

Design of a Low-Cost Home Automation System with Auditory and Haptic Feedback to Support the Autonomy of People with Visual Impairment: A Pilot Study in La Maná, Ecuador

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ABSTRACT:

Visual impairment affects an estimated 2.2 billion people worldwide, and access to assistive technology remains disproportionately limited in low- and middle-income regions. This study reports the design and pilot usability evaluation of a low-cost home automation prototype (under US\$300) built with voice-controlled lighting and appliances, door-status sensing, ultrasonic obstacle detection, haptic and auditory feedback, and an emergency alert function, developed for households in the canton of La Maná, Cotopaxi, Ecuador. Fifteen participants with visual impairment (8 total blindness, 5 low vision, 2 partial blindness) completed a single-session, pre-post pilot combining the System Usability Scale (SUS), a five-task performance checklist, and semi-structured interviews. Overall task success was 88.0% (66/75 instances), with the door-status and emergency-alert tasks completed without error by all participants. The change in SUS score between the initial expectation and post-use ratings was not statistically significant (Wilcoxon $W = 28.0$, $p = 0.121$); however, prior technology familiarity strongly predicted post-use usability (Spearman's $\rho = 0.860$, $p < .0001$). Findings suggest the prototype is technically viable and safety-relevant tasks perform reliably, but perceived usability depends heavily on users' prior exposure to assistive or voice-based technology, and voice-command syntax flexibility needs improvement to accommodate regional vocabulary.

Keywords: home automation, visual impairment, assistive technology, Internet of Things, usability evaluation.

1. Introduction

Vision loss is not a rare condition. At least 2.2 billion people worldwide live with some degree of near or distance vision impairment, and roughly half of those cases were preventable or remain unaddressed (World Health Organization, 2026). Ecuador is no exception to this pattern. As

of 2023, 480,776 people are represented on the country's National Disability Registry, and visual impairment accounted for 12% of that population, around 55,000 people nationally (National Council for Disability Equality, 2023; Ministry of Public Health of Ecuador, 2023). Utilization of assistive technologies for inclusion outside large urban areas in the country remains

uneven and under-documented (García Rivas, 2024). And extrapolating to the canton of La Maná, Cotopaxi (population 53,793, 2022 census; National Institute of Statistics and Censuses, 2022), you get an estimated 165 to 170 residents with visual impairment, a population large enough to matter, and small so that hardly any of the assistive technology built for it comes from anywhere in the vicinity. That gap is the starting point for this paper.

Most of the literature in smart-home solutions for blind and low-vision users comes from well-resourced settings. Farooq et al. (2022), to put it differently, developed an IoT-enabled walking stick equipped with ultrasonic obstacle detection, water sensing, and GPS tracking, a truly powerful device but one constructed from components and infrastructure that all need to meet a minimum level of availability and technical support. Periša et al. (2025) introduced a predictive smart-home framework with AI and machine learning in predicting an individual user's needs when inside their own house. Okolo et al. (2024) reviewed more widely the exploration of navigation assistance systems and found the same story repeating in all studies: true improvements in independence, true technical sophistication, and very little validation of these outside high-income countries.

The wearable and haptic aspects of this literature tell the same tale. Khusro et al. (2022) assessed vibration-pattern feedback for obstacle avoidance in indoor environments and concluded it reduced collision rates as compared to a white cane alone, and a recent scoping review by Tang and Huang (2025) counted dozens of similar haptic navigation prototypes that have been tested since 2019, most studies done at university laboratories but not in participants' home environments. Dos Santos et al. (2025) is a partial exception: their NavWear backpack (developed and tested in Brazil) was assessed alongside, rather than as the replacement for, a white cane; participants reported feeling safer and less frustrated, a framing that was close to what we wanted to achieve here. Extensive reviews of the field (Abidi et al., 2024; Mashiata et al., 2022) eventually come to the same conclusion as the

smart-home literature above: strong technical progress and few real-world adoption examples. Home automation for visual impairment borrows from the ambient-assisted-living literature with similar pattern for more than ten years (Rashidi and Mihailidis, 2013; Cicirelli et al., 2021).

This is important: Assistive technology doesn't fail because it has no good ideas. It fails due to access issues. Tangcharoensathien et al. (2018) highlight four common gaps in low and middle-income countries: lack of awareness among the people who would benefit, product designs developed without input from the people who will genuinely be using them, fragile local supply chains, and, perhaps most critically for such a technical field, a lack of evidence on whether any of it actually works once it reaches someone's home. Álvarez Ariza and Pearce (2022), in a systematic review on open-source assistive hardware, argue a related point: Arduino- and Raspberry Pi-based platforms have already lowered the cost of building these devices, but most of that work is still tested in labs, not in the kitchens or hallways where people would use it on a regular basis.

Home automation is a natural fit for closing part of that gap for people with visual impairment specifically, because so much of what makes a home usable, knowing a light is on, confirming a door is locked, sensing that something is in the way, is visual information other people take for granted. Voice-controlled lighting, door sensors that speak instead of blink, and haptic obstacle alerts do not require a person to see; they route the same information through hearing and touch instead. Mocrii et al. (2018) describe the general architecture that makes this feasible now in ways it was not a decade ago: cheap microcontrollers, low-power wireless protocols, and cloud or edge platforms that do not need a data center to run. That same connectivity is not free of risk: Vardakis et al. (2024) catalogue how voice-controlled hubs, locks, and remote dashboards create attack surfaces that a home like the ones in this study, without dedicated IT support, is poorly placed to defend, a tradeoff we return to in the Discussion. What is missing is not the technology. It is a version of it built, priced, and

tested for a rural Ecuadorian household rather than a research lab in Zagreb or a smart-home showroom.

This study addresses that gap directly. We designed and built a low-cost home automation prototype, voice-controlled lighting and appliances, door-status sensing, obstacle detection, and an emergency alert function, using components that together cost under \$300, aimed specifically at households in La Maná. We then ran a pilot usability evaluation with people from the local blind and low-vision community to find out two things: whether the system actually works the way it is supposed to when a real person with visual impairment uses it, and whether using it changes how autonomous they feel managing their own home. The goal is not to out-engineer the systems already published elsewhere. It is to show that a version of this technology can exist for communities the existing literature has mostly skipped over, and to leave behind a design and evaluation protocol that other researchers in similar settings across Latin America could adapt.

2. Methodology

• Design

This is a mixed-methods, single-group, pre-post pilot study. We are borrowing the design used in comparable assistive-device papers (Farooq et al., 2022; Periša et al., 2025): build the prototype first, then test it with real users and measure whether their usability ratings and task performance change between an initial walkthrough and hands-on use. A control-group design would be methodologically cleaner, but it is not realistic here, the population of visually impaired residents in La Maná is small enough (an estimated 165 to 170 people) that splitting it into treatment and control arms would leave both groups too small to say anything with confidence.

• Participants

Fifteen subjects were enrolled under the assumption of power based on a calculation for a Wilcoxon signed-rank test ($\alpha = 0.05$, power = 0.80, assuming a large effect size of $d \approx 0.8$), with increasing weights up to account for the possibility of attrition. We recruited participants

from two already existing organizations in the canton: Association of the Blind 18 de Mayo and Foundation of People with Disabilities Will of God by non-probabilistic convenience and snowball sampling. Eligibility criteria were diagnosed visual impairment (total blindness, partial blindness, or low vision), age 18 or older, residing in the canton and ability to provide informed consent; exclusion was considered for severe uncorrected hearing loss and individuals with cognitive impairments that would complicate consent. The last sample ($N = 15$) included 8 men and 7 women, the mean age was 49.3 years ($SD = 18.0$, between 19 and 82 years); total blindness (8), low vision (5), partial blindness (2). Seven participants had low technology familiarity, five medium technology familiarity and three high technology familiarity; 12 lived in living arrangements with family and 3 lived alone.

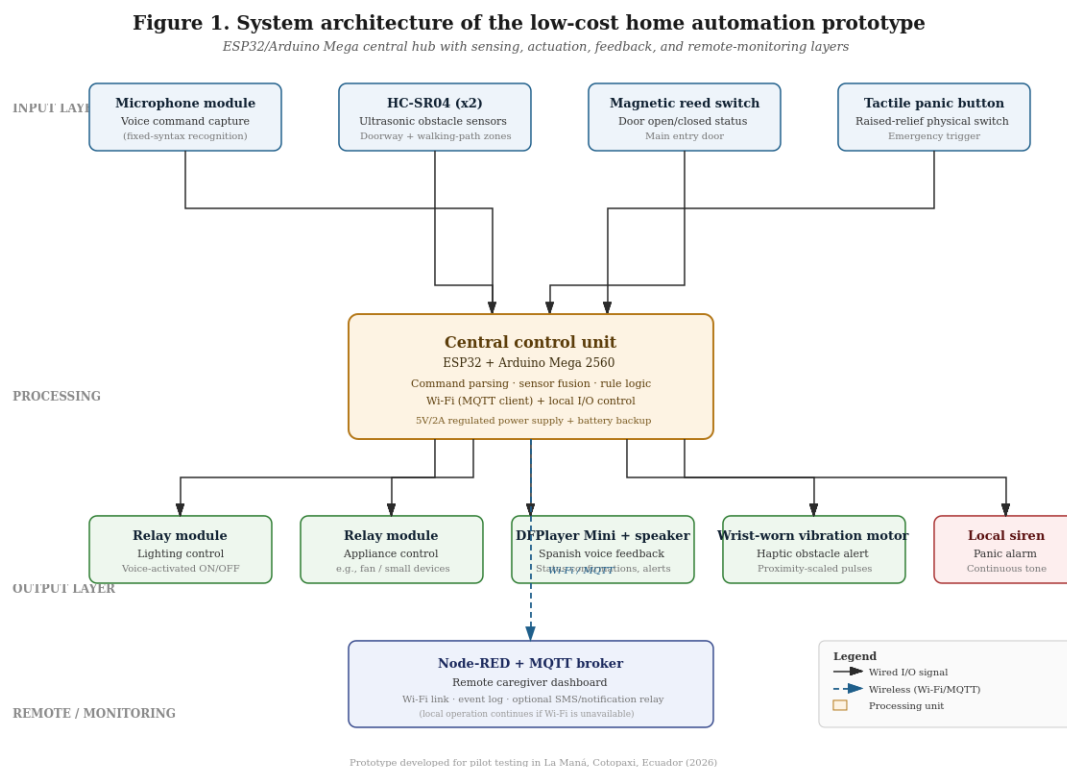
• Instruments

The prototype (Figure 1) runs on an ESP32/Arduino Mega 2560 central hub controlling relay modules for lights and small appliances, two HC-SR04 ultrasonic sensors for obstacle and doorway detection, a magnetic reed switch on the main entry door, a DFPlayer Mini module with speaker for Spanish-language voice feedback, a wrist-worn vibration motor for haptic alerts, a raised-relief tactile panic button, and a Node-RED/MQTT dashboard for optional remote caregiver monitoring; the system continues local operation if Wi-Fi is unavailable. Usability was measured with the System Usability Scale (Brooke, 1996), a 10-item, 5-point Likert instrument administered orally in Spanish before and after the hands-on session, read aloud rather than handed to the participant. SUS scores were interpreted against Bangor et al.'s (2009) adjective-rating benchmarks; a 2025 systematic review of usability studies with visually impaired users found SUS to be the single most common evaluation instrument in this population, which guided the choice here (Adnan et al., 2025). Task performance was logged on a structured checklist covering completion time, success/partial/failure status, error count, and whether the researcher had to intervene. A short semi-structured

interview closed each session, covering perceived usefulness, difficulties, sense of security and independence, daily-use confidence, suggested

changes, and concerns about cost, maintenance, and power/connectivity reliability.

Figure 1. System architecture of the low-cost home automation prototype



Note. Prototype developed and pilot-tested in La Maná, Cotopaxi, Ecuador (2026).

• Procedure

Each participant went through three phases. First, orientation: the researcher described the system and let participants handle the components before anything was “tested,” followed by the first SUS administration based on that initial impression. Second, task-based testing: five representative tasks, turning a light on and off by voice, noticing and avoiding a simulated obstacle, checking whether a door was open or closed, operating an appliance by voice, and triggering the emergency alert, performed in the participant's own home where feasible or in a controlled simulated space when it was not. Third, closing: the second SUS administration, now based on actual use, followed by the interview. Sessions ran 45 to 60 minutes. Fieldwork took place between 12 May and 4 June 2026, following a protocol reviewed by the

Comité Institucional de Ética en Investigación of Universidad Técnica de Cotopaxi. Consent was obtained through an orally read informed-consent script, documented by signature or fingerprint with an institutional witness from the collaborating association.

• Data Analysis

Task metrics were extracted descriptively (mean, SD, range) per task and aggregated across the sample. Pre- and post-intervention SUS scores were compared with the Wilcoxon signed-rank test, chosen over a paired t-test because a sample this size cannot support the normality assumption the t-test requires. Interview data was thematically analyzed, coded inductively around autonomy, trust in the system, and perceived risk. Using Spearman correlation, task performance and SUS change were compared to age and prior familiarity with technology.

3. Results

In fifteen subjects the full protocol (8 men, 7 women; mean age 49.3 years; SD = 18.0, age range 19–82) was completed. Eight met with total

blindness, five with low vision, and two with partial blindness; seven reported their technology knowledge as low, five medium, and three high. Twelve lived with relatives; three lived alone.

Table 1. SUS scores before and after hands-on use

	Mean	SD	Min	Max
SUS – expectation (pre)	72.83	18.44	32.5	100.0
SUS – real use (post)	68.33	24.90	12.5	97.5
Difference (post – pre)	–4.50	9.46	—	—

Six participants achieved higher scores after hands-on usage, one experienced no change, and eight scored lower. Wilcoxon signed-rank test

failed to yield a statistically significant difference between pre- and post use SUS scores ($W=28.0$, $p=0.121$).

Table 2. Task performance (N = 15 participants, 75 task instances)

Task	Success rate	Mean time (s)	SD	Required assistance
T1 – Voice-activated light	93.3%	13.4	7.9	6.7%
T2 – Obstacle detection	73.3%	28.5	16.5	26.7%
T3 – Door status check	100%	16.1	6.8	0%
T4 – Voice-activated appliance	73.3%	25.1	16.3	26.7%
T5 – Emergency button	100%	9.1	4.2	0%

The overall task success rate was 88.0% (66 out of 75). Single-action, non-voice T3 and T5 tasks were executed by all participants without any mistakes. T2 and T4 accounted for nearly all partial completions or requests for assistance, related to two common issues observed during fieldwork: inflexible voice-command syntax (participants using a regional term "fan" instead of the recognized "ventilator") and difficulty distinguishing the vibration alert from the auditory alert during the obstacle-detection task.

The post-usage SUS scores were associated with technology familiarity (Spearman's $\rho = 0.860$, $p < .0001$): Users who were already familiar with a smartphone screen reader or voice assistant rated the system as much more usable compared to users who hadn't used it. There was also a

negative, borderline-significant association between age and change in SUS score ($\rho = -0.476$, $p = 0.073$), indicating that older participants had a lower probability of rating the system positively upon actual use than prior. The types of SUS scores after use also depended on disability type, with participants with total blindness scoring the lowest and the most varied ($M = 59.7$, $SD = 29.5$) and those with low vision the highest ($M = 79.0$, $SD = 16.1$).

4. Discussion

The headline result here is not the one we went in expecting. Hands-on use of the prototype did not produce a statistically significant improvement in perceived usability; if anything, the average SUS score dropped slightly, and more

participants rated the system worse after using it than better. That is worth sitting with rather than explaining away. A four-point movement in either direction, in a sample of 15, is well within the range one would expect from noise alone, and the wide standard deviation on the post-use score (24.90, nearly a third larger than the pre-use SD) tells its own story: this was not a uniform experience across participants.

What actually explains the variation is more informative than the null result on its own. Technology familiarity predicted post-use usability almost perfectly ($\rho = 0.860$). That is consistent with Bangor et al. (2009), who argued that raw SUS scores only become meaningful once interpreted relative to what a given user already knows how to do. Someone who has spent years using TalkBack or VoiceOver already has a mental model for voice interaction; someone who has not is learning two things at once, a new device and a new way of interacting with devices in general. Periša et al. (2025) reported a related pattern in their smart-home framework for people with disabilities: predictive systems help more once a baseline of comfort with the technology already exists, and struggle to establish that baseline on their own. This is not unique to home automation: Cao et al. (2024) found the same familiarity effect driving older adults' acceptance of voice assistants generally, and a rapid review of voice-assistant use across the disability community found abandonment concentrated among users encountering voice interaction for the first time rather than among any particular disability type (Esquivel et al., 2024).

The task-level data indicates something more fixable: T2 and T4, the two tasks that had the lowest success rates and the highest assistance rates, both required getting the exact wording of a voice command right. That's a design flaw, not a concept flaw. "Abanico" failing where "ventilador" succeeds is the kind of problem a slightly larger synonym dictionary solves; it does not require rethinking the system, it requires building it for how people in La Maná actually talk, rather than for standardized textbook Spanish. Farooq et al. (2022) sidestepped a

version of this issue in their smart stick by keeping the interaction almost entirely non-verbal (buttons, vibration), which in hindsight may be worth borrowing more of here.

The post-use SUS scores correlated strongly with technology familiarity (Spearman's $\rho = 0.860$, $p < .0001$): participants who already used a smartphone screen reader or voice assistant rated the system far more usable than those with limited prior exposure. A negative, borderline-significant association between age and the change in SUS score was also observed ($\rho = -0.476$, $p = 0.073$), suggesting that older participants were somewhat more likely to rate the system less favorably after real use than they had expected beforehand. Post-use SUS scores also varied by disability type: participants with total blindness scored lowest and most variably ($M = 59.7$, $SD = 29.5$), while those with low vision scored highest ($M = 79.0$, $SD = 16.1$).

None of this weakens the case for the system. Overall, task success was 88% and two things that are critical for safety – whether a door was left open and whether an emergency alert was triggered – were accomplished without a single misstep or demand for assistance across all 15 participants. That is perhaps the outcome that matters most for a device built to prevent falls and ensure home security. It means only that the question of whether the system makes people feel more autonomous requires a more nuanced solution than a single-session pilot and a general usability instrument alone can provide; indeed, multiple participants independently articulated an apprehensive concern in interviews, regarding their investment in the system as contingent on factors that the SUS score misses or fails to capture, such as whether the system still works during a power outage, whether the Wi-Fi in their neighborhood is sufficiently stable, and whether local technical support can be called if anything breaks.

Limitations. Our sample is small and non-probabilistic, and is gathered using convenience and snowball sampling through only one local association, limiting the potential applicability of these findings even within La Maná. One session

of the pilot was recorded for each participant, failing to differentiate between the “this system does not work for me” and “I haven’t had enough time to learn it,” a distinction that is critical given how strongly familiarity predicted the outcome. The System Usability Scale, although also a common tool, is a general-purpose scale for an item as specific to physical safety; a scale designed specifically for trust and risk perception, rather than general usability, may have captured what several interview responses were really hinting at.

5. Conclusion

This research designed, built, and pilot-tested a home automation prototype under US\$300 in order to enable individuals with visual impairment, living in a rural Ecuadorian canton largely absent from the existing assistive-technology literature, to support their independence. The system reliably carried out the two safety-critical functions (door-status checking and emergency alerting), with perfect completion rates in all participants, while voice-command tasks associated with appliance and lighting control had more variable performance, attributed to inflexible command syntax.

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Far from the hypothesis, hands-on use did not lead to a statistical rise in perceived usability at the group level; the most significant predictor of a good perception was a participant's prior experience with assistive or voice-based technology, not the device. That finding reimagines what “success” means for low-cost assistive technology deployed in communities with mixed prior exposure to digital tools: technical reliability is essential but not enough, and onboarding or extended time of training may be as important as the hardware.

Future work should implement the pilot on a larger, multi-site sample of Cotopaxi to determine whether the technology-familiarity effect holds; implement a longer time duration of field deployment to differentiate between learning-curve consequences and the actual usability bounds; expand the voice-recognition vocabulary to take account of regional and colloquial terms; and add battery and connectivity redundancy directly informed by participants' recurring concerns about power outages and inconsistent Wi-Fi service in rural parts of the canton.

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8. Author Declaration

The authors confirm that this work is original and has not been submitted for publication elsewhere.

The authors declare no conflicts of interest.