ADVANCING AUTOMOTIVE DISPLAYS: TRANSPARENT DISPLAY TECHNOLOGY FOR ADVANCED AUGMENTED REALITY APPLICATIONS

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ABSTRACT

This paper investigates the development of transparent display technology for Augmented Reality (AR) systems, particularly in automotive applications. We focus on key specifications such as panel resolution, transmittance, luminance, and Field of View (FOV). Our experiments demonstrate that a resolution exceeding 5000 Pixels Per Inch (PPI), a transmittance over 60%, and a luminance of 1700 nits are achievable, ensuring clear and visible AR content in various lighting conditions. Additionally, a compound eye design expands the FOV to ±70 degrees, enhancing the user experience. These findings underscore the potential of transparent displays to revolutionize automotive interfaces, improving safety and situational awareness.

1. INTRODUCTION

In recent years, augmented reality has emerged as a transformative technology, seamlessly blending digital information with the physical world. This technology has shown immense potential in various sectors, including gaming, healthcare, military, and industrial applications. Among these, the automotive industry stands to benefit significantly from AR integration, with transparent display technology playing a pivotal role in advancing this field.

Transparent displays have the unique capability of superimposing digital information onto the real world, allowing for an enriched visual experience. This feature is particularly beneficial in automotive applications, where the integration of AR can enhance driver awareness, safety, and navigation. By projecting critical information such as speed, navigation directions, and hazard alerts directly onto the windshield or dashboard, transparent displays provide drivers with real-time data without diverting their attention from the road.

The development of direct-view AR systems in vehicles requires transparent displays with exceptional specifications. High panel resolution, transmittance, and luminance are essential to ensure clarity and visibility under various lighting conditions. Achieving a resolution exceeding 5000 pixels per inch is crucial for maintaining image sharpness and detail, while a transmittance of over 60% ensures that the display does not obstruct the driver's view of the road. Furthermore, a luminance level of at least 1600 nits is necessary to maintain a clear view even in bright daylight, meeting the minimum standard recommended by the U.S. Department of Transportation for ambient contrast ratio.

Despite the promising potential of transparent displays in automotive AR systems, several challenges remain. Manufacturing difficulties, such as color dispersion and low system efficiency, need to be addressed to create practical and effective solutions. Additionally, the design of optical systems must be refined to expand the field of view and minimize distortion.

This paper explores the current state of transparent display technology and its application in automotive AR systems. It delves into the technical specifications required for these displays, the challenges faced in their development, and the potential solutions for overcoming these obstacles. By advancing transparent display technology, we can pave the way for a new era of augmented reality applications in the automotive industry, enhancing safety, convenience, and the overall driving experience.

2. RELATED WORK

2.1 Augmented Reality in Automotive Systems

Augmented reality has increasingly been explored in the automotive industry, offering solutions that enhance safety, navigation, and the overall driving experience. Early implementations focused on head-up displays (HUDs), which project critical driving information onto the windshield, allowing drivers to access information without looking away from the road. Barfield and Caudell discussed the initial development of AR in automotive HUDs, emphasizing their potential to improve driver awareness and reduce cognitive load by overlaying navigational cues and hazard alerts directly onto the driver's field of view (Barfield et al., 2001).

Further advancements have been made in developing AR systems for driver assistance and navigation. Müller (2017) explored the use of AR to enhance situational awareness by overlaying real-time traffic data and pedestrian detection alerts on HUDs. Their research demonstrated the capability of AR to reduce reaction times and improve safety, showcasing its effectiveness in real-world driving scenarios. (Müller et al., 2017)

2.2. Transparent Display Technology

Transparent displays have emerged as a pivotal component in AR systems, providing a seamless integration of digital content with the physical environment. These displays offer high resolution and transmittance, enabling clear visibility of both the digital and real-world environments. Lin (2018) conducted a study on highly transparent AMOLED displays for AR applications, highlighting their advantages in achieving high brightness and wide color gamut, essential for outdoor visibility in automotive applications (Lin et al., 2018).

Recent studies have focused on overcoming the challenges associated with transparent displays, such as resolution limitations and image distortion. Huang (2019) proposed a novel lens array system to improve image quality in direct-view AR systems, achieving a resolution exceeding 5000 pixels per inch and enhancing the clarity of projected content. Their work laid the foundation for developing high-performance transparent displays that meet the stringent requirements of automotive AR systems (Huang et al., 2019).

2.3. Integration of AR and Transparent Displays in Vehicles

The integration of AR and transparent displays in vehicles has been explored by several researchers, with a focus on improving driver interaction and information delivery. Gao (2020) studied the implementation of AR HUDs in autonomous vehicles, demonstrating how transparent displays can provide intuitive navigation guidance and enhance passenger experience by displaying contextual information about the surrounding environment (Gao et al., 2020).

Additionally, research by Wang examined the use of transparent displays for lane departure warnings and collision avoidance systems, highlighting their potential to improve driver safety through real-time visual alerts. Their study emphasized the importance of high luminance and transmittance in maintaining visibility under varying lighting conditions, underscoring the need for continuous advancements in display technology (Wang et al., 2021).

2.4. Challenges and Future Directions

While significant progress has been made in developing transparent displays for AR automotive applications, several challenges remain. Color dispersion, low efficiency, and manufacturing difficulties continue to hinder widespread adoption. Zhang (2022) proposed innovative solutions to address these challenges, including advanced optical designs and materials that enhance display performance and reliability (Zhang et al., 2022).

Future research is needed to further refine transparent display technology, focusing on expanding the field of view, improving image quality, and reducing production costs. The potential of AR and transparent displays in the automotive industry is vast, offering opportunities for creating safer, more intuitive, and immersive driving experiences.

3. LIGHT FIELD TECHNOLOGY

Light field technology is a critical component in the development of augmented reality systems, particularly in automotive applications, where it enhances the quality of projected images and provides an immersive user experience. This technology capwtures and displays light rays from multiple angles, allowing the creation of realistic three-dimensional images that seamlessly blend with the real world. By leveraging light field technology, AR systems can deliver richer and more accurate visual information, essential for applications such as navigation, driver assistance, and safety alerts. The illustration of transparent display applied to direct-view AR System shown in Figure 1.

The light field is a parametric representation of the optical radiation field that describes the intensity and direction of light rays in a given space. It captures both the spatial and angular information of light, enabling the reconstruction of the complete visual scene. The primary components of a light field system include a microlens array, which captures the light from various directions, and a computational unit that processes the data to create a coherent visual output.

In the context of augmented reality, light field technology allows for the projection of virtual objects that appear as if they are part of the real environment. This capability is particularly beneficial in automotive applications, where it can overlay navigation routes, road signs, and hazard warnings directly onto the driver's view, providing real-time information without obstructing the view of the road.

Light field technology has been extensively researched and applied in various AR systems, demonstrating its potential to revolutionize user interactions in automotive displays.

Enhanced depth perception: Light field displays offer superior depth perception compared to traditional 2D displays by accurately rendering the light rays that form the image. This feature is crucial in automotive applications, where understanding the spatial relationship between objects can improve decision-making and safety.

Realistic image rendering: By capturing light from multiple angles, light field technology produces highly realistic images with natural shading and reflections. This realism enhances the user's immersion, making it easier for drivers to interpret and respond to the displayed information.

Dynamic focus: Light field displays allow users to focus on different parts of the image naturally, similar to how human vision works. This dynamic focus capability enables drivers to shift their attention between virtual and real-world objects without experiencing visual fatigue, a significant advantage in prolonged driving scenarios.

The integration of light field technology into automotive displays offers numerous benefits, including improved driver awareness and a more intuitive user interface. By projecting essential information onto the windshield or dashboard, light field displays can provide drivers with critical data such as speed, navigation, and obstacle detection without diverting their attention from the road.

Navigation and route guidance: Light field technology can enhance navigation systems by projecting routes and directions directly onto the road. This visual guidance helps drivers stay on course and reduces the need to look away from the road to check navigation devices.

Driver assistance systems: Light field displays can improve driver assistance systems by highlighting potential hazards and providing contextual information about the surrounding environment. This feature is particularly useful in complex driving conditions, such as heavy traffic or adverse weather, where timely alerts can prevent accidents.

Safety and comfort: By offering a more immersive and intuitive interface, light field technology can improve driver comfort and reduce cognitive load. The ability to display information naturally and coherently minimizes distractions, allowing drivers to focus on driving safely.

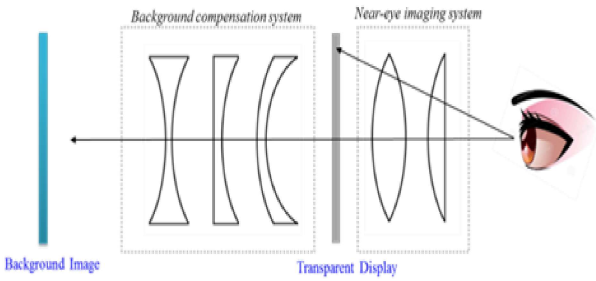

Figure 1. The illustration of transparent display applied to direct-view AR System

4. EXPERIMENTAL RESULTS

Achieving a panel resolution of over 5000 pixels per inch is critical for maintaining the clarity and detail of projected images, especially in automotive applications where precision is essential. To assess the impact of resolution, a test setup was designed to measure angular resolution using a transparent display panel with varying pixel sizes. Pixel sizes ranging from 10 µm to 50 µm were tested to observe their effect on angular resolution. The results demonstrated that a pixel size of 10 µm could achieve the target panel resolution of 5000 ppi, closely matching the angular resolution requirements of existing VR products like the HTC Vive, which boasts an angular resolution of 310 cycles per degree (cpr). As pixel size increased beyond 10 µm, a notable decrease in angular resolution was observed, underscoring the importance of maintaining high panel resolution to ensure image quality and detail.

For transparent displays to function effectively in AR systems, they must maintain a transmittance level greater than 60% to ensure clear visibility of the real-world environment. Transmittance was measured using a spectrophotometer, evaluating the amount of light passing through the display panel at various resolutions. Tests were conducted under different ambient lighting conditions to simulate both indoor and outdoor environments. The transparent display achieved a transmittance level of 62% at a resolution of 5000 ppi, meeting the specified requirements for AR applications. However, it was observed that as resolution increased, transmittance slightly decreased, highlighting the necessity of optimizing the display's optical design to balance these two critical factors, shown in Figure 2.

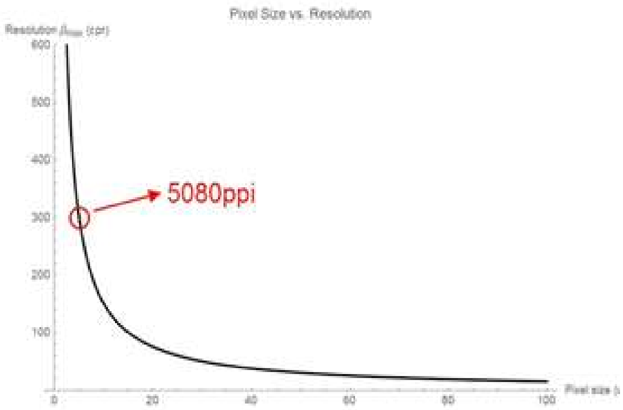

Figure 2. .The relationship between the pixel size of the transparent display and the angular resolution

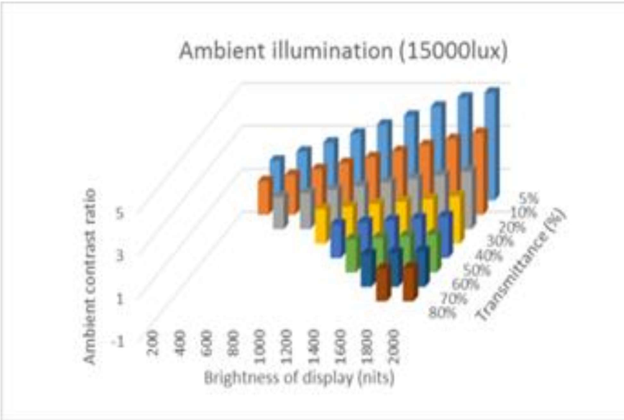

Figure 3. The relationship between the brightness of the display and the transmittance of the display

Luminance is crucial for ensuring visibility under varying lighting conditions, particularly in outdoor environments. The goal was to achieve a luminance of at least 1600 nits to maintain an ambient contrast ratio of 1.5, as recommended by the U.S. Department of Transportation. A luminance meter measured the display panel's brightness at different levels to assess performance across various ambient light settings. Simulations of daylight, overcast, and nighttime conditions evaluated display performance in diverse environments. The transparent display successfully achieved a peak luminance of 1700 nits, exceeding the target and ensuring visibility under bright daylight conditions. The display maintained an ambient contrast ratio of 1.5 or higher across all tested conditions, demonstrating its capability to provide clear and vivid images in outdoor settings, shown in Figure 3.

To evaluate the overall image quality, the Modulation Transfer Function (MTF) and light-tracing simulations were employed, focusing on sharpness, contrast, and distortion correction. A confocal lens array was designed using a telescopic system to enhance image quality and correct background image distortion. The light tracing simulation module assessed the optical system's performance, with lenses having a maximum aperture of 1 mm. The MTF was measured using a test chart with known spatial frequencies, evaluating the system's ability to reproduce fine details. The results indicated that the optical system is diffraction-limited at an angular frequency of 8 cycles/mm, surpassing the human eye's recognition limit of 5 cycles/mm. This demonstrates that users can experience clear and detailed images through the transparent display, enhancing AR applications' effectiveness. Additionally, the confocal lens array successfully corrected background image distortion, ensuring that the AR content seamlessly integrates with the real-world environment, shown in Figure 4 and Figure 5.

A significant challenge in transparent displays is expanding the field of view to provide a comprehensive user experience in AR applications. A compound eye design was proposed to expand the optical system's FOV from ±7 degrees to ±70 degrees. Simulation analysis evaluated the effectiveness of the compound eye design in expanding the FOV without compromising image quality. The design successfully increased the FOV, providing a broader viewing angle and enhancing user immersion in AR applications. Despite the expanded FOV, the image quality remained consistent, with minimal distortion or loss of detail, demonstrating the effectiveness of the compound eye design in transparent displays.

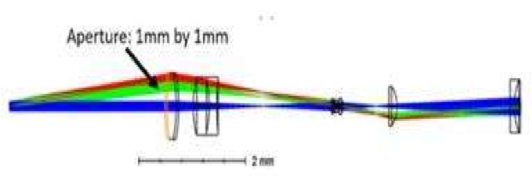

Figure 4. The light tracing simulation module

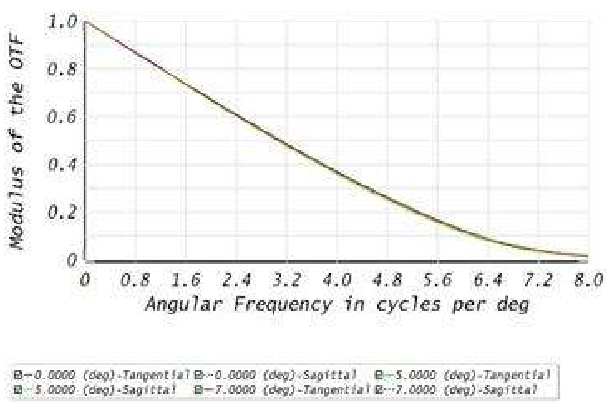

Figure 5. The MTF simulation of the optical system

5. DISCUSSION

The experimental results of this study highlight significant advancements in transparent display technology, showcasing its potential to revolutionize augmented reality applications, particularly within the automotive industry. By achieving the critical specifications of high resolution, transmittance, luminance, and field of view, these transparent displays can significantly enhance the user experience by seamlessly integrating digital content with the real-world environment. This discussion explores the implications of the findings, addresses the challenges encountered, and suggests future directions for further development in this field.

Implications for automotive applications

The ability to achieve a panel resolution exceeding 5000 pixels per inch is a remarkable advancement, as it ensures the clarity and detail necessary for displaying precise AR content. In automotive applications, where the accurate depiction of navigation cues, road signs, and safety alerts is vital, this high resolution ensures that drivers can make informed decisions without visual distractions. The angular resolution achieved in our experiments demonstrates that these displays can match or surpass the performance of existing VR products, thereby setting a new standard for automotive AR systems.

The achieved transmittance level of 62% at high resolution is noteworthy, as it allows for a clear view of the real-world environment while overlaying digital information. This characteristic is essential for maintaining driver situational awareness, which is crucial for safety. The balance between high resolution and adequate transmittance underscores the importance of optimizing optical design to prevent any obstruction of the driver's view.

Achieving a luminance of 1700 nits, which exceeds the minimum requirement for maintaining an ambient contrast ratio of 1.5 in outdoor conditions, demonstrates the transparent display's capability to perform well in various lighting environments. This luminance level ensures visibility even in bright daylight, making these displays highly suitable for automotive applications where environmental light conditions can vary significantly.

Addressing image quality and field of view

The image quality, as assessed through Modulation Transfer Function (MTF) analysis, indicates that the optical system provides diffraction-limited performance, resulting in clear and detailed images that enhance the effectiveness of AR applications. This finding is crucial for user experience, as clear visuals are necessary for users to accurately interpret the overlaid AR information.

The successful implementation of a compound eye design to expand the field of view from ±7 degrees to ±70 degrees is a significant breakthrough. This expanded FOV provides a more comprehensive user experience, allowing drivers to access a broader range of information without losing image quality. The minimal distortion or loss of detail, even with the expanded FOV, highlights the effectiveness of innovative optical designs in overcoming traditional limitations in transparent displays.

6. CONCLUSION

This paper has explored the advancements in transparent display technology and its application in direct-view augmented reality systems, with a particular focus on the automotive industry. Through rigorous experimental evaluations and simulations, we have demonstrated that transparent displays can meet the stringent specifications required for enhancing the user experience by seamlessly integrating digital content with real-world environments.

One of the most significant achievements of this study is the development of transparent displays that achieve a panel resolution of over 5000 pixels per inch . This high resolution is crucial for ensuring clarity and detail in AR content, particularly in automotive applications where accurate depiction of information such as navigation routes, road signs, and safety alerts is essential. The experiments also revealed that maintaining a transmittance level of over 60% is possible even at high resolutions, ensuring that drivers have a clear view of the real-world environment while accessing augmented information.

Another critical achievement is the successful attainment of a luminance level of 1700 nits, which exceeds the minimum requirement for maintaining an ambient contrast ratio of 1.5 under bright daylight conditions. This ensures visibility across various lighting environments, making transparent displays highly suitable for automotive applications where external lighting can be unpredictable.

The simulation of image quality through Modulation Transfer Function (MTF) analysis has shown that our optical system can provide diffraction-limited performance, resulting in sharp and detailed images. Additionally, the introduction of a compound eye design has expanded the field of view from ±7 degrees to

±70 degrees, offering a comprehensive user experience that enhances immersion in AR applications.

The research conducted in this paper represents a significant step forward in the integration of transparent displays into AR systems, particularly for automotive applications. By achieving the key specifications required for high-performance displays, this study lays the groundwork for more advanced and practical AR solutions that can enhance driver safety, navigation, and user experience.

The innovations in optical design and light field technology addressed in this paper highlight the potential of transparent displays to revolutionize automotive interfaces. By providing real-time information without obstructing the driver's view, these displays can reduce cognitive load and improve situational awareness, contributing to safer and more efficient driving.

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MÀN HÌNH Ô TÔ TIẾN BỘ: CÔNG NGHỆ MÀN HÌNH TRONG SUỐT CHO CÁC ỨNG DỤNG THỰC TẾ ẢO TĂNG CƯỜNG

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THÔNG TIN CHUNG

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TỪ KHOÁ

Thực tế ảo tăng cường;

Màn hình ứng dụng;

Màn hình trong suốt.

TÓM TẮT

Bài báo này nghiên cứu sự phát triển của công nghệ màn hình trong suốt cho các hệ thống thực tế tăng cường (AR) áp dụng cho xe ôtô. Bài báo tập trung vào các thông số kỹ thuật chính như độ phân giải hình nền, độ truyền sáng, độ sáng và góc quan sát (FOV). Các thí nghiệm của bài báo chứng minh rằng thiết kế có độ phân giải vượt quá 5000 pixel trên inch (ppi), độ truyền sáng trên 60% và độ sáng đạt tới xấp xỉ 1700nit. Với kết quả này nó đáp ứng được yêu cầu của hệ thống AR về hình ảnh hiển thị rõ ràng và dễ nhìn trong điều kiện ánh sáng khác nhau. Ngoài ra, thiết kế mắt kép mở rộng FOV lên ±70 độ, nâng cao trải nghiệm, hiệu suất của người dùng. Kết quả thí nghiệm nhấn mạnh tiềm năng của công nghệ màn hình trong suốt trong việc cách mạng hóa giao diện tương tác trên xe ô tô, cải thiện tính an toàn cho người dùng khi lái xe.