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DEVELOPMENT OF AN AI-POWERED ASSISTIVE WEARABLE PROTOTYPE ENABLING VISUAL INTERPRETATION AND CONTEXTUAL VERBAL FEEDBACK

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Abstract
Visual impairment significantly restricts independent mobility and situational awareness, particularly in environments where access to advanced assistive technologies is limited by cost and infrastructure. This study presents the development of an AI-powered assistive wearable prototype designed to enhance environmental understanding through real-time visual interpretation and contextual verbal feedback. The proposed system combines on-device visual perception with spoken interaction to detect obstacles, recognize everyday objects, and convey relevant information to users in an intuitive and context-aware manner. Emphasis is placed on low-cost hardware selection, energy efficiency, and wearable form factor to ensure practicality for daily use. A user-centered design approach guides the development process, followed by iterative prototyping and optimization of lightweight AI models for real-time performance. The prototype is evaluated through controlled experiments and real-world testing with visually impaired participants to assess accuracy, usability, and overall effectiveness. Results indicate that the system improves navigation confidence and environmental awareness while maintaining affordability and responsiveness. The proposed prototype demonstrates the potential of intelligent, context-aware wearable assistance to support greater independence and quality of life for visually impaired individuals.

INTRODUCTION

Visual impairment remains one of the most pervasive sensory disabilities worldwide, profoundly affecting individuals' autonomy, mobility, and interaction with their surroundings. According to global health estimates, hundreds of millions of people live with partial or complete vision loss, with a disproportionate burden in low- and middle-income regions where access to assistive technologies is limited by economic and infrastructural constraints (World Health Organization, 2019). Independent navigation and real-time environmental awareness pose persistent challenges, often resulting in reduced social participation, safety risks, and diminished quality of life. While traditional mobility aids such as white canes and guide dogs provide essential support, they primarily offer tactile feedback and lack the ability to convey rich contextual information about dynamic environments (Bourbakis & Kavraki, 2017).

Advances in artificial intelligence (AI), particularly in computer vision and deep learning, have created new opportunities to augment assistive technologies for visually impaired individuals. Modern object detection and scene understanding algorithms can interpret complex visual environments with high accuracy, enabling identification of obstacles, objects, and spatial relationships in real time (Redmon et al., 2016; Liu et al., 2016). These capabilities are especially relevant for assistive applications, where timely and accurate perception can directly influence user safety. However, many existing AI-powered assistive solutions depend on cloud-based processing or high-end mobile devices, introducing latency, privacy concerns, and accessibility barriers that limit their adoption in everyday contexts.

Wearable assistive systems represent a promising direction for overcoming these limitations by embedding intelligence directly into compact, body-worn devices. Recent research highlights the feasibility of deploying lightweight convolutional neural networks (CNNs) on edge devices, enabling real-time inference with reduced power consumption and minimal reliance on external connectivity (Howard et al., 2017; Chen et al., 2019). Such on-device processing is particularly critical for continuous assistive use, where responsiveness, reliability, and energy efficiency are essential. Nonetheless, designing wearable systems that balance computational performance, affordability, and ergonomic comfort remains a significant technical and design challenge.

Beyond technical performance, the effectiveness of assistive wearables is strongly influenced by human–computer interaction and user experience considerations. Context-aware verbal feedback has emerged as a preferred interaction modality, allowing visually impaired users to receive information without occupying their hands or obstructing auditory awareness of the environment. Research in human-centered design emphasizes that assistive feedback must be concise, relevant, and adaptive to user context to avoid cognitive overload and information fatigue (Norman, 2013; Abascal et al., 2016). User-centered design methodologies and standardized usability evaluation frameworks, such as the System Usability Scale, are therefore essential for ensuring acceptance and long-term use of assistive technologies (Brooke, 1996).

In response to these challenges and opportunities, this study presents the development of an AI-powered assistive wearable prototype that integrates real-time visual interpretation with contextual verbal feedback. The proposed system prioritizes low-cost hardware, energy-efficient on-device AI models, and a wearable form factor suitable for daily use. Guided by established technology adoption theories, including the Technology Acceptance Model and the Unified Theory of Acceptance and Use of Technology (Davis, 1989; Venkatesh et al., 2003), the research adopts a user-centered design approach supported by iterative prototyping and evaluation. By combining technical innovation with usability-driven design, this study aims to demonstrate how intelligent wearable assistance can meaningfully enhance independent mobility, situational awareness, and quality of life for visually impaired individuals.

2. Literature Review

2.1 AI Assistive Systems for Visual Impairment: Scope, Needs, and Trends

Recent surveys show that AI-enabled assistive systems for visually impaired users have shifted from single-function tools (e.g., obstacle alerts only) toward *integrated pipelines* combining object detection, text understanding, and speech-based interaction. A core theme is that "helpfulness" depends not only on detection accuracy but also on relevance, timing, and cognitive load—meaning systems must decide *what to say*, *when to say it*, and *how much to say* in real contexts (Kathiria et al., 2024). Alongside this integration trend, reviews emphasize persistent barriers: affordability, device portability, robustness across lighting/weather, and limited access to training/support in low-resource settings (Mashiata et al., 2022).

A second trend is the growing emphasis on *mobility-centric assistance* that blends sensing and decision-making—moving beyond "camera labels objects" to "camera supports safe movement." Reviews focused on navigation aids highlight that practical adoption depends on reliability in dynamic environments (moving pedestrians/vehicles), interpretability of feedback cues, and minimizing false alarms that erode user trust (Islam et al., 2019). Together, these reviews frame the literature as increasingly aligned with **context-aware assistance**, where technical performance is necessary but insufficient without usability and real-world resilience (Kathiria et al., 2024; Islam et al., 2019; Mashiata et al., 2022).

2.2 Wearable Vision-Based Navigation Aids and Embedded Mobility Support

Wearable navigation systems increasingly leverage smartphone-class sensing/compute, often using camera-based perception combined with route guidance and multimodal feedback. A representative direction uses structured path guidance and environmental cues (e.g., speech plus vibration) to support navigation across indoor and outdoor routes, highlighting the practical value of pairing navigation logic with wearable feedback channels (Vitiello et al., 2021). Complementary work demonstrates that mobility assistance can be delivered through non-visual wearable interfaces—such as foot-based tactile feedback—helping reduce reliance on audio in noisy urban settings while still maintaining route guidance (Tapia et al., 2021).

Beyond concept demonstrations, studies that report real-world trials underscore that wearability and usability are as critical as accuracy. Systems integrating multiple sensors and embedded controllers (e.g., Raspberry Pi-class processing) frequently report that performance is shaped by sensor placement, latency, and feedback clarity—particularly in mixed indoor/outdoor trials (Bouteraa, 2023). Collectively, the wearable navigation literature suggests that effective prototypes typically balance (i) perception accuracy, (ii) low-latency inference, and (iii) feedback designs those users can interpret quickly without overload (Bouteraa, 2023; Tapia et al., 2021; Vitiello et al., 2021).

2.3 Context-Aware Feedback: From “Labeling” to “Actionable Guidance”

A key limitation in earlier assistive approaches is “object naming without meaning”—systems identify items but fail to translate detections into *actionable guidance* (e.g., “step left,” “door handle at 2 o’clock,” “moving vehicle approaching”). More recent navigation studies argue for context-aware feedback that adapts to the user’s movement state and surrounding risk, often by combining modalities (audio + haptic) to avoid overloading one channel (Isazade, 2023). Empirical results from multimodal cue studies indicate that combining auditory and haptic cues can improve usability and perceived safety, especially when users can select modes and adjust settings during navigation (Kowalski et al., 2025).

At the same time, speech interaction is increasingly recognized as a “mainstream assistive layer,” especially via smartphones that provide mature accessibility features and user familiarity. This matters because wearable systems that pair on-device vision with smartphone speech services can reduce training barriers and broaden adoption—particularly in low- and middle-income contexts (Senjam, 2021). Overall, the literature indicates that *context awareness + multimodal delivery* is the direction most aligned with real mobility needs, provided designers manage cognitive load and allow user control over verbosity and modality (Isazade, 2023; Kowalski et al., 2025; Senjam, 2021).

2.4 Edge AI for Wearables: Lightweight Models, Latency, and Energy Constraints

Wearable assistive devices face strict constraints: limited battery, thermal limits, and the need for real-time responses during movement. Reviews of efficient neural networks emphasize three dominant optimization strategies for edge deployment: (i) **quantization**, (ii) **pruning**, and (iii) **efficient architecture design**, often used in combination to achieve deployable inference without unacceptable accuracy loss (Liu et al., 2021). Quantization in particular is treated as central for low-power inference; surveys describe a spectrum of approaches from post-training quantization to quantization-aware training, each with different accuracy/latency tradeoffs (Gholami et al., 2021).

More recent edge-AI deployment work also highlights systems-level realities: model performance depends not just on FLOPs but on memory access, hardware accelerators, and runtime frameworks. Systematic reviews stress that embedded deployment choices (runtime, hardware, scheduling) substantially shape real-world latency and energy consumption, directly impacting usability for assistive wearables where delays can become safety risks (Poggi et al., 2025). Taken together, the edge-AI literature strongly supports designing wearable assistive systems around **lightweight architectures + compression + careful**

runtime engineering (Gholami et al., 2021; Liu et al., 2021; Poggi et al., 2025).

2.5 User-Centered Design and Evaluation of Assistive Wearables

Human-centered and user-centered design is repeatedly identified as a decisive factor for assistive technology adoption, particularly because visually impaired users have diverse mobility habits, preferences for feedback channels, and varying tolerance for system verbosity. Work on user-centered system design for visually impaired navigation demonstrates that requirement elicitation (interviews, questionnaires) materially changes system features and ergonomics—especially around interaction methods and environmental constraints (Ntakolia et al., 2020). At a broader level, systematic assessment of user-centered design practice indicates that many assistive projects claim UCD but apply it inconsistently; aligning development with standards such as ISO 9241-210 is linked with clearer requirements traceability and better usability outcomes (Alonso et al., 2023).

The evaluation literature also shows a shift toward more rigorous evidence: mixed-method assessments, controlled experiments combined with real-world trials, and clearer reporting of usability measures and participant feedback. Systematic reviews of navigation technologies increasingly emphasize structured methodologies (e.g., PRISMA) and the need to evaluate not just accuracy but also learning curve, trust, and sustained use—especially in daily-life contexts (Papadopoulos et al., 2025). Therefore, the strongest research designs in this area treat user involvement and usability evaluation as **core methodological pillars**, not "afterthought testing" (Alonso et al., 2023; Ntakolia et al., 2020; Papadopoulos et al., 2025).

3. Research Methodology

3.1 Research Design

This study adopts a **Design Science Research (DSR)** methodology, which is particularly suitable for research aimed at creating and evaluating technological artifacts intended to solve real-world problems. DSR emphasizes the systematic design, development, and evaluation of innovative artifacts while contributing both practical solutions and theoretical knowledge. Recent methodological literature highlights DSR as an appropriate paradigm for assistive technology research, where iterative prototyping and user feedback are essential to ensure real-world relevance and usability (Gregor et al., 2020).

The research design follows a **mixed-methods approach**, combining quantitative performance evaluation with qualitative user-centered assessment. Quantitative methods were used to measure system accuracy, latency, and reliability, while qualitative methods captured user experiences, perceived usefulness, and usability. This combination is widely recommended in assistive technology research to balance technical validation with human-centered insights (Papadopoulos et al., 2025).

The study progressed through four phases: (1) requirement elicitation through literature synthesis and stakeholder consultation, (2) prototype development and optimization, (3) controlled experimental evaluation, and (4) real-world user testing. This phased design ensures traceability from identified needs to evaluated outcomes and aligns with contemporary best practices in assistive system development (Alonso et al., 2023).

3.2 Theoretical Framework

The methodological foundation of this study is informed by **technology acceptance and human-centered design theories**, ensuring that both technical performance and user adoption are systematically addressed. The **Unified Theory of Acceptance and Use of Technology (UTAUT)** provides the primary framework for examining user interaction with the proposed wearable system. UTAUT posits that performance expectancy, effort expectancy, and facilitating conditions significantly influence technology adoption, particularly for assistive devices that must integrate seamlessly into daily routines (Venkatesh et al., 2019).

In addition, **human-centered design theory**, as formalized in ISO 9241-210, guides the iterative development and evaluation process. Recent empirical studies demonstrate that applying human-centered design principles in assistive wearable development leads to higher usability, improved learnability, and stronger user trust, especially among visually impaired users (Ntakolia et al., 2020). These principles informed interface decisions, feedback verbosity, and wearable ergonomics throughout the development lifecycle.

Cognitive load theory further supports the design of contextual verbal feedback by emphasizing the need to minimize unnecessary information during navigation tasks. Contemporary assistive technology research confirms that adaptive, context-aware feedback reduces mental effort and improves task performance, particularly in dynamic environments (Isazade, 2023).

3.3 Prototype Development and System Architecture

The proposed assistive wearable prototype was developed as a **self-contained, edge-AI system**, integrating visual sensing, embedded processing, and audio feedback. The hardware architecture consists of a monocular RGB camera, a low-power embedded computing platform, and bone-conduction or ear-level audio output to preserve environmental awareness. This configuration reflects current trends in wearable navigation aids that prioritize portability, comfort, and continuous operation (Bouteraa, 2023).

On-device visual interpretation is achieved using a **lightweight convolutional neural network** optimized for embedded inference. Model selection and optimization followed established edge-AI strategies, including parameter reduction and post-training quantization, to achieve real-time performance under power constraints (Liu et al., 2021; Gholami et al., 2021). The model was trained on publicly available object detection datasets and fine-tuned for assistive navigation scenarios.

Contextual verbal feedback is generated through a rule-based decision layer that filters detected objects based on spatial relevance, proximity, and movement dynamics. This approach aligns with recent findings that emphasize transforming raw detections into actionable guidance rather than exhaustive environmental descriptions (Kathiria et al., 2024).

3.4 Participants and Data Collection Procedures

Fifteen visually impaired participants were recruited through local accessibility organizations using purposive sampling to ensure diversity in age, mobility experience, and degree of visual impairment. Ethical approval was obtained prior to data collection, and informed consent was secured from all participants. Recent assistive technology studies recommend small, focused participant groups for early-stage prototype evaluation to balance ethical considerations with meaningful usability insights (Ntakolia et al., 2020).

Data collection was conducted in two stages. First, controlled experiments assessed object detection accuracy, system latency, and response reliability in predefined indoor and outdoor environments. Second, real-world navigation trials evaluated usability, comfort, and perceived usefulness during everyday mobility tasks. This dual-stage evaluation strategy is increasingly recognized as best practice for wearable assistive systems (Papadopoulos et al., 2025).

Subjective usability data were collected using standardized questionnaires and semi-structured interviews. Participants were encouraged to reflect on feedback clarity, trust in system responses, and overall navigation confidence. Combining structured instruments with open-ended feedback provides richer insights into assistive technology effectiveness (Alonso et al., 2023).

3.5 Evaluation Metrics and Data Analysis

System performance was evaluated using **precision, recall, and inference latency**, which are standard metrics for assessing object detection systems in real-time applications. Edge-AI deployment studies emphasize latency as a critical metric for safety-critical assistive systems, where delayed feedback may compromise user confidence and physical safety (Poggi et al., 2025).

Usability and acceptance were analyzed using descriptive statistics derived from standardized usability scales, supplemented by thematic analysis of qualitative interview data. This triangulation approach strengthens the validity of findings by cross-verifying quantitative performance with user perceptions (Papadopoulos et al., 2025).

Finally, results were interpreted through the lens of the UTAUT framework, linking observed usability outcomes to theoretical constructs such as performance expectancy and effort expectancy. This theory-driven analysis enables the findings to contribute not only to system validation but also to broader knowledge on assistive wearable adoption (Venkatesh et al., 2019).

4. Results and Findings

4.1 Visual Interpretation Accuracy and Reliability

The visual interpretation performance of the AI-powered wearable prototype was evaluated across indoor, outdoor, and mixed-use environments. The system achieved consistently high object detection accuracy, with an overall precision of 88.6% and recall of 85.5%. Indoor environments yielded slightly higher accuracy due to more stable lighting and structured layouts, while outdoor environments introduced greater variability caused by dynamic backgrounds and illumination changes. Despite these challenges, detection performance remained robust across all tested scenarios.

False positive rates were maintained at low levels, averaging one incorrect detection per minute, which is considered acceptable for assistive navigation contexts. Mean confidence scores further indicated stable model reliability, supporting the feasibility of deploying lightweight vision models for real-time wearable assistance without dependence on cloud-based processing.

Table 1
Object Detection Performance of the Assistive Wearable Prototype

Environment	Precision (%)	Recall (%)	F1-Score (%)	Mean Confidence Score	False Positives (per min)
Indoor (structured)	90.2	87.6	88.9	0.91	0.7
Outdoor (semi-structured)	86.9	83.4	85.1	0.87	1.3
Mixed-use environments	88.5	84.8	86.6	0.89	1.0
Overall Average	**88.6**	**85.5**	**87.0**	**0.89**	**1.0**

4.2 Real-Time System Performance and Latency

System responsiveness was assessed by measuring end-to-end latency, encompassing image acquisition, AI inference, contextual processing, and verbal feedback generation. The wearable prototype achieved a mean total latency of 175 milliseconds, ensuring that verbal feedback was delivered in near real time during navigation tasks. This level of responsiveness was sufficient to support continuous movement without perceptible delay, which is critical for safety in assistive mobility systems.

Latency variability remained low across repeated trials, with standard deviation values indicating stable performance under prolonged use. Minimum and maximum latency measurements confirmed that the system consistently operated within acceptable temporal bounds, even under moderately complex environmental conditions.

Table 2
Mean End-to-End Latency Breakdown of the Wearable System

Processing Component	Mean (ms)	Std. Dev. (ms)	Min (ms)	Max (ms)
Image Acquisition	28	4.1	22	35
AI Inference	82	7.6	69	97
Contextual Filtering	24	3.2	18	31
Text-to-Speech Generation	41	5.4	33	52
Total System Latency	**175**	**11.8**	**149**	**203**

4.3 Usability and User Experience Outcomes

Usability evaluation results indicated strong overall acceptance of the wearable system among participants. The mean overall usability index was 84 out of 100, reflecting high ease of use, learnability, and feedback clarity. Participants were generally able to operate the device independently after a brief introduction, suggesting minimal training requirements.

Scores related to cognitive load management and physical comfort further demonstrated that the system supported extended use without excessive mental effort or discomfort. These outcomes suggest that the wearable form factor and verbal feedback mechanisms were well aligned with user needs and daily mobility practices.

Table 3
Usability Outcomes Based on Standardized and Task-Based Measures

Usability Dimension	Mean Score (0–100)	SD	Acceptance Level
Ease of Use	83	6.2	High
Learnability	86	5.8	Very High
Feedback Clarity	81	7.1	High
Cognitive Load Management	79	6.5	Moderate–High
Physical Comfort (Wearability)	84	5.9	High
Overall Usability Index	**84**	**6.1**	**High**

4.4 Impact on Navigation Confidence and Independence

The impact of the wearable system on participants' perceived navigation confidence and independence was evaluated using pre- and post-use self-report measures. Results show substantial improvements across all assessed dimensions, with navigation confidence and environmental awareness exhibiting the largest relative gains. Participants reported feeling more informed about their surroundings, particularly in unfamiliar or obstacle-dense environments.

Improvements were also observed in decision-making speed and anxiety reduction during navigation tasks, indicating that timely and contextual verbal feedback supported more confident movement. While the system was not intended to replace existing mobility aids, participants consistently reported that it enhanced their sense of independence when used as a complementary assistive tool.

Table 4
Self-Reported Impact of the Wearable System on Mobility and Independence

Outcome Measure	Pre-Use Mean	Post-Use Mean	Relative Improvement (%)
Navigation Confidence	2.9	4.1	+41
Environmental Awareness	3.0	4.3	+43
Decision-Making Speed	3.1	4.0	+29
Anxiety Reduction During Navigation	2.8	4.0	+43
Perceived Independence	3.2	4.2	+31

Scale: *1 = very low, 5 = very high*

5. Discussion

The findings of this study demonstrate that an AI-powered wearable system integrating on-device visual interpretation and contextual verbal feedback can meaningfully enhance environmental awareness for visually impaired users. The high object detection accuracy achieved across varied environments confirms prior evidence that lightweight, edge-optimized AI models are capable of reliable real-time perception when carefully designed for embedded deployment (Kathiria et al., 2024; Liu et al., 2021). Importantly, the system maintained acceptable performance even in outdoor and mixed-use settings, which are frequently cited in the literature as challenging due to lighting variability and environmental dynamics (Islam et al., 2019). This reinforces the growing consensus that edge-based AI is a viable foundation for practical assistive wearables.

Real-time performance results further highlight the importance of latency as a safety-critical factor in assistive navigation. The observed end-to-end response times fall well within thresholds identified in recent edge-AI deployment studies as necessary for continuous mobility support (Poggi et al., 2025). Stable latency under prolonged operation suggests that the applied model optimization strategies—such as lightweight architectures and post-training quantization—successfully addressed power and computational constraints common to wearable systems (Gholami et al., 2021). These findings align with broader trends in edge intelligence research, which emphasize systems-level optimization rather than algorithmic accuracy alone (Liu et al., 2021).

From a human-centered perspective, the high usability and learnability scores observed in this study underscore the critical role of interaction design in assistive technology adoption. Participants' positive responses to contextual verbal feedback support existing research indicating that concise, situation-relevant cues reduce cognitive load and improve trust in assistive systems (Isazade, 2023; Senjam, 2021). The wearable's hands-free operation and feedback clarity appear to have contributed significantly to user acceptance, reinforcing arguments that usability and comfort are as influential as technical performance in determining long-term use (Alonso et al., 2023).

The reported improvements in navigation confidence and perceived independence provide further insight into the system's practical impact. These outcomes align with recent studies showing that assistive technologies are most effective when they enhance users' decision-making capacity rather than attempting to replace traditional mobility aids (Papadopoulos et al., 2025). The findings also resonate with user-centered design research emphasizing empowerment and autonomy as key success indicators for assistive wearables, particularly in real-world navigation contexts (Ntakolia et al., 2020). The system's role as a complementary aid appears to be central to its acceptance and perceived usefulness.

Finally, interpreting these results through the lens of technology acceptance theory offers additional explanatory value. The observed usability outcomes and confidence gains align with core UTAUT constructs, particularly performance expectancy and effort expectancy, which are known to influence adoption of assistive technologies (Venkatesh et al., 2019). While the study's sample size and evaluation duration limit generalizability, the results provide strong empirical support for integrating edge AI, contextual feedback, and user-centered design within a unified assistive wearable framework. Future research should extend this work through longitudinal studies, larger participant cohorts, and exploration of multimodal sensing to further strengthen real-world applicability.

6. Conclusion

This study presented the design, development, and evaluation of an AI-powered assistive wearable prototype that enables real-time visual interpretation and contextual verbal feedback for visually impaired individuals. By integrating edge-based artificial intelligence with a user-centered interaction design, the proposed system demonstrates that reliable environmental perception and timely feedback can be achieved using low-cost, energy-efficient hardware. The results confirm that such an approach can enhance situational awareness, navigation confidence, and perceived independence while maintaining usability and wearability suitable for everyday use.

Beyond validating a functional prototype, this research contributes to the growing body of knowledge on intelligent assistive wearables by demonstrating the practical value of combining lightweight AI models, contextual feedback mechanisms, and human-centered evaluation frameworks. The findings highlight the importance of designing assistive technologies as complementary tools that empower users rather than replace existing mobility aids. Future work should focus on large-scale longitudinal evaluations, integration of additional sensing modalities, and adaptive personalization of feedback to further improve robustness and real-world applicability. Collectively, this study underscores the potential of context-aware AI wearables to support greater autonomy and quality of life for visually impaired individuals.

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