DESIGNING A BRAILLE SELF-LEARNING SYSTEM: A USER-CENTERED DEVELOPMENT APPROACH

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ABSTRACT

This research delves into the need for a user-centered Braille self-learning system to address the difficulties visually impaired individuals encounter when accessing appropriate learning resources. The study's objective extends beyond the mere development of a learning device. It focuses on exploring and understanding unique user requirements to optimize the design and implementation of an inclusive and efficient Braille self-learning system. Initial research leveraged detailed surveys and interviews to comprehend visually impaired users' unique needs and preferences. These invaluable insights shaped the system design, underlining the importance of user-centered and inclusive design principles. The emphasis is on devising a strategy to ensure a user-centered design based on extant literature. The developed system underwent concentrated usability testing focusing on learnability, accessibility, and portability. User feedback, collected via a survey, was then analyzed. The data analysis underscored the system's robust performance concerning these dimensions while identifying them as potential areas for further enhancement. The study's primary contribution lies in implementing and analyzing a user-centered Braille self-learning system specifically tailored to visually impaired individuals' needs, highlighting the transformative potential of technology in fostering independent learning. Areas for improvement, particularly in refining learnability and compatibility with a broader range of assistive technologies, point towards substantial strides in promoting a more inclusive educational environment.

Keyword: User-centered, Braille, Self-learning, User feedback, Learnability, Accessibility, Portability, Usability testing.

I. INTRODUCTION

Visually impaired or blind (VIB) have long utilized Louis Braille's invention, the Braille system, for reading and writing (Liu et al., n.d.). Occasionally, this method is also known as a dual-set Braille pattern. Braille patterns are used to represent numbers, symbols, and alphabetical patterns. Each symbol consists of two columns of three dots. These six dots are positioned variously to represent a variety of symbols (Figure 1) (Šepić, Ghanem, and Vogel 2015), and combinations of these Braille letters create words with meaning.

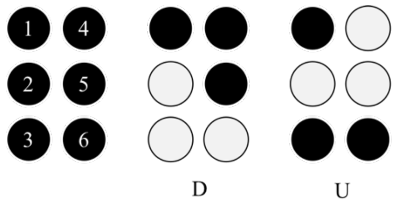

Figure1 Braille dot diagram

While numerous researchers have created Braille learning applications and assistive devices, many have not adequately prioritized user experience or feedback in their designs (Adnan et al. 2020; Amrulloh, Fauzi, and Kawuri 2019; Jawasreh, Ashaari, and Dahnil 2017). This lack of emphasis often leads to devices that fall short of meeting the Braille learning needs of the VIB, necessitating a more user-friendly approach. In response to this identified gap, we propose an approach: by adequately prioritizing user experience and feedback from the onset, we aim to develop a Braille learning system that truly meets the needs of VIB individuals. Thus, our research focuses on incorporating a user-centered approach to develop a dedicated Braille self-learning system tailored to the needs of VIB.

A. Research background

Beyond the financial impediment, the physical design of numerous conventional Braille devices often restricts their use. Many of these devices are bulky and cumbersome, hindering portability and limiting their utility beyond the confines of a home or classroom setting (Aranas 2019). The result is a circumscribed learning environment, deterring VIB from practicing Braille in diverse settings and situations. The limitations of traditional Braille devices extend to their user interaction and feedback mechanisms. These devices generally provide limited interaction options and possess inadequate feedback mechanisms. Such constraints can hinder user progress and lead to a lack of motivation to continue learning (Hoskin et al. 2022). Finally, an important facet to consider is the ability of the device to receive and incorporate user feedback. Some traditional Braille learning devices do not have effective feedback channels that allow users to conveniently relay their questions and suggestions(Tsangaris et al. 2022). This presents a significant obstacle to implementing agile development practices, which rely heavily on continuous user feedback to drive iterative improvement.

In conclusion, while traditional Braille-assisted learning systems have made laudable strides in making education and information accessible to VIB, much room remains for improvement. Addressing these constraints in future developments of Braille learning systems can result in more effective and user-friendly devices.

B. Problem statement

This research addresses two critical issues related to assistive devices for visually impaired and blind (VIB) individuals:

This research addresses critical issues related to assistive devices for VIB individuals. A significant concern that stands out is the apparent neglect of user experiences in these devices' design and evaluation process. Despite the availability of numerous innovations in Braille learning devices, few have given due consideration to the experiences of VIB individuals using these devices. Current studies often lack a comprehensive evaluation of learners' experiences with these computer-assisted teaching platforms or assistive devices. This gap in research leaves us uncertain if the existing software and hardware truly satisfy the real needs of the learners.

For example, researchers have developed assistive gloves for learning Chinese Braille (Chou et al., 2021), Braille Cubes (Tang, 2013), and other devices incorporating freehand finger tap motions and haptic rings (Gupta et al., 2016). However, these devices often fail to account for VIB individuals' practical needs and experiences. As a result, the design and functionality of these learning systems may fall short of meeting user requirements.

Therefore, the central issue that needs addressing is the development of Braille learning applications that fulfill users' needs. This calls for a comprehensive understanding of the learners' needs before designing and conducting thorough usability evaluations. It is also crucial to continually improve learning applications and auxiliary equipment based on learners' feedback (Nahar et al., 2019). This research emphasizes a more user-centered design process, intending to better address the practical needs of users in the design of Braille learning applications and assistive devices.

Furthermore, existing Braille learning devices often lack portability and versatility. Current tools and systems limit learners' ability to learn Braille in diverse contexts, such as home, school, or elsewhere. This constraint hinders learners' portability to learn and practice according to their schedules, preferences, and circumstances.

To tackle this, we propose developing flexible and versatile Braille learning systems. These systems should facilitate self-directed learning and teacher-guided instruction, per the learner's preferences and circumstances. Designed with a user-centered approach, these systems should not only make Braille education more accessible but also foster greater confidence, independence, and adaptability in VIB learners. This study underscores the urgent need for user-centered, flexible, and versatile Braille learning applications and assistive devices by addressing these issues.

C. Research questions and objectives

According to the problem statement, the main research questions of this study are summarized as follows.

1. RQ 1. What are the specific needs and preferences of the VIB concerning Braille learning devices and braille learning modes?
2. RQ 2. How to design and develop assistive devices that effectively support the learning of Braille for VIB and design a better learning mode for Braille
3. RQ 3. How can a Braille learning device be enhanced in terms of learnability, accessibility, and portability to support learning across various scenarios and environments more effectively?

The research objectives of this paper can be summarized as follows:

1. RO 1: To investigate the specific needs and preferences of VIBs (Visually Impaired Individuals) concerning Braille learning devices, focusing on three key dimensions: learnability, accessibility, and portability, through surveys.
2. RO 2: To design and develop a user-centered Braille self-learning device to address VIBs' identified needs that effectively support Braille learning, as informed by surveys and literature review.
3. RO 3: To incorporate learnability, accessibility, and portability in the design of Braille learning applications and an assistive device enabling users to learn effectively in different scenarios and environments and expanding the accessibility and applicability of Braille learning resources. Improvement of the device through usability testing and user feedback enhances the performance and user experience.

D. Research scope

The foundational step in our investigation focuses on discerning VIB individuals' specific needs and preferences regarding Braille learning devices and their learning methodologies. We utilized surveys as our principal research method to ensure a nuanced understanding of these requirements. The insights derived from these surveys will be instrumental in shaping the direction of subsequent developments to ensure alignment with the genuine needs of the VIBs.

Based on these insights, the research will be directed toward designing and developing a Braille Self-Learning System. This system will focus on user-centered device design, considering the feedback and requirements expressed by the VIB community and exceptional education professionals. The aim is to craft a comprehensive and adaptive learning instrument tailored to its user's requirements, emphasizing learnability, accessibility, and portability.

Concluding our research will be the phase centered on evaluating the Braille Self-Learning System's effectiveness and usability through user testing and feedback. This iterative feedback mechanism will aid in confirming the system's potential and performance, ensuring that it stands up to its intended purpose. The continuous refinement based on feedback further underscores our commitment to serving the evolving needs of its users, enhancing the system's overall user experience.

II. LITERATURE REVIEW

A. Technology In Learning Braille

According to different learning scenarios, we divide Braille learning devices into Braille learning tools and Braille self-learning systems.

The table1 provides descriptions and advantages of Braille learning tools.

Table 1 Summary of Current Braille Learning Tool

References	Device Description	Advantage
(Dhar et al., 2017)	An interactive keyboard driver for Bengali Braille Embosser, operated by a single AVR microcontroller.	Facilitates independent writing and reading for impaired individuals by providing audio feedback and storing written text.
(Sultana et al. 2017)	A system assisting impaired individuals with Braille input/output and display.	Enables learning, reading, writing in Braille, and English-Braille conversion in a cost-effective, portable device.
(Duarte-Barón et al. 2016b)	A mechatronic device that facilitates learning of the Braille literacy system, integrated with a tutor software.	Ergonomic, easy to use, provides clear audible feedback, portable, lightweight, facilitates autonomous learning, and encourages the use of both hands in the learning process.
(Kavitha, Privadarshini, and Saradha 2018)	A Braille Teaching System that uses wireless transmission of letters sent by a tutor with a tactile interface using solenoid actuators.	Enables efficient teaching of Braille codes, even by a tutor without prior knowledge of Braille, and provides better perception of Braille codes for students.
(Srinivasan	A wearable device for challenged	Enhances mobility for visually

2020)	individuals that guides the user's arm to a certain pose to grab a desired object, using a cable-driven exoskeleton arm and a vision-based, machine-learning object-detection model.	challenged individuals, enabling them to perform daily tasks more efficiently, such as opening doors and finding objects.

The table1 provides descriptions and advantages of Braille self-learning systems

Table2 Summary of Current Braille self-learning systems

References	Device Description	Advantage
(Jawasreh, Ashaari, and Dahnil 2017)	A user-friendly Braille Finger Puller device with two learning processes, allowing users to practice Braille language independently and measure their progress.	Enables efficient, independent learning of Braille language, with features that allow for self-testing and progress tracking.
(Wagh et al. 2016)	A Braille-based system with a keypad, microphone, Beaglebone Black processor, and Braille cell.	Optimizes cost and speed, positively impacting Braille literacy for VIB.
(Amarthiya Sai E M et al., 2021)	The Braille Keyboard and Printer are portable devices that enable VIB to read and write in Braille.	The low-cost Braille keyboard and printer work on text-to-speech technology and can be used with a PC monitor as a display.
(Alluri et al., 2020)	The design of a smart controller that enables self-learning for VIB, incorporating features such as text-to-braille conversion, visual-to-speech conversion, eye tracking, and hand sign language to speech.	The handheld portable device described offers a versatile solution for VIB, allowing them to efficiently learn various skills and access information through different modes of communication.
(M et al., 2022)	The Braille self-learning system is a hardware and software solution that incorporates a Braille keypad and microphone for input and converts Braille characters into speech output to facilitate effective learning for VIB.	The system provides VIB with a user-friendly and interactive tool to learn Braille, combining tactile input with auditory feedback, enhancing the learning experience, and promoting independent learning.

Braille learning tools and braille self-learning devices both primarily support Braille literacy among impaired individuals. However, their usability, cost, accessibility, and usability differ significantly.

Table3 Comparing Braille Learning Tools vs. Self-Learning Systems

References	Type	Usability	Cost	Accessibility	Independence
(Dhar et al., 2017)	Braille learning tools	Good (Easy to use with interactive features)	Not Mentioned	Partial (Interfaces with PC keyboard)	Moderate (Enables independent writing and reading, but requires a PC keyboard.)

(Sultana et al. 2017)	Braille learning tool	Good (Easy to use with a simple interface)	Moderate (Affordable for most users)	Extensive (Can be used by impaired individuals)	High (Allows users to learn Braille independently)
(Duarte-Barón et al. 2016b)	Braille learning tool	Good (Designed for comfort, motivation, and permanence)	Not Mentioned	Extensive (Wireless communication with a computer)	High (Promotes autonomy of impaired people)
(Kavitha, Privadarshini, and Saradha 2018)	Braille learning tool	Good (Designed for easy use by impaired individuals)	Not Mentioned	Extensive (Can be used anywhere, anytime)	Moderate (Need to study under the guidance of the teacher)
(Srinivasan 2020)	Braille learning tool	Good (Easy to use with clear instructions)	Moderate (Affordable for most users)	Extensive (Accessible to all users)	High (Designed for independent use)
(Jawasreh, Ashaari, and Dahnil 2017)	Self-learning	Excellent (Self-learning, user-friendly, works on text-to-speech technology)	Low (Designed to be a low-cost solution)	Extensive (Works with a mobile device via Bluetooth)	High (Designed for self-learning without the need for a Braille teacher)
(Wagh et al. 2016)	Self-learning	Excellent (User-friendly, independent, and portable)	Low (Optimized for cost and speed of operation)	Extensive (Designed for impaired individuals)	High (Designed to be independent and user-friendly)
(Amarthiya Sai E M et al., 2021)	Self-learning	Good (Designed to be user-friendly and self-learning)	Low (Designed to be low-cost)	Extensive (Bluetooth module for wireless data transformation)	High (Self-learning system)
(Alluri et al., 2020)	Self-learning	Excellent (Designed for various disabilities, not just visual impairment)	Not Mentioned	Extensive (Can be used anywhere, anytime)	High (Allows for independent learning)
(M et al., 2022)	Self-learning	Good (Designed with user-friendly interface)	Not Mentioned	Not Mentioned	High (Designed for independent use)

In conclusion, the table demonstrates that braille learning tools and self-learning systems offer valuable features for learning Braille. However, self-learning systems promote independence and self-guided learning, making them a more favorable option for VIB seeking to learn Braille without relying heavily on external assistance.

B. Hardware Design in Braille Learning Devices

The prominence of Braille contacts is the essential design link in Braille display devices. The driver requires a simple structure, small size, light material, simple processing technology, easy manipulation, and fast response. According to different driving methods, Braille display devices are mainly divided into five types: Piezoelectric ceramic type, memory alloy type, electromagnetic type, pneumatic type, and electric stimulation type.

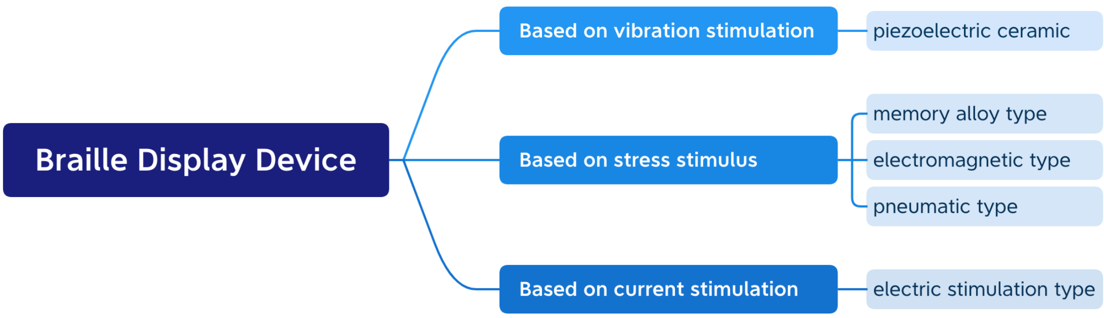

Figure2 Classification of Braille display devices

As elucidated in Table 4, a comprehensive evaluation of Braille display devices underscores the Electromagnetic type's pronounced advantages. It boasts a rapid response speed, ensuring users receive immediate and consistent tactile feedback, a cornerstone for adequate Braille comprehension. User assessments highlight its superior comfort, suggesting its adaptability for extended reading sessions without inducing user discomfort. Its enhanced interactivity points to a refined user interface, fostering a more intuitive engagement. Despite its moderate physical dimensions, the device delivers a robust tactile force, ensuring clear Braille character discernment. In juxtaposition with other devices, the Electromagnetic variant stands out, positioning itself as a leading choice that adeptly addresses the multifaceted requirements of Braille readers.

Table4 Performance Comparison of Braille Display Device

Braille display devices type	Device size	responding speed	perceived comfort	Device complexity	Tactile force	interactivity	stability	real-time	noise control
Piezoelectric ceramic	Moderate	Faster	Moderate	Complex	Moderate	Good	Moderate	Good	Moderate
Memory alloy	Small	Slower	Good	Simple	Moderate	Moderate	Good	Bad	Good
Electromagnetic	Moderate	Faster	Good	General	Strong	Better	Good	Good	Moderate
Pneumatic	Big	Slow	Good	Complex	Week	Moderate	Moderate	Bad	Moderate
Electric stimulation	Small	Fast	Poor	Simple	No Mention	Moderate	Good	Bad	Good

C. Microcontrollers in Hardware Development

In the design of Braille learning devices, the choice of microcontroller is crucial as it influences the device's functionality, efficiency, and cost. This section offers a neutral comparison of several microcontrollers commonly considered for such applications(Dahunsi et al. 2022; Nooruddin and Valles 2023):

Table5 Comparative Analysis of Microcontrollers

Microcontroller	Performance	Power Consumption	Cost	Size
ESP32	High	Low	Low	Small
ESP8266	Moderate	Low	Low	Small
Arduino Uno	Moderate	Moderate	Low	Medium
Arduino Nano	Moderate	Moderate	Low	Small
Raspberry Pi Pico	High	Low	Low	Small
STM32 series	High	Low	Moderate	Varies
Nordic nRF series	High	Low	Moderate	Varies

D. Enhancing Learnability, Accessibility, and Portability in Hardware Design

Braille learning devices serve as pivotal tools for the visually impaired. To ensure these devices effectively cater to users, considerations of learnability, accessibility, and portability in hardware design become paramount.

1. Learnability: The crux of any educational tool lies in its ability to facilitate effective learning. Much research emphasizes the transformative potential of interactive learning experiences in Braille learning devices. Devices that meld audio and tactile guidance can help users of all ages learn Braille more quickly and effectively(Encinas et al. 2020). The cognitive process of learning Braille is multifaceted, and incorporating feedback mechanisms encompassing visual, tactile, and auditory channels, has been posited to enhance mental assimilation and retention(Sun and Chen 2022).
2. Accessibility: Accessibility transcends mere device usage; it encapsulates the ethos of inclusivity. The multifarious sensory needs of the visually impaired necessitate diverse information representation techniques. Ensuring compatibility with techniques like Braille or tactile lettering has been championed as a linchpin for accessibility. The learning trajectory is often punctuated with errors, and devices

architected with a focus on error minimization and facile rectification mechanisms have been lauded for their potential to enhance user experience and confidence(Santander Vinokurova et al. 2021). Devices with intuitive controls and interfaces can significantly truncate the learning curve, fostering rapid acclimatization(Debevc et al. 2020).

3. Portability: In an era of mobility, the portability of Braille learning devices emerges as a non-negotiable—the spatial footprint of devices, especially in comparison to contemporary gadgets like smartphones or tablets. Compact designs have been extolled for their potential to enhance portability and user comfort(Debevc et al. 2020. Beyond mere size, devices' weight and ergonomic design play a pivotal role in their portability. The infusion of wireless technologies, such as Bluetooth, into device design, has been heralded for its potential to foster uninterrupted interfacing with auxiliary digital ecosystems(Wang et al. 2022).

III. METHODOLOGY

A. PRELIMINARY FIELD STUDY

The survey was titled "Survey on Designing Braille Learning Devices." The main objective was to understand better VIBs' experiences, needs, and preferences when using Braille learning devices. The survey was administered at a particular education school in Quanzhou City, Fujian Province, China. The school currently has 199 VIB students (118 boys and 81 girls), which formed the survey population.

Figure3 Investigation process

Drawing from the survey feedback, we pinpointed the primary requirements of the VIB community for a Braille learning tool. Our response was the design of the User-Centered Braille Self-Learning System. At its core, this system emphasizes Accessibility, Learnability, and Portability. Integrated modules ensure tactile and auditory feedback, while the system's voice recognition provides an intuitive user experience. Its network connectivity keeps the device up-to-date, and the data monitoring function offers real-time tracking of learners' progress. The design prioritizes ease of use and affordability, aiming to democratize Braille learning for a broader audience. With three distinct operational modes - Basic Learning, Exercise, and Self-Learning - we have meticulously crafted this system to cater to diverse user needs.

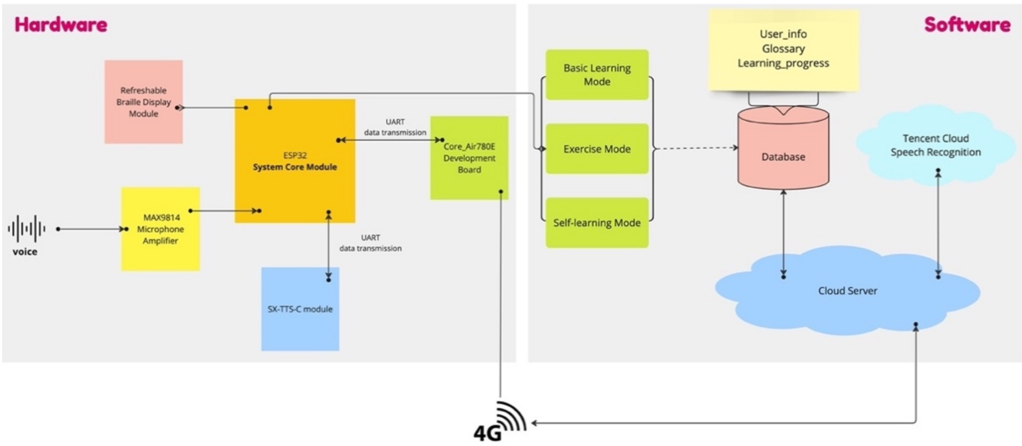

Figure4 Overall System Design Concept Diagram

B. HARDWARE DEVELOPMENT

The devised system operates primarily on the ESP32 microcontroller, which serves as its core unit. ESP32 orchestrates the interaction with all other modules, managing the system's overall operations.

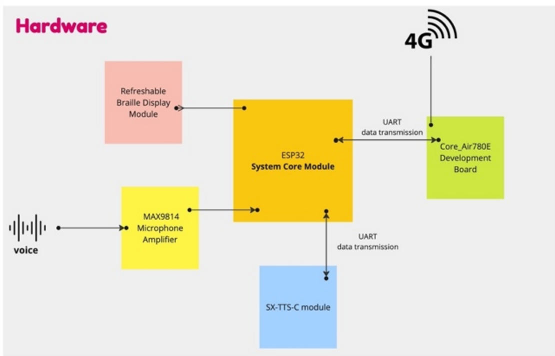

Figure5 Overall System Design Concept Diagram (Hardware)

A key module connected to the ESP32 is the Core_Air780E Development Board, which allows access to 4G internet connectivity. This feature facilitates data exchange between the local hardware and cloud-based services.

Additionally, the ESP32 is connected to the SX-TTS-C Module, a critical component for generating audible feedback. Its primary function is to produce voice outputs for commands transmitted by the ESP32, thus establishing an aural user interface.

The MAX9814 Microphone Amplifier module is another integral part of the system, interfacing directly with the ESP32. It captures and encodes ambient sounds, forwarding this encoded audio data to the ESP32 for additional processing. Consequently, this capability enables the system to interact with its environment via audio.

Finally, the Refreshable Braille Display Module is a notable component linked to the ESP32. Contrary to off-the-shelf Braille display modules, which can be prohibitively expensive, this module was designed and built from scratch. The ESP32 controls the module's operation, manipulating its pin voltage levels and governing the movement of the six electromagnets on the Braille Display Module. This design enables precise control over the rise and fall of the Braille dots, presenting a tactile interface for VIBs to interact with digital information.

C. SOFTWARE DEVELOPMENT

The device primarily uses voice recognition for user inputs, designed to be simple and effective. A button press triggers the voice command initiation process. Users begin providing voice inputs after the sound of the first beep and cease their inputs either at the sound of the second beep or when the button is released.

The designed procedure aims to minimize the technological complexity for users, making the device user-friendly and accessible. In the upcoming sections, the three distinct modes of operation, namely 'Learning Mode', 'Search Mode', and 'Story Mode', are elaborated. These modes are carefully structured to accommodate various learning styles and to provide an adaptable learning environment.

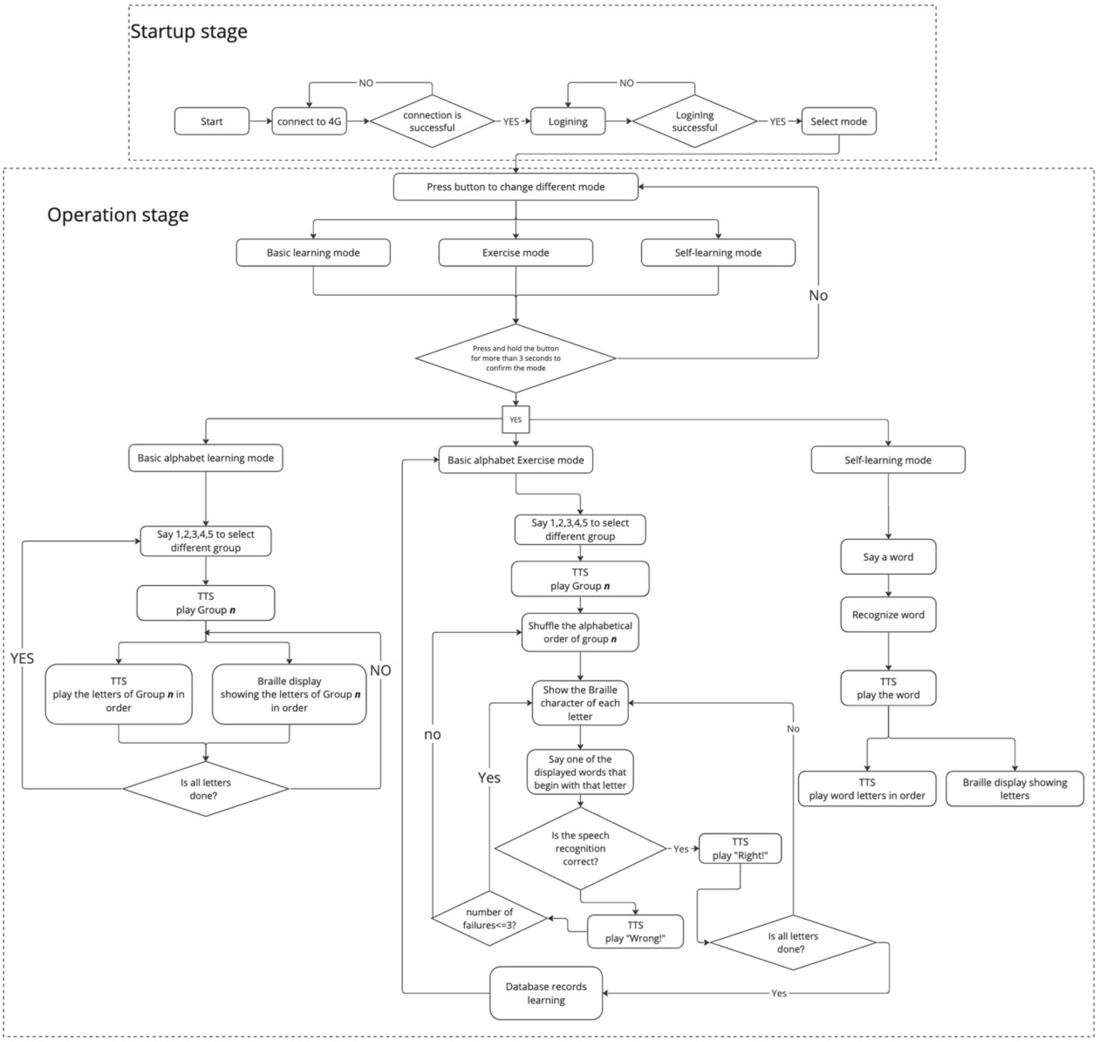

Figure6 Overall System Design Concept Diagram (Software)

D. USABILITY TESTING

To guarantee the usability and effectiveness of the Braille learning system, we conducted comprehensive usability testing in collaboration with Quanzhou Special Education School, the same school we partnered with for our preliminary study.

Throughout the development of the Braille learning device, three significant hardware iterations were undertaken to address evolving usability requirements.

Table 6 Iterative Hardware Developments and Improvements

Iteration	Features Introduced	Feedback/Issues	Improvements/Enhancements
1st	Basic Braille learning modes	Issues in navigation	Enhanced user interface navigation
	Early version of speech recognition	Speech recognition accuracy	Improved speech recognition algorithms
	Preliminary Braille display module	Display responsiveness	Improved tactile feedback on Braille display
2nd	Exercise scenarios	Complexities in learning scenarios	Simplified learning content
	Integrated user feedback system	Non-intuitive feedback mechanisms	More intuitive feedback system
	Enhanced speech recognition with noise filtering	Inaccurate recognition of English letters using 8k_en	Switched to 8k_zh for higher accuracy in recognizing English letters
3rd	Self-learning system	Difficulty understanding the self-learning system feedback	Introduced clearer voice prompts for the self-learning system
	Refined tactile feedback on the Braille display	Delays in Braille display during prolonged use	Hardware optimizations to counteract display delays
	-	Ergonomic considerations	Redesign for enhanced ergonomics and portability

IV. RESULTS AND DISCUSSION

The results obtained from the usability testing serve as a valuable diagnostic tool for assessing the Braille learning system's current performance and laying the foundation for its further improvement. The system exhibits numerous strengths while revealing certain areas that demand more attention in subsequent development phases.

While the learnability of the system was rated reasonably positively, it is noteworthy that it scored marginally lower than other dimensions. Although this suggests that the system is generally understandable and easy to grasp, it also hints at possible complexities encountered by some users. To address this, we recommended that future improvements focus on creating a more intuitive user interface and a comprehensive guided tutorial. It could significantly enhance the learning curve, making the system more accessible to a broader audience, irrespective of their tech-savviness.

The accessibility dimension, though well-received, exhibited some variability, highlighting a potential for further improvements. Ensuring that the learning platform is universally accessible, especially to those with varying levels of visual ability, is paramount and could mean expanding compatibility with more assistive technologies and introducing design elements that cater more holistically to a broader spectrum of visual abilities.

The high scores in effectiveness, efficiency, user satisfaction, portability, and system reliability signify the system's commendable performance and reinforce the system's potential as a powerful learning tool, adaptable to diverse learning needs while ensuring reliability. While these strengths should be maintained in future updates, addressing the identified areas that need improvement is equally important.

The reliability analysis, as indicated by a high Cronbach's alpha, confirms the internal consistency of the survey instrument. This assurance of reliability strengthens the findings of the analysis. Similarly, the validity analysis reveals significant factor loadings and communalities, attesting to the strong relationship between the observed variables and the underlying factors, thereby crediting the survey's findings.

In conclusion, the findings from the usability testing offer a largely positive evaluation of the Braille learning system, with noted areas for enhancement. The system's efficacy, efficiency, user satisfaction, portability, and reliability are commendable, while improvements in learnability and accessibility could further enhance the user experience. Future system iterations should, therefore, incorporate user feedback and leverage these findings to drive user-centered improvements, ultimately optimizing the platform's potential to meet the varied needs of its users.

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