IJARCCE ISSN (O) 2278-1021, ISSN (P) 2319-5940

International Journal of Advanced Research in Computer and Communication Engineering

Impact Factor 8.471 ⁙ Peer-reviewed & Refereed journal ⁙ Vol. 15, Issue 6, June 2026

DOI: 10.17148/IJARCCE.2026.15631

Intelligent Accessibility Middleware Using AI for Dynamic Inclusive User Interfaces

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Abstract- Artificial Intelligence (AI) is increasingly being integrated into accessibility systems to support adaptive and inclusive user interfaces for users with diverse accessibility needs. This paper reviews recent research on AI-driven accessibility middleware and adaptive interface technologies published between 2015 and 2026. The study examines the use of machine learning, natural language processing, computer vision, reinforcement learning, and generative AI in improving digital accessibility and interface personalization. Existing approaches related to browser-based accessibility tools, automated remediation systems, adaptive user interfaces, and behavioral analytics are comparatively analyzed. The paper also discusses the significance of accessibility standards such as WCAG, WAI-ARIA, and ADA in the development of intelligent accessibility solutions. Current research trends, evaluation methods, implementation challenges, and ethical concerns associated with AI-based accessibility systems are identified. The review indicates that AI technologies have improved automation and personalization capabilities in accessibility support; however, challenges related to cognitive accessibility, transparency, fairness, and real-time adaptation continue to require further research. The paper concludes by outlining future directions for the development of reliable, user-centered, and standards-compliant accessibility middleware systems.

Keywords: Accessibility, adaptive user interfaces, artificial intelligence, assistive technology, middleware systems, inclusive design, natural language processing, computer vision, WCAG.

I. INTRODUCTION

Digital accessibility refers to the design of digital systems and interfaces that can be effectively used by individuals with diverse physical, sensory, cognitive, and motor abilities [1]. Accessibility standards such as the Web Content Accessibility Guidelines (WCAG), WAI-ARIA, and the Americans with Disabilities Act (ADA) have established important principles for creating inclusive digital experiences [2],[4]. Despite these guidelines, many modern web and mobile interfaces continue to present accessibility barriers due to dynamic content rendering, complex interaction models, inconsistent semantic structures, and limited accessibility testing during development.

Recent advances in Artificial Intelligence (AI) have introduced new possibilities for improving accessibility in digital environments. AI-based systems are increasingly being used to support automatic content generation, interface adaptation, speech and image processing, accessibility remediation, and personalized user interaction. Technologies such as machine learning, natural language processing, computer vision, and reinforcement learning are now being explored to develop adaptive interfaces capable of responding to different user requirements in real time [5], [6].

Research in this area has expanded significantly in recent years, particularly with the emergence of intelligent accessibility tools and AI-assisted interface personalization. Existing studies have examined adaptive user interfaces, AIdriven assistive technologies, browser-based accessibility tools, and automated accessibility evaluation systems. However, many of these studies focus on specific technologies or isolated accessibility solutions rather than integrated middleware frameworks that dynamically support accessibility across multiple interface environments.

This review focuses on AI-driven accessibility middleware and adaptive user interface systems designed to improve inclusive interaction in modern digital platforms. The paper comparatively analyzes existing approaches, major AI techniques, accessibility standards, evaluation methods, current research trends, and implementation challenges. In addition, the review identifies important research gaps related to cognitive accessibility, ethical AI integration, personalization, and real-time adaptive interaction. The objective of this study is to provide a structured overview of current developments while highlighting future directions for intelligent and standards-compliant accessibility systems.

II. LITERATURE SURVEY / RELATED WORK

Recent research has increasingly explored the application of Artificial Intelligence (AI) in digital accessibility, adaptive interfaces, and assistive technologies. Several review and mapping studies have examined how AI techniques are being integrated into accessibility-focused systems to improve usability and interface personalization for users with diverse needs.

Kristić et al. conducted a systematic literature review on machine learning approaches for adaptive accessible user interfaces and observed that supervised learning methods remain the dominant technique in accessibility-related applications [5]. Their analysis also indicated that adaptive interfaces are more commonly implemented than fully intelligent autonomous systems, particularly in mobile-based environments. The study highlighted the growing interest in personalization mechanisms but noted the limited use of reinforcement learning and generative AI models in accessibility adaptation.

Similarly, Campoverde-Molina and Luján-Mora presented a systematic mapping study focused on AI applications in web accessibility [6]. Their work identified increasing adoption of AI-assisted remediation tools, automated alt-text generation, accessibility evaluation systems, and large language model-based interface support. The study emphasized that recent accessibility research is gradually shifting from rule-based correction systems toward more context-aware and intelligent approaches.

Research on AI-driven assistive technologies has also expanded beyond traditional accessibility support. Bhavana et al. reviewed AI applications across visual, auditory, cognitive, and motor impairment domains and proposed an Accessibility Impact Score (AIS) framework for evaluating assistive systems [7]. Their findings suggested that AI-enhanced assistive devices, particularly computer vision-based systems and adaptive wearable technologies, can improve user interaction and accessibility performance compared to conventional assistive solutions.

From a human-computer interaction perspective, Xu et al. investigated adaptive human-AI interaction models designed for neurodivergent users, including individuals with autism spectrum disorder, ADHD, and dyslexia [8]. The study discussed the importance of participatory design, personalization, and ethical AI practices in the development of inclusive systems. It also pointed out that many existing studies lack long-term user evaluation and standardized assessment strategies.

In addition to interface adaptation and assistive technologies, recent studies have examined accessibility-focused AI evaluation frameworks. Waters proposed an AI Testing, Evaluation, Verification, and Validation (TEVV) framework aimed at improving fairness, usability, and accessibility assessment in intelligent systems [9]. The framework highlighted the need for systematic validation processes to identify accessibility barriers, bias, and inconsistencies in AI-driven applications.

Although existing literature demonstrates significant progress in AI-assisted accessibility research, several limitations remain evident. Many studies focus on specific accessibility tasks such as alt-text generation or interface customization rather than integrated middleware architectures capable of supporting dynamic accessibility across platforms. In addition, cognitive accessibility, real-time personalization, and explainable AI-based adaptation remain comparatively underexplored. These limitations indicate the need for more comprehensive and user-centered accessibility frameworks, which motivates the focus of the present review.

TABLE I COMPARATIVE SUMMARY OF RECENT AI-BASED ACCESSIBILITY RESEARCH

Study	Focus	Contribution	Limitation
Kristić et al.	Adaptive UI	ML-based accessibility review	Limited RL analysis
Campoverde-Molina et al.	Web accessibility	AI accessibility mapping	Limited implementation study
Bhavana et al.	Assistive systems	AIS evaluation framework	Broad scope
Xu et al.	Neurodiversity	Inclusive AI interaction study	Limited longitudinal evaluation
Waters	Accessibility evaluation	TEVV framework	Mostly conceptual

Table I summarizes recent AI-based accessibility studies and compares their focus areas, contributions, and limitations. The comparison indicates that most existing research emphasizes adaptive interfaces and accessibility evaluation, while comparatively fewer studies address real-time personalization and cognitive accessibility support.

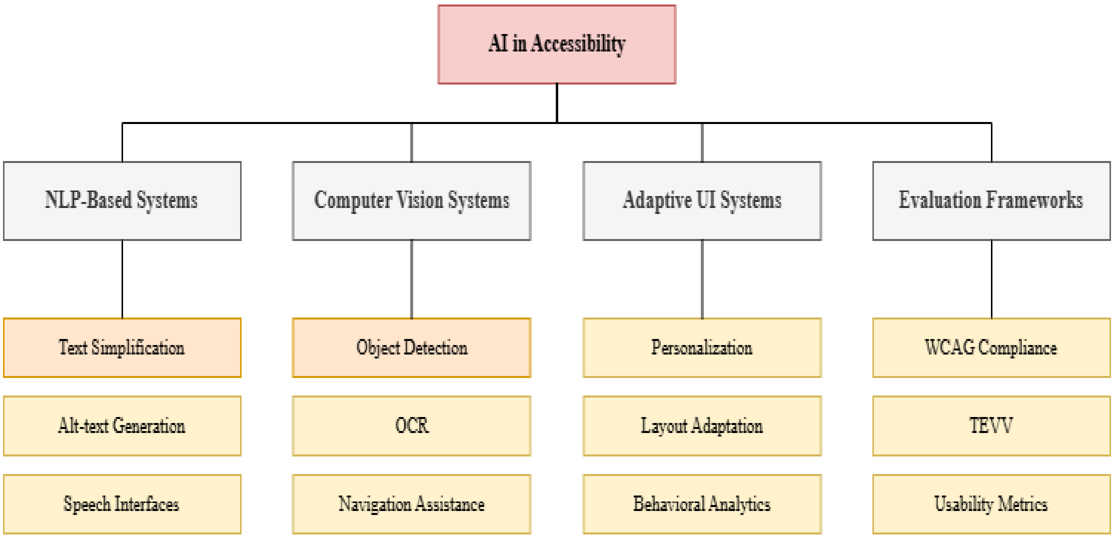

Fig. 2. Classification of AI applications in accessibility research.

Figure 2 illustrates the major categories of AI techniques currently used in accessibility research, including NLP-based systems, computer vision applications, adaptive interfaces, and accessibility evaluation frameworks.

III. GROWTH OF RESEARCH IN AI-BASED ACCESSIBILITY SYSTEMS

Research on AI-driven accessibility systems has expanded considerably during the last decade, particularly after 2020. Increasing awareness of digital inclusion, advancements in machine learning technologies, and growing regulatory emphasis on accessibility compliance have contributed to the rapid development of intelligent accessibility solutions. Recent studies indicate that accessibility research has gradually shifted from traditional rule-based assistive approaches toward adaptive and data-driven systems capable of dynamic interface personalization [5], [6].

Several literature reviews and mapping studies have highlighted this growth trend. Kristić et al. observed a noticeable increase in publications related to adaptive accessible user interfaces and machine learning-based accessibility applications in recent years [5]. Similarly, Campoverde-Molina and Luján-Mora identified a growing number of studies focused on AI-supported web accessibility, automated remediation systems, and large language model-based accessibility enhancement techniques [6].

The expansion of AI capabilities such as natural language processing, computer vision, speech recognition, and generative AI has further accelerated research activity in this field. Industry initiatives including Microsoft's AI for Accessibility program and accessibility-focused development frameworks have also encouraged wider adoption of intelligent accessibility technologies. In addition, the increased dependence on digital platforms during and after the COVID-19 pandemic emphasized the importance of accessible digital services for education, healthcare, communication, and remote work environments.

Recent research trends also demonstrate a gradual transition toward multimodal accessibility systems capable of combining text, speech, image processing, and behavioral adaptation within unified frameworks. At the same time, researchers have started exploring personalized accessibility support through reinforcement learning, adaptive user modeling, and AI-assisted interface generation. These developments indicate that accessibility research is evolving beyond static compliance checking toward intelligent and context-aware accessibility ecosystems.

Figure 3 presents an approximate trend of research publications related to AI-driven accessibility systems between 2010 and 2022 based on observations reported in recent review and mapping studies.

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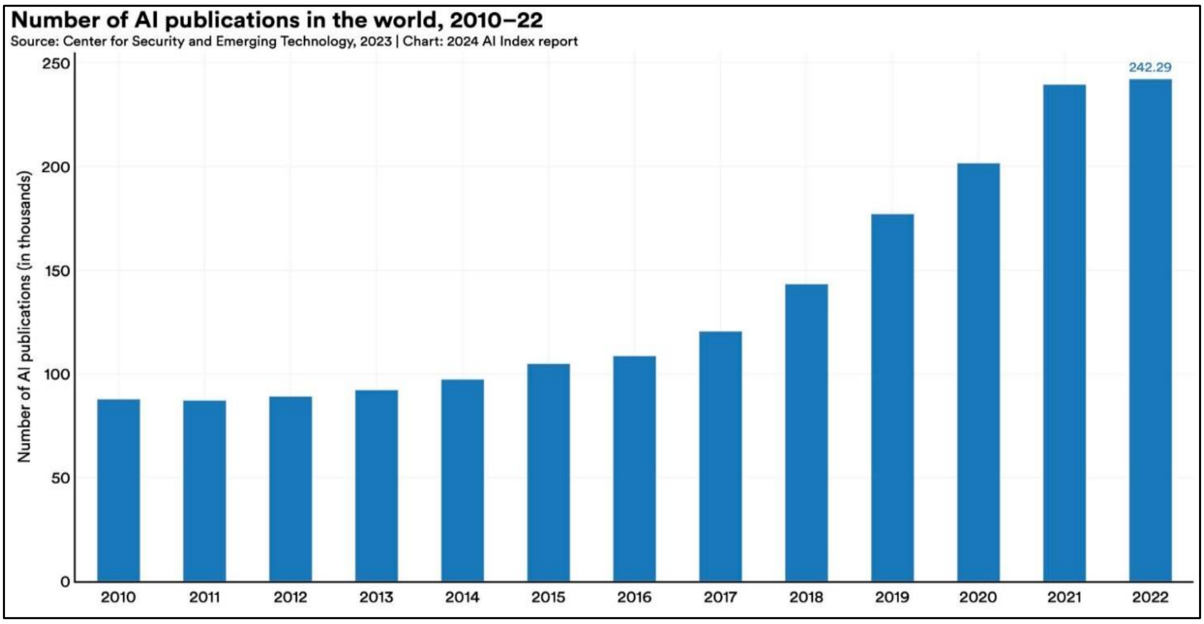

Fig.3: Research trend in AI-based accessibility studies from 2015 to 2025.

The increasing number of publications indicates growing academic and industrial interest in intelligent accessibility technologies. The trend also reflects the broader integration of AI techniques into user-centered interface design and digital inclusion research.

IV. ACCESSIBILITY CHALLENGES IN MODERN WEB INTERFACES

Modern web applications increasingly rely on dynamic content rendering, client-side scripting, multimedia integration, and interactive user interface components. While these technologies improve usability and responsiveness for many users, they also introduce significant accessibility challenges for individuals who depend on assistive technologies such as screen readers, keyboard navigation systems, and voice interaction tools.

Single-Page Applications (SPAs) developed using frameworks such as React, Angular, and Vue frequently update interface content dynamically without fully communicating these changes to assistive technologies. As a result, users may experience difficulties related to focus management, content announcement, navigation continuity, and semantic interpretation [6]. Accessibility issues are particularly common in dynamically generated menus, modal dialogs, interactive dashboards, and form validation systems.

Visual accessibility barriers also remain widespread across modern digital platforms. Poor color contrast, reliance on color-only indicators, inaccessible typography, and missing alternative text for images continue to affect users with low vision, blindness, and color-vision deficiencies [1], [7]. Similarly, many interfaces still provide limited keyboard accessibility for interactive elements, making navigation difficult for users with motor impairments.

In addition to technical accessibility limitations, cognitive accessibility challenges have gained increasing attention in recent years. Complex layouts, excessive information density, inconsistent navigation structures, and rapidly changing content may create difficulties for neurodivergent users and individuals with cognitive disabilities. Traditional ccessibility guidelines provide important compliance standards; however, they often offer limited support for dynamic personalization and context-aware adaptation.

Recent accessibility audits have shown that a large proportion of public web pages continue to contain detectable accessibility violations related to WCAG compliance [9]. These findings indicate that accessibility cannot rely solely on static design rules and manual evaluation practices. Consequently, AI-driven middleware systems are being explored as a potential solution for providing real-time accessibility adaptation, automated remediation, and personalized interface support based on user interaction context and accessibility requirements.

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TABLE II COMMON ACCESSIBILITY CHALLENGES IN MODERN WEB INTERFACES

Challenge	Affected Users	Typical Issue	Possible AI-Based Support
Poor color contrast	Low-vision users	Inaccessible visual elements	Automatic contrast adjustment
Missing alt-text	Blind users	Unreadable image content	AI-generated image descriptions
Keyboard inaccessibility	Motor-impaired users	Navigation difficulty	Adaptive keyboard support
Dynamic content updates	Screen reader users	Missing announcements	Intelligent content notification
Complex layouts	Cognitive users	Information overload	Personalized UI simplification

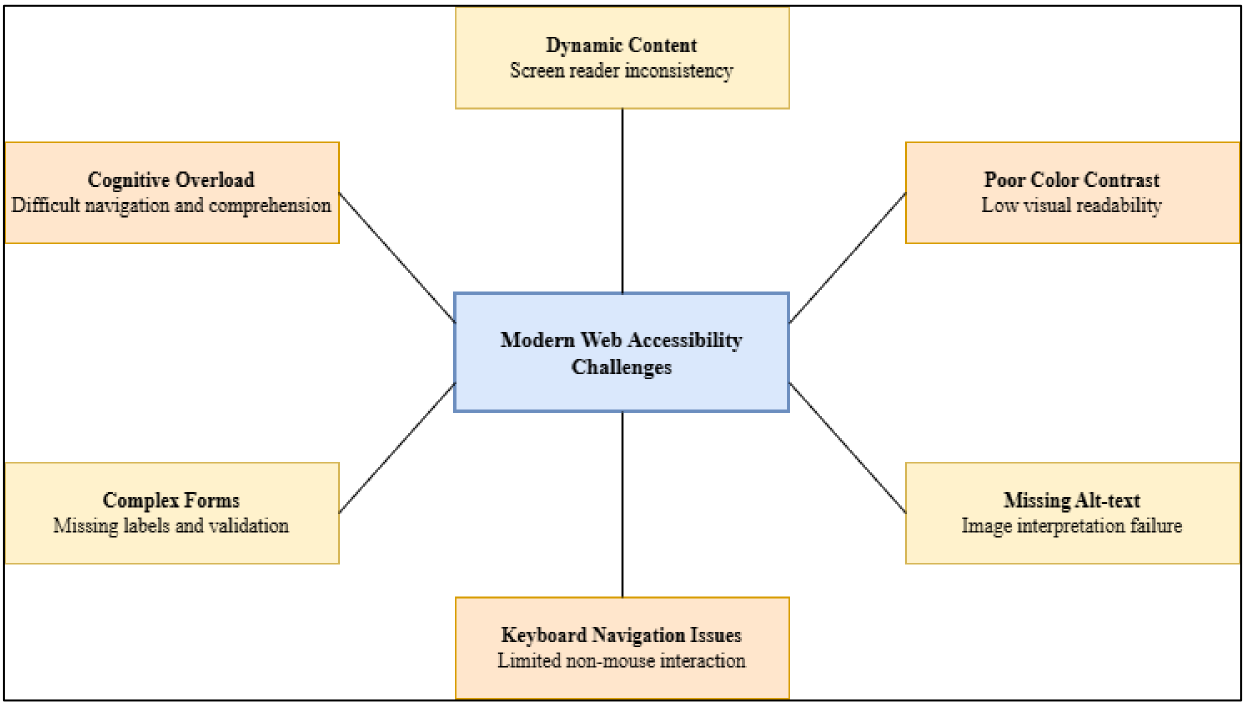

Fig-3: Major accessibility barriers in modern web interfaces.

The figure illustrates that accessibility challenges are not limited to visual impairments alone but also involve interaction, navigation, cognitive processing, and assistive technology compatibility.

V. EXISTING ACCESSIBILITY STANDARDS

AI-driven accessibility middleware and adaptive interface systems must operate within established accessibility standards and regulatory frameworks. These standards define the technical and usability requirements necessary for creating inclusive digital environments and serve as the foundation for accessibility evaluation and compliance.

The Web Content Accessibility Guidelines (WCAG), developed by the World Wide Web Consortium (W3C), remain the most widely recognized international accessibility standard [1]. WCAG is based on four core principles requiring digital content to be perceivable, operable, understandable, and robust (POUR). The guidelines define multiple testable success criteria across conformance levels A, AA, and AAA. Recent versions, including WCAG 2.1 and WCAG 2.2, place greater emphasis on mobile accessibility, cognitive accessibility, and adaptive interaction support. Many AI-based accessibility systems attempt to automate WCAG-related tasks such as alternative text generation, color contrast adjustment, accessibility testing, and interface remediation.

IJARCCE ISSN (O) 2278-1021, ISSN (P) 2319-5940

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In addition to WCAG, the WAI-ARIA specification provides semantic enhancement mechanisms for dynamic and interactive web components [2]. ARIA attributes allow developers to define interface roles, states, labels, and live regions that improve compatibility with assistive technologies. Accessibility middleware systems may use ARIA-based enhancements to improve screen reader interpretation, announce dynamic content updates, and provide semantic labeling for custom interface components that are not natively accessible.

Legal and policy frameworks also play a major role in shaping accessibility practices. In the United States, the Americans with Disabilities Act (ADA) establishes requirements for equal access to digital services and public-facing technologies [3]. Recent guidance from the U.S. Department of Justice has reinforced the expectation that websites and applications should comply with recognized accessibility standards such as WCAG. Similar accessibility regulations have also emerged internationally, including the European Accessibility Act and other digital inclusion policies.

Although existing standards provide important technical guidance, many accessibility challenges in modern dynamic interfaces still require intelligent adaptation and real-time support mechanisms. Consequently, AI-driven accessibility middleware is increasingly being explored as a complementary approach for improving accessibility compliance, personalized interaction, and adaptive usability across different user contexts.

VI. TECHNIQUES AND ADAPTIVE ACCESSIBILITY SYSTEMS

Artificial Intelligence (AI) techniques are increasingly being integrated into accessibility systems to support adaptive interaction, automated remediation, and personalized user experiences. Recent research demonstrates that machine learning, natural language processing, computer vision, and adaptive interface technologies can significantly improve accessibility support across modern digital platforms [5], [6].

Machine learning methods are widely used for accessibility prediction, interface adaptation, and accessibility evaluation tasks. Supervised learning models are commonly applied to identify accessibility issues, classify interface components, and recommend suitable interface adjustments based on user requirements [5]. In recent years, reinforcement learning and adaptive optimization techniques have also been explored for dynamically adjusting interface layouts and interaction patterns according to user behavior and accessibility feedback.

Natural language processing (NLP) techniques contribute to content-level accessibility improvements. Current applications include automated alt-text generation, text simplification, speech interaction support, and accessibility remediation for web content. Large language models (LLMs) are increasingly being used to identify WCAG-related issues and generate accessibility-aware interface modifications [12]. NLP-based systems can also support users with cognitive disabilities by simplifying complex textual information and improving content readability.

Computer vision techniques play an important role in supporting users with visual impairments. Deep learning-based image recognition and optical character recognition (OCR) systems enable object detection, scene understanding, image captioning, and navigation assistance. These technologies are commonly integrated into assistive devices and accessibility middleware to improve interaction with visual content [11].

Adaptive user interface systems further extend accessibility support by personalizing interface behavior according to user preferences, interaction patterns, and environmental conditions. Examples include automatic font adjustment, contrast enhancement, multimodal interaction support, and context-aware interface adaptation. Some accessibility middleware systems also analyze user interaction patterns to identify possible accessibility difficulties and provide real-time assistance.

Browser extensions and AI-driven middleware solutions represent practical deployment approaches for accessibility adaptation. These systems can dynamically modify webpage structure, improve semantic labeling, provide reading assistance, and automate accessibility corrections during runtime interaction. Although such approaches offer promising accessibility support, researchers have noted that automated accessibility overlays may not fully address all usability and compliance requirements without proper evaluation and user-centered design practices.

From a human-computer interaction perspective, accessibility systems must balance automation with usability, transparency, and user control. Adaptive systems should avoid disruptive interface modifications and instead provide understandable and consistent accessibility support mechanisms. Recent studies also emphasize that accessibility should be integrated into mainstream interface design processes rather than treated as a separate or optional feature [8].

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Overall, current research trends indicate a gradual shift toward multimodal and context-aware accessibility systems that combine language, vision, interaction analysis, and adaptive personalization to improve inclusive digital experiences.

TABLE IV AI TECHNIQUES USED IN ACCESSIBILITY SYSTEMS

AI Technique	**Major Accessibility Applications**	**Advantages**	**Limitations**
Machine Learning	Accessibility prediction, interface adaptation, user preference modeling	Supports personalized accessibility features	Requires quality training data
NLP / LLMs	Text simplification, alttext generation, accessibility remediation	Improves content accessibility and automation	May generate inaccurate or biased outputs
Computer Vision	Object detection, OCR, scene understanding, navigation assistance	Enhances support for visually impaired users	Performance varies across environments
Reinforcement Learning	Dynamic UI adaptation and accessibility optimization	Learns continuously from user interaction	Limited real-world deployment

VII. CHALLENGES AND LIMITATIONS

Despite significant progress in AI-driven accessibility systems, several technical, practical, and ethical challenges continue to limit their effectiveness and large-scale adoption. One of the major limitations is the uneven accessibility coverage provided by current AI solutions. Most existing systems primarily focus on visual accessibility tasks such as image captioning, object recognition, and screen-reader support, while cognitive, neurodiverse, and situational accessibility requirements remain comparatively underexplored.

Another major challenge involves the reliability and accuracy of AI-generated accessibility adaptations. Large language models and computer vision systems may occasionally generate incorrect alt-text descriptions, inaccurate interface labels, or misleading accessibility recommendations. In some cases, automated accessibility corrections may satisfy technical compliance checks while still failing to provide meaningful usability improvements for real users. Such inconsistencies create concerns regarding the practical dependability of AI-assisted accessibility systems.

The lack of diverse and disability-inclusive datasets also remains a critical issue. Many machine learning models are trained using limited accessibility data that may not adequately represent users with varying sensory, motor, cognitive, or linguistic needs. As a result, accessibility systems may generalize poorly across different user populations and interaction contexts. This problem becomes more significant in adaptive systems that rely heavily on user behavior modeling and personalization techniques.

Real-time adaptive accessibility introduces additional complexity. Dynamic interface modifications may confuse users if changes occur without sufficient transparency or user control. Excessive automation can negatively affect usability, particularly for individuals who rely on consistent navigation patterns and predictable interaction behavior. Therefore, balancing intelligent adaptation with interface stability remains an important design challenge from a human-computer interaction perspective.

Computational overhead and deployment limitations also affect practical implementation. Advanced AI models such as deep learning systems and large language models often require substantial computational resources, making real-time processing difficult on low-power devices, mobile platforms, and browser-based environments. Furthermore, many AI accessibility tools still struggle to integrate seamlessly across web, mobile, desktop, and immersive platforms such as AR and VR systems.

Privacy and ethical concerns present another significant challenge. Accessibility personalization frequently depends on behavioral analytics, interaction tracking, speech data, or biometric information, all of which involve sensitive user data.

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Without proper privacy safeguards, transparent consent mechanisms, and responsible AI practices, such systems may introduce security risks and reduce user trust.

Finally, the absence of standardized evaluation frameworks and benchmarking datasets limits the ability to compare accessibility systems objectively. Current evaluation approaches often rely on small-scale user studies, automated WCAG audits, or isolated experimental environments. More comprehensive and participatory evaluation methodologies involving people with disabilities are required to ensure that future accessibility technologies remain reliable, inclusive, and practically effective.

VIII. FUTURE SCOPE

The future of AI-driven accessibility systems lies in the development of intelligent, adaptive, and user-centered interfaces capable of supporting diverse accessibility needs in real time. Although recent advances in machine learning, computer vision, and large language models have improved accessibility automation, current systems still provide limited personalization and incomplete accessibility coverage across different disability groups.

One important research direction involves the development of multimodal accessibility frameworks that combine vision, speech, language processing, gesture recognition, and behavioral analysis within a unified adaptive system. Such frameworks could provide more flexible interaction support for users with multiple or changing accessibility requirements. Similarly, real-time adaptive interfaces capable of learning continuously from user interaction remain an emerging area with significant potential.

Future systems should also focus more strongly on cognitive and neurodiverse accessibility, which remains comparatively underexplored in current research. AI-driven text simplification, attention-aware interfaces, adaptive reading environments, and personalized interaction models may significantly improve digital accessibility for users with cognitive disabilities, dyslexia, autism spectrum disorders, and age-related impairments.

Another critical research direction involves explainable and trustworthy AI for accessibility. Users should be able to understand why interface adaptations occur and maintain control over accessibility preferences. Transparent AI decisionmaking and privacy-preserving personalization mechanisms will therefore become increasingly important as accessibility systems collect larger volumes of behavioral and interaction data.

In addition, the research community would benefit from standardized datasets, accessibility benchmarks, and evaluation frameworks specifically designed for AI-based accessibility systems. Current evaluation practices remain fragmented and often rely on small-scale testing environments. More collaborative and participatory research involving people with disabilities throughout the design and evaluation lifecycle is necessary to ensure that future accessibility technologies remain inclusive, reliable, and ethically responsible.

IX. CONCLUSION

This review examined the growing role of artificial intelligence in improving digital accessibility through adaptive user interfaces, intelligent middleware systems, and automated accessibility support mechanisms. The study analyzed recent developments in machine learning, natural language processing, computer vision, and personalization techniques that aim to enhance accessibility for users with diverse disabilities across modern digital environments.

The review highlights that AI technologies have significantly improved capabilities such as automated accessibility evaluation, alt-text generation, interface adaptation, and accessibility remediation. At the same time, the findings indicate that current accessibility solutions still face important limitations related to reliability, personalization, privacy, cognitive accessibility, and standardized evaluation practices. Although standards such as WCAG and WAI-ARIA continue to provide the foundation for accessible design, AI-driven systems are increasingly being explored as complementary tools for dynamic and context-aware accessibility support.

The study also emphasizes that accessibility should not be treated solely as a technical compliance problem. Effective accessibility systems require human-centered design, participatory development practices, transparent AI behavior, and continuous usability evaluation involving people with disabilities. Future accessibility research must therefore focus on creating intelligent systems that balance automation, usability, ethical responsibility, and user control.

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Overall, AI-driven accessibility middleware represents a promising direction for building more inclusive digital experiences. With continued interdisciplinary research and responsible implementation practices, AI technologies have the potential to make future user interfaces more adaptive, accessible, and equitable for all users.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my guide, **Mr Naveen Sharma**, for providing valuable guidance, encouragement, and continuous support throughout the preparation of this review paper. Their suggestions and technical knowledge greatly helped in improving the quality of this work. I am also thankful to the faculty members of **School of Computational Sciences, GNA University, Phagwara**, for their support and motivation during the completion of this paper. Furthermore, I would like to acknowledge the researchers, authors, and publishers whose research papers and publications provided important insights related to "Intelligent Accessibility Middleware Using AI for Dynamic Inclusive User Interfaces" . Their contributions helped in understanding the current advancements and challenges in this field. Finally, I express my gratitude to my family and friends for their constant encouragement and support throughout this work.

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