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Augmented Reality Applications in the Automotive Industry

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***Abstract*—This research paper examines the implications and transformative capabilities of Augmented Reality (AR) within the automotive landscape. We examine how AR catalyses radical changes across various automotive functions, from design and manufacturing to customer engagement and vehicle operation. While AR is poised to elevate operational efficiencies significantly, it also presents challenges, such as AR content authoring complexity and hardware constraints that restrict mass consumer adoption. This paper surveys the current AR state-of-the-art technology, systems and pivotal automotive applications. The primary objective is to offer a thorough comprehension of the underlying concepts, methodologies, and applications that underpin the integration of AR within the automotive industry. It concludes by discussing potential barriers to AR implementation and outlines future avenues for research, including software scalability and the integration of cloud and edge computing to alleviate device limitations.**

***Index Terms*—Augmented Reality (AR), Automotive Industry, User Experiences, AR Work Instructions (ARWI), Development Tools.**

I. Introduction

Augmented Reality (AR) is an evolving technology that can significantly impact various industries, particularly the automotive sector. AR enhances user experiences and operational efficiency by overlaying digital information in the real world. This paper aims to offer an in-depth examination of the current advancements in the AR technology, its growing relevance, and its practical applications in the automotive industry. We cover the spectrum of AR applications from design, manufacturing, and assembly to end-user functionalities such as vehicle maintenance and driving assistance. Moreover, we delve into the broader scope of AR as a catalyst for comprehensive digitization within the automotive field.

The paper is structured as follows: Section II outlines the research questions and methodology. Section III delves into the core concepts and techniques related to AR, providing foundational knowledge. Section IV concentrates on the specific applications of AR in the automotive industry. The paper wraps up in Section V, where we discuss conclusions and outline potential avenues for future research in this area.

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II. Method

In this study, we systematically explore the application of Augmented Reality (AR) within the automotive sector, aiming to understand its varied applications in enhancing efficiency, precision, and user engagement. Our objective encompasses the assessment of AR methodologies, platforms, and the inherent challenges specific to the automotive realm. We particularly probe the efficacy and limitations of prominent AR platforms such as ARKit and ARCore when applied to automotive contexts. Moreover, we critically discuss the issues associated with the prevalent AR tools and technologies in the automotive industry.

We undertook a thorough manual search on Google Scholar to derive comprehensive insights, focusing on conference proceedings and journal articles. We included Peer-reviewed articles that either presented extensive AR literature surveys, AR technical concepts or showcased concrete case studies related to AR applications in the automotive sector. Given the rapid advancements in AR technology, we narrowed our search to application case study papers published between January 1st 2015 and July 30th 2023. Additionally, to capture a broader perspective, we referenced prominent augmented reality products and solutions that have been widely discussed online but might not have found their way into academic literature. The following research questions steered our research:

RQ1. What are the classifications of AR techniques and methodologies?
RQ2. Since 2015, which AR platforms and applications have been instrumental in the automotive industry?
RQ3. What are the potential constraints and challenges in harnessing AR within the automotive domain?

III. Augmented Reality Concepts

The essence of AR resides in its interactive augmentation of the real-world environment with virtual computer-generated data. AR seamlessly integrates computer-generated sensory inputs into the physical environment. In contrast to Virtual Reality (VR), which immerses users entirely in simulated settings, AR enhances the user's immediate reality by blending digital elements. An AR System inherently comprises three core characteristics: a real-world environment overlaid with digital elements, real-time interaction, and precise positioning/tracking of digital elements within the physical environment [1–3]. Mixed Reality (MR) blends real and virtual elements, allowing interaction between the two [4].

Various domains utilise AR, including gaming, industrial, educational, medical, and commercial, for example in the Medical professionals training domain [5], Professionals used AR for visualizing patient data during surgery, practicing procedures virtually, and aiding in diagnostics. AR allows trainees to practice tasks and scenarios in a controlled environment.

A. Differentiating AR, VR, and MR

While Augmented Reality (AR) and Mixed Reality (MR) utilize digital information to enhance real-world perception, MR foster deeper interaction and integration between virtual and physical elements, resulting in a more immersive experience. AR focuses on enhancing the real world with limited interaction with the physical environment, whereas MR aims to integrate virtual objects into the real world, enabling interaction and responsiveness. AR commonly serves informational overlays, gaming, and navigation, while MR is applied in disciplines like architectural design, industrial training, and collaborative innovation, emphasizing the integration of virtual and real elements. According to Milgram and Kishino's taxonomy [6], Mixed Reality is a broader term encompassing Augmented Reality, which lies between the virtual and real worlds. Augmented Virtuality (AV) within this continuum involves introducing real-world elements into a predominantly virtual environment, effectively bringing real-world objects or data into a virtual context.

The distinction between AR, MR and VR may blur due to the growing use of MR within VR headsets. Integrating outward-facing cameras and advanced environment-scanning technology will progressively enhance headset users' perception of their surroundings. This trend is poised to result in most VR headsets incorporating mixed-reality functionalities. In this study, the term "AR" is applied broadly, encompassing cases where the real environment is enriched with virtual objects. As a result, devices and applications related to Mixed Reality (MR) are considered, given the significant overlaps between AR and MR, particularly in the automotive sector.

B. AR displays, rendering, tracking, and interaction

*1) **Displays**:* Currently, AR displays are constrained by their size and cost due to limitations in processing power and display technology. The electronics within AR glasses are expensive and bulky. Users currently can use large goggles or rely on smartphones for AR interactions. Nevertheless, as these components become smaller and more affordable and seamlessly integrate into eyewear without adding much weight, dedicated AR displays will differentiate themselves from VR headsets that provide full visual immersion. This advancement will greatly enhance the user-friendly AR experience for consumers.

Handheld Displays (HHDs): Portable devices, like smartphones and tablets, offer accessible AR capabilities. They present a cost-effective solution to access AR content. Handheld AR is found to practical use in displaying manuals, 3D models, and diagrams on top of real-world objects. These devices commonly operate on iOS or Android platforms.

Head-Mounted Displays (HMDs): Wearable devices, including smart glasses and headsets, provide AR capabilities. Unlike smartphones, they are designed for constant use and can be seen as extensions of our bodies. They are always accessible, making them efficient for brief interactions, unlike devices that need to be taken out of a pocket. Sensor and actuator placement is crucial in wearables. The head is ideal for devices like glasses, earphones, and cameras since it allows hands-free use and offers more privacy. HMDs offer hands-free interaction, ideal for users who need both hands for tasks. A typical AR headset comprises five main components: sensor, camera, display, powerful processor, and connectivity. Table I presents four currently available HMDs, along with a comparison of their specifications and cost.

Head-Up Displays (HUDs): HUDs are becoming increasingly popular to keep drivers focusing on roads. By overlaying visuals on the windshield, HUDs improve the drivers' view of the environment outside the car, creating stronger awareness of the surroundings. Ma et al.'s study [7] emphasised the pivotal role of effective design principles in harnessing the potential of HUDs to improve driving experiences and safety outcomes.

Table III highlights the display modes utilized in the papers reviewed in section IV-A based on the type of applications tested.

*2) **Rendering Techniques**:* Augmented Reality (AR) enhances automotive applications by overlaying textual instructions, 2D images, 3D models, videos, and audio, as in the examples shown in Figure 1 and Figure 2. The overlaid elements must adapt to their environment for effective AR to ensure visibility and visual coherence. The research in [8–11] indicate multiple Visualization factors are involved, including:

Depth: The depth adjustments, such as size and level of detail, are critical for other visualization aspects like occlusion and spatial understanding. Accurate depth measurements are essential in sectors like automotive maintenance.

Occlusion: Graphical elements could be fully or partially occluded based on their interaction with other virtual or physical objects. Phantom Rendering is a popular method for occlusion, especially in automotive design and maintenance. As these calculations can be greatly complex in some situations, the X-ray or "see-through" visualization is commonly utilized. It is the change of the transparency of rendered objects to intuitively deduce their depth and the parts they would be occluding. Such visualizations are commonly used in medical applications.

Abstract visualization displays a simplified 3D model, prioritizing user clarity by omitting complex details . In contrast, concrete visualization offers detailed 3D models, closely replicating real-world vehicle parts as shown in figure 1. According to Jasche et al. [12], task complexity should guide the choice of visualization type: concrete visualization reduces errors but can be more time-consuming and complex to create.

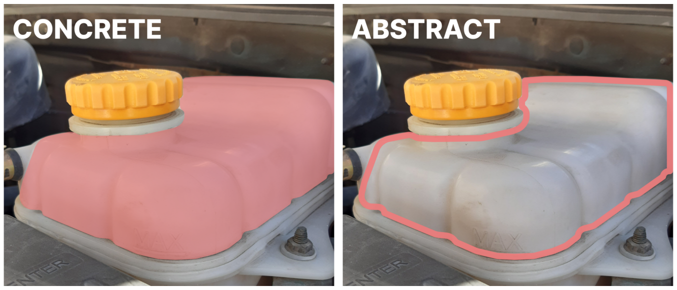

Fig. 1: Concrete and abstract visualizations

*3) **Tracking**:* Tracking is crucial for accurately aligning virtual objects within a real-world augmented reality (AR) setting. It involves dynamically localizing objects in 3D space and continuously measuring their position relative to a standard coordinate system. The concept of 6 Degrees of Freedom (6DoF) is important, allowing for tracking along three rotational and three directional axes. 6DoF is especially vital when users employ Head-Mounted Displays (HMDs). Although simpler 3 Degrees of Freedom (3DoF) systems exist, they limit the AR experience [3, 13].

Three primary tracking methods are prevalent: Sensor-based, Vision-based, and Hybrid systems. The choice of tracking method depends on the application and its specific needs. Hybrid systems are increasingly favoured for their ability to overcome the limitations of sensor and vision-based tracking. In [13], Rabbi et al. argued that sensor and vision-based tracking don't offer ultimate solutions; hence, a hybrid solution has been implemented to overcome their limitations.

Sensor-based Tracking: Active sensors are utilized to continuously measure the position, and orientation of the camera. Sensor-based tracking can be divided into four categories: optical, Magnetic, Acoustic, and Inertial [1, 14, 15]. While each type has pros and cons, factors like precision, cost, and resolution influence the choice. For instance, optical tracking is cost-effective but sensitive to lighting changes, while magnetic tracking can be disturbed by nearby metallic objects.
Optical tracking employs video cameras and epipolar geometry to align with global coordinates and is relatively cost-effective but can be compromised by lighting changes. Magnetic tracking [1] relies on magnetic fields to ascertain camera position, though it is generally less accurate than optical systems and is vulnerable to interference from metallic objects nearby. Acoustic tracking uses ultrasound sensors, determining position and orientation based on the time it takes for waves to travel; however, it may be affected by ambient noise. Lastly, Inertial tracking [15] is the use of inertial sensors, such as accelerometers and gyroscopes, to track the position and orientation of a device or object in real-time. Inertial tracking is often used in conjunction with other tracking technologies like optical tracking to improve accuracy.

Vision-based Tracking: In contrast to the sensor based technique, vision based tracking utilizes image processing methods instead of sensors for the camera pose detection. It can be further categorized into Marker-based and Markerless-based systems. Marker-based systems use fiducial markers like QR codes AprilTag, or ARUco for alignment [14], The markers can be of thousand different designs offering a wide range of fiducial markers to be used that can be of a rectangular or circular shape. However, marker-based tracking poses some limitations; one of which is the tight need for markers that make interaction less smooth.

On the other hand, markerless systems rely on visual cues and algorithms such as Structure From Motion (SFM) and Model-Based tracking [16]. Since it depends on visual cues rather than examining raw pixels, markerless-based tracking has drawn more attention from the AR sector.

Hybrid Tracking: Hybrid tracking introduces an approach that aggregates multiple tracking techniques at once to offer more accurate and efficient tracking of the AR environment. This method combines multiple tracking techniques to enhance accuracy. For example, Simultaneous Localization and Mapping (SLAM) switches between different tracking methods based on environmental condition [17].

Fig. 2: Audi Q4 e tron 2021 AR-HUD

*4) **Interaction**:* Human-computer interaction (HCI) is a cornerstone of AR applications, as it allows users to manipulate and interact with digital content while allowing collaboration within AR spaces. Various interaction methods are used, depending on the AR modality employed in the system.
Gesture-based interaction is prevalent in AR systems, allowing intuitive navigation and task execution through hand movements. Two main methods capture gestures: computer vision and sensors. Computer vision uses cameras and frameworks like Mediapipe to recognize gestures based on image frames. Sensor-based approaches, like gesture-tracking gloves, offer higher accuracy by capturing hand landmarks but are less common due to installation complexities. Some devices, like Microsoft Kinect, combine both methods for enhanced reliability and functionality [18, 19].

TABLE I: Comparison of popular Head-Mounted Displays (HMDs) available for purchase.

Name	Epson BT-45C	Meta Quest Pro	Microsoft HoloLens 2	Apple Vision Pro
Display	2x Si-OLED binocular Native passthrough 1920x1080 per-eye	2x LCD binocular Camera passthrough 1800x1920 per-eye 90hz	binocular Native passthrough 1440x936 per-eye 60hz	Micro-OLED 4K Displays Camera passthrough 90hz + HDR
FOV	34° diagonal	96° diagonal	52° diagonal	TBA
System	Android 11 Qualcomm Snapdragon XR1 Adreno 615 GPU 4GB Ram + 64GB Storage	Android Qualcomm Snapdragon XR2+ Adreno 650 GPU 12GB Ram + 256GB Storage	Windows Holographic Qualcomm Snapdragon 850 Adreno 630 GPU 4GB Ram + 64GB Storage	VisionOS Apple M2 + R1 Chips
Connectivity	USB 3.0 Type-C Wifi + Bluetooth 5.0	USB Type-C Wifi Streaming Wifi 6E + Bluetooth	USB Type-C Wifi 5 + Bluetooth	TBA
Price	$1600	$1500	$3500	$3500

Touch-based interaction is another method primarily employed in handheld AR devices. For example, automotive AR apps may allow users to touch and move virtual elements to reveal obscured components, offering an intuitive, tactile way to interact with the virtual environment. Touch-based and Gesture-based interaction can be used together. Kim et al. [19], introduced a method for manipulating AR objects using touch and hand gestures on handheld devices. This technique allows for 6DoF in manipulating virtual objects, improving usability in one-handed AR environments. It showed that this approach outperforms existing screen touch-based and vision-based methods.

Voice-based interaction This method uses voice commands to execute specific actions within the AR environment. This form of interaction is particularly useful for situations where the user needs to focus on the task at hand. The system's voice recognition technology translates spoken words into meaningful commands. However, there are concerns about its effectiveness in noisy work environments, which could impact its reliability.

Gaze-based interaction is an emerging technique that offers a hands-free experience by tracking the user's eye movements. It is currently integrated into specialized AR glasses that also support gesture detection. This method is still experimental and requires further research for deployment in critical operations. Hands-free methods can particularly be advantageous for tasks that require the user's hands to be completely free [20].

IV. AR in the Automotive Industry

AR provides enhanced interactive experiences and assists in complex tasks, including navigation, assembly, maintenance, training and design. Boboc, R.G., et al. [21] presented a thorough evaluation of existing AR systems in the automotive industry, synthesising 55 works published up to 2019. The study showed that the amount of research has grown year after year since 1999. Today, the AR automotive application development field is still growing, and table II provides an overview of the surveyed applications within this paper.

A. Automotive Industry Applications

1) 'In-car' systems: AR head-up displays (HUDs) assist drivers with navigation and dashboard functions, enhancing driving when well-designed but compromising safety when poorly executed [7]. Studies indicate that HUDs' placement can occasion drivers distraction, and specific User Interface (UI) types influence usability and glance behaviour [22, 23]. HUDs also foster trust in automated vehicles (AVs), with user preferences noted for different route display options [24]. Passenger-targeted AR systems, like Berger et al.'s interactive car door, improve user experience by offering entertainment and external information [25]. The automotive market currently fosters a number of HUD-equipped car models. More than 30 brands released in 2022 vehicles with HUDs, including Audi, BMW, and Mercedes-Benz, with 12, 16, and 14 car models respectively [26].

2) Assembly: AR assists technicians with tasks like panel alignment, reducing errors and improving efficiency. AR glasses specifically lower the cognitive load on operators. The proposed prototype in [27] provides the operator with AR instructions to reduce errors in panel alignment. These instructions mainly target correcting the gap and flushness measured by sensors. After experimenting with their prototype, the authors concluded that their system reduces execution time and hence enhances productivity through the instant availability of information in the operator's field of view, suggesting that less skilled operators could perform similar tasks. Similarly in [28], through experiments conducted in an automotive factory, it has been concluded that the utilization of AR glasses in assembly tasks reduces the cognitive load of the operator accomplishing them.

3) Maintenance: As technicians are exposed to a wide variety of car models, they constantly face the need of going through car manuals and guide books. In order to facilitate this task, AR instructions are commonly used in this domain, whether it is for car repair or periodic maintenance procedures. Even novice AR users are able to perform better while executing unfamiliar tasks using HMD devices [38]. Moreover, AR applications on HHDs can also be helpful in the delivery

TABLE II: AR applications in the automotive industry.

System	Showcased	Display Type
ARmedia Dealer 2.0 [29]	2015, Renault Innovation Day	HHD, HMD
Digital holographic system for automotive augmented reality head-up-display [30]	2018, IEEE 27th International Symposium on Industrial Electronics (ISIE)	HUD
Using Augmented Reality and Mobile Technologies to Train Automotive Technicians [31]	2018, IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE)	HHD
AR DriveSim [23]	2019, Frontiers in Robotics and AI	HUD
Bosch Common Augmented Reality Platform (CAP) [32]	2019, Consumer TechnologyAssociation (CES)	HHD, HMD
Training Assistant for Automotive Engineering Through Augmented Reality [33]	2019, International Conference on Augmented Reality, Virtual Reality and Computer Graphics	HHD
WorxAR [34]	2019, AAAA/ Collision Repair Expo in Melbourne	HHD, HMD
MARMA: Mobile Augmented Reality Maintenance Assistant [35]	2020, Machines	HHD
An AR-enabled interactive car door to extend in-car infotainment systems for rear seat passengers [25]	2021, Conference on Human Factors in Computing Systems (CHI)	HUD
An augmented reality approach for supporting panel alignment in car body assembly [27]	2021, Journal of Manufacturing Systems	HHD, HMD
Augmented Reality Maintenance Assistant Using YOLOv5 [36]	2021, Smart Services: Artificial Intelligence in Service Systems	HHD
AVAR: Avanza Augmented Reality [37]	2022, International Journal of Advanced Science Computing and Engineering	HHD

of maintenance instructions for low-skilled operators [35]. The instructions are displayed as a series of steps composed of CAD models, animations, text and audio. Furthermore, the use of spatial AR in maintenance procedures can improve the error rates in complex tasks [39].

4) Training: Teaching automotive mechanics to new operators can be costly in terms of time and financial resources [31]. Their training includes 3 main activities that could be optimized by being converted into AR experiences: components introduction, assembly and disassembly, and function simulation [33]. As a consequence, training operators to deal with advanced and contemporary car types such as hybrid cars [40] is considerably appealing to automotive factories.

5) Design, Prototyping, and Testing: In a teaching setting, AR was proven to aid students in decreasing product design time and error rate [41]. Future work aims to create a collaborative platform for multiple users to simultaneously evaluate designs using different AR devices and explore integrating VR and holographic displays to enhance product design processes further.

6) Safety: As the automotive sector advances towards the car of the future, numerous technology companies, including BMW, are developing in-vehicle collision avoidance systems (CAS) integrated into vehicles' HUDs to enhance driving safety. AR has the potential to visually augment existing safety systems [42], such as side blind zone alert (SBZA), lane drift warning (LDW), lane change warning (LCW), following distance indication (FDI), forward collision warning (FCW), rear cross traffic alert (RCTA), and adaptive cruise control (ACC). Furthermore, AR can assist drivers with cognitive or visual impairments when navigating under hazardous conditions, like nighttime driving [43]. Nonetheless, these in-car technologies have limitations. They might divert drivers' attention between the AR visual alerts and actual road conditions, which studies suggest cannot be processed simultaneously. There's a risk of drivers becoming overly dependent on the AR system, potentially overlooking essential cues. This overreliance is notably prevalent among younger drivers [44].

TABLE III: Summary of AR applications types and mediums in the automotive industry.

Type	HUD	HHD	HMD
In-car	X		
Assembly			X
Maintenance		X	X
Training		X	X
Prototyping			X

B. Authoring of AR instructions

Authoring and generating instructions are significant barriers hampering the widespread adoption of AR guides within Industry 4.0. This challenge arises from the limited scalability and adaptability inherent in developing AR Work Instruction

(ARWI) applications, as highlighted in [45]. The involved process encompasses several stages, such as the creation of trained object recognition models, database enrichment with textual, 2D, and 3D elements, crafting the AR environment by mapping database objects to their spatial positions and animating them, and culminating in the application's construction [33]. As a result, the tight coupling of the instructions to the numerous device models and their complexity explains why their authoring is a mostly manual task. Consequently, recent research to improve the process is discussed in this section.

Efforts were exerted to automate various phases of the process. Most reviewed studies centred their automation approach on generating a step-by-step procedure from a video stream showing an expert conducting the task. Augmented reality via expert demonstration authoring (AREDA) [46], along with systems introduced in [47–49], employed detection tools like external cameras and head-mounted displays (HMDs) to identify and trace both tools and the actions executed. In some cases, other techniques were used to increase the operation's reliability, such as voice commands. The authors consistently aimed to establish a fast, simple, scalable, and reliable authoring system.

C. Development Platforms

AR development platforms exhibit varying features, compatibility, and tracking methods. Table IV displays notable AR platforms used in automotive applications. Google's *ARCore* is designed for Android-based AR experiences but lacks comprehensive 3D object detection. Integration with Mediapipe and TensorFlow is possible, but often insufficient for complex 3D automotive components. Apple's *ARKit*, tailored for iOS, excels in 3D vision, using LiDAR sensors in newer devices for precise 3D scanning and detection, but with a caveat: tracking is limited to pre-scanned models.

Wikitude, a proprietary AR SDK, supports Android and iOS, offering advanced features like cloud model recognition and an AR Studio for model management. However, it's not open-source. *Vuforia* emphasizes computer vision for tracking and integrates well with Unity, showcasing unique ”VuMarks.”

Finally, *Unity* provides broad AR support and integrates with ARCore, ARKit, and Vuforia, ideal for simulations and prototyping but has a steep learning curve. Similarly, the *Unreal* engine offers high-quality visuals suitable for professional simulations but demands in-depth mastery.

TABLE IV: Key AR Platforms for automotive applications

	ARCore	ARKit	Vuforia	Wikitude
2D Image Tracking	•	•	•	•
3D Object Tracking	○	○	•	•
Languages	Java, Kotlin	Swift, Obj-C	iOS, Android, UWP, Unity	Android, iOS, JavaScript, Unity C#, Flutter, + others
Cross-platform	No	No	Yes	Best
License	Open Source	Open Source	Commercial	Commercial

V. Conclusion and Future Work

Augmented Reality (AR) is reshaping the automotive industry. Its most prominent applications are in 'in-car' systems like head-up displays (HUDs), assembly lines, maintenance, and training. Beyond its immediate applications, AR holds the potential to catalyze further digitization within the automotive ecosystem. Car manufacturers, Original Equipment Manufacturers (OEMs), and equipment producers, for example, can leverage AR to replace traditional printed user manuals and repair instructions. This shift not only enhances operational efficiency but also reduces costs and positive environmental impact. While AR has the potential to enhance efficiency and safety, its design can also pose risks if not executed properly. Major hurdles must be addressed, particularly in developing AR work instructions.

A key hurdle for Augmented Reality (AR) is ensuring a seamless and lifelike user experience without causing user strain or discomfort. Current AR displays and development platforms still pose barriers to the broader adoption of augmented reality technology. However, more cost-effective and lightweight displays—especially stand-alone HMDs with their own open development platforms—could revolutionize the AR landscape. Such platforms would simplify the process for developers to create and upload applications to AR app stores, thereby significantly accelerating the rate of AR adoption. This demands sophisticated hardware capable of handling the computational aspects of AR. However, many devices may lack the required processing power, battery longevity, or sensor capabilities. Additionally, high costs evidenced by premium devices like Apple's Vision Pro and Microsoft's HoloLens 2, restrict AR's widespread consumer adoption. Mitigating these challenges could involve optimizing applications using Unity or Unreal Engine software and offloading computational tasks through cloud services or edge computing. The advent of AR in the automotive sector has unlimited potential applications and impacts. Despite considerable advances, several avenues still need deeper exploration.

- Comprehensive safety evaluations for AR in various driving conditions.
- Development of adaptive AR systems to minimize driver distraction.
- Optimizing assembly and maintenance tasks using machine learning algorithms.
- Exploring multi-user AR for remote collaboration.
- Creating user-friendly authoring tools for easier AR application development.
- Addressing ethics and privacy concerns related to AR technology.

The scope for AR in the automotive industry is vast, with technological, ethical, and practical challenges awaiting solutions. Further research in these avenues not only promises to enhance the capabilities of AR but also poses an opportunity to revolutionize the automotive industry at large.

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