The Research on the Autonomous Vehicles: A Bibliometric Analysis

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Abstract—Autonomous vehicles (AVs) can create human social welfare by reducing traffic accidents, improving traffic efficiency, reducing cost, etc. However, there is a lack of systematic analysis of AVs research. This study used CiteSpace visualization software to conduct bibliometric analysis, and data were collected from 2663 valid documents in the Web of Science (WoS) from 2001 to 2021. By analyzing the annual volume of publications, major distribution, co-occurrence of authors, institutions, keywords, and cluster analysis of AVs research in the past two decades, this study reveals the historical evolution, hotspots and trends in AVs research, which is helpful for researchers to have a comprehensive understanding of this knowledge field and have a more objective and scientific basis for AVs further research from a quantitative perspective.

Keywords-Autonomous vehicles; Bibliometric analysis; CiteSpace; Quantitative research

1 INTRODUCTION

With the development of the global economy, public transport problems in urban development are becoming more and more serious, such as traffic jams, low efficiency, environmental pollution and so on. In addition, some reports show that more than 90% of traffic accidents are caused by human errors [1, 2]. Integrating technology and urban life is considered a feasible method to solve the problems of urban development [3], especially in transportation. AVs technology aims to realize the optimal flow of traffic and send people or things to designated destinations efficiently through the automatic traffic planning system/program, which will change the current modes of people's trips, cargo transportation or logistics [4]. AVs are gradually becoming an important part of the development process of smart cities and are the key to solving urban traffic problems.

AVs concept was first proposed in 1918 [3, 5], then Francis P. Houdina and his team created the world's first AVs (named Linriccan Wonder) in 1925 [3]. Eureka Project PROMETHEUS, one of the first large AVs research, was conducted between 1987 and 1995 and promoted the testing of AVs on highways [1]. The DARPA Grand Challenge, organized by the U.S. Department of Defense in 2004, is an AVs competition with no human intervention. In real urban environments, AVs completed the first benchmark test in 2007 [2, 6]. More and more global car companies are entering AVs research and development and opening the market layout. Google's AVs have logged thousands of miles on real roads [2, 7]. Seven AVs manufacturers (Bosch, Delphi, Google, Nissan, Mercedes-Benz, Volkswagen, and Tesla) filed the first disengagement reports testing AVs on public roads in 2016 [8]. Baidu has announced

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that the Apollo, a driverless car, has officially rolled off the production line and begun trial operation in a real environment in 2018.

AVs can bring a lot of convenience and benefits to human society to a large extent, mainly reflected in reducing traffic accidents, improving traffic efficiency, reducing pollution and reducing transportation costs. For example, by comparing the driving behavior differences between AVs and human-driven vehicles in speed control, Zhang et al. find that AVs can control vehicle speed more effectively and verify that the AVs are more fuel efficient for the two driving speeds [9]. However, since the concept of AVs was put forward until now, it has gone through more than 100 years of development, and it is still cautious about putting it on the market. AVs research is not a problem that can be solved by any one technology or only one discipline. Bonnefon et al. discussed social dilemmas in extreme cases from the perspectives of the government, the public, consumers and manufacturers [2]. It can be seen that AVs involve technology, law, market, society and other aspects, and the research on AVs is becoming more and more important.

In the past, researches on AVs were mostly from a qualitative perspective, and there was a serious lack of quantitative analysis of the current research status of AVs. This study aims to understand AVs' overall academic research situation through a quantitative method -- bibliometric analysis. This study used CiteSpace visual analysis software to conduct a bibliometric analysis. From literature in volume and major distribution, the authors/institutions/keywords co-occurrence analysis and keyword clustering analysis and so on, of AVs in the academic research of the overall situation and the future research trends for the objective and scientific analysis allow researchers to understand the knowledge of the field fully and can provide a reference for the future research direction.

2 MATERIALS AND METHODS

2.1 Data Collection

In order to understand the overall research status and trend analysis of AVs research, the data collection is extracted from the WoS database through the following settings. First, the keywords are related to AVs, such as "driverless car", "self-driving car", "autonomous vehicle", and "pilotless automobile". Secondly, the source categories are selected as Science Citation Index Expanded (SCI) and Social Sciences Citation Index (SSCI). Finally, the literature was published from 2001 to 2021. After data cleaning and comparison by two researchers, two experts from AVs (a professor from a Chinese university and a technical consultant from a famous automobile brand) were invited to test the content validity of literature titles and keywords. Finally, a total of 2663 valid documents were extracted for bibliometric analysis.

2.2 Bibliometric Analysis

Bibliometric analysis is quantitative research in a certain knowledge field using scientific methods, such as data and statistics, to understand the research status and trend prediction in this field, which has considerable objectivity [10, 11]. This study utilized CiteSpace 6.1.R3 to make a scientific knowledge graph in AVs, which is an important tool in bibliometric analysis. This study takes 2663 valid documents as research objects to present the development and evolution of AVs and analyze key nodes, enabling researchers to observe and analyze the research status and trend of this field from a more intuitive and objective perspective.

3 RESULTS

3.1 Publication Volume

By combing the volume of AVs studies published in the past two decades (2001-2021), it can be found that AVs research has gone through two periods (see Figure 1). The first phase is the exploratory period (2001-2015), which focuses on the system, design, mobile robot and algorithm. For example, the most cited research at this stage is that of Dissanayake et al., who proposed a utility function to make the closed-loop behavior of autonomous vehicles adaptive and distributed [12]. The second phase is the evolution period (2016-2021), focusing on model predictive control, tracking, optimization, and autonomous vehicle storage. For example, the most cited research at this stage is that of Ji et al., who proposed a collision-free path planning and tracking framework for AVs by superimposing trigonometric functions of roads and exponential functions of obstacles to construct a three-dimensional virtual danger potential field and using a multi-constraint model predictive control to set up tracking tasks [13]. AVs are a typical multidisciplinary and interdisciplinary research area, which has potential research value both in practice and in academia.

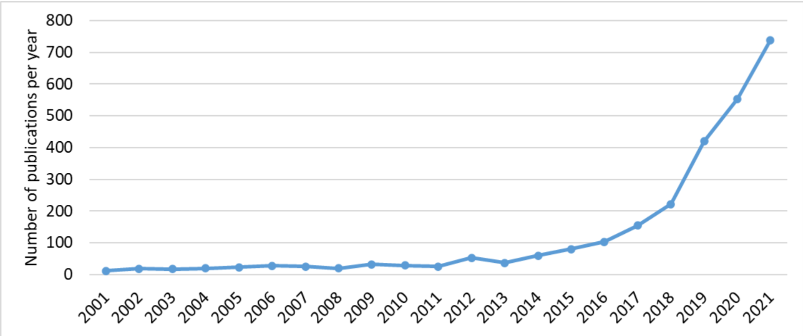

Figure 1. Publication Volume Distribution.

3.2 Major Distribution

By sorting out the major distribution of AVs research in the past two decades, it can be seen that the research mainly focuses on science and engineering (see Figure 2), and nearly half of the literature belongs to interdisciplinary research. The data results show that the number of Engineering Electrical Electronic publications is 896, accounting for 33.65%; the number of Transportation Science Technology articles is 714, accounting for 26.81%; publications in other disciplines accounted for less than 15%. For example, the number of articles published in Robotics is 292, accounting for 10.97%; Computer Science Information Systems published 284 papers, accounting for 10.66%, etc. In general, from the perspective of major distribution, AVs research is the largest in engineering and transportation disciplines, and the research in other related fields of computer science is relatively average, and the proportion is not high.

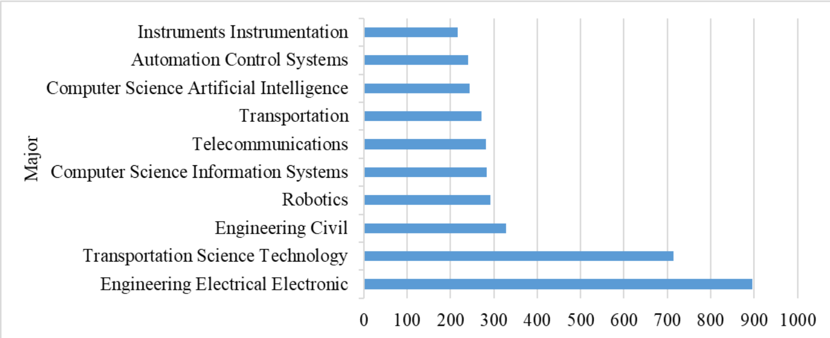

Figure 2. Major Distribution.

3.3 Performance of Authors

This study analyzed the authors of AVs research. A total of 20 authors (i.e., Banu Yetkin Ekren, Charles Malmborg, and Debjit Roy) published more than ten articles, as shown in Table 1. Zhao et al. proposed a method for obtaining accurate and real-time information on objects near AVs by fusing 3D Light detection, Ranging sensors, and convolutional neural networks [14]. In addition, after analyzing the co-occurrence of authors, it is found that some authors cooperate closely and form a cooperative group of authors.

Table 1 AVs Research Authors

No.	Count	Author	No.	Count	Author
1	18	Ekren, Banu Yetkin	11	11	Zheng, Nanning
2	16	Malmborg, Charles	12	11	Zhao, Xiangmo
3	15	Roy, Debjit	13	11	Levin, Michael W.
4	15	Heragu, Sunderesh S	14	11	De Koster, Rene B
5	14	Kockelman, Kara	15	10	Merzouki, Rochdi
6	13	Cao, Dongpu	16	10	Ni, Jun
7	13	Li, li	17	10	Gong, Yeming
8	12	Krishnamurthy, Ananth	18	10	Zhao, Wanzhong
9	11	Jo, Kichun	19	10	Xu, Xianhao
10	11	Milanes, V.	20	10	Lerher, Tone

3.4 Performance of Institutions

The study used CiteSpace to conduct a co-occurrence analysis of the published institutions in AVs research. Table 2 shows the top 10 published institutions. Through the co-occurrence of AVs publishing institutions, it can be found that this study sorted out and summarized the information of the top 10 institutions with the number of publishing (see Table 1), such as Tsinghua University, Tongji University, University of Michigan, Massachusetts Institute of Technology, etc. The number of articles published exceeded 30.

Table 2 AVs Research Institutions (Top 10)

No.	Count	Year	Institutions
1	72	2007	Tsinghua University
2	46	2017	Tongji University
3	43	2012	University of Michigan
4	40	2002	Massachusetts Institute of Technology
5	38	2015	Beijing Institute of Technology
6	38	2015	University of Texas at Austin
7	32	2004	Jilin University
8	32	2003	Nanyang Technological University
9	31	2016	Southeast University
10	30	2002	Georgia Institute of Technology
11	30	2001	University of California, Berkeley

3.5 Keywords and Co-words Analyses

Keywords can represent the main content of the whole paper, and the distribution and centrality of the frequency of keywords can explore the development frontier and research hotspots of a certain knowledge field. A centrality value greater than 0.1 is considered important, and the higher the value, the higher the importance of the keyword in this knowledge field [15]. This study used keywords as node types for co-occurrence analysis to identify research hotspots. The time scale is set as 2001 to 2021; the time interval is set as 1; the data extraction object is set as the top 50; the pruning method is the pathfinder and pruning the merged network. Ultimately generating 735 nodes and 1204 connections, the network density is 0.0039, and the autonomous vehicle is the keyword with the highest frequency, as shown in Figure 3. The frequency in the co-occurrence map is presented in the form of the size of nodes, and the centrality is represented in the form of the thickness of lines. The red diamond is the keywords that are frequently cited in a short time, such as system, autonomous vehicle storage, navigation, and path planning.

In addition, 19 keywords with a centrality value greater than 0.1 are sorted out in this study. Table 3 shows the top 10 keywords, including system (0.31, 273), collision avoidance (0.29, 69), control system (0.26, 19), autonomous vehicle (0.24,1149), fuzzy logic (0.23, 9), allocation (0.21, 7), adaptive cruise control (0.2, 66), motion planning (0.19, 45), algorithm (0.18, 121), and cooperative control (0.16, 9). Among them, the centrality value of the system is 0.31, ranking the highest, representing the important position of the system in the field of AVs research.

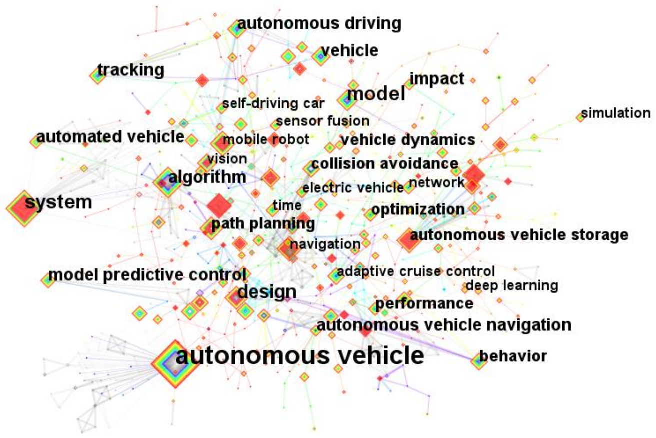

Figure 3. AVs Keywords Co-occurrence Knowledge Graph.

Table 3 Keywords of AVs Research (Centrality > 0.1, Top 10)

No.	Centrality	Count	Year	Keywords
1	0.31	273	2001	system
2	0.29	69	2001	collision avoidance
3	0.26	19	2004	control system
4	0.24	1149	2001	autonomous vehicle
5	0.23	9	2001	fuzzy logic
6	0.21	7	2014	allocation
7	0.2	66	2013	adaptive cruise control
8	0.19	45	2001	motion planning
9	0.18	121	2004	algorithm
10	0.16	9	2006	cooperative control

3.6 Research Trend Analysis

This study generated a keyword clustering time chart (see Figure 4) for AVs research literature data in the past two decades (2001-2021). The data results show that Modularity Q is 0.8963, indicating that the data is valid and the clustering of AVs research is clearly defined. The Harmonic mean is 0.9641, indicating that the network homogeneity of the AVs study is good. After clustering, twelve research subjects are generated. It is the autonomous vehicle, feature extraction, convolutional neural network, autonomous navigation, performance analysis, motion control, path tracking, mobile robot, public transit, reinforcement learning, game theory, and smart city. The clustering information and keywords contained in each cluster are shown in Table 4.

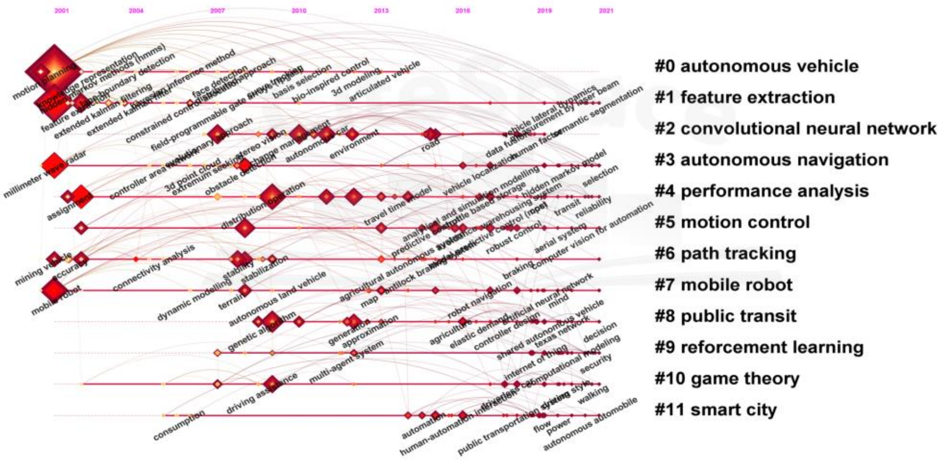

Figure 4. AVs Research Keyword Clustering Time Chart (2001-2021).

Table 4 The Keywords Clustering Results

ClusterID	Cluster Lable	Silhouette	Average Year	Size	Keywords, Examples
0	autonomous vehicle	0.991	2006	52	driving simulator analysis; autonomous intersection management; distributed and asynchronous algorithm; decision matrice; description logic; bio-inspired control
1	feature extraction	0.995	2007	47	acoustic measurement; evolutionary algorithm; multisensor data fusion; interacting multiple model; environment perception; measurement by laser beam
2	convolutional neural network	0.935	2013	41	agile software engineering; evolutionary approach; behavior prediction; human-robot interaction; human factor
3	autonomous navigation	0.897	2014	37	millimeter wave radar; extremum seeking; feature detection; augmented reality; social dilemma; hidden Markov model; autonomous agent
4	performance analysis	0.96	2015	35	ant colony clustering algorithm; analytical and simulation modeling; risk assessment; autonomous vehicle storage
5	motion control	0.933	2016	34	nonholonomic constraint; model predictive control; robust control; predictive control; steering control; vehicle dynamics
6	path tracking	0.925	2009	33	nonlinear system; acoustic telemetry; connectivity analysis; constrained optimal control; automatic guidance

7	mobile robot	0.918	2013	32	behavioral planning; response; responsibility; dynamic modeling; intention
8	public transit	0.905	2016	31	infrastructure; traffic control; economics; transportation system; public transportation; genetic algorithm; time model
9	reinforcement learning	0.829	2017	31	collective behavior; cloud computing; mobile edge computing; clustering algorithm; adaptation model; heuristic algorithm; decision making
10	game theory	0.917	2016	31	area restricted search; artificial potential field; motion sickness; intelligent transportation; driving style; mobility
11	smart city	0.947	2016	31	CO_2 emission; consumption; control strategy; public transportation system; connected and automated vehicle; technology acceptance; user equilibrium; situation awareness

According to the time chart of keyword clustering (see Figure 4), the study reveals the main evolution trend of the two stages. From 2001 to 2015, there are many nodes and lines, indicating that the main research topics in this period are the autonomous vehicle (i.e., driving simulator analysis, autonomous intersection management, distributed and asynchronous algorithm, etc.), feature extraction (i.e., acoustic measurement, evolutionary algorithm, multisensor data fusion, etc.), autonomous navigation (i.e., millimeter wave radar, extremum seeking, feature detection, etc.). From 2016 to 2021, AVs research mainly focused on motion control (i.e., nonholonomic constraint, model predictive control, robust control, etc.), public transit (i.e., infrastructure, traffic control, economics, public transportation, genetic algorithm, etc.), reinforcement learning (i.e., cloud computing, mobile edge computing, clustering algorithm, adaptation model, etc.), game theory (i.e., area restricted search, artificial potential field, motion sickness, etc.), and smart city (i.e., CO_2 emission, control strategy, connected and automated vehicle, technology acceptance etc.), it still has great research potential in the future. For example, Levin used dispatch and simulation methods to study the scheduling of AVs and the equation describing the maximum set of demands that can be satisfied when an appropriate scheduling policy is selected and validate preliminary results for large city networks [16]. Jian et al. proposed a path-planning framework that adaptively adjusts the planning process according to the changes in traffic scenes and then provides different path-planning algorithms to ensure the safety and flexibility of the driving process [17].

4 DISCUSSION AND CONCLUSION

This study reveals the historical evolution, hotspots and trends in AVs research by analyzing the annual volume of publications, major distribution, co-occurrence of authors, institutions, keywords, and cluster analysis of AVs research in the past two decades.

In terms of the volume of publications, AVs research has gone through two stages, including the exploratory period and the evolution period, and the current stage is the second stage. From the perspective of major distribution, AVs research mainly focuses on Engineering Electrical Electronic and Transportation Science Technology, with relatively little research on other disciplines. In the future, the research on other disciplines can be further expanded. From the co-occurrence of authors, the cooperation between authors in AVs research is relatively close, but the cooperation is more in the same field. The cross-research between natural science and social science can be strengthened in the future. The main research institutions of AVs are Tsinghua University, Tongji University, University of Michigan, Massachusetts Institute of Technology, etc. The close connection between institutions improves the validity of AVs research, and future research can expand the cooperation between institutions with different disciplinary backgrounds. In terms of research hotspots, autonomous vehicle, system, algorithm and other subjects have attracted the most attention of scholars over the years. At the same time, system, collision avoidance, control system and other topics have important research status in AVs research, which can provide a reference for future research. From the perspective of research trends, future AVs research has great research potential in the fields of motion control, public transit, reinforcement learning, game theory, and smart city. For example, the smart city cluster can further study keywords such as CO_2 emission, public transportation system, connected and automated vehicle, and user equilibrium.

To sum up, the study is helpful for researchers to have a comprehensive understanding of AVs knowledge field and have a more objective and scientific basis for AVs further research from a quantitative perspective.

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