The Role of Virtual Reality in Autonomous Vehicles' Safety

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***Abstract*—Virtual Reality (VR) has played an important role in the development of autonomous robots. From Computer Aided Design (CAD) to simulators for testing automation algorithms without risking expensive equipment, VR has been used in a wide range of applications. Most recently, Autonomous Vehicles (AV), a special application of autonomous robots, became a major focus of the scientific and practitioner community for road and vehicle safety improvements. However, recent AV accidents shed a light on the new safety challenges that need be addressed to fulfill those safety expectations. This paper presents a systematic literature mapping on the use of VR for AV safety and assimilates this literature to create a vision of how VR will play an important role in the development of safety in AV.**

Keywords—Autonomous vehicles, virtual reality, safety

I. INTRODUCTION

One of the highest expectations about Autonomous Vehicles (AV) is related to the safety improvements of transportation systems. A significant reduction of the accidents rate is expected by the elimination of the need for a human driver and, consequently, possible human errors. Thus, this expectation relies on the belief the AV will overperform humans in the tasks involved in the process of driving a vehicle.

However, the recent accidents involving AVs have demonstrated that the scientific community and industry still have a long path forward before reaching acceptable AV Safety levels. For example, accidents involving Uber's AV [1] and Tesla's autopilot [2][3] resulted in life losses. Also, Google has officially reported 272 failures and 13 near misses for its self-driving cars [4].

A recent study about the impact of Artificial Intelligence (AI) on AV safety [5] presented an analysis of 59 studies selected from 4870 initially retrieved papers from multiple indexing databases, using level 5 exclusion criteria defined by [6]. Among the findings, significant gaps were found in AV testing, AV verification and validation (V&V), AV Safety Certification, and safety-oriented AV Design. In other words, the current state of the art about AV is not properly addressing the fundamental safety assurance concepts to the AV deployment. This lack of research could jeopardize the complete adoption of this new promising technology by society.

Virtual Reality (VR) is a digital environment that allows users to experience and interact with the environment as if it were real [7]. VR has been used for training (humans) since its inception in the 1960s [8]. In the last decades, VR has been used for training purposes in several fields [9], such as Education [10], Health [11] and Business [12]. VR is particularly useful as it can simulate situations that could be dangerous or life threatening in the real world [13]. Thus, it can provide training possibilities that otherwise would be costly, risky or even impossible in the physical world [14].

Considering the VR affordances, there is a great potential for its application for AV safety as a training, research and test bed tool. VR can be used to train and test interactions between humans and AVs in a realistic environment and without the physical risks of the real environments. Also, it makes the evaluation of users' behaviors in virtual and controlled scenarios possible. Using VR environments as research, test and training tools allows for greater control of the stimuli the user [15] and the AV's algorithms are exposed to, and improves the reliability of the research, training and testing, as well as the generalizability of the results.

In addition, the use of VR for training AVs' AI algorithms seems to be a promising and unexplored field. For example, [16] used a simulation and 3D engines for training of deep learning approaches for object classification – a task that usually relies on human annotations. The results indicated the viability of the simulation-only training approach for classifying real world imagery. This kind of training can reduce significant costs and time to generate reliable data sets for AV image recognition.

In this context, the present paper intends to deal with the potential of using VR as an instrument to help in filling the gaps on AV safety assurance observed in literature [5] and, consequently, using VR to improve AV safety. After an extensive literature search, no study was found mapping and organizing the related literature to provide a complete vision of the field. Therefore, this paper presents a Systematic Literature Mapping aiming to present a clear picture of the state-of-the-art of the literature in VR on AV safety.

II. METHODOLOGY

The Systematic Literature Mapping was the selected method for the current study. Based on the process proposed by [17], a 4-steps approach [18] was used in this study: (1) Definition of research questions; (2) Identification of search string and source selection; (3) Study selection criteria; and (4) Data mapping.

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Also, some of the recommendations from [19]–[22] for extracting, analyzing, interpreting and reporting the literature-based findings were considered when they were suitable for an adopted protocol. Finally, the protocol used for the present mapping study encompassed information extraction from the paper's abstract review. However, when the study's abstract did not state clearly its main contributions, the paper was completely reviewed to extract this information.

Because of the multidisciplinary topic, a multi-disciplinary research team was involved in the present study. The team encompassed: VR, AV safety, and system safety researchers.

A. *Definition of Research Question*

The first step was to define the research question. In order to focus the study and support the research goal of presenting a clear picture of the state-of-the-art in literature in VR on AV safety, the following research question was posed: *What is the role of VR in AV safety studies?*

B. *Identification of Search String and Source Selection*

The following step was to define a search strategy, which was structured through the selection of source databases and the appropriated search terms. Aiming to find relevant studies and the completeness of the search, no limit was set on the publications' date range. Thus, all the papers available through August/2019 were considered, including early access which could potentially return papers in-press for 2020. Also, a broad selection of online databases indexing scientific literature were considered: ACM, Engineering Village, ScienceDirect, Scopus, SpringerLink, ACM DK and IEEExplore.

Right after, the search string was designed based on the most representative terms used in the scientific literature (Virtual Reality, Safety, Autonomous Vehicle) after an exploratory research and a sensitivity analysis. The exploratory research was done using Google Scholar search with distinct combinations of synonyms of the candidate search terms. Based on those results, the sensitivity analysis of each term was performed. Finally, after many iterations, the selected string with Boolean operators was: *("safety" AND "virtual reality" AND "autonomous vehicle")*.

On each database, the appropriated options were selected to limit the search process to the Title-Abstract-Keyword (TAK) field set. This is an important measure to reduce the number of non-related or duplicated studies retrieved. However, it was observed that not all databases support a search limited on TAK field set, leading to an inflated number of papers found (e.g. SpringerLink). This is because the search returns true to the Boolean search string for papers where the keywords were found in the paper body or even in its references. Table 1 shows the initial number of papers found per database. An order of magnitude from 10 to 100 times higher in retrieved studies illustrates the issue in limiting searches to TAK fields on SpringerLink.

Right after, data preparation was performed. The information (metadata) available for each paper found was collected by exporting the search results from each database to a csv, xls or txt file (according to the available options). Then, the files were imported, and its fields were tabulated into a spreadsheet.

TABLE 1. NUMBER OF PAPERS PER DATABASE

Database	Search Result
SpringerLink	114
IEEEXplore	31
ACM DL	2
Science Direct	1
Scopus	48
Engineering Village	22
TOTAL	**218**

C. *Study Selection Criteria*

The study selection process had 3 steps. The first step ensured that only the studies with the TAK fields returning positive to the Boolean search expression would be selected. This was performed using a spreadsheet macro developed by the authors. After this check, only 97 papers remained as a sample from the initial 218 retrieved papers.

The second step removed the duplicated entries (using the spreadsheet "Remove Duplicate" tools). Due to the reasonable number of remained results, we applied the level 5 exclusion criteria from [6]: book chapters (non-peer reviewed and not proceedings), editorials, notes and reports were removed from the selected sample. This step resulted in 59 papers.

In the third step, titles, abstracts and keywords of the remaining 59 peer reviewed papers were scrutinized to check their alignment with the research goals. After careful examination, 11 papers were considered out of scope of this research. Consequently, they were excluded from the sample to the literature mapping. Finally, 48 papers were the sample considered in this study (Table 2).

The drop from 218 to 48 papers is considered a reasonable result in a systematic mapping study. It occurred for many reasons, such as: misuse of the terminology; correct use of the terminology in the context of an example within a paper that did not actually focus on the topic; or lack of restricted search in TAK fields on some databases (e.g. SpringerLink).

D. *Data Mapping*

The data mapping process was performed, categorizing the 48 sample papers over 1 category to answer the research questions. The categorization process was based on the agreement of the reviewers. Hence, the reviewers might have the same opinion about the codes selected to categorize each paper on each distinct category. When the opinions were not convergent, a debate was prompted until a common understanding could be found. The codes were created using the recently proposed "extended Dynamic Driving Tasks (DDT) model" [6], as illustrated in Fig. 1.

The extended-DDT model [6] is an adaptation of the DDT model proposed in [23]. It considers that driving a vehicle involves, in a high-level of abstraction, 3 main activities: Perception, Control and Actuation. In an AV, they are performed by Machine Perception (MP), Machine Control (MC) and Machine Actuation (MA) components, respectively. In extended-DDT model, a Human-in-the-loop (HIL) component is considered, which implement the Human-Machine Interaction (HMI) among humans (driver) and MP, MC and MA. All those components, including the environment, is the system (AV) being modeled.

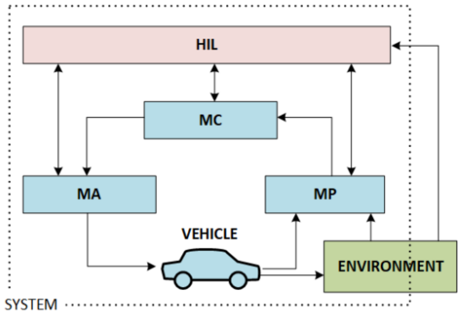

Fig. 1. The extended-DDT model [6]

III. Results and Discussion

Table 2 lists the studies references, why VR is used, their main contributions, and their type: (E)xperimental, (D)escriptive or (T)heoretical. Most identified studies are related to HIL (19 studies; 40% of the total), followed by studies related to MC (14; 29%). Then, the next largest group of studies are related to a broad System view (8; 17%). The remaining papers are related to MP (7; 15%). Finally, no studies were found related to MA. The Vehicle and the Environment components are involved in some studies. However, they are combined to the other components which are the focus of the investigation. Because they are not the main research topics, these codes were not assigned to any paper.

Fig. 2 shows the distribution of each study topic over the years. HIL-related studies were identified first in 2008. However, they started to be published consistently over the years only after 2015. In fact, in 2015, 2016, 2018 and 2019 (up to August), they were predominant. Also, all the early access papers (2020) retrieved are related to HIL.

The oldest study (published in 1997) was related to MC. Only almost a decade later, in 2006, another study related to MC was found. Then, from 2009 until 2019, the studies related to MC are more consistently present. The years with the highest number of studies related to MC are 2010 and 2018, when 3 studies were found in each year.

The oldest study related to MP was dated from 1999 and the last one from 2018. They are not evenly distributed, which means there are reasonable gaps in the time range in which there were no studies related to the topic. In 2017, the highest number of studies (2) related to the topic in a year was found. Also, so far in 2019 no study was identified in this topic.

Finally, the oldest study related to the system was from 2013, much later than the other topics. Between 2013 and 2016 few studies were identified. Only from 2017 on, the topic seems to have got some consistent traction and a growth trend was found: 1 paper was identified in 2017, 1 paper in 2018 and 2 papers in 2019, which is the highest number of studies in a year related to this topic.

The following subsections present a brief overview of the studies' research problems organized by each code (extended-DDT component). The brief overview was based on the information retrieved from the paper's abstracts, as preconized by the Systematic Literature Mapping protocol. Then, the following section presents the discussion for the research question.

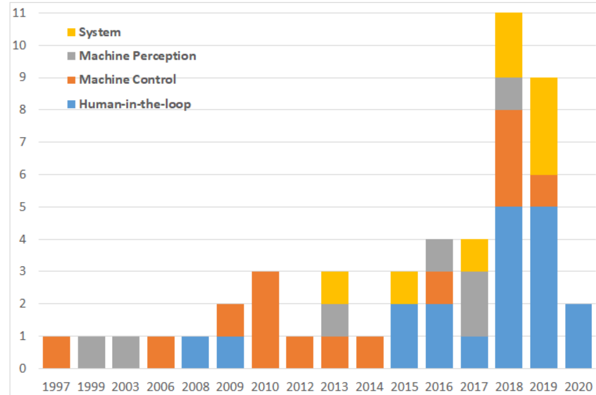

Fig. 2. Studies topic distribution over the years

A. *Human-in-the-loop* (HIL)

AV-pedestrian interaction. Most of the HIL studies (9; 47%) investigated the relationship between pedestrian and AVs. Those studies investigated: trust between AVs and pedestrians [24], pedestrian attitudes towards vehicle maneuvering in close proximity [25], testing procedures for collision avoidance in scenarios with pedestrian in the loop [26], V&V testbed for the AV faced with realistic pedestrian behavior in critical [27], worst case traffic scenarios [28], realistic pedestrian simulation [29], pedestrian suggestions for external features on full AVs [30], comparison of child and adult pedestrian perspectives of external features on AVs [31], and pedestrian perception of AVs with external interacting features [32].

Alternatively, the studies related to pedestrians could be coded as "environment" studies. In fact, pedestrians are in the environment where the AV systems work. However, in the present study, the authors decided to code those studies as HIL for the following reasons: (1) the reference model - extended-DTT – proposed a single component (HIL) to encompass all the human related aspects [6] regardless they are users or pedestrians; (2) it allows the examination of the user actions and interactions [6] as suggested by [33]; (3) it supports a necessary human-centered and holistic view [34] to better support the complexity of the human behavior and its interaction to the system [6]; and (4) "it avoids the misconceptions of the too logical designs from some engineering designs and helps to consider and accept human behavior the way it is, not the way engineers would wish it to be" [6] as warned by [35].

There are many situations that would impose a reasonable complexity for the situation analysis. They can be avoided by the authors' decision. A good example is the situation where a family leaves a restaurant and the father uses an app in his phone to ask the AV to pick them up. The AV automatically leaves the parking lot and moves towards the family's location. Is the father a pedestrian? What about his family? They are outside the car, but they are the users. In fact, the father can control the car from his phone by changing the pick-up location or canceling the request. Is he the driver? When they are about to enter the car, are they part of the environment? Or the unique complexity of the situation would be better understood as a HIL interaction? This is just an illustration of the type of complexity that coding decision can avoid.

Driver – AV interaction. Almost the same number of HIL studies (8; 42%) investigated the relationship between a human driver and AVs. Subjects investigated were: driver AV interaction [36], autonomous overtaking behavior of AV [37], evaluation of the human factor in the AV context [38], analysis of individual driving experience in autonomous and human-driven vehicles using a driving simulator [39], analysis of preference for autonomous driving under different traffic conditions [40], human driver in dilemma zones (intersections) [41], test interface of advanced driver assistance systems for elder driver [42], and multi-modal take-over request [43].

Passengers – AV interaction. Finally, few studies (2; 11%) investigated the relationship between the car passengers in general and AVs. They investigated motion sickness [44], and gesture interaction guidelines for adjusting AV dynamics using passenger elicitation [45].

B. *Machine Control* (MC)

A variety of subjects related to MC were found. In fact, there was no concentration of topics, except that 2 papers were related to intersection control [46][47] and 2 papers were related to lane change control [48][49]. It is noteworthy one of the papers related to lane change control was focused on double-lane change control [49] instead of single-lane change. The other topics found were: platooning control [50], distributed control [51], decision making in tactical situations [52], control systems test and validation [53], path-planning and path-following controller [54], AV maneuver test [55], path-tracking control [56], control in high-speed and loose-surface ground [57], overtaking stationary and moving obstacles [58], and speed control in narrow environment with a pre-defined path [59].

C. *System*

Most of the studies (5; 63%) related to the System were related to V&V [60][61][62][63][64], which is a critical issue for AVs. The 3 (37%) remaining papers were related to moral dilemma [65], operational simulation [66], and AV training [67].

D. *Machine Perception* (MP)

Most of the studies (4; 57%) related to MP were related to MP testing [68][69][70][71], which is another very critical issue for AVs. The 3 (43%) remaining papers were related to communication quality [72], virtual MP simulation [73], and MP training [74].

IV. The Role of VR to the AV Safety

Robotics have leveraged VR for many decades. In fact, the partnership between robotics and VR can be found in literature since at least the 80s [75]. Also, for example, Computer Aided Design (CAD) has assumed an important role in assisting robots design since the 80s [76][77]. Another example is the contribution of the simulators such as Gazebo, a 3D dynamic multi-robot environment that recreates the world's complexity mobile robots will encounter [78]. These simulators have enabled quick and efficient testing of new concepts, strategies, and algorithms [78] in an emulated physical environment without causing hazards to people and risking expensive equipment. These are examples of how VR contributed to the reduction of time, costs, and safety risks in the systems' development lifecycle.

AVs are considered autonomous robots [79] in a vehicle form-factor which can navigate in the infrastructure built for regular vehicles (with human drivers). Thus, it is reasonable to expect that VR can also have an important role in the AV development, as it has in other mobile robots. Safety is the most critical concern about AVs nowadays, and the findings from these studies indicate VR has the potential to play an important role on supporting the researches to address this issue.

In fact, VR can be used to generate realistic virtual scenarios to train MI exhaustively. This can eliminate the need of the manual annotation because VR systems can generate the scenes and the annotation meta-data about the scene's content automatically [74]. Also, it enables the generation of a wide range of odd cases [28][65] and near-accident [65] situations which can be used to enhance MP and MC training. Thus, VR has potential to considerably reduce costs and risks of MI training process, as well as scale it [74]. However, those opportunities are being underexplored - only two studies were found leveraging those possibilities [64][71]. Although some studies used the scenarios' generation capability [28][65], they do it for other goals than leveraging AV safety.

VR can also support the AV's V&V process for risky situations, reducing losses and costs compared to real setups [61][63]. Also, it can scale the process to cover a wide range of scenarios [65] and reduce AVs MP, MC and MA safety risks. Also, VR can be used as testbeds for testing the effectiveness of different HMI designs under an AV failure [43], near accident [65], dilemmatic [28][65] or worst-case scenario [41]. In fact, at Stanford University, a car was adapted and integrated into a virtual cave coupled with a driving simulator software, creating a cost-effective laboratory to investigate many aspects related to the HIL factor, such as drivers' behaviors and emotions [80]. Although studies investigating the HIL factor were found, there are only a few, indicating those opportunities seem to be also underexplored.

VR can also be an important tool to help users to learn to interact with distinct HMI [43][45][42]. A recent study about the use of head-mounted display VR in education and training highlighted how VR has been effective in learning psychomotor skills (such as HMI interaction in AVs) [8]. Users can wear VR headsets to learn how each interface works and how to interact with them in a controlled environment, reducing risks. Studies exploring this VR potential exist, but there is room for many more studies as the vehicles enhance their autonomy and require new behaviors regarding passenger and pedestrian interaction.

VR, such as driving simulators, can be used in the driving exam to test users' expertise to support semi-autonomous vehicles or AVs when needed. It can also be used to train users to regain the car control and react properly in dangerous situations without risking their lives [57]. For example, Mok et al. [81] investigated the time necessary for drivers to shift from performing secondary activities to regaining control of the car using a virtual environment (VE) and a car simulator for a partially automated vehicle. They found that few drivers were able to deal with road hazard situations within 2 seconds or less, what is often not enough time to safely avoid accidents [81]. In this example, VR was paired with a vehicle simulator to create a realistic simulation. It allowed the researchers to identify the minimum time drivers would need to regain the car control in hazardous situations without exposing participants to risks. This kind of necessary investigation would be very counterproductive or dangerous – even unethical – if made in real conditions. Given the fast pace that VR and AI have been evolving and the few studies exploring the potential of VR for applications beyond human-centered ones, there is significant room for research into new machine-centered applications of VR.

V. Concluding Remarks

There are high expectations on the traffic safety benefits that will be brought by AVs. However, to fulfill those expectations, AV's MI will need to exceed human performance in the next few years. This will demand new approaches to perform MI training and testing in a broader scope of scenarios, at a larger scale and at lower costs and risks. Also, relying on human drivers as a system's monitor and fallback creates a very complex HIL factor, which requires deep investigation on how the HMI will work in odd situations, such as the imminence of an accident.

Supported by the present study, we can conclude that VR has an underexplored potential to contribute to the deployment of sthe AV safety. Most of the few studies identified (19; 40%) concern the relationship between humans and vehicles. Indeed, this is an expected finding considering the human-centered characteristic of VR. In fact, VR is recognized as an excellent alternative in studies or simulations to avoid the risks of physical set-ups where people could be injured [13].

In several cases, replacing the human with the machine (AV) in the center of VR would be beneficial to AV deployment, mainly regarding safety and costs. But, very few studies in which the VR was applied in a machine-centered approach (AV, either the system or its components) were found. In fact, only one study used VR to train the AV MP [74], indicating a lack of studies in this field. Therefore, there is a promising field of study and cross-fertilization to both VR, AV and Safety Engineering communities.

This paper was a first step towards a systematic study about how VR is being used to deploy and improve AV safety. It dealt only with the research question "*What is the role of VR in AV safety studies?*". Its findings can contribute to organizing the literature, mapping the important topics and identifying potential topics for a future research agenda on the uses of VR in AV safety research. A future systematic study considering a broader scope of immersive technologies is under work.

TABLE 2. TYPE OF STUDY {(E)XPERIMENTAL. (D)ESCRIPTIVE OR (T)HEORETICAL}, REFERENCE, VR USE AND CONTRIBUTIONS

T	Ref.	VR Use	Contributions
HUMAN-IN-THE-LOOP			
E	[24]	AV-pedestrian interaction	Participants crossed before the vehicle (w/interface) stopped versus after the vehicles stopped (w/o interface). Vehicle's motion and cues were most useful than cues on the pedestrian.
E	[25]	AV-pedestrian interaction	At signalized crosswalks the AV's driving behavior had little impact on trust. At unsignalized crosswalks it was a major determinant of trust.
E	[26]	Simulate maneuvering scenarios	VR environments seemed sufficiently convincing to evoke consistent responses.
E	[36]	Hand gesture interface (HGI) to control AV	Semi-autonomous controlling using the HGI significantly reduced drivers' perceived workload.
E	[39]	Driving experience in several road conditions	Experienced drivers opted for conventional driving due to flexibility and fun. Novices opted for autonomous driving due to easiness and safety. Both driving methods were interchangeably preferred depending on the road and traffic conditions.
E	[40]	Real-world driving scenarios	Experienced drivers opted for conventional driving due to flexibility and fun. Novices opted for autonomous driving due to easiness and safety. Both driving methods were interchangeably preferred depending on the road and traffic conditions.
E	[41]	Virtual traffic environment	AV onto roads with human drivers did not eliminate collisions. Human factors are impediments to their implementation.
E	[30]	AV-pedestrian interaction in a crosswalk	AV Receptivity increased with external features. Most favored interfaces: (1) Visual: walking silhouette or 'braking' (text); (2) Audible: verbal message. Most positive to the features: Females and 30+ age. Less positive to AV and features: those who often do mistakes/aggressive behaviors toward road users. Who intentionally violates traffic rules and who gets distracted on the road were more cautious in the AVs presence and liked the external features.
E	[45]	Highly AVs ride plots from gesture interaction	Knowledge of passengers' gesture interaction with AVs for adjusting vehicle dynamics in aspects of intentions, gesture collections, consensus extent among the participants, gesture characteristics, gesture design mental models, and initial gesture interaction design guidelines.
E	[31]	AV-pedestrian interaction	Children relied entirely on AVs communicating features to judge their safety and adopted a riskier strategy than adults.
E	[43]	Take-over request scenarios	Effective multi-modality for take-over request based on human factors by drawing the quantitative/qualitative data based on scenarios for take-over request and combinations of vehicle alert modalities of visual, auditory, and tactile aspects
E	[32]	AV-pedestrian interaction	Insights into AV-pedestrian interaction when passengers are in the vehicle's driver seat.
D	[37]	Overtaking behavior	The result applied to the virtual AV MP improved the reality of virtual traffic environment.
D	[44]	Reduce motion sickness in AV	Demonstrated the use of vection w/ VR headset to reduce the motion sickness effect.
D	[28]	Challenging traffic scenarios for AV-pedestrian interactions	Testbed applicable within different integration levels of the automated driving function and enabled a high level of behavioral realism.
D	[29]	Autonomous pedestrians	Results from simulation of the pedestrians' motion using a new concept called "smart obstacle"
D	[38]	Cooperative Adaptive Cruise Control (CACC).	CACC VR platform allowed incorporating live real-world driving data.
D	[42]	Test AV's functions and interfaces	A practical approach to test functions and interfaces of the self-driving car for elder drivers using an immersive virtual reality environment for a HIL simulation test.

T	[27]	Pedestrian scenarios	Proposal of a method for pedestrian in the Loop testing.
MACHINE CONTROL			
E	[46]	Multiple vehicles interaction	Validated realistic parameters of AV to safely traverse an intersection in Autonomous Intersection Management.
E	[55]	Maneuvering scenarios	Mix Hidden Markov models were effective at finding motion patterns in maneuver data from highways and country roads.
E	[56]	AV's path tracking	Simulator was an efficient tool for regenerating a realistic and high-fidelity AV ride experience when trajectory curvature and AV turning angles were small. Its Motion Cueing Algorithm took into consideration the human motion sensation (vestibular system mathematical model).
D	[50]	Leader-follower platoon and overtaking	Demonstrated the effectiveness of the simple and practical approach.
D	[51]	Agent-vehicle interaction concurrent operation	Contribution to theoretical development of distributed supervisory control and robustness.
D	[52]	Human and automated driving	Assessment of requirements in complex situations to guide the development of automated routines.
D	[53]	Car movement in real time	The approach presented made possible to test and to validate the control system with low cost and increased safety.
D	[54]	Autonomous navigation and collision detection	Experimental results showed that the navigation method proposed is promising for real-world applications.
D	[48]	Urban traffic and driver decision rules	Model reliability and effectiveness were validated by both simulations and real road experiments. Algorithm provided satisfactory velocity control actions and safe change lanes decision in a real urban environment.
D	[57]	Vehicle control techniques teaching	Weight transfer used in car control needed for simulation algorithms were quantified. Experienced Rally drivers were used to capture the unique methods for vehicle control during high-speed maneuvers on gravel test courses.
D	[47]	Road intersections	It highlights the need for mitigations against cybersecurity concerns with an intersection manager.
D	[49]	Vehicle behavior for double lane change and step steer input test	Results showed that the 9 degrees-of-freedom vehicles closely followed the simulation trends with acceptable error at both conditions.
D	[58]	Overtaking stationary and moving obstacles.	Lateral controller showed satisfactory performance even in existence of noises and disturbances.
D	[59]	AVs predefined paths	Results of an analysis on velocity variation for an AV navigating in narrow environment and following a predefined path.
MACHINE PERCEPTION			
D	[68]	Road environment with realistic dynamic models of vehicles	The prototyped application could be directly embedded in real prototypes in order to test it in real conditions.
D	[69]	Multi-agent real-time AV framework	The system provided reproducibility, full control of the environment and a flexible mix of real and virtual components in simulation experiments.
D	[70]	Verify MP and MC algorithms	The resulting tool provided reproducibility, full control of the environment and a flexible mix of real and virtual components in simulation experiments demonstrated with a pre-crash control solution with a laser range finder sensor.
D	[71]	3D x 2D pose detection sensor for uneven ground	A 3-D pose detection sensor based on an optical approach suitable for uneven ground is presented and evaluated against a 2-D method using a virtual test environment.
D	[72]	AV w/ Global Navigation Satellite System (GNSS) fault detection	The integrity augmentation system was demonstrated to successfully detect GNSS errors and respond by issuing predictive (caution flags) and reactive (warning flags) in a timely manner for a range of trajectories and maneuvers.
D	[73]	Virtual sensor verification	The study showed the possibility of developing advanced vehicle controllers without using a tire model to reduce development time, mainly in off-road applications, and remove the need for online estimation of tire properties due to pressure, wear, and age.
T	[74]	Train models for assisted/autonomous driving	It summarized how manual data annotation can be automated.
SYSTEM			
E	[65]	Moral dilemmas	It showed that equal number of targets on 2 sides of the scenario made more participants prefer to protect the ones complying with traffic rules.
D	[60]	Test AV design process stages	Different levels of virtualization for sensors, agents, scenarios and environments were successfully demonstrated on multiple AV implementation examples.
D	[61]	V&V of Autonomous features	Conceptual overview of the new Drive-in Driver-in-Loop simulator for V&V of AV's features.
D	[66]	Virtual AV mirroring a physical AV prototype	It proposed that the virtual model used can act as a valid substitution for the physical model in ML training, allowing risk reduction.
D	[62]	Realistic urban traffic	A distributed holistic simulation framework of realistic urban traffic environments integrated to an ego-vehicle and linked to a pedestrian simulator using a developed pedestrian behavior model.
D	[63]	VE w/ input from sensors and vehicle dynamic models	Validation platform, including perception, planning and control algorithm using different virtual and physical validation approaches.
T	[64]	Road scenarios to test vehicle software	It proposed research directions and potential approaches from the perspective of test criteria and test case generation.
T	[67]	Training and Testing AVs algorithms	It identified that dynamic data generated on-demand was needed to improve the current results in training AVs.

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