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Special edition

A systematic review of hardware technologies for small-scale self-driving cars

Uma revisão sistemática das tecnologias de hardware para carros autônomos de pequena escala

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ABSTRACT

Autonomous vehicle (AV) technology has the potential to revolutionize the transportation and logistics industry, making it more efficient and safer. However, testing such technologies is often limited by time, space, and cost constraints. Therefore, in recent years, several initiatives have emerged to test autonomous software and hardware on scaled vehicles. In order to provide guidance for future research, this systematic literature review was conducted to provide an overview of the literature surrounding small-scale self-driving cars, summarizing the current autonomous platforms deployed and focusing on the hardware developments in this field. Through the use of databases such as Web of Science, Scopus, Springer Link, Wiley, ACM Digital Library, and the TRID, 38 eligible studies that present small-scale testing of self-driving cars were identified and reviewed. The results indicated that publications on the topic are relatively new, with only the last four years showing an increase in the number of publications. Additionally, most papers only presented preliminary results, highlighting the potential for further research and development in the field. Research papers predominantly focused on software rather than hardware.

Keywords: Autonomous vehicles; Small-scaled vehicles; Self-driving cars

RESUMO

A tecnologia de veículos autônomos (AV) tem o potencial de revolucionar o setor de transporte e logística, tornando-o mais eficiente e seguro. No entanto, testar essas tecnologias geralmente é limitado por restrições de tempo, espaço e custo. Por isso, nos últimos anos, várias iniciativas surgiram para testar software e hardware autônomo em veículos em pequena escala. A fim de fornecer orientação para pesquisas futuras, esta revisão sistemática da literatura foi realizada para trazer uma visão geral da literatura sobre carros autônomos de pequena escala, resumindo as atuais plataformas autônomas implantadas e focando nos desenvolvimentos de hardware neste campo. Por meio do uso de bancos de dados como Web of Science, Scopus, Springer Link, Wiley, ACM Digital Library e TRID, 38 estudos elegíveis que apresentam testes em pequena escala de carros autônomos foram identificados e revisados. Os resultados indicaram que as publicações sobre o tema são relativamente novas, sendo que apenas nos últimos quatro anos houve aumento no número de publicações. Além disso, a maioria dos trabalhos apresentou apenas resultados preliminares, destacando o potencial para novas pesquisas e desenvolvimento no campo. Trabalhos de pesquisa são predominantemente focados em software em vez de hardware.

Palavras-chave: Veículos autônomos; Veículos de pequena escala; Carros autônomos

1 INTRODUCTION

The World Health Organization has reported that approximately 3,700 fatalities occur daily worldwide as a result of traffic accidents, with over 50 million individuals sustaining injuries annually (Who, 2018). Brazil is ranked fourth in terms of the number of deaths caused by such accidents, with 80 deaths per day in 2020. According to literature, approximately 90% of these accidents are attributed to human error (Sam; Velanganni; Evangelin, 2016).

The 21st century has brought a wave of challenges to existing transportation systems, with an increased demand for innovative technologies. Autonomous vehicles (AVs), such as self-driving cars, are at the forefront of these challenges. Thanks to advances in connectivity and control, AVs can potentially offer numerous benefits to society and city infrastructure. Mobility can be increased for people with disabilities and the elderly (Zhang *et al.*, 2019), while a substantial decrease in the number and severity of accidents (Xu *et al.*, 2018) and a reduction in congestion and emissions (Fagnant; Kockelman, 2015) can be expected. All of these benefits, when applied correctly, can result in a more efficient use of the infrastructure.

The concept of self-driving cars is the partial or complete movement of a vehicle with little or no human assistance (Hussain; Zeadally, 2019). For a successful and safe operation, it is important for AVs to have the ability to accurately interpret the semantic meaning of the scene and dynamic activities (Daily *et al.*, 2017). Moreover, in order to efficiently operate and ensure safety, AVs must understand the current state of the traffic and their surroundings, as well as be able to proactively anticipate their future behavior. However, this poses a complex problem due to the practical limitations of observing the surrounding environment, as well as the computational resources that are needed to execute prediction algorithms (Mozaffari *et al.*, 2022). Overall, self-driving cars require a range of sophisticated features to operate safely and effectively.

Testing AVs can be an expensive and time-consuming endeavor. Simulations have been used as an alternative, but can often lack the necessary fidelity when attempting to replicate the real world. To bridge this gap, recent efforts have emerged for testing autonomous software-hardware on scaled vehicles. Unlike North America, Europe, and Asia, third world countries such as Brazil does not have legislation that permits the field testing of AVs. This lack of legislation has brought attention to the need for a generic vehicle model for education and research purposes. Several attempts to respond to this need have been made (Vedder; Vinter; Jonsson, 2018). However, in order to test and develop AV technologies, especially in Brazil, a viable solution is to resort to studies with miniature vehicles. This way, realistic mobility scenarios can be created in a controlled environment, providing all the necessary safety rules and regulations.

This systematic review seeks to explore the current body of literature relevant to small-scale self-driving cars, particularly with respect to their underlying hardware technologies. This review is especially pertinent as the deployment of self-driving cars is still in its nascent stage, and is therefore a growing area of interest in both research and industry. The goal of this literature review is to provide an overview of the current trends, research efforts, and advancements in the development of scaled AVs. Through the examination of this literature, we hope to gain further insight into the hardware technologies used to enable the effective functioning of AVs and identify gaps in the reviewed papers to provide guidance for future research. This will be achieved by addressing the following research questions:

RQ1: What characterizes existing literature on small-scale self-driving cars?

RQ2: Which hardware is used in the studies?

The remainder of this paper is structured as follows: In Section II, the research methods for systematic literature review are summarized; Section III presents the results based on the proposed methodology; research gaps and connections between the reviewed papers are discussed in Section IV; and, finally, Section V presents the conclusions.

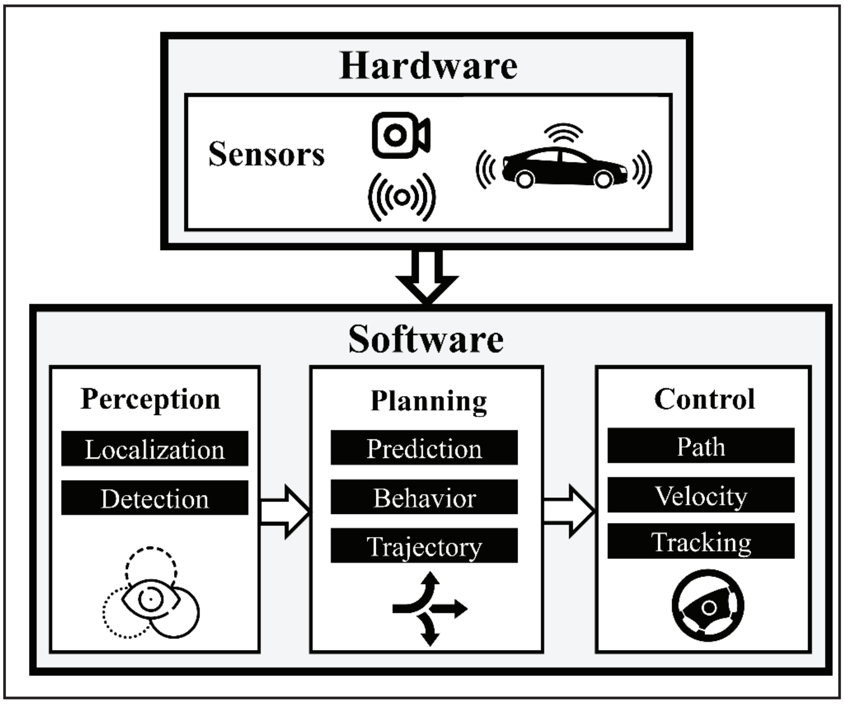
2 RESEARCH METHODS

For this systematic review, we want to display the hardware efforts in the field of scaled self-driving cars, and therefore we use the following (*Perception – Planning – Control*) pipeline proposed by Pendleton *et al.* (2017), depicted in figure 1, to map and categorize the research papers. By presenting vehicle setups (i.e., sensors, computation hardware, and experimental environment), we provide a clear overview of the hardware employed for research.

Perception refers to the ability of an autonomous system to collect information and extract relevant knowledge from the environment. In other words, it covers all algorithms that provide solutions for mapping, localization, or object detection. *Planning* refers to the software process of making purposeful decisions to bring the vehicle from a start location to a goal location while avoiding obstacles and optimizing designed heuristics. *Control* refers to the vehicle's ability to execute the planned actions generated by the higher-level processes.

The current body of research regarding hardware in scaled self-driving cars is incomplete and relatively disorganized, only touching upon some of the pertinent details. Consequently, it is essential to examine and compile the existing knowledge in order to gain a complete understanding of the subject. The purpose of this paper is to successfully undertake this task, thus providing a comprehensive overview of the field.

Figure 1 – Self-driving car system overview



Source: Authors (2023)

This section will discuss the research methods used in the systematic literature review. The steps required for this review include defining the research questions (RQs), creating a review protocol (which includes selecting suitable search terms and digital libraries), selecting eligible studies (including establishing inclusion and exclusion criteria), extracting necessary data (identifying applicable studies and categorizing them), interpreting the results, and reporting the overall findings.

2.1 Search methods

This systematic review adopts a hybrid approach, combining both a systematic literature review and a systematic literature mapping. A systematic literature review is an approach that seeks to identify, evaluate, and interpret all available research relevant to a particular research area (Kitchenham; Charters, 2007), while systematic mapping is utilized when there is limited evidence or the topic is far-reaching (Petersen *et al.*, 2008). This research paper applies elements of both these approaches; Question 1

(RQ1) is treated primarily as a systematic mapping and Question 2 (RQ2) is studied in more detail via a systematic review. In essence, the process of the two methods is identical and are the cornerstone of this systematic review (Kitchenham; Charters, 2007; Petersen *et al.*, 2008).

In order to identify studies that present autonomous platforms for small-scale self-driving cars, six electronic databases were searched: Web of Science, Scopus, Springer Link, Wiley, ACM Digital Library, and TRID – Transport Research International Documentation. The terms included in the search strategy were divided into two categories: those related to self-driving or autonomous vehicles, and those related to scaled vehicles. The two categories were then grouped in order to create a comprehensive search string, the complete list of which is shown in table 1. After conducting previous research on potential keywords, it became clear that most papers may be related to autonomous racing, as corroborated by (Betz *et al.*, 2022). As such, keywords to contemplate these terms were created for the final search string.

Table 1 – Search terms

	Terms	Keywords
(i)	Self-driving or autonomous vehicles	(“autonomous racing” OR “autonomous vehicle” OR “self-driving” OR “autonomous racecar”)
(ii)	Scaled vehicle	(“f1tenth” OR “f1/10” OR “scaled vehicle” OR “mushr” OR “miniature” OR “AutoRally” OR “RC car” OR “DeepRacer”)
(iii)		#(i) AND #(ii)

Source: Organized by the authors (2023)

“f1tenth” and “f1/10” are related to the F1tenth platform, originally founded at the University of Pennsylvania (O’Kelly *et al.*, 2020a; O’Kelly *et al.*, 2019). There are multiple F1tenth autonomous racing competitions around the world where students, researchers, and hobbyists can race against each other. “mushr” is related to the MuSHR platform (Srinivasa *et al.*, 2019), developed at Washington University. “AutoRally” is related to the AutoRally platform, which is a 1:5-scale autonomous vehicle testbed originally founded at Georgia Tech University (Goldfain *et al.*, 2019). "DeepRacer" is related to the Amazon platform for scaled AVs (Balaji *et al.*, 2020). "RC car" stands for Remote-Controlled car.

The last search was conducted on October 21st, 2022 and any duplicates were removed. The authors first conducted an independent screening of the studies based on Title, Abstract and Keywords (TAK) in order to make sure that the studies met the criteria for inclusion. Once the full texts were retrieved, they were assessed for eligibility, and any disagreements between researchers were resolved through discussion and consensus. In addition to the search on digital libraries, the Backwards Snowball Analysis (BSA) was used to screen the reference lists of included studies for any relevant studies that may have been missed. Combining the search on digital libraries with the BSA is a highly recommended practice when carrying out a systematic literature review due to the increased accuracy of the results (Mourão *et al.*, 2020).

2.2 Eligibility criteria

To be included in this systematic review, a study had to meet the following inclusion criteria: published in an English-language peer-reviewed journal or conference proceedings; report autonomy software and findings on small-scale self-driving cars; conducted field experiments (i.e., not simply a simulation); and focus on unmanned ground scaled vehicles (i.e., not an aircraft or water vehicle).

Studies were excluded if: is simply a literature review; non-English papers; papers that are not accessible in full text from normal research libraries or cannot be obtained in other ways; preliminary reports, that were later followed by an extended version – typically, this would be a workshop paper that later expanded into a journal article, and in that case only the latter was kept; results or methodology are not discussed in detail or depth; it only presents vehicle construction (i.e., no experimental validation); the scaled car is not described properly; and it does not directly assess autonomous driving.

3 RESULTS

The electronic database search yielded 2382 results, of which 2310 studies remained after the removal of duplicates. Subsequently, title and abstract screenings were conducted on the remaining studies, and 118 studies were considered to meet the inclusion criteria. Further assessment of the full-text versions led to the exclusion of eighty-two studies, leaving only 36 studies eligible. Moreover, two additional studies were identified through the backwards snowball analysis (BSA). As table 2 shows, the initial number of papers found per database was recorded. A flowchart for the study selection process is presented in figure 2.

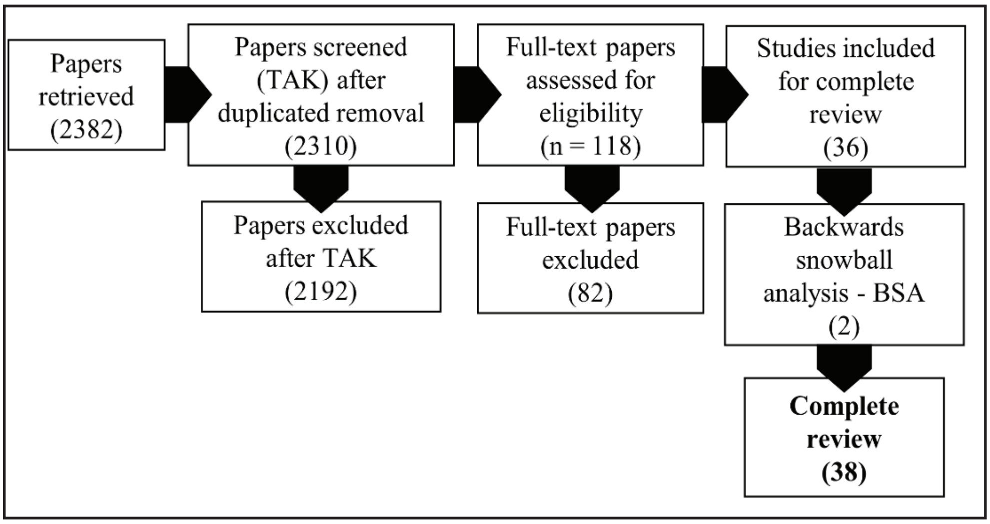
Table 2 – Papers identified through database search

Database	#Entries
Web of Science	51
TRID	11
Scopus	1885
ACM	72
Springer Link	310
Wiley	53
Total	2382

Source: Organized by the authors (2023)

There was a considerable drop in the number of studies, from the initial 2382 to the final 38 papers selected, due to various reasons such as misuse of terminology, correct use of terminology, but in a paper that did not actually focus on the topic, results not discussed in depth, and scaled car not properly described. These were mostly conference papers that only presented early work, and papers that presented only simulation were excluded since this review also focused on vehicles' hardware.

Figure 2 – Flowchart for the study selection process



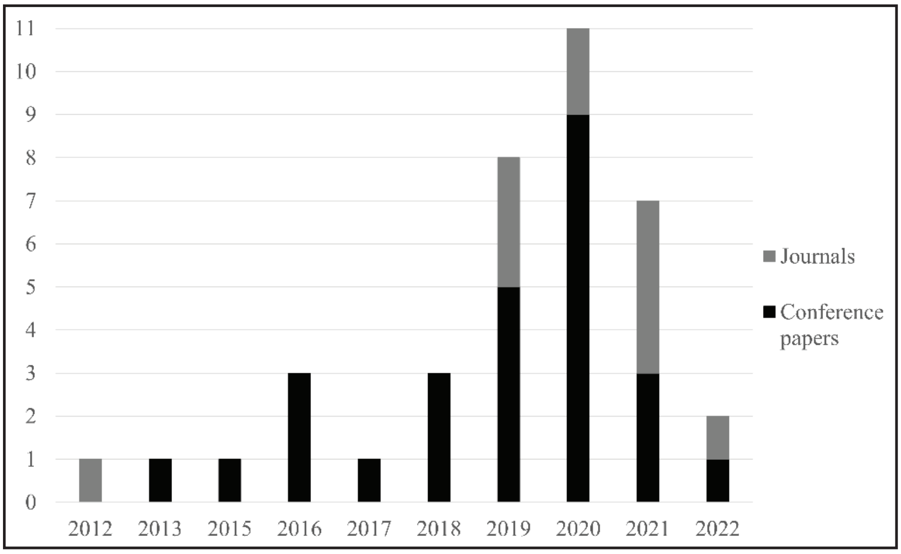
Source: Authors (2023)

For the 82 full-text papers excluded, the main reasons for exclusion were: no full text (n = 5); not a journal or conference paper (n = 2); presents only simulation (n = 14); results not presented (n = 20); only presented vehicles' construction (n = 5); review of previous literature findings (n = 1); only describes an education platform or curriculum to teach autonomous systems (n = 4); scaled car not properly described (n = 11); only summarizes a competition for scaled autonomous vehicles (n = 2); did not directly assess autonomous driving (n = 8); methodology not detailed (n = 4); and results presented in another study considered (n = 6).

3.1 Characteristics of the literature (RQ1)

The 38 papers reviewed in this article were published between 2012 and 2022, as evidenced by figure 3. It is of importance that publications on this topic are relatively new, with a notable rise in the number of publications only in the last four years. Of the papers that were included in this systematic review, the majority, 27 papers (71%), were found in conference proceedings, whilst only 11 papers (29%) were published in journals, as seen in Tables 3 and 4. This indicates that there is a potential to see an increase in publications related to this topic in journals in the coming years.

Figure 3 – Number of publications per year



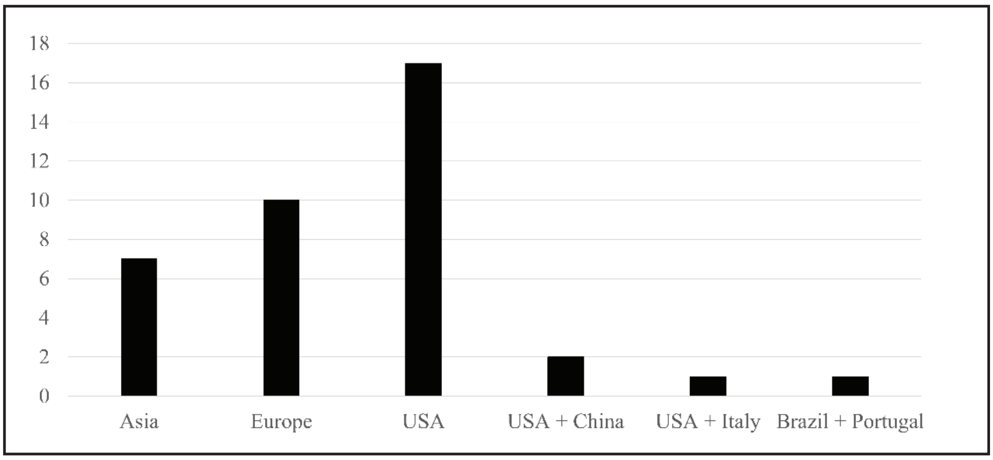
source: Authors (2023)

The paper authors were mostly distributed across the regions of North America, Europe, and Asia (see figure 4). The Asian papers were from Japan (1), Republic of Korea (2), Indonesia (2), Vietnam (1) and Hong Kong (1). North American papers are all from USA (17). The European were from Portugal (1), Switzerland (2), Italy (2), Germany (1), Switzerland + Spain (1), Czech Republic (2) and England (1). There were also papers from multi-region partnerships: Brazil + Portugal (1), USA + China (2) and USA + Italy (1).

The data collected from 38 papers indicated that there were a total of 158 authors affiliated with these publications, with an average of 4.16 authors per paper. Furthermore, it was observed that there were 137 distinct authors, and that 13 of those authors were featured in multiple papers. A total of 15 countries from across the world were represented in the studies. The authors were grouped by their country of affiliation rather than their country of birth.

In recent years, the field of autonomous vehicle technology has seen a continuous development, leading to the emergence of a new research field: Autonomous Racing (Betz *et al.*, 2022). Researchers are developing software and hardware for high-performance racecars which are designed to operate autonomously under challenging and dynamic conditions, such as high speeds, accelerations and low reaction times. This topic has become recurrent in scaled self-driving cars, with many of them derived from remote-controlled (RC) cars with additional hardware such as sensors, cameras, and Electronic Control Units (ECUs). Out of 38 papers reviewed, 20 (53%) are focused on Autonomous Racing.

Figure 4 – Number of publications per region



Source: Authors (2023)

Table 3 – Journal papers by publication venue

Publication Venue	Nº of Publications	Papers
Control Engineering Practice	5	(ALCALÁ *et al.*, 2020; RIBEIRO *et al.*, 2021)
IEEE Control Systems Magazine	1	(GOLDFAIN *et al.*, 2019)
IEEE Robotics and Automation Letters	2	(CAI *et al.*, 2021; DREWS *et al.*, 2019)
IEEE Transactions on Control Systems Technology	3	(LINIGER; LYGEROS, 2019; ROSOLIA; BORRELLI, 2020; YOU; TSIOTRAS, 2021)
IEEE Transactions on Intelligent Transportation Systems	1	(LA *et al.*, 2012)
IEEE Transactions on Intelligent Vehicles	1	(MURALEEDHARAN; OKUDA; SUZUKI, 2022)
IEEE Transactions on Robotics	1	(WANG *et al.*, 2021)

Source: Organized by the authors (2023)

Table 4 – Conference papers by publication venue

Publication Venue	Nº of Publications	Papers
16th International IEEE Annual Conference on Intelligent Transportation Systems	1	(Bae *et al.*, 2013)
20th International Conference on Control, Automation and Systems	1	(Hossain *et al.*, 2020)
23rd International Conference of Hybrid Systems: Computation and Control	1	(IVANOV *et al.*, 2020)
2nd International Conference of Industrial, Mechanical, Electrical, Chemical Engineering	1	(Anindyaguna; Basjaruddin; Saefudin, 2016)
37th International Conference on Machine Learning	1	(Sinha *et al.*, 2020)
4th International Conference on Green Technology and Sustainable Development	1	(Do *et al.*, 2018)
European Control Conference	2	(Baur; Bascetta, 2019; Carrau *et al.*, 2016)
IEEE Conference on Control Technology and Applications	1	(Berntorp *et al.*, 2018; Hu; Chen; Delbruck, 2019)
IEEE International Conference on Artificial Intelligence Circuits and Systems	1	(Hu; Chen; Delbruck, 2019)
IEEE International Conference on Autonomous Robot Systems and Competitions	1	(Vasconcelos Filho *et al.*, 2020)
IEEE International Conference on Robotics and Automation	4	(Hyldmar; He; Prorok, 2019; O'kelly *et al.*, 2020b; Williams *et al.*, 2016, 2018)
IEEE Winter Conference on Applications of Computer Vision	1	(Chowdhuri; Pankaj; Zipser, 2019)
IEEE/RSJ International Conference on Intelligent Robots and Systems	4	(Ahn *et al.*, 2015; Kannapiran; Berman, 2020; Klapalek *et al.*, 2021; Pagot; Piccinini; Biral, 2020)
IFAC PapersOnLine	2	(Bryan; Boler; Bevly, 2021; Kloeser *et al.*, 2020)
International Conference on Electronics and Renewable Systems	1	(Hamzah *et al.*, 2022)
16th European Conference on Computer Vision	1	(Jahoda; Cech; Matas, 2020)
Design Automation Conference	1	(Andert; Khayatian; Shrivastava, 2017)
Robotics: Science and Systems	1	(Wagener *et al.*, 2019)
SAE Technical Papers (2021)	1	(Verma *et al.*, 2021)

Source: Organized by the authors (2023)

The majority of studies involve the development of a path planning system for autonomous navigation. However, one notable exception is the study by Carrau *et al.* (2016), which instead focuses on the development of a controller to improve the computation time of the Electronic Control Unit (ECU). Path planning were addressed as a motion planning problem. Motion planning for car-like vehicles is a difficult problem due to the vehicle's nonholonomic constraints and the non-convex environment in which the vehicle is operating (Lavalle, 2006).

Numerous approaches to motion planning were presented, with a variety of software developed to focus on a range of tasks, such as autonomous car-following (Jahoda; Cech; Matas, 2020), overtaking (Anindyaguna; Basjaruddin; Saefudin, 2016), platooning (Vasconcelos Filho *et al.*, 2020), drifting stabilization (Baur; Bascetta, 2019), cornering maneuvers (You; Tsiotras, 2021), and vehicle-to-vehicle interaction, both cooperative and non-cooperative (Hyldmar; He; Prorok, 2019). Additionally, several studies have explored the dynamics of lateral and longitudinal path following (Bryan; Boler; Bevly, 2021; Pagot; Piccinini; Biral, 2020; Ribeiro *et al.*, 2021), as well as obstacle detection and avoidance, and lane tracking (Bae *et al.*, 2013; Hamzah *et al.*, 2022; Hossain *et al.*, 2020; Kannapiran; Berman, 2020; Muraleedharan; Okuda; Suzuki, 2022; Verma *et al.*, 2021). Furthermore, one paper developed an algorithm for tracking predefined trajectories in order to facilitate localization (La *et al.*, 2012), and another investigated path planning for competitive racing with other cars (Sinha *et al.*, 2020; Wang *et al.*, 2021).

Several research studies have proposed *end-to-end* approaches which employ Neural Networks (NNs) to solve the autonomous driving task (Cai *et al.*, 2021; Chowdhuri; Pankaj; Zipser, 2019; Do *et al.*, 2018; Drews *et al.*, 2019; Goldfain *et al.*, 2019; Hamzah *et al.*, 2022; Hossain *et al.*, 2020; Hu; Chen; Delbruck, 2019; Ivanov *et al.*, 2020; Jahoda; Cech; Matas, 2020; Kannapiran; Berman, 2020; Verma *et al.*, 2021). These studies have focused on a complete software package that deals with the entire *perception-planning-control* pipeline, instead of just focusing on a specific part. Moreover, in O'Kelly *et al.*

(2020b), a toolchain was developed that jointly optimizes various elements such as racing strategy, planning methods, control algorithms and vehicle parameters for an autonomous racecar.

3.2 Hardware used on the studies (RQ2)

The small-scale self-driving cars used in the selected papers were mainly developed for the purpose of testing autonomous software. These vehicles are typically derived from remote-controlled (RC) cars, but with additional hardware, such as sensors and electronic control units (ECUs), added to transform them into autonomous vehicles. As noted in Betz *et al.* (2022), these small-scale cars are able to reach high speeds and accelerations, comparable to their real-world counterparts. This review identified nine different scales, ranging from 1:5 to 1:43, as summarized in Table 5.

Most papers (19; 50%) utilized a 1:10 scale car. Of those, 10 papers implemented the proposed F1tenth (O'Kelly *et al.*, 2020a; O'Kelly *et al.*, 2019) Chassis configuration (Andert; Khayatian; Shrivastava, 2017; Bryan; Boler; Bevly, 2021; Chowdhuri; Pankaj; Zipser, 2019; Vasconcelos Filho *et al.*, 2020; Hu; Chen; Delbruck, 2019; Ivanov *et al.*, 2020; Klapalek *et al.*, 2021; O'kelly *et al.*, 2020b; Sinha *et al.*, 2020; Verma *et al.*, 2021), while two employed the Tamiya scaled RC car chassis (Ahn *et al.*, 2015; Muraleedharan; Okuda; Suzuki, 2022). Additionally, two papers used the Berkeley Autonomous RaceCar (BARC) platform (Alcalá *et al.*, 2020; Rosolia; Borrelll, 2020). Unfortunately, no papers were retrieved with the MuSHR (Srinivasa *et al.*, 2019) or DeepRacecar (Balaji *et al.*, 2020) chassis configurations.

Nine papers (24%) deployed 1:5 scale cars, eight of which were from the proposed AutoRally chassis – HPI Baja 5SC RC trophy truck (GOLDFAIN *et al.*, 2019). The other one used the vehicle platform ToMi (BAHNIK *et al.*, 2020). The three papers (8%) that deployed 1:43 scale cars used the Kyosho dnano RC car chassis (Carrau *et al.*, 2016; Kloeser *et al.*, 2020; Liniger; Lygeros, 2019).

Table 5 – Vehicles' scale

Scale	Nº of Papers	% of Papers	Papers
1:5	9	24%	(Bae *et al.*, 2013; Drews *et al.*, 2019; Goldfain *et al.*, 2019; Jahoda; Cech; Matas, 2020; Ribeiro *et al.*, 2021; Wagener *et al.*, 2019; Williams *et al.*, 2016, 2018; You; Tsiotras, 2021)
1:8	1	3%	(Pagot; Piccinini; Biral, 2020)
1:10	19	50%	(Ahn *et al.*, 2015; Alcalá *et al.*, 2020; Andert; Khayatian; Shrivastava, 2017; Anindyaguna; Basjaruddin; Saefudin, 2016; Baur; Bascetta, 2019; Bryan; Boler; Bevly, 2021; Chowdhuri; Pankaj; Zipser, 2019; Do *et al.*, 2018; Vasconcelos Filho *et al.*, 2020; Hossain *et al.*, 2020; Hu; Chen; Delbruck, 2019; Ivanov *et al.*, 2020; Klapalek *et al.*, 2021; Muraleedharan; Okuda; Suzuki, 2022; O'kelly *et al.*, 2020b; Rosolia; Borrelli, 2020; Sinha *et al.*, 2020; Verma *et al.*, 2021; Wang *et al.*, 2021)
1:14	1	3%	(La *et al.*, 2012)
1:16	1	3%	(Hamzah *et al.*, 2022)
1:20	1	3%	(Cai *et al.*, 2021)
1:24	1	3%	(Hyldmar; He; Prorok, 2019)
1:28	1	3%	(Kannapiran; Berman, 2020)
1:43	3	8%	(Carrau *et al.*, 2016; Kloeser *et al.*, 2020; Liniger; Lygeros, 2019)
Not specified (Chassis: 25x20 cm)	1	3%	(Berntorp *et al.*, 2018)

Source: Organized by the authors (2023)

The sensor setup on these scaled cars usually utilizes monocular cameras (i.e., Raspberry Pi, IMX219-200, Pixy CMUcam5, DAVIS 240C, Point Grey FL3-U3-32S2C-CS, XIMEA xiQ, Mobotix Q24), stereo cameras (i.e., ZED, Intel Realsense d435 and d435i, Optitrack), 2D LiDARs (Hokuyo 10LX, Hokuyo UTM-30lx), Inertial Measurement Unit (IMU), indoor GPS or wheel-speed sensors. As a main computation platform these vehicles normally use an Arduino microcontroller platform (Models: Uno, Mega 2560s, Nano board), Odroid XU4, a Raspberry Pi board computer (Models: Raspberry Pi 4b, Raspberry

Pi 3 Single Board Computer (SBC), Raspberry Pi Zero W, Raspberry Pi computer) or an embedded Graphics Processing Unit (GPU) system like the NVIDIA Jetson (Models: Nano, TX1, TX2, NX, AGX Xavier). GPU gives the possibility to speed up the inference of NNs and is mostly used in studies.

4 DISCUSSION

The majority of the papers reviewed presented preliminary results, often simply indicating that the study's aim had been achieved, whether that be reducing lap time, successful overtaking, or obstacle avoidance. Unfortunately, many of the papers presented lacked a discussion section, providing only a brief overview of their experimental results. When considering the total number of papers reviewed, only 29% had been published in journals, thereby suggesting that the field is yet to be fully mature.

Though the hardware utilized in the studies is varied, one trend is clearly visible: the scale. Out of the total number of papers, 50% were found to have a 1:10 scale, while 24% had a 1:5 scale. This 1:10 scale is broadly used in competitions and has gained a thriving online community. Furthermore, the platforms are created with inexpensive and readily available components, enabling an easily building and control of AVs. In addition to this, the F1tenth (O'kelly *et al.*, 2020a; O'kelly *et al.*, 2019) community has introduced an open-source simulation environment and competitions that have gained momentum at a global level. We believe that these communities have a great influence in popularizing information regarding AVs. As such, they have considerable potential in spreading awareness regarding research and studies related to this technology.

In Goldfain *et al.* (2019), the authors from Georgia Institute of Technology introduced the AutoRally platform (1:5 scale), a breakthrough for the field of scaled autonomous vehicles, which has since been employed by a number of others studies, as evidenced by the findings of this systematic review. Following the initial paper by Goldfain *et al.* (2019), the authors have continued to build upon their own research, producing multiple papers in succession (Drews *et al.*, 2019; Goldfain *et al.*, 2019;

Williams *et al.*, 2016, 2018), in addition to other research conducted by other groups. Academic research groups, such as the one from the Georgia Institute of Technology, are vital for the advancement of knowledge in a particular field. Such groups provide a platform for scholars and researchers to come together and collaborate, allowing them to share ideas, resources, and expertise, leading to more innovative and high-quality research outcomes.

As most of the papers presented only preliminary results, suggestions for future studies are focused on improving or expanding their models or testing the models in a more complex environment. Future studies in a more complex environment were also suggested. Generally, a complex environment refers to testing models in traffic scenarios that are more similar to those in real life. There are no suggestions on improving hardware.

In Carrau *et al.* (2016) and Pagot, Piccinini and Biral (2020), they seek to improve software computation time. This is another research gap that requires more attention. It is vital that models suitable for real-time applications are developed and improved in order to guarantee the lowest possible software execution times and the absence of any delay. If the software fails to respond to changing conditions in a timely manner, the vehicle may not be able to make the necessary split-second decisions in order to avoid dangerous situations.

Given the significant computational power requirements of self-driving vehicles, it is essential that the main computation platform supplies adequate computing power. Unfortunately, small-scale self-driving cars are often developed using low-cost platforms, which can pose a challenge in terms of computational power. To bridge this gap, GPU systems such as those from NVIDIA are gaining popularity. These systems provide a cost-effective way to ensure that self-driving vehicles possess the necessary computational power for reliable operation.

A monocular camera (single- eyed) system, which utilizes a single camera sensor to capture video, is limited in its capabilities when compared to a stereo vision system. A stereo vision system consists of two cameras, separated from each other, that capture simultaneous video images. This type of system provides numerous advantages, such as being able to obtain a depth map, which is something that a monocular camera system cannot do. As a result, key benefits such as allowing for more accurate and detailed information can be gained through the utilization of a stereo vision system (LU *et al.*, 2018). A stereo vision system is a powerful tool in the field of robotics, and it can be used for a variety of applications. Most notably, it can be used to estimate depth maps based on the parallax principle, which does not require the aid of infrared sensors like other methods do. Additionally, it can also capture more detailed data than an infrared-based system (Seitz *et al.*, 2006). We firmly believe that utilizing stereo cameras to enhance the performance of software models is a necessity and more studies should incorporate them in order to improve the performance of the models employed.

In Hossain *et al.* (2020), an experiment was conducted which tested the proposed model's ability to traverse a maze environment freely or with obstacles in both a real-world and simulated setting. The results of this experiment showed that the model had difficulty avoiding the obstacle when trained using raw LiDAR data. The LiDAR sensor used was a Hokuyo UTM-30lx 2D LiDAR, which is generally the same type of sensor used by the papers included in this review. Small-scale self-driving cars are typically built using low-cost platforms, so implementing a 3D LiDAR is often not cost-effective, as a single 3D LiDAR can be more expensive than the entire platform. The primary difference between 2D and 3D LiDAR is the amount of information they capture about their environment; 3D LiDAR captures more data than 2D LiDAR.

2D LiDAR sensors are capable of scanning their surrounding environment in a single, horizontal plane, producing a two-dimensional point cloud that reflects the distance to objects in that plane. In contrast, 3D LiDARs are able to scan in both the horizontal and vertical planes, creating a three-dimensional point cloud that reflects the distance to objects in all three dimensions. This higher level of detail is crucial in the development of autonomous vehicles, as it allows the sensor to not only detect the presence and position of objects, but also their height and depth. This additional information is invaluable when creating a detailed, accurate map of the environment. To ensure the most effective use of the software models in future research, we strongly recommend the use of 3D LiDAR sensors for autonomous vehicles on a scaled level.

In the reviewed papers, Ultrasonic Sensor and Radar, two popular sensors used in real-world testing, were not employed. It is our belief that these sensors can potentially help to advance the field of scaled autonomous vehicles. Ultrasonic Sensor is a low-cost device that is capable of producing accurate results for measuring the distance from any material, regardless of its color, even in dusty or inclement weather conditions. Additionally, Radars can accurately measure the distance and direction of the target, as well as its speed (ROSIQUE *et al.*, 2019). Utilizing these sensors could be a major step in furthering the development of scaled autonomous vehicles.

5 CONCLUSIONS

This paper presented a systematic literature review on small-scale self-driving cars, investigating the current state of the literature surrounding the hardware for scaled autonomous vehicles and identifying gaps in the reviewed papers to provide guidance for future research. It was based on an initial sample of 2382 retrieved papers, from which 38 studies were selected and mapped to answer the proposed research questions.

Most papers presented only preliminary results, yet the models presented were robust. Many of the papers had similar goals, such as reducing lap time, successful overtaking, and obstacle avoidance. While most papers came from Conference Proceedings, which usually present early results or incomplete works, there is still a great potential in the field to grow and mature. A popular suggestion for future studies was to improve the model (software) further, with no mention on improving the hardware.

We conclude that additional research is required to supplement the majority of studies that were reviewed. The current research has highlighted gaps that need to be addressed in order to match the hardware capabilities currently tested by the automotive industry. This serves as a reminder of the need for comprehensive and rigorous research moving forward. The magnitude and breadth of the challenges presented is evidence of it. Although the hardware can be updated, small-scale self-driving cars can be used as a realistic and reliable way to test autonomous software.

The idea of small-scale self-driving cars being used as a practical way to test autonomous software may be a viable option. Updating the necessary hardware is not only possible, but may prove to be a beneficial approach for a number of reasons. These scaled cars can provide a more realistic testing environment for software developers and engineers, allowing them to observe the performance of their technology in a safer environment. Overall, utilizing small-scale self-driving cars for testing autonomous software can be an effective and efficient way of evaluating the technology.

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REFERENCES

AHN, H. *et al.* Experimental testing of a semi-autonomous multi-vehicle collision avoidance algorithm at an intersection testbed. *In*: **IEEE International Conference on Intelligent Robots and Systems**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2015. p. 4834–4839. Disponível em: https://ieeexplore.ieee.org/document/7354056. Acesso em: 25 ago. 2022.

ALCALÁ, E. *et al.* Autonomous racing using Linear Parameter Varying-Model Predictive Control (LPV-MPC). **Control Engineering Practice**, [*s. l.*], v. 95, 2020. Disponível em: https://www.sciencedirect.com/science/article/pii/S0967066119302187?via%3Dihub. Acesso em: 25 ago. 2022.

ANDERT, E.; KHAYATIAN, M.; SHRIVASTAVA, A. Crossroads: Time-Sensitive Autonomous Intersection Management Technique. *In*: **Proceedings - Design Automation Conference**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2017. Disponível em: https://dl.acm.org/doi/10.1145/3061639.3062221. Acesso em: 25 ago. 2022.

ANINDYAGUNA, K.; BASJARUDDIN, N. C.; SAEFUDIN, D. Overtaking assistant system (OAS) with fuzzy logic method using camera sensor. *In*: **2016 2nd International Conference of Industrial, Mechanical, Electrical, and Chemical Engineering, ICIMECE 2016**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2016. p. 89–94. Disponível em: https://ieeexplore.ieee.org/document/7910420. Acesso em: 25 ago. 2022.

BAE, I. *et al.* Path generation and tracking based on a Bézier curve for a steering rate controller of autonomous vehicles. *In*: **IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC**. [*S. l.: s. n.*], 2013. p. 436–441. Disponível em: https://ieeexplore.ieee.org/document/6728270. Acesso em: 25 ago. 2022.

BAHNIK, M. *et al.* Visually Assisted Anti-lock Braking System. *In*: **IEEE Intelligent Vehicles Symposium, Proceedings**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2020. p. 1219–1225. Disponível em: https://ieeexplore.ieee.org/document/9304807. Acesso em: 25 ago. 2022.

BALAJI, B. *et al.* DeepRacer: Autonomous Racing Platform for Experimentation with Sim2Real Reinforcement Learning. **Proceedings - IEEE International Conference on Robotics and Automation**, [*s. l.*], p. 2746–2754, 2020. Disponível em: https://ieeexplore.ieee.org/document/9197465. Acesso em: 25 ago. 2022.

BAUR, M.; BASCETTA, L. An experimentally validated LQR approach to autonomous drifting stabilization. *In*: **18th European Control Conference, ECC 2019**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2019. p. 732–737. Disponível em: https://ieeexplore.ieee.org/document/8795883. Acesso em: 25 ago. 2022.

BERNTORP, K. *et al.* Control Architecture Design for Autonomous Vehicles. *In*: **2018 IEEE Conference on Control Technology and Applications (CCTA)**. [*S. l.: s. n.*], 2018. p. 404–411. Disponível em: https://ieeexplore.ieee.org/document/8511371, Acesso em: 25 ago. 2022.

BETZ, J. *et al.* Autonomous Vehicles on the Edge: A Survey on Autonomous Vehicle Racing. **IEEE Open Journal of Intelligent Transportation Systems**, [*s. l.*], v. 3, p. 458–488, 2022. Disponível em: https://arxiv.org/abs/2202.07008. Acesso em: 25 ago. 2022.

BRYAN, W. T.; BOLER, M. E.; BEVLY, D. M. A Vehicle-Independent Autonomous Lane Keeping and Path Tracking System. *In*: **IFAC-PapersOnLine**. [*S. l.*]: Elsevier B.V., 2021. p. 37–44.

CAI, P. *et al.* Vision-Based Autonomous Car Racing Using Deep Imitative Reinforcement Learning. **IEEE Robotics and Automation Letters**, [*s. l.*], v. 6, n. 4, p. 7262–7269, 2021. Disponível em: https://ieeexplore.ieee.org/document/9488179. Acesso em: 25 ago. 2022.

CARRAU, J. V. *et al.* Efficient implementation of Randomized MPC for miniature race cars. *In*: **2016 European Control Conference, ECC 2016**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2016. p. 957–962. Disponível em: https://ieeexplore.ieee.org/document/7810413. Acesso em: 25 ago. 2022.

CHOWDHURI, S.; PANKAJ, T.; ZIPSER, K. MultiNet: Multi-modal multi-task learning for autonomous driving. *Em*: **Proceedings - 2019 IEEE Winter Conference on Applications of Computer Vision, WACV 2019**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2019. p. 1496–1504. Disponível em: https://ieeexplore.ieee.org/document/8658798. Acesso em: 25 ago. 2022.

DAILY, M. *et al.* Self-Driving Cars. **Computer**, [*s. l.*], v. 50, n. 12, p. 18–23, 2017. Disponível em: https://ieeexplore.ieee.org/document/8220479. Acesso em: 25 ago. 2022.

DO, T.-D. *et al.* Real-Time Self-Driving Car Navigation Using Deep Neural Network. *In*: **2018 4th International Conference on Green Technology and Sustainable Development (GTSD)**. [*S. l.*]: IEEE, 2018. p. 7–12. Disponível em: https://ieeexplore.ieee.org/document/8595590. Acesso em: 25 ago. 2022.

DREWS, P. et al. Vision-based high-speed driving with a deep dynamic observer. IEEE Robotics and Automation Letters, [s. l.], v. 4, n. 2, p. 1564–1571, 2019. Disponível em: https://ieeexplore.ieee.org/document/8630018. Acesso em: 26 ago. 2022.

FAGNANT, D. J.; KOCKELMAN, K. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. **Transportation Research Part A: Policy and Practice**, [*s. l.*], v. 77, p. 167–181, 2015. Disponível em: https://www.sciencedirect.com/science/article/pii/S0965856415000804?via%3Dihub. Acesso em: 25 ago. 2022.

GOLDFAIN, B. *et al.* AutoRally: An Open Platform for Aggressive Autonomous Driving. **IEEE Control Systems**, [*s. l.*], v. 39, n. 1, p. 26–55, 2019. Disponível em: https://arxiv.org/abs/1806.00678. Acesso em: 25 ago. 2022.

HAMZAH, M. S. *et al.* Development of Single-board Computer-based Self-Driving Car Model using CNN-Controlled RC Car. *In*: **Proceedings of the International Conference on Electronics and Renewable Systems, ICEARS 2022**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2022. p. 1805–1812.

HOSSAIN, S. *et al.* Deep Reinforcement Learning-based ROS-Controlled RC Car for Autonomous Path Exploration in the Unknown Environment. *In*: **International Conference on Control, Automation and Systems**. [*S. l.*]: IEEE Computer Society, 2020. p. 1231–1236. Disponível em: https://ieeexplore.ieee.org/document/9268370. Acesso em: 25 ago. 2022.

HU, Y.; CHEN, H. M.; DELBRUCK, T. Slasher: Stadium racer car for event cameraend-to-end learning autonomous driving experiments. *In*: **2019 IEEE International Conference on Artificial Intelligence Circuits and Systems (AICAS)**. [*S. l.: s. n.*], 2019. p. 29–33. Disponível em: https://www.zora.uzh.ch/id/eprint/184202/. Acesso em: 25 ago. 2022.

HUSSAIN, R.; ZEADALLY, S. Autonomous Cars: Research Results, Issues, and Future Challenges. **IEEE Communications Surveys and Tutorials**, [*s. l.*], v. 21, n. 2, p. 1275–1313, 2019. Disponível em: https://ieeexplore.ieee.org/document/8457076. Acesso em: 25 ago. 2022.

HYLDMAR, N.; HE, Y.; PROROK, A. A Fleet of Miniature Cars for Experiments in Cooperative Driving. *In*: **2019 International Conference on Robotics and Automation (ICRA)**. [*S. l.: s. n.*], 2019. p. 3238–3244. Disponível em: https://ieeexplore.ieee.org/document/8794445. Acesso em: 25 ago. 2022.

IVANOV, R. *et al.* Case study: Verifying the safety of an autonomous racing car with a neural network controller. *In*: **HSCC 2020 - Proceedings of the 23rd International Conference on Hybrid Systems: Computation and Control, part of CPS-IoT Week**. [*S. l.*]: Association for Computing Machinery, Inc, 2020. Disponível em: https://arxiv.org/abs/1910.11309. Acesso em: 25 ago. 2022.

JAHODA, P.; CECH, J.; MATAS, J. Autonomous Car Chasing. *In*: **16th European Conference on Computer Vision, ECCV 2020**. [*S. l.: s. n.*], 2020. p. 337–352. Disponível em: https://cmp.felk.cvut.cz/ftp/articles/cech/Jahoda-ECCVw-2020.pdf. Acesso em: 25 ago. 2022.

KANNAPIRAN, S.; BERMAN, S. Go-CHART: A miniature remotely accessible self-driving car robot. *In*: **IEEE International Conference on Intelligent Robots and Systems**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2020. p. 2265–2272. Disponível em: https://ieeexplore.ieee.org/document/9341770. Acesso em: 25 ago. 2022.

KITCHENHAM, B.; CHARTERS, S. Guidelines for performing Systematic Literature Reviews in Software Engineering. Version 2.3. **Technical Report EBSE-2007-01, Keele University, U.K., University of Durham, Durham, U.K.**, 2007.

KLAPALEK, J. *et al.* Car Racing Line Optimization with Genetic Algorithm using Approximate Homeomorphism. *In*: **IEEE International Conference on Intelligent Robots and Systems**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2021. p. 601–607. Disponível em: https://ieeexplore.ieee.org/document/9636503. Acesso em: 25 ago. 2022.

KLOESER, D. *et al.* NMPC for racing using a singularity-free path-parametric model with obstacle avoidance. *In*: **IFAC-PapersOnLine**. [*S. l.*]: Elsevier B.V., 2020. p. 14324–14329. Disponível em: https://www.sciencedirect.com/science/article/pii/S2405896320317845?via%3Dihub. Acesso em: 27 ago. 2022.

LA, H. M. *et al.* Development of a small-scale research platform for intelligent transportation systems. **IEEE Transactions on Intelligent Transportation Systems**, [*s. l.*], v. 13, n. 4, p. 1753–1762, 2012. Disponível em: https://ieeexplore.ieee.org/document/6248708. Acesso em: 25 ago. 2022.

LAVALLE, S. M. **Planning Algorithms**. [*S. l.*]: Cambridge University Press, 2006. doi: 10.1017/CBO9780511546877

LINIGER, A.; LYGEROS, J. Real-Time Control for Autonomous Racing Based on Viability Theory. **IEEE Transactions on Control Systems Technology**, [*s. l.*], v. 27, n. 2, p. 464–478, 2019. Disponível em: https://arxiv.org/abs/1701.08735. Acesso em: 25 ago. 2022.

LU, Y. *et al.* A survey on vision-based UAV navigation. **Geo-Spatial Information Science**, [*s. l.*], v. 21, n. 1, p. 21–32, 2018. Disponível em: https://www.tandfonline.com/doi/full/10.1080/10095020.2017.1420509. Acesso em: 25 ago. 2022.

MOURÃO, E. *et al.* On the performance of hybrid search strategies for systematic literature reviews in software engineering. **Information and Software Technology**, [*s. l.*], v. 123, 2020. Disponível em: https://arxiv.org/abs/2004.09741. Acesso em: 27 ago. 2022.

MOZAFFARI, S. *et al.* Deep Learning-Based Vehicle Behavior Prediction for Autonomous Driving Applications: A Review. **IEEE Transactions on Intelligent Transportation Systems**, [*s. l.*], v. 23, n. 1, p. 33–47, 2022. Disponível em: https://ieeexplore.ieee.org/document/9158529. Acesso em: 25 ago. 2022.

MURALEEDHARAN, A.; OKUDA, H.; SUZUKI, T. Real-Time Implementation of Randomized Model Predictive Control for Autonomous Driving. **IEEE Transactions on Intelligent Vehicles**, [*s. l.*], v. 7, n. 1, p. 11–20, 2022. Disponível em: https://ieeexplore.ieee.org/document/9366366. Acesso em: 26 ago. 2022.

O'KELLY, M. *et al.* F1/10: An Open-Source Autonomous Cyber-Physical Platform. [*s. l.*], 2019. Disponível em: http://arxiv.org/abs/1901.08567. Acesso em: 26 ago. 2022.

O'KELLY, M. *et al.* F1TENTH: An Open-source Evaluation Environment for Continuous Control and Reinforcement Learning. **Machine Learning Research**, [*s. l.*], v. 123, p. 77–89, 2020a. Disponível em: http://proceedings.mlr.press/v123/o-kelly20a.html. Acesso em: 25 ago. 2022.

O'KELLY, M. *et al.* TUNERCAR: A Superoptimization Toolchain for Autonomous Racing. *In*: **2020 IEEE International Conference on Robotics and Automation (ICRA)**. [*S. l.: s. n.*], 2020b. p. 5356–5362. Disponível em: https://ieeexplore.ieee.org/document/9197080. Acesso em: 25 ago. 2022.

PAGOT, E.; PICCININI, M.; BIRAL, F. Real-time optimal control of an autonomous RC car with minimum-time maneuvers and a novel kineto-dynamical model. *In*: **IEEE International Conference on Intelligent Robots and Systems**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2020. p. 2390–2396. Disponível em: https://ieeexplore.ieee.org/document/9340640. Acesso em: 25 ago. 2022.

PENDLETON, S. D. *et al.* Perception, planning, control, and coordination for autonomous vehicles. **Machines**, [*s. l.*], v. 5, n. 1, 2017. Disponível em: https://www.mdpi.com/2075-1702/5/1/6. Acesso em: 25 ago. 2022.

PETERSEN, K. *et al.* Systematic Mapping Studies in Software Engineering. **Proceedings of the 12th international conference on Evaluation and Assessment in Software Engineering**, [*s. l.*], p. 68–77, 2008. Disponível em: https://www.scienceopen.com/hosted-document?doi=10.14236/ewic/EASE2008.8. Acesso em: 27 ago. 2022.

RIBEIRO, A. M. *et al.* A comprehensive experimental validation of a scaled car-like vehicle: Lateral dynamics identification, stability analysis, and control application. **Control Engineering Practice**, [*s. l.*], v. 116, 2021. Disponível em: https://www.sciencedirect.com/science/article/pii/S096706612100201X?via%3Dihub. Acesso em: 25 ago. 2022.

ROSIQUE, F. *et al.* **A systematic review of perception system and simulators for autonomous vehicles research**. [*S. l.*]: MDPI AG, 2019. Disponível em: https://www.mdpi.com/1424-8220/19/3/648. Acesso em: 26 ago. 2022.

ROSOLIA, U.; BORRELLI, F. Learning How to Autonomously Race a Car: A Predictive Control Approach. **IEEE Transactions on Control Systems Technology**, [*s. l.*], v. 28, n. 6, p. 2713–2719, 2020. Disponível em: https://ieeexplore.ieee.org/document/8896988. Acesso em: 27 ago. 2022.

SAM, D.; VELANGANNI, C.; EVANGELIN, T. E. A vehicle control system using a time synchronized Hybrid VANET to reduce road accidents caused by human error. **Vehicular Communications**, [*s. l.*], v. 6, p. 17–28, 2016. doi: 10.1016/j.vehcom.2016.11.001

SEITZ, S. M. *et al.* A Comparison and Evaluation of Multi-View Stereo Reconstruction Algorithms. *In*: **IEEE Computer Society Conference on Computer Vision and Pattern Recognition - Volume 1 (CVPR'06)**. [*S. l.*]: IEEE, 2006. p. 519–528. Disponível em: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1640800. Acesso em: 25 ago. 2022.

SINHA, A. *et al.* FormulaZero: Distributionally Robust Online Adaptation via Offline Population Synthesis. *Em*: **Proceedings of the 37th International Conference on Machine Learning, PMLR. 119:8992-9004**. [*S. l.: s. n.*], 2020. Disponível em: https://arxiv.org/abs/2003.03900. Acesso em: 27 ago. 2022.

SRINIVASA, S. S. *et al.* MuSHR: A Low-Cost, Open-Source Robotic Racecar for Education and Research. [*s. l.*], 2019. Disponível em: https://arxiv.org/abs/1908.08031. Acesso em: 25 ago. 2022.

VASCONCELOS FILHO, E. *et al.* Towards a Cooperative Robotic Platooning Testbed. *In*: **2020 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)**. [*S. l.: s. n.*], 2020. p. 332–337. Disponível em: https://ieeexplore.ieee.org/document/9096132. Acesso em: 25 ago. 2022.

VEDDER, B.; VINTER, J.; JONSSON, M. A Low-Cost Model Vehicle Testbed with Accurate Positioning for Autonomous Driving. **Journal of Robotics**, [*s. l.*], v. 2018, 2018. Disponível em: https://www.hindawi.com/journals/jr/2018/4907536/. Acesso em: 26 ago. 2022.

VERMA, A. *et al.* Implementation and Validation of Behavior Cloning using Scaled Vehicles. *In*: **SAE Technical Papers 2021**. [*S. l.: s. n.*], 2021. Disponível em: https://saemobilus.sae.org/content/2021-01-0248/. Acesso em: 25 ago. 2022.

WAGENER, N. *et al.* An Online Learning Approach to Model Predictive Control. *In*: **Robotics: Science and Systems 2019**. [*S. l.: s. n.*], 2019. Disponível em: https://arxiv.org/abs/1902.08967. Acesso em: 28 ago. 2022.

WANG, M. *et al.* Game-Theoretic Planning for Self-Driving Cars in Multivehicle Competitive Scenarios. **IEEE TRANSACTIONS ON ROBOTICS**, [*s. l.*], v. 37, n. 4, p. 1313, 2021. Disponível em: https://ieeexplore.ieee.org/document/9329208. Acesso em: 25 ago. 2022.

WHO. **Global status report on road safety 2018**: summary. World Health Organization, 2018 (WHO/NMH/NVI/18.20). Licence: CC BY-NC-SA 3.0 IGO). Geneva, Switzerland, 2018.

WILLIAMS, G. *et al.* Aggressive driving with model predictive path integral control. *In*: **Proceedings - IEEE International Conference on Robotics and Automation**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2016. p. 1433–1440. Disponível em: https://ieeexplore.ieee.org/document/7487277. Acesso em: 26 ago. 2022.

WILLIAMS, G. *et al.* Best Response Model Predictive Control for Agile Interactions between Autonomous Ground Vehicles. *In*: **Proceedings - IEEE International Conference on Robotics and Automation**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2018. p. 2403–2410. Disponível em: https://ieeexplore.ieee.org/document/8462831. Acesso em: 25 ago. 2022.

XU, Z. *et al.* What drives people to accept automated vehicles? Findings from a field experiment. **Transportation Research Part C: Emerging Technologies**, [*s. l.*], v. 95, p. 320–334, 2018. Disponível em: https://www.sciencedirect.com/science/article/pii/S0968090X18302316?via%3Dihub. Acesso em: 25 ago. 2022.

YOU, C.; TSIOTRAS, P. High-Speed Cornering for Autonomous Off-Road Rally Racing. **IEEE Transactions on Control Systems Technology**, [*s. l.*], v. 29, n. 2, p. 485–501, 2021. Disponível em: https://ieeexplore.ieee.org/document/8910615. Acesso em: 27 ago. 2022.

ZHANG, T. *et al.* The roles of initial trust and perceived risk in public's acceptance of automated vehicles. **Transportation Research Part C: Emerging Technologies**, [*s. l.*], v. 98, p. 207–220, 2019. Disponível em: https://www.sciencedirect.com/science/article/pii/S0968090X18308398?via%3Dihub. Acesso em: 25 ago. 2022.

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