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Present and future of vehicle navigation systems: Deep integration of technological innovation and intelligent driving

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Abstract. Vehicle navigation systems are one of the essential tools for automotive intelligence development, playing a crucial role in the process. This study discusses the components, operation principles, classification, and latest technological advances of Vehicle navigation systems, aiming to reveal the current state of the latest technological applications of the system in the automotive industry. The study indicates that the core value of vehicle navigation systems lies in precise positioning, enhanced driving safety, intelligent route planning, and other aspects. At present, the market of vehicle navigation systems is witnessing steady growth and faces intense competition from mobile phone navigation. To hold the upper hand in the competition, the industry should utilize policy support from the government, facing up to challenges and seeking solutions to current problems. In the future, the vehicle navigation system should deeply integrate with artificial intelligence (AI), providing diverse, tailored navigation services for customers. These services should cover driving skills, driving habits, etc. Meanwhile, through constant technological innovation, user experience optimization, and the application of deep learning, the vehicle navigation system is expected to achieve more efficient human-machine interaction and enhanced driving safety and comfortability, thereby improving its competitiveness in the market and turning it into an indispensable intelligent companion for drivers.

Keywords: vehicle navigation system, terrain detection and segmentation, autonomous driving positioning

1. Introduction

The automotive industry is one of the core driving forces of economic and social development. As an intelligent navigation tool, the vehicle navigation system enables users to effectively and precisely plan their routes. By integrating satellite communications with electronic maps, the system can precisely locate the positions of vehicles and provide detailed and accurate routes and path calculations. No matter in the city or the wild, the system plays a crucial role, providing thorough guidance for vehicles and making driving more convenient, effective, and safer. Currently, vehicle navigation is a widely used type of navigation application. Meanwhile, the application of navigation systems in automotive technology holds great potential. As the economy advances rapidly, the number of vehicles in China surges as well, leading to the emergence of various types of traffic accidents and congestion. Especially in cities in China, the issue of traffic congestion and subsequent traffic accidents is prominent. Therefore, the application and development of vehicle navigation systems is essential for addressing the issue, enhancing transport efficiency, and decreasing driver's workload [1,2]. After decades of update and iteration, the vehicle navigation system has undergone several phases including ground-based radio, satellite positioning, integrated intelligence, and the internet era. It has been developing while its market demand continues to grow.

With technological development and innovation, the vehicle navigation system has advanced beyond merely providing routing guidance to expand visions that the sensors of vehicles cannot cover, enhancing beyond-visual-range perceptions. This advancement allows for all-weather operation and significantly increases driving safety and convenience. However, there are defects existing in current vehicle navigation technologies, such as susceptibility to external interference and lack of intelligent route planning. The major technical issue is the accuracy and real-time performance of positioning. In recent years, studies on technologies and applications related to vehicle navigation systems have expanded rapidly, including the technological achievements of remote communication, human-computer interaction, augmented reality, and intelligent connectivity. These achievements demonstrate the breakthroughs of technical barriers in positioning and data networking, improving system accuracy, stability, and continuity [3].

This paper will discuss the current state of the vehicle navigation system's application, explore its operation principles, list the categories of navigation systems, and present key technologies as well as existing issues. To address these problems and challenges, it is required to continuously innovate and optimize technologies to enhance user experience and service quality, promoting the sustainable and healthy development of vehicle navigation systems.

2. Introduction of vehicle navigation systems

2.1. Components of vehicle navigation systems

Vehicle navigation systems are composed of a navigation satellite terminal, an onboard computer, navigation software, a display, Geographic Information System (GIS) software, and Database Management System (DBMS) software. The navigation satellite terminal is used to receive satellite positioning signals to pinpoint the current location of the vehicle. Its main function is to collect real-time location of vehicles and position itself and update data continuously to provide the latest calculations for traffic management information. Along with programming technology and map data, it offers users multimedia information services. The GIS map displays geographic data in graphical form, providing users with a clearer view. DBMS is a large software system used for operating and managing databases, allowing for the establishment, use, and maintenance of databases to ensure their security and integrity. Users can access the data in the database through the DBMS, and database administrators also use the DBMS for database maintenance.

2.2. Operation principles of vehicle navigation systems

The navigation system begins processing when the driver inputs the destination. This information is then received by the vehicle's positioning system to identify the exact location, sending it to the navigator. The navigator then compares this with the map stored in the memory card, allowing the car's current location to be displayed on the screen. Using a cellular network, the onboard terminal transmits the vehicle's current position and speed information to the server at the control centre. By analyzing and integrating the information, the server then determines whether the current road segment is congested and assesses the severity of the congestion [4]. After calculating the optimal route based on traffic conditions and the electronic map, the navigation system transmits this information to the driver, guiding them to follow the best route. If the vehicle deviates from the suggested route, the navigation system will recalculate the optimal path. During the journey, the voice prompts provided by the navigation system will guide the driver to reach the destination.

2.3. Classification of vehicle navigation systems

2.3.1. Global Positioning System (GPS)

Navigation systems based on GPS primarily rely on the signals of GPS satellites of the United States to locate vehicle positions and provide navigation service. Typically, the system contains a single or more receivers that receive signals from satellites, calculating the vehicle's precise location on Earth. GPS can provide all-weather and real-time navigation worldwide, featuring multifunctionality, wide applicability, and rich data. The GPS navigation is superior in many aspects with various signal services, precise and stable coverage globally, anti-jamming capabilities and confidentiality, inter-satellite links for autonomous operation, and a 24/7 ground monitoring capability [5].

2.3.2. BeiDou navigation satellite system (BDS)

BDS is an independently developed navigation system by China. Similar to GPS, it includes one or more receivers that receive signals from satellites to calculate the precise location of a vehicle on Earth. Featuring triple-frequency signals, it is more accurate and has stronger anti-jamming capability compared to the dual-frequency employed by GPS. Triple-frequency signals can better penetrate buildings and other obstacles, providing more stable positioning services, especially in complex environments such as urban canyons or areas with strong electromagnetic interference. Additionally, BDS employs a distributed antenna system (DAS) to ensure accuracy and reliability. It allows stable positioning services even in cases of weak signals or with the presence of jamming. This design enables BDS to outperform GPS in multipath interference and weak signal environments. Additionally, BDS features short message communication, a capability not available by GPS. This feature allows users to send messages in environments without mobile signal coverage, which is essential for emergency communications and rescues. In cases of natural disasters and other emergencies, this feature facilitates timely communication, enhancing the stability and practical value of the system [6].

2.3.3. GPS/Beidou integrated navigation system

This system combines the strengths of GPS and BDS, providing location with higher accuracy and reliability. It usually consists of one or more AI algorithms to select the optimal between GPS and BDS, thereby ensuring the best navigation performance.

2.3.4. Map-based navigation system

Being independent of satellite signals, this type of navigation system provides navigation service by analyzing road and traffic information stored in map databases. Typically, the system contains one or more high-precision map databases and a set of complex algorithms to calculate the optimal route based on the user's current location and destination.

2.3.5. Real-time traffic navigation system

This type of system combines map data and information on real-time traffic to provide users with the most precise routes. It usually includes one or more sources of real-time traffic information, such as road sensors or communication data from other vehicles, along with a set of algorithms to adjust the recommended route based on real-time traffic conditions.

3. Advances and applications of vehicle navigation systems

3.1. Application of terrain detection and segmentation technology in-vehicle navigation systems

GPS and BDS are the most commonly used in vehicle navigation. With the rapid advancement of AI, 5G communication, and big data, smart cars have become a major focus in the global automotive industry. Meanwhile, as technologies in perception, decision-making, and control have matured, the market for autonomous driving has seen exponential growth over the past decade. This leap forward is largely due to improvements in vehicles' ability to recognize their surroundings, specifically through precise terrain detection and segmentation by navigation systems. This technology is crucial for ensuring the safety and reliability of autonomous vehicles. Both GPS and BDS now utilize the terrain detection and segmentation technology.

Today's terrain detection and segmentation have evolved from traditional computer vision methods to more advanced machine learning and deep learning techniques. This technology combines data from multiple sensors to accurately understand and interpret the surrounding terrain. Integrating Light Detection and Ranging (LiDAR), radar, cameras, and other sensors [7], significantly enhances a vehicle's ability to perceive its environment, ensuring both the performance and safety of autonomous driving.

While allowing vehicles to accurately detect and differentiate between different types of terrain, this technology also offers an unparalleled level of detail in understanding their surroundings. It can identify things like roads, sidewalks, overpasses, and obstacles, as well as more challenging terrains like rugged mountain paths, construction sites, or mines [8]. This understanding helps navigation systems perform smoothly on both city streets and complex off-road environments, avoiding obstacles and ensuring the safety of both passengers and the vehicle [9].

Additionally, by integrating data from multiple sensors and analyzing the surrounding environment, this technology enables vehicles to create detailed environment maps. These maps provide real-time, accurate navigation to users, helping to avoid potential hazards while adjusting speed and path as needed. This enhances the vehicle's ability to navigate around obstacles, debris, and other hazardous conditions, ensuring smooth, safe, and efficient travel. Overall, this advanced navigation technology boosts the vehicle's ability to efficiently and autonomously explore its surroundings, unlocking new potential for scientific research, resource exploration, and disaster response [10].

Terrain segmentation is an extension of terrain detection. It categorizes the different types of terrain that have been identified and divides the field of view into various classes. This detailed classification is essential for autonomous vehicles to make smart decisions about speed, steering, and path planning.

At present, the latest terrain segmentation technology has evolved into deep learning techniques, particularly convolutional neural networks (CNNs)—a type of feedforward neural network characterized by convolutional computations and deep structures, and one of the representative algorithms of deep learning [11]—and semantic segmentation models [12]. These models are trained on extensively labelled datasets to accurately classify each pixel in an image into different terrain categories. Recent innovations include generative adversarial networks, which enhance the resolution and accuracy of real-time segmentation maps. In addition, transfer learning techniques allow these models to adapt to new, unseen environments with minimal additional training [13]. This adaptability is especially beneficial for autonomous vehicles operating in diverse scenarios and unpredictable terrain conditions, ensuring safe and efficient navigation across different landscapes.

3.2. Application of vehicle positioning and navigation systems in autonomous driving

AI is one of the leading new productive forces in China. It is widely applied across various industries and seamlessly integrated into the automotive sector. As an advanced version of intelligent vehicles, autonomous cars have transitioned from being a concept in science fiction to becoming a reality in our everyday lives. With their emergence, road safety is enhanced and traffic flow and road resources are optimized, introducing cutting-edge technologies into daily lives.

The research of autonomous cars can be dated to the mid-20th century by the United States, followed by countries such as the United Kingdom, France, Germany, Japan, and South Korea to develop their autonomous vehicles. Relatively, China has a later start in this field. However, it witnesses encouraging progress with a strong potential to surpass others. Baidu, Tencent, JD, BAIC, GAC, and other companies have all successfully developed driverless cars. Furthermore, Apollo Go, a robotaxi service developed by Baidu has already started operations in cities including Wuhan. As autonomous cars become more commonly used, the accuracy of various driving parameters and the operation efficiency have become key concerns for the public.

The positioning and navigation system of autonomous cars is a critical component of autonomous driving technology. Its key elements include accurate positioning of vehicles, precise alignment between the vehicle and the map, and accurate route planning throughout. Autonomous cars have a high demand for high-precision navigation information and detailed road data to ensure safety and operation efficiency in complex environments. Therefore, traditional road-level positioning and navigation systems have become inadequate, being unable to meet the growing demands [14].

3.2.1. Lane-level positioning and navigation system

Lane-level positioning and navigation systems are the foundation of precise navigation and the key to the future of transportation. Currently, most autonomous cars on the market use lane-level positioning and navigation systems. As the name suggests, the core technologies of this system include lane-level positioning, lane-level map matching, and lane-level route planning [15].

Positioning technology is an integral component of the navigation system for autonomous vehicles. Except for merely determining the vehicle's location, it captures precise data on the vehicle's orientation, providing solid data support for the decision-making of the autonomous driving system. Since driverless cars need to autonomously perform complex maneuvers such as route planning, and obstacle avoidance, serious consequences can be caused even with the least noticeable positioning error. For instance, if a driverless car is mispositioned for just a few decimeters, it could wrongly guide the vehicle into an adjacent lane, potentially leading to collisions or traffic accidents. Therefore, the positioning accuracy of autonomous vehicles must reach lane-level precision or even higher.

In addition to the strict requirements for high precision, factors like real-time performance, stability, and cost-effectiveness are noteworthy. Currently, positioning technologies including the integration of Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS), as well as methods like LiDAR, cameras, and wheel odometry are positioning technologies are widely used.

In complex and ever-changing navigation environments, it is challenging for a single navigation system to meet all challenges. This highlights the importance of combining GNSS and INS. GNSS excels in open outdoor environments with its high precision and global coverage, while INS demonstrates unique advantages in signal-blocked or interfered areas for its independent navigation capability independent of external signals. Therefore, the combination is not simply overlapping but involves carefully designing diverse integration strategies based on specific needs to achieve outstanding navigation performance. This has led to the development of GNSS/INS integrated navigation technology, which processes multiple navigation data sources for more precise and reliable positioning [16,17]. Typically, the integration methods are categorized into three main types, loose coupling, tight coupling, and deep coupling [18]. The loose coupling method is known for its simplicity by cleverly combining the independently computed positioning results of GNSS and INS to achieve efficient collaboration [19]. Tight coupling enhances the depth and accuracy of integration even further. It directly uses raw GNSS data to update INS measurements, allowing stable positioning outputs even in complex environments with fewer than four visible satellites. This showcases its remarkable adaptability and reliability. Deep coupling achieves the integration at a hardware level, further leveraging GNSS information to improve the performance of the integrated navigation system.

Laser radar sensors measure the distance to a target using multiple laser beams. Each beam calculates the distance based on the time it takes for the signal to return to the receiver and the infrared intensity of the obstacle. Cameras, as another positioning technology developed under computer vision, use their perceptual information for navigation and localization. Wheel odometers measure the number of pulses from the wheel encoders with precision, allowing for accurate calculations of wheel speed and the distance travelled. They have been widely applied in the autonomous driving sector for their significant cost-effectiveness.

3.2.2. Map-matching technology

Map matching plays a crucial role in the positioning and navigation systems of autonomous vehicles. The core of the technology lies in the seamless integration of the data of real-time vehicle position and the precise digital map data, thereby determining the relative coordinates of vehicles on the map accurately. On this basis, the system can comprehensively plan and optimize the best driving route from the starting point to the destination.

Initially focusing on precise positioning at the road level, map-matching technology ensures that vehicles can accurately align with the correct road [20]. As sensor technology advances rapidly and lane information becomes increasingly detailed, map-matching algorithms have evolved to achieve exceptional lane-level positioning capabilities. Presently, this technology satisfies the pressing needs of the rapidly evolving autonomous driving technology by precisely mapping positional data to specific lanes on a lane-level map.

3.2.3. Route planning

The route planning technology aims to automatically devise the optimal driving route from the starting point to the destination by accurately mapping the coordinates to their corresponding positions on the map [21]. Traditional electronic maps have a positional accuracy range from five to ten meters approximately, which reflects a broader road network perspective. However, to meet the demands of lane-level navigation with high precision, the lane-level road network data model has emerged. This model enhances the details of lane-level maps by incorporating comprehensive lane environment information, thus enabling more refined positioning and navigation services.

In summary, the positioning and navigation technology for autonomous cars is a highly integrated, complex, and sophisticated system. By leveraging precise positioning, high-accuracy map matching, sensor fusion, and intelligent route planning, autonomous cars can achieve accurate positioning, smart navigation, and autonomous decision-making in intricate and changeable road environments, laying a solid foundation for future intelligent transportation systems.

4. Conclusion

China has been witnessing booms in economy and technology, which is accompanied by a transformation of cars from luxury items into widely accessible tools of transportation. Statistics show that in recent years, the number of cars in China has skyrocketed, adding millions of new vehicles each year. This astonishing figure not only reflects the rising living standards of the population but also indicates vast development prospects for the automotive-related industries. In this context, vehicle navigation systems play an essential role in automotive intelligence and convenience and expand their market size and share at an unprecedented speed. The system is no longer exclusive to high-end models but has now become a common feature in middle and lower-end vehicles.

As one of the cores of modern automotive technology, vehicle navigation systems integrate advanced technologies such as satellite positioning, map navigation, and real-time traffic information, providing drivers with an unparalleled travel experience. To address existing shortcomings, technical personnel are working to overcome the limitations of single and fixed navigation modes, accelerating the integration of navigation with AI and machine learning algorithms. They are also gradually enhancing the understanding and predictive capabilities of the systems regarding driver needs, providing more detailed and personalized navigation services. Furthermore, as autonomous driving technology keeps advancing and commercialization accelerates, vehicle navigation systems will become increasingly significant and valuable as an essential part of autonomous driving technology.

In recent years, as the number of cars in China continues to rise, the demand for smart and convenient travel has also been increasing. It has promoted rapid growth in the vehicle navigation system market, which has maintained a double-digit annual growth rate. While mobile navigation quickly captured the market due to its convenience, real-time updates, and user-friendly interaction, vehicle navigation systems have demonstrated strong positioning and signal reception capabilities. These capabilities are gained through the leverage of satellite navigation and ground enhancement technologies, as well as a high level of integration with automotive systems. However, vehicle navigation systems still face challenges in connectivity, data update speed, and human-machine interaction. Government policy support, especially in promoting satellite navigation applications, provides strong assurance for the future development of vehicle navigation systems.

In conclusion, the trend of closely integrating vehicle navigation systems and AI will prevail. To be truly trusted by drivers, vehicle navigation systems should continue to innovate and enhance user experience, leading the automotive sector into a future with greater intelligence and convenience.

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