig. 2 is related to the command messages that are sent by the AVP and AVO sub-module. The two sub-modules are able to act over the vehicle, but the circumstances in which these messages are sent are different. AVO commands are generated based on the vehicle route (an origin point and a destination point) and the obstacles (objects on the road, other vehicles, interdicted areas, pedestrians, etc.), and their messages are sent in order to make the vehicle navigate correctly. On the other hand, the AVP monitors environmental obstacles in order to detect if any of them is in a situation that was not predicted by the AVO – for example, a pedestrian crossing in an undue area. If such an unsafe situation occurs, AVP sends messages that enable the emergence brakes or lead to a maneuver. In addition, the AVP also monitors whether the speed of the vehicle and its direction can be applied considering the surrounds of the vehicle. In other words, the environment is checked (determining nearby obstacles) and then the speed and direction of the vehicle are verified in order to determine whether they agree with the given scenario. In the last situation, if a problem is detected, the same messages can be sent by AVP.

It can be thought that the obstacle detection process - present in both AVO and AVP - is continuously performed. However, it is important to remember that the data acquisition in AVP needs to be much more reliable than in AVO. In addition, this separate data acquisition by sub-module creates greater independence between them that could avoid the common cause failure mode and enables the effectiveness of the fallback plan present in the AVP. The fallback plan is triggered when a hazardous situation is detected by the AVP sub-system, while monitoring the RTS elements behaviors. Besides, it is also activated due to a malfunction of the AVO that is also detected by the AVP. So, when it is required, it informs how the vehicle should act in order to achieve a fail-safe state.

The goal of the fallback plan is to eliminate hazards to passengers, while continuing to provide the required service. As a consequence, the AVP sub-module is designed to support degraded modes of operation in the event of failure and to continue to provide protection, hence providing a high safety integrity level. This behavior depends on what generated the risk situation, which may be a mechanical failure, or a failure to acquire data, or a malfunction of any of the systems, or due to an unexpected situation. Thus, depending on the failure that has happened the AVP controls the vehicle differently. Therefore, the emergence control messages are sent based on the failure and the situational state of the vehicle. The next section presents more details about the interaction of the AVC with the vehicular system.

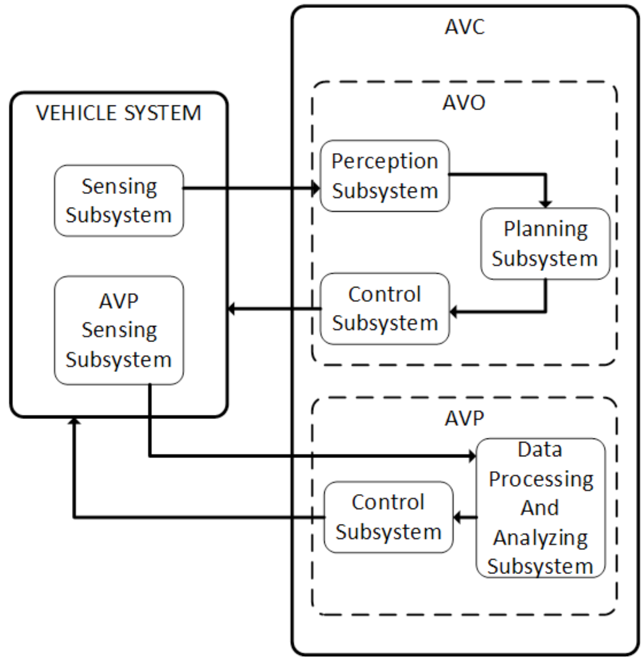

Fig. 2. High-level AVC module structure

III. AVC AND AUTONOMOUS VEHICLE SYSTEMS

In the previous section, the AVC module and its sub-modules AVP and AVO were presented. It was presented that AVC was based on an analogy with standardized practices of the railway transportation system. In addition, the functionalities of each sub-module have been explained in order to show that they can represent the necessary functions for the proper operation of an autonomous vehicle. In this way, this section presents more details about the interaction between the AVC and the vehicular systems, emphasizing the advantages that the AVC module provides to the autonomous vehicular system.

It is worth adding that the Society of Automotive Engineers (SAE) published some recommended practices which present driving automation levels in on-road motor vehicles, including the functional definitions for these advanced driving automation levels [9]. This document defines some of the vehicle's systems, describes each driving automation level and detail how such systems are used in each of the driving automation levels.

Some systems definitions based on the SAE document [9] are presented in this paper. The interaction of these systems with the AVC module is also introduced, including the necessary adaptations for such interaction between the vehicle and the AVC module.

A. SAE Documentation

SAE presented the definition of Dynamic Driving Task (DDT), which is the system that contains the functions required to operate a vehicle in on-road traffic. To explain the functionalities of this system, they described their interpretation about the necessary driver effort in order to drive properly. They present three types of driver effort: *strategic* (involves trip planning, best routes to take, etc.), *tactical* (involves maneuvering the vehicle in traffic during a trip, selecting an appropriate speed, etc.), and *operational* (involves micro-corrections to steering, braking and accelerating to maintain lane position in traffic or to avoid hazardous event in the vehicle's pathway). Although they have presented these three efforts, they only consider tactical and operational are considered as part of the DDT. So, based on these functionalities, they presented a schematic view of the DDT (Fig. 3).

SAE also defines the levels of driving automation (0 - 5) and, for each level, it informs who controls the DDT (system or driver). In this paper, the proposed AVC module is intended to be applied to fully autonomous vehicles (SAE Level 5). This was adopted since it is easier to propose a design strategy without having to consider possible interactions with the driver. However, it is important to know that the driver can request the vehicle to stop any activity that it may be performing, but it is the Automated Driving System (ADS), which is the one that performs the complete DDT and fallback DDT, that is responsible for discontinuing the activity in a safe way.

Considering the basic information provided by SAE documentation, it is possible to insert the AVC module within the DDT scope.

B. AVC and DDT

The objective is to present that the proposed design strategy (AVC module) can be used in the autonomous vehicle control. It has already been presented that, regarding functionality, this module addresses the necessary actions to have an efficient control. Thus, this section aims to present how the AVC addresses the vehicle's dynamics considering a relatively simple vehicular system – in this case, DDT. It is also worth pointing out that the dynamic that will be considered is the one directed towards fully autonomous vehicles.

Analyzing Fig. 2, it is possible to notice that the AVC module presents the same dynamics presented in DDT, albeit with different systems organization. Fig. 4 identifies what would be the DDT in the structure proposed by the AVC. One difference is with respect to the planning system, which is not present in DDT. We decided to allocate the planning system together with the other systems because the idea is to make the vehicle system as simple as possible, so that there is not so much difference among vehicles, but rather among drivers (different AVO sub-modules). In addition, we wanted to maintain the relationship shown in Fig. 1 and, since the driver is represented almost entirely by the AVC, it is plausible that the planning system is in the AVC module.

Another difference regards the AVP sub-module. When talking about complete automation, it is expected that no external control is taken, so it is the system responsibility to evaluate and make the necessary decisions for certain actions and then apply them. Considering what has been previously presented, in the case of DDT, the latter evaluates and makes a decision. However, when there is an error in this system, it is the ADS who takes control, once it basically represents the driver's action. No documentation about the ADS structure was presented at SAE documentation, only examples of how it would act when a failure occurs.

The ADS is represented in the AVC module by the AVP sub-module. One difference is that the AVP will always monitor the vehicle's environment and condition so that it can act whenever it detects an error. As mentioned in the previous section, the behavior of the AVP is based on the failure and the situational state of the vehicle, which are considered as the other elements around the vehicle that are related to it.

Therefore, is possible to conclude that the proposed AVC module may be suitable for fully autonomous vehicles. However, there is still need for a more detailed evaluation of the whole system, including testing to better evaluate this proposal and also to improve the behavior of the AVP.

Final Remarks

In this paper, a design strategy that may be applied in the development of fully autonomous vehicles is presented. The proposed AVC module has the objective to properly control the autonomous vehicle by separating its functionalities into two sub-modules (AVO and AVP).

The proposal to separate the operational layer from the protection layer in the task of managing the autonomous vehicle movement would facilitate:

- The analysis of safety levels, because the AVP should be analyzed separately, since it is the responsible for keeping the vehicle safe;
- The repair and detection of possible errors, since the modules would be separated;
- The process of developing the whole system, since it would already be possible to identify the critical points, devoting more time and investment to them.

The main contribution of this proposal is the AVP sub-module, which provides a protection layer to the autonomous vehicle mission by deciding the best behavior when the vehicle faced a hazardous situation. We believe that the AVP sub-module should not take ethical decisions, for example, choosing a vehicle to compromise when a critical situation of imminent collision occurs. This can be avoided with a well specified fall back plan.

This strategy was proposed given the importance of ensuring safety at autonomous vehicles when hazardous situations suddenly occur, due to, for example, an unexpected weather event or a system failure.

Therefore, the proposal is shown to be a potential solution to circumvent, at least conceptually, the gap related to the safety assurance of autonomous vehicles. Besides, it may facilitate the safety level analysis, and may even be used to develop safety-related software.

The next steps of this research involve the development of the AVC module in an implementable way that enables its test and validation. Then, more tests are going to be performed in order to improve the protection layer (AVP sub-module) and, when this is done, the idea is to apply the AVC module to others levels of driving automation (those who have human intervention).

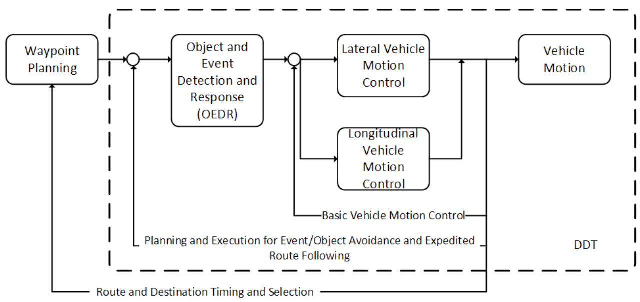

Fig. 3. Scheme presented by SAE that shows the part of the system that represents the DDT [9]

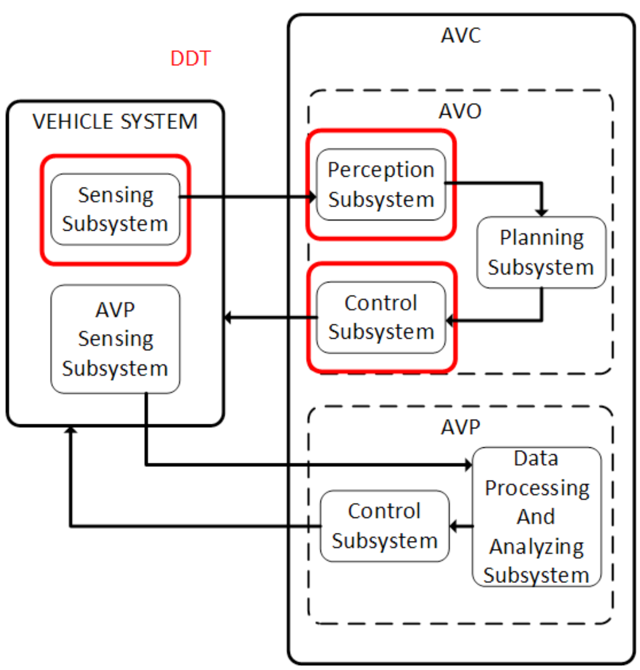

Fig. 4. Representing DDT at the high-level AVC module

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